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Low-pressure Metamorphism in the Ryoke Metamorphic Belt in the Yanai District, Southwest Japan

By

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with 4 figures

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Abstract: The Ryoke metamorphic belt is one of the typical low-pressure type metamorphic belts in the world. It is composed of granitoids (Older and Younger Ryoke granitoids) and associated metamorphic complex (Ryoke metamorphic rocks) of Cretaceous age. The Ryoke metamorphic rocks in the Yanai district, southwest Japan, show three different phases of ductile deformation. During the first phase (D1), a distinct foliation parallel to lithologic layering was formed under the thermal peak conditions of the low-pressure facies series metamorphism. The second phase deformation (D2) led to the formation of mylonitic shear zones and nappes. Deformation of the third phase (D3) was responsible for the formation of the upright folds with E-W trending axes. The movement picture of D1 during and immediately before the intrusion of the Older Ryoke granitoids was of extension tectonics. After D1, the nappes and upright folds of the metamorphic rocks and granitoids were formed during D2 and D3 probably under compressional stress field. The regional Ryoke metamorphism has been divided into two phases, M0 and M1. The metamorphism of M0 was of nearly medium-pressure facies series (*ca.* 30°C / km) and that of M1 was of low-pressure facies series (*ca.* 40 ~ 50°C / km). On the basis of the mineral assemblages crystallized under M1, the Ryoke metamorphic rocks are divided into four metamorphic zones: biotite zone, cordierite zone (460 ~ 590°C, 2.5 ~ 3.5 kbar), sillimanite zone (630 ~ 690°C, 3 ~ 5 kbar), and garnet zone (730 ~ 770°C, 5.5 ~ 6.5 kbar). Because the intrusion of the Older Ryoke granitoids has a strong time and spatial association with M1, it is suggested that the heat sources of M1 are the emplacement of the Older Ryoke granitoids. By using 1-D numerical simulation, the thermal model for M1 was developed by heat conduction with fluid advection caused by intrusion of a granodiorite sheet at intermediate crustal levels. The results of the thermal model nearly consist with the petrologically estimated highest metamorphic temperatures during M1. Garnet crystals from the sillimanite zone are chemically zoned and show several kinds of zoning patterns. The observed overall zoning patterns in the garnets with different radii are well reproduced by the numerical analysis. These results suggest that the temperature-time path gives a good explanation for M1. Therefore, it can be said that the sheet-like Older Ryoke granitoids intruded at intermediate crustal levels (≈ 15-km-depth) are a heat source of M1. In conclusion, the Ryoke metamorphic rocks firstly were heated under medium-pressure facies conditions, and then they were further heated under low-pressure facies conditions caused by the intrusion of the Older Ryoke granitoids.

Contents

I. INTRODUCTION

Evolution of the continental crust is a central question of the earth science. In general, active continental margins are composed of granitoids and associated low-pressure type metamorphic complex (e.g. Miyashiro, 1961, 1994). The granitoids and low-pressure type metamorphic rocks commonly form low-pressure type metamorphic belt (LPM). To clarify the evolution of the continental crust, it is necessary that the formation processes of LPM are considered especially with reference to two aspects such as emplacement mechanism of the granitic magma and thermal evolution of the metamorphic rocks.

The Ryoke metamorphic belt of southwest Japan (Fig. 1) is mainly composed of a large volume of Cretaceous granitoids (Ryoke granitoids) and associated low-pressure type metamorphic rocks (Ryoke metamorphic rocks), and then has been regarded as a typical example of low-pressure type metamorphic belt. The low-pressure Ryoke metamorphic belt is adjacent to the high-pressure Sambagawa metamorphic belt, separated by the Median Tectonic Line (MTL), in southwest Japan and both are of Jurassic-Cretaceous age. The Ryoke granitoids have been divided into sill-like granitoids (Older Ryoke granitoids) and stock-like ones (Younger Ryoke granitoids) on the basis of their intrusion forms (e.g. Hara, 1962; Hara *et al.*, 1980, 1991; Okudaira *et al.*, 1993). Many geological observation, as described in the following paragraphs, indicates that the low-pressure facies series Ryoke metamorphism has a strong spatial and time association with emplacement of the Older Ryoke granitoids.

(1) Distribution of the Older granitoids correlates with that of the high-grade metamorphic rocks (e.g. Suwa, 1973; Okudaira *et al.*, 1993).

(2) Throughout the higher grade metamorphic zones, distinct contact aureoles caused by the intrusion of the Older granitoids are lacking (e.g. Koide, 1958; Nishimura *et al.*, 1985; Nureki *et al.*, 1992).

(3) Isograds of the low-pressure type metamorphism are roughly parallel to the boundaries of the Older granitoids (e.g. Ishioka, 1974; Kutsukake, 1977; Okudaira *et al.*, 1993).

(4) Geological and petrological structures of the high-grade metamorphic rocks are compatible with those of the Older granitoids (e.g. Koide, 1958; Okamura, 1960; Nureki, 1960; Hara, 1962; Hara *et al.*, 1991; Okudaira *et al.*, 1993).

