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METAMORPHIC ZONATION AND FORMATION OF GRANULITE IN THE SHIZUNAI AREA, THE HIDAKA METAMORPHIC BELT, HOKKAIDO, JAPAN

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Abstract: The central part of the Hidaka Metamorphic Belt (HMB) is divided into six metamorphic zones: lower-biotite, upper-biotite, garnet, sillimanite-muscovite, garnet-cordierite and orthopyroxene zones. A significant temperature gap with lithological contrast is recognized between the sillimanite-muscovite and garnet-cordierite zones.

In the garnet-cordierite and orthopyroxene zones, marked prograde zoning profiles occur in garnets in amphibolites. Geothermometry and diffusion modeling for the zoning profiles of these garnets suggest that the rims were formed under upper amphibolite-facies and granulite-facies conditions, with a brief and rapid increase in temperature at peak metamorphism. The latest pulse of SHRIMP zircon dating of granulite (Early Miocene) in the Hidakahorobetsu River area may explain the granulite-facies metamorphism recorded the garnet rims, which occurred just before the uplift episode indicated by K-Ar ages.

key words: Hidaka Metamorphic Belt, metamorphic zonation, granulite, prograde zoning in garnet, Early Miocene

1. Introduction

The N-S trending Hidaka Metamorphic Belt (HMB) extends some *ca.* 140 km, with a width of 10-20 km through the axis of Hokkaido, Japan. The belt is composed of metamorphic rocks (the greenschist-facies to the granulite-facies) and felsic to mafic Tertiary plutonic rocks (KOMATSU *et al.*, 1983, 1989; MAEDA *et al.*, 1986; SHIMURA, 1992). The HMB was produced by collision of the westward migrating Pacific Plate with the Eurasia Plate; this movement began in the Paleogene (KIMURA, 1981, 1986). K-Ar dating studies (*e.g.* ARITA *et al.*, 1993; SAEKI *et al.*, 1995) indicate Miocene uplift (16-19 Ma) of the western part of the HMB. Granulite facies metamorphism is inferred to have occurred at *ca.* 55 Ma, according to whole rock Rb-Sr dating (*e.g.* OWADA *et al.*, 1991).

New zircon U-Pb SHRIMP dating, however, indicates Early Miocene (20-23 Ma) age for a tonalite intrusion and a surrounding granulite in the Hidakahorobetsu River area (WATANABE *et al.*, 1997; WATANABE *et al.*, in prep.). These data give a new insight on granulite formation.

We have studied the metamorphic zonation, focusing especially on prograde zoning preserved in coarse grained garnets from the higher grade part of the belt to investigate the thermal history of the HMB associated with granulite formation.

Abbreviation of mineral names is after KRETZ (1983), except Phe (phengite) and Oamp (orthoamphibole).

2. Geological Outline

From west to east, the axial zone of the southern part of Hokkaido consists of the Idon'nappu belt (Mesozoic-Paleogene accretionary complex), the Poroshiri ophiolite, the Hidaka Metamorphic Belt (HMB), and the Nakanogawa group (Mesozoic-Paleogene complex) (Fig. 1). The HMB is separated from the Poroshiri ophiolite by the Hidaka Main Thrust (HMT), whereas the eastern side of the HMB passes gradually into the Nakanogawa group (*e.g.* KOMATSU *et al.*, 1989). The upper part of the HMB is dominated by pelitic and psammitic metamorphic rocks, whereas the lower part (the western part) of the belt is dominated by mafic metamorphic rocks.