(5) Radiometric ages of the metamorphic rocks are roughly compatible with those of the Older granitoids (e.g. Shigeno and Yamaguchi, 1976; Higashimoto *et al.*, 1983; Banno and Nakajima, 1992; Nakajima *et al.*, 1993; Nakajima, 1994; Suzuki *et al.*, 1994).

From these observations, Ishioka (1974), Kutsukake (1977), Okudaira *et al.* (1993, 1994), and Miyashiro (1994) suggested that the Older Ryoke granitoids are syn-metamorphic intrusions and the low-pressure facies series Ryoke metamorphism was resulted form thermal effects of the emplacement of the Older granitoids. In order to clarify this suggestion, the author investigated (1) the tectonic histories for emplacement of the Older granitoids and the low-pressure facies series metamorphism of the Ryoke metamorphic belt, (2) possible thermal model using simple 1-D numerical simulation for the low-pressure facies series metamorphism, and (3) an evaluation of validity of the model examined by numerical analysis based on chemical zoning in garnet.

In this paper, the tectonic histories of the Ryoke metamorphic belt in the Yanai district are summarized. The thermal modeling and its examination have been discussed in Okudaira (1996a, b).

II. OUTLINE OF GEOLOGY

The Yanai district (Fig. 1) mainly consists of the Older Ryoke granitoids (Gamano granodiorite and Tengatake-Nagano migmatite), Younger Ryoke granitoids (Kibe and Namera granites), and their associated Ryoke metamorphic rocks of Cretaceous age (e.g. Nureki, 1960; Okamura, 1960; Kojima and Okamura, 1968; Higashimoto *et al.*, 1983; Nishimura *et al.*, 1985; Hara *et al.*, 1991; Ikeda, 1991, 1993; Nureki *et al.*, 1992; Okudaira *et al.*, 1993, 1995a; Nakajima, 1994). Iwakuni granite (Higashimoto *et al.*, 1983), which is one of the Hiroshima granitoids, occurs in the northern part of the district. The Gamano granodiorite most widely occurs in the district, and is mainly composed of hornblende-biotite tonalite and hornblende-bearing biotite tonalite~granodiorite. The Gamano granodiorite concordantly intruded in the high-grade metamorphic rocks, and its foliation defined by preferred shape orientation of plagioclase, biotite, and hornblende is harmonic in trend with that of the metamorphic rocks. Because the mineralogical and chemical features of the Gamano granodiorite are of metaluminous I-type granitoid, the granodiorite was not *in situ* generated from the middle crustal rocks but was originated from the lower crust and the upper mantle (e.g. Honma, 1974; Kagami *et al.*, 1992).

The metamorphic rocks are mainly derived from pelites, psammites, and cherts, with subordinate amounts of calcareous and basic rocks, which are considered to belong to the Jurassic accretionary complex (Kuga Group: e.g. Kojima, 1953; Higashimoto *et al.*, 1983; Takami *et al.*, 1990). They were regionally metamorphosed under low-pressure facies series metamorphic conditions (M1). Following Okudaira *et al.* (1993, 1996a), the Ryoke metamorphic rocks formed during M1 has been divided into four metamorphic zones such as biotite, cordierite, sillimanite, and garnet zones (Fig. 1). After M1, the Kibe, Namera, and Iwakuni granites distributed in the north of the studied area locally metamorphosed the surrounding rocks (M2).

III. DEFORMATION

A. LARGE-SCALE STRUCTURES

On the basis of the features of the large-scale structures, the Ryoke metamorphic belt in the district can be divided into three structural domains such as northern, central and southern domains (Okudaira *et al.* 1993) (Fig. 2). The geological structure of the northern domain is characterized by gentle upright folds with a fold axis gently plunging toward ESE (Fig. 2). The Tengatake-Nagano migmatite are placed in the northern domain, and intruded cutting across the lithologic layering and foliation in the metamorphic

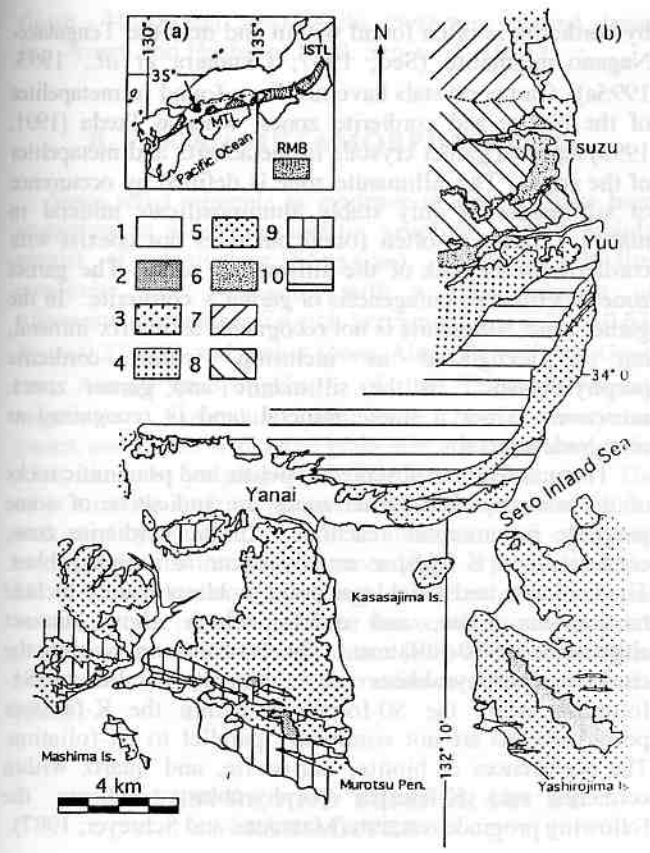

Fig. 1 (a) Outline map showing the location of the Ryoke metamorphic belt of southwest Japan. RMB: Ryoke metamorphic belt. MTL: Median Tectonic Line. ISTL: Itoigawa-Shizuoka Tectonic Line. (b) Geological and metamorphic zonation map of the Yanai district, southwest Japan. 1: alluvium. 2: Tertiary volcanics. 3: Iwakuni granite. 4: Kibe granite. 5: Gamano granodiorite. 6: Tengatake-Nagano migmatite. 7 - 10 : Ryoke metamorphic rocks (7 biotite zone, 8 cordierite zone, 9 sillimanite zone, 10 garnet zone).

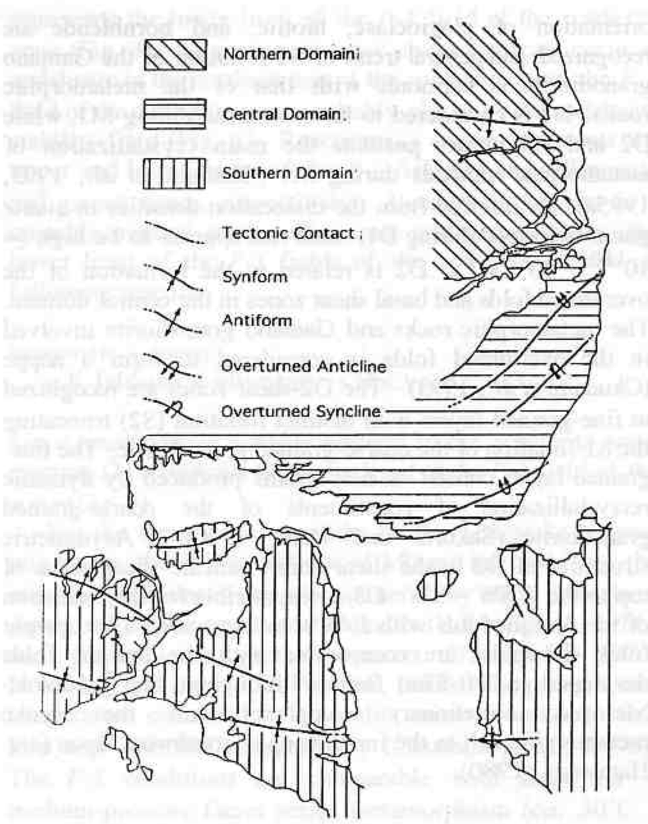

Fig. 2 Structural domains (northern, central, and southern domains) in the Yanai district. Axial traces of major folds are also illustrated.

rocks at low angles and across the lower level of lithostratigarphy toward the north. The geological structure of the southern domain is also characterized by gentle folds in upright fashion and of WNW-ESE to E-W trend (Fig. 2). The geological structure of the central domain is characterized by overturned folds which axial surfaces gently dipping toward NNE ~ NE, and therefore significantly differs from that of the northern and southern domains (Fig. 2). The Gamano granodiorite intruded in the central and southern domains (Fig. 2). The Gamano granodiorite and the metamorphic rocks of the sillimanite and garnet zones are involved in the overturned folds. When the overturned folds are unfolded to flat-lying state, the Gamano granodiorite is underlain by the metamorphic rocks of the garnet zone, while the former is overlain by the latter of the sillimanite zone (Okudaira *et al.*, 1993). It can be said that the Gamano granodiorite intruded between the garnet and sillimanite zones, as sheet-like body.

B. DEFORMATION EVENTS

In the Gamano granodiorite and metamorphic rocks, deformation structures produced during three different phases (D1, D2, and D3) of ductile deformation have been recognized (Okudaira *et al.*, 1993, 1995a). D1 and D3 are of the penetrative type, and D2 is of non-penetrative type. A distinct foliation (S1-foliation) parallel to lithologic layering is recognized in all the rocks. Many intrafolial folds (F1-folds) with axial plane parallel to S1-foliation and rotated and non-rotated boudinages are recognized. In the biotite zone, extensional crenulation cleavage (ECC) are also recognized. ECC is considered to be formed under a foliation-parallel extension with some non-coaxial components (e.g. Platt and Vissers, 1980). The composition of ECC-forming biotite coincides with that of S1-forming biotite, the ECC occurred simultaneously with S1-foliation. The S1-foliation and ECC are comparable with *Y* and *R*1 of Riedel shear fractures, respectively, and then the shear sense inferred from the geometrical relationship between the ECC and S1-foliation is top to the N ~ NNE (Okudaira *et al.*, 1995a). The Gamano granodiorite intruded into large-scale extensional fracture zones produced during D1 (Okudaira *et al.*, 1995a). In the Gamano granodiorite, S1-foliation defined by shape preferred orientation of plagioclase, biotite, and hornblende are recognized, and general trend of S1-foliation of the Gamano granodiorite is harmonic with that of the metamorphic rocks. D1 is considered to have occurred during M1, while D2 and D3 phases postdate the main crystallization of metamorphic minerals during M1 (Okudaira *et al.*, 1993, 1995a). As inferred from the dislocation densities in quartz grains deformed during D1, strain rate appears to be high ($\approx 10^{-10} \sim 10^{-7}\ s^{-1}$). D2 is related to the formation of the overturned folds and basal shear zones in the central domain. The metamorphic rocks and Gamano granodiorite involved in the overturned folds is considered to form a nappe (Okudaira *et al.*, 1993). The D2-shear zones are recognized as fine-grained layers with distinct foliation (S2) truncating the S1-foliation of the coarse-grained granodiorite. The fine-grained layers consist of new grains produced by dynamic recrystallization of constituents of the coarse-grained granodiorite (Sakurai and Hara, 1990). Asymmetric structures of D2 in the shear zones indicate shear sense of top to the WSW ~ SW. D3 is responsible for the formation of the upright folds with E-W trending axes. The upright folds (F3-folds) are comparable with the upright folds developed in left-hand fashion throughout the Paleozoic-Mesozoic accretionary complexes and the Ryoke metamorphic belt in the Inner Zone of southwest Japan (e.g. Hara *et al.*, 1980).

IV. METAMORPHISM

A. LOW-PRESSURE FACIES SERIES METAMORPHISM (M1)

Regional metamorphic zonation of the Ryoke metamorphic rocks in the Yanai district has been proposed by many authors (Nureki, 1960; Higashimoto *et al.*, 1983; Nishimura *et al.*, 1985; Ikeda, 1991, 1993; Nureki *et al.*, 1992; Okudaira *et al.*, 1993; Nakajima, 1994). However, the proposed metamorphic zonation slightly differs from each other. In Okudaira *et al.*, (1993, 1995a) and this study, on the basis of mineral parageneses of the matrix-forming minerals in pelitic and psammitic rocks, that is, except for cherts and metasomatized rocks, the Ryoke metamorphic rocks are divided into four metamorphic zones such as biotite, cordierite, sillimanite, and garnet zones. The distribution of those zones are shown in Fig. 1. The biotite and cordierite zones, the sillimanite zone, and the garnet zone are equivalent to the northern, southern, and central structural domains, respectively (see Figs. 1 and 2). The critical mineral parageneses, which are occurred as matrix-forming minerals, are as follows:

biotite zone: biotite + muscovite,
cordierite zone: biotite + muscovite + K-feldspar + cordierite ± andalusite,
sillimanite zone: biotite + K-feldspar + sillimanite + garnet or cordierite,
garnet zone: biotite + K-feldspar + cordierite ± garnet.

The first appearance of K-feldspar and cordierite defines the start of the cordierite zone. Andalusite occurs in northern part of the cordierite zone, but sillimanite always mantled by cordierite is often found within and near the Tengatake-Nagano migmatite (Seo, 1987; Okudaira *et al.*, 1993, 1995a). Garnet crystals have not been found in metapelites of the biotite and cordierite zones, whereas Ikeda (1991, 1993) reported garnet crystals in metacherts and metapelites of the zones. The sillimanite zone is defined by occurrence of sillimanite as only stable aluminosilicate mineral in matrix. Garnet is often found but does not coexist with cordierite in the rock of the sillimanite zone. The garnet zone is defined by paragenesis of garnet + cordierite. In the garnet zone, sillimanite is not recognized as matrix mineral, but is recognized as inclusion within cordierite porphyroblasts. In the sillimanite and garnet zones, muscovite is not a stable mineral, and is recognized as retrograde mineral.

Textural features observed in pelitic and psammitic rocks of the cordierite and garnet zones are indicative of some prograde metamorphic reactions. In the cordierite zone, cordierite and K-feldspar usually occur as porphyroblast. The cordierite and K-feldspar porphyroblasts mainly include biotite, muscovite, and quartz, which show distinct alignment, as S0-foliation. The S0-foliations within the cordierite porphyroblasts are commonly parallel to S1-foliation, while the S0-foliations within the K-feldspar porphyroblasts are not commonly parallel to S1-foliation. The occurrences of biotite, muscovite, and quartz within cordierite and K-feldspar porphyroblasts indicate the following prograde reaction (Massonne and Schreyer, 1987):

$$\text{biotite} + \text{muscovite} + \text{quartz} = \text{cordierite} + \text{K-feldspar} + H_2O. \quad (1)$$

The prograde *P-T* path of the cordierite zone probably intersects reaction (1).

In the garnet zone, cordierite and garnet occur as porphyroblast. The cordierite porphyroblasts mainly include biotite, quartz, and sillimanite with small amount of hercynite [Fe / (Fe + Mg + Zn): X_{Fe} = 0.70-0.83] and garnet ($Alm_{76}Pyp_{11}Sps_{11}Grs_2$), showing faint alignment, as S0-foliation which is parallel to S1-foliation. The garnet porphyroblasts contain quartz, graphite, ilmenite, biotite, and sillimanite, which show no distinct alignment and do not seems to have subjected to any rotation. These texture is interpreted to have been produced by a high temperature-low pressure static reaction near pluton (Amato *et al.*, 1994). The occurrences of biotite, sillimanite, and quartz within the cordierite porphyroblasts indicate the following prograde reactions (Holdaway and Lee, 1977):

$$\text{biotite} + \text{sillimanite} + \text{quartz} = \text{cordierite} + \text{K-feldspar} + \text{garnet} + H_2O. \quad (2)$$

The prograde *P-T* path of the garnet zone probably intersects univariant reaction (2). Hercynite included within cordierite porphyroblasts indicates high-Zn component of (Zn / (Fe + Mg + Zn): X_{Zn} = 0.05-0.18. 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 (Loomis, 1972; Atkin, 1978; Stoddard, 1979). Although staurolite has not been found in the Yanai district, staurolite as inclusion within biotite and andalusite porphyroblasts has been reported in the Mikawa Plateau

(Hazu - Hongu-san area), Aichi Prefecture, central Japan (e.g. Asami and Hoshino, 1980; Seo *et al.*, 1981).

B. PRE-M1 METAMORPHISM (M0)

Some relict minerals as evidence of pre-M1 have been recognized in a few metapelitic xenoliths, which mainly consist of plagioclase (An_{24-38}), K-feldspar, biotite, muscovite, and cordierite, with a small amount of sillimanite, corundum, Zn-rich hercynite (X_{Fe} = 0.39-0.63, X_{Zn} = 0.27-0.5), and garnet (core: $Alm_{69}Pyp_{15}Sps_{14}Grs_2$; rim: $Alm_{66}Pyp_9Sps_{22}Grs_3$), of the Tengatake-Nagano migmatite. Corundum, sillimanite, Zn-rich hercynite, garnet, and biotite with large grain size are considered to be relict minerals, judging from their textural features. The other minerals such as plagioclase, K-feldspar, and biotite with small grain size, as well as muscovite and cordierite, correspond with the mineral assemblage crystallized under M1 of the cordierite zone, though quartz is lacking. It can be said that the relict minerals in the xenoliths probably are products of pre-M1 metamorphism (M0) and the xenoliths were re-equilibrated under M1 conditions (Okudaira *et al.*, 1993).

C. PRESSURE AND TEMPERATURE ESTIMATES

Matrix-forming minerals crystallized in metapelites under M1 are analyzed to estimate the *P-T* conditions for the thermal peak of M1. Garnet-biotite (Thompson, 1976; Holdaway and Lee, 1977; Perchuk, 1977) and two feldspar (Stormer, 1975; Stormer and Whitney, 1977; Haselton *et al.*, 1983) geothermometers are used for temperature estimate, and garnet-cordierite (Aranovich and Podlesskii, 1983) and garnet-aluminosilicate-quartz-plagioclase (GASP: Powell and Holland, 1988) geobarometers are used for pressure estimation. In high-grade metamorphic zones, it is one of difficult works to clarify paragenetic relations between metamorphic minerals in a rocks. The garnets with small grain radius (< *ca.* 0.4 mm) of the sillimanite zone and almost of garnets of the garnet zones show chemical zoning which consists of unzoned core and reverse zoned rim (Okudaira *et al.*, 1993; Okudaira, 1996a). The composition of unzoned core probably crystallized near the peak metamorphic conditions, while the that of reverse zoned rim was re-equilibrated during retrograde metamorphism (Okudaira, 1996a). While biotite, cordierite, and plagioclase show no compositional zoning within them. However, biotite shows the variation in Ti content from grain to grain within one thin section (Ikeda, 1991). Ikeda (1991) has suggested that biotite with low-Ti content was synchronously associated with the formation of reverse zoning in garnet during retrograde metamorphism. Therefore, the peak *P-T* conditions in the sillimanite and garnet zones may be estimated by using the compositions of the unzoned core of garnet and those of biotite, which is not in contact with the garnet and have high Ti contents, cordierite, and plagioclase. As inferred from the mineral paragenesis of the cordierite zone, reaction (1) curve represents the lower limit of the *P-T* field of the cordierite zone (Fig. 3). Moreover, because aluminosilicate occur as andalusite in the northern part of the cordierite zone, the *P-T* field of the cordierite zone probably places in the andalusite stability field (Fig. 3). Reaction (2) curves represents the upper and lower limits of the *P-T* fields of the sillimanite and garnet zones, respectively. Because muscovite is a unstable mineral in the sillimanite and garnet zones, the lower limit of the *P-T* fields of the zones is defined as following reaction:

muscovite + quartz
= K-feldspar + sillimanite + H_2O. (3)

Since muscovite is a stable mineral in the cordierite zone, reaction (3) represents the upper limit of the *P-T* field of the zone (Fig. 3).

For the metapelitic xenoliths in the Tengatake-Nagano migmatite, the *P-T* conditions of M0 are inferred from the core compositions of the relict minerals by using corundum-garnet-sillimanite-spinel geobarometer (Bohlen *et al.*, 1986) and garnet-biotite geothermometers (Thompson, 1976; Holdaway and Lee, 1977; Perchuk, 1977). The pressure and temperature estimated by the relict minerals are *ca.* 6±1 kbar and 700±50°C, respectively (Okudaira *et al.*, 1993). The *P-T* conditions are comparable with those for a medium-pressure facies series metamorphism (*ca.* 30°C / km: cf. Miyashiro, 1961, 1994; Spear, 1993). In contrast, the retrograde temperature estimation for the relict garnet rim and matrix-forming biotite have been calculated to be 530 ~ 560°C by using the garnet-biotite geothermometers (Thompson, 1976; Holdaway and Lee, 1977; Perchuk, 1977) (Okudaira *et al.*, 1993). As mentioned above, the other minerals such as plagioclase, K-feldspar, biotite with a small size, muscovite, and cordierite correspond with the mineral assemblage of the cordierite zone during M1, and their estimated temperatures are comparable with the peak temperatures of the cordierite zone (460 ~ 590°C). Therefore, it is clear that M0 for the xenoliths predates M1. Since the rim of the relict garnet at least was re-equilibrated with the matrix-forming minerals at M1, the pair of the relict garnet rim and the matrix-forming cordierite can estimate the pressure of the cordierite zone at M1. The estimated pressure is estimated to be ca. 2.5 ~ 3.5 kbar by using garnet-cordierite geobarometer (Aranovich and Podlesskii, 1983) (Okudaira *et al.*, 1993).

In summary, the metamorphic *P-T* conditions of the cordierite zone, sillimanite zone, and garnet zone are 460 ~ 590°C at 2.5 ~ 3.5 kbar, 630 ~ 690°C at 3 ~ 5 kbar, and 730 ~ 770°C at 5.5 ~ 6.5 kbar, respectively. The *P-T* fields of the cordierite, sillimanite, and garnet zones are also illustrated in Fig. 3. This figure illustrates that the estimated metamorphic temperature continuously increases from the cordierite zone, through the sillimanite zone, to garnet zone. The metamorphic field gradient is *ca.* 40 ~ 50°C km^{-1}, which is comparable with that for the typical low-pressure facies series metamorphism (cf. Miyashiro, 1961, 1994; Spear, 1993).

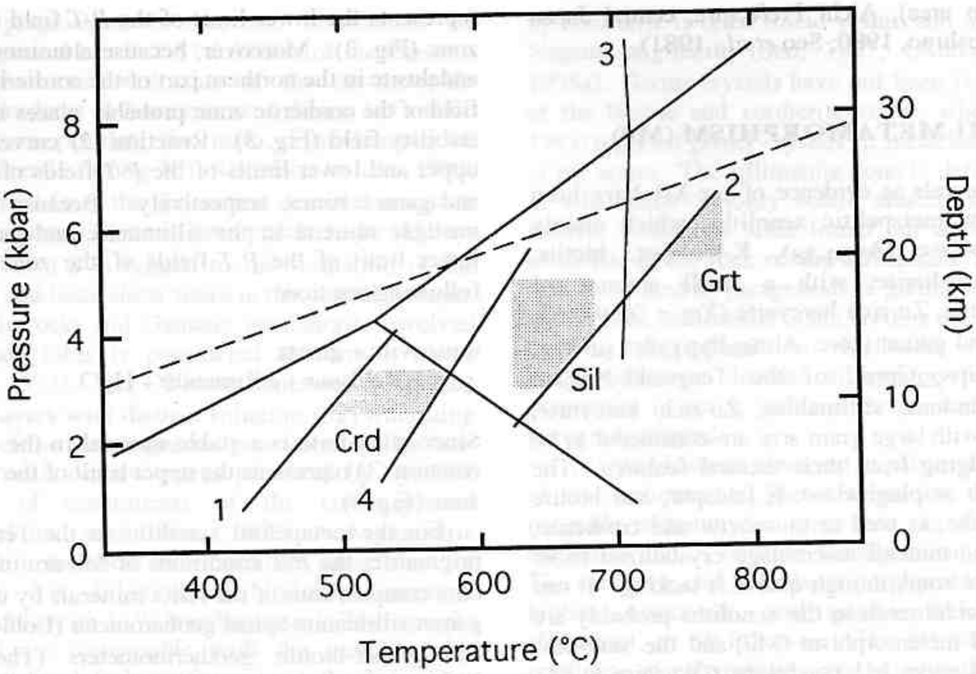

Fig. 3 *P-T* fields of the cordierite zone (Crd), sillimanite zone (Sil), and garnet zone (Grt). Reaction curves for aluminosilicate polymorphs after Salje (1986), 1) Ms + Bt + Qtz = Crd + Kfs + H_2O after Massonne & Schreyer (1987), 2) Bt + Sil + Qtz = Crd + Kfs + Grt + H_2O after Holdaway & Lee (1977), 3) St = Grt + Sil + He + H_2O after Richardson (1968), and 4) Ms + Qtz = Kfs + Als + H_2O after Kerrick (1972). Abbreviations of minerals are followed by Kretz (1983). Dashed line represents geothermal gradient of 30°C km^{-1}.

V. TECTONIC HISTORIES

As mentioned in the preceding pages, the Ryoke metamorphism is mainly divided into M0 and M1. The former is nearly medium-pressure facies series metamorphism (*ca.* 30°C km^{-1}) and the latter is low-pressure facies series one (*ca.* 40 ~ 50°C km^{-1}). The geothermal gradient at M0 is comparable with that of surface heat flow of *ca.* 100 mW m^{-1}. This high heat flow is not adequate to the steady state heat flow at continental margin (cf. Turcotte and Schubert, 1982). Hara *et al.* (1991), Banno and Nakajima (1992), and Nakajima (1994) suggested that the tectonic setting responsible for the Ryoke plutono-metamorphism cannot be explained by the ordinary subduction model, and then needs an episodic thermal event. The intrusion of the Older Ryoke granitoids could have resulted in M1. Based on the geological observations, the *T-t* path for M1 calculated from simple 1-D numerical simulation was proposed by Okudaira (1996b). In Okudaira (1996a), to examine the *T-t* path, the chemical zonings of garnets were simulated for the *T-t* path using a numerical model of diffusion in combination with its growth mechanism, and they were compared with the natural ones. Because the simulated zoning profiles in different radii well fit the natural ones, it is suggested that the path is reasonable for M1. Therefore, M1 could have resulted from intrusion of the Older Ryoke granitoids at intermediate crustal levels. Consequently, it can be said that the Ryoke metamorphic rocks were firstly heated under medium-pressure facies conditions (M0), and then they were further heated under low-pressure facies conditions (M1) by intrusion of the Older Ryoke granitoids.

Geochronological constraints for the tectonic histories of the Ryoke metamorphic belt in the Yanai district are described as below. The rocks of the Kuga Group were accreted at the eastern margin of the Asian continent, until *ca.* 140 Ma (Takami *et al.*, 1990). The Gamano granodiorite show the Rb-Sr ages of 102±4 and 91±5 Ma (Shigeno and Yamaguchi, 1976), the K-Ar ages of 89.5±4.5 Ma (Higashimoto *et al.*, 1983), the U-Pb age of 101.0±1.9 Ma (Nakajima *et al.*, 1993), and the CHIME age of 95.2±3.9 Ma (Suzuki *et al.*, 1994). The Ryoke metamorphic rocks show the Rb-Sr ages of 91.9±11.3 and 95.4±7.8 Ma (Shigeno and Yamaguchi, 1976), and the CHIME ages of 98.8±3.3 and 98.4±4.2Ma (Suzuki *et al.*, 1994). There is no difference between the ages of the Gamano granodiorite and metamorphic rocks.

The Shimonoseki Subgroup, which is upper part of the Lower Cretaceous Kanmon Group, consists of volcanic rocks and non-marine sediments, and formed during Aptian (123.5 ~ 112 Ma) to Albian (112 ~ 97 Ma), and deposited in the back- or central-arc extensional sedimentary basin (e.g. Sakai *et al.*, 1992; Itaya *et al.*, 1993; Nakada and Takeda, 1995). High-Mg andesites (HMA's) have also been found (e.g. Imaoka *et al.*, 1989, 1993). HMA's are characteristically found in crustal extension region (e.g. Tatsumi, 1995). The activity of the HMA's of the Shimonoseki Subgroup was *ca.* 105 ~ 107 Ma (Imaoka *et al.*, 1993). Because these ages of HMA's are nearly comparable with those of the Gamano granodiorite and

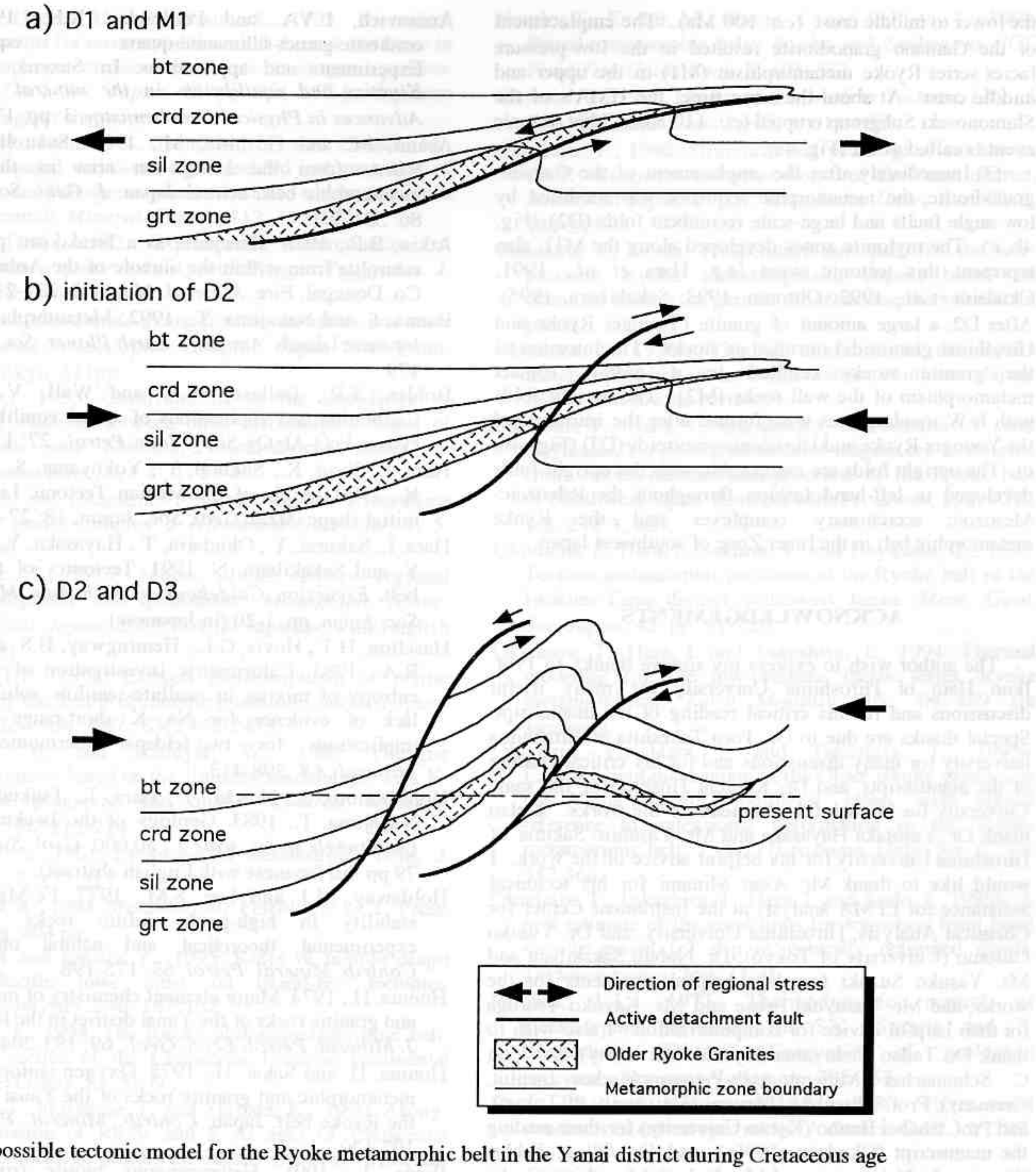

Fig. 4 A possible tectonic model for the Ryoke metamorphic belt in the Yanai district during Cretaceous age

metamorphic rocks, the formation of the extensional sedimentary basin and the activity of the HMA's of the Shimonoseki Subgroup were closely related to the Ryoke plutono-metamorphism (e.g. Imaoka *et al.*, 1989; Itaya *et al.*, 1993; Nakada and Takeda, 1995).

Finally, the tectono-metamorphic processes of the Ryoke metamorphic belt in the Yanai district are summarized as follows.

(1) The accretion of the sedimentary rocks of the Kuga Group at the eastern margin of the Asian continent, until *ca.* 140 Ma.

(2) The generation of magma (Older Ryoke granitoids) at the lower crust, which caused the medium-pressure facies series Ryoke metamorphism (M0) at the upper and middle crust. At about the same time, the non-marine sediments of the Shimonoseki Subgroup filled the back- or central-arc basin which was created by extensional tectonics (*ca.* 120 ~ 100 Ma). 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 were generated. The Gamano granodiorite, which is one of the Older Ryoke granitoids, ascended along the northward dipping large-scale extensional fracture zones from

the lower to middle crust (*ca.* 100 Ma). The emplacement of the Gamano granodiorite resulted in the low-pressure facies series Ryoke metamorphism (M1) in the upper and middle crust. At about the same time, the HMA's of the Shimonoseki Subgroup erupted (*ca.* 110 Ma). This tectonic event is called as D1 (Fig. 4a).

(3) Immediately after the emplacement of the Gamano granodiorite, the metamorphic sequence was modified by low-angle faults and large-scale recumbent folds (D2) (Fig. 4b, c). The mylonite zones developed along the MTL also represent this tectonic event (e.g. Hara *et al.*, 1991; Okudaira *et al.*, 1992; Ohtomo, 1993; Sakakibara, 1995). After D2, a large amount of granite (Younger Ryoke and Hiroshima granitoids) intruded as stocks. The intrusion of the granite stocks resulted in a narrow contact metamorphism of the wall rocks (M2). The upright folds with E-W trending axes were formed after the intrusion of the Younger Ryoke and Hiroshima granitoids (D3) (Fig. 4b, c). The upright folds are comparable with the upright folds developed in left-hand fashion throughout the Paleozoic-Mesozoic accretionary complexes and the Ryoke metamorphic belt in the Inner Zone of southwest Japan.

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