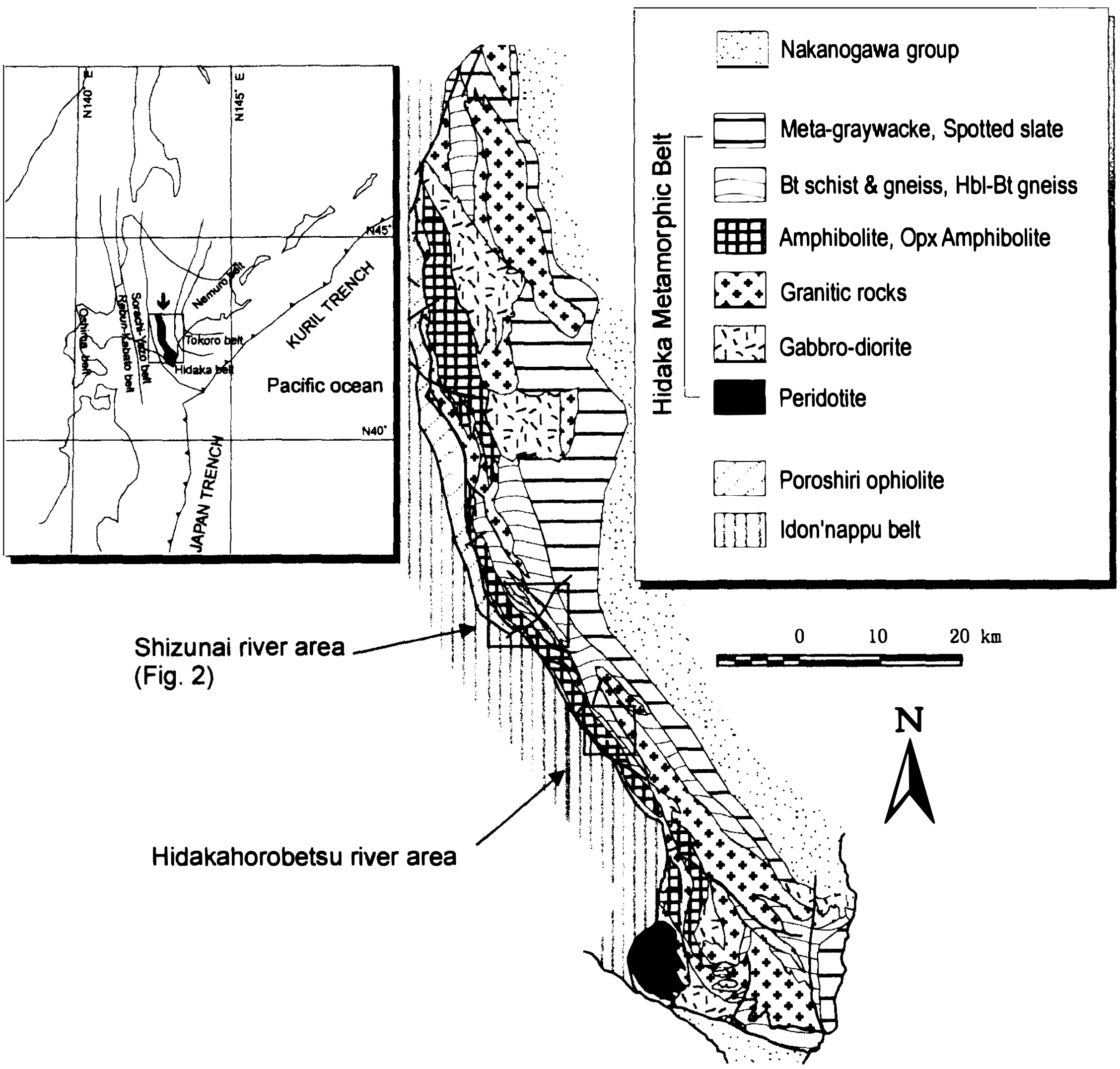

*Fig. 1. Simplified geological map of the Hidaka Metamorphic Belt (*KOMATSU *et al., 1989). The tectonic division of Hokkaido is modified from* KIMIMAMI *et al. (1986).*

The study area on the Shizunai River is located in the central part of the HMB. The general foliation in the area trends NW-SE and dips NE. Five lithologic units have been mapped in the upper part and two units in the lower part (Fig. 2). The eastern boundary of the lower part is sheared and the width of the sheared zone is *ca.* 250 m.

Units and their lithologies in the upper part are:

1) Meta-graywacke unit: weakly metamorphosed graywacke with chlorite and minor amount of biotite.
2) Spotted slate unit: slates with biotite, chlorite, and muscovite. Biotite spots (aggregations) 1-2 mm in diameter are occasionally present.
3) Biotite schist unit: weakly-foliated biotite-chlorite and biotite-muscovite schist.
4) Biotite gneiss unit: well-foliated biotite-muscovite gneiss, with 1-5 mm thick compositional layering, and rare intercalated epidote-amphibolite layers. This unit is intruded by biotite-muscovite tonalite as shown in Fig. 2.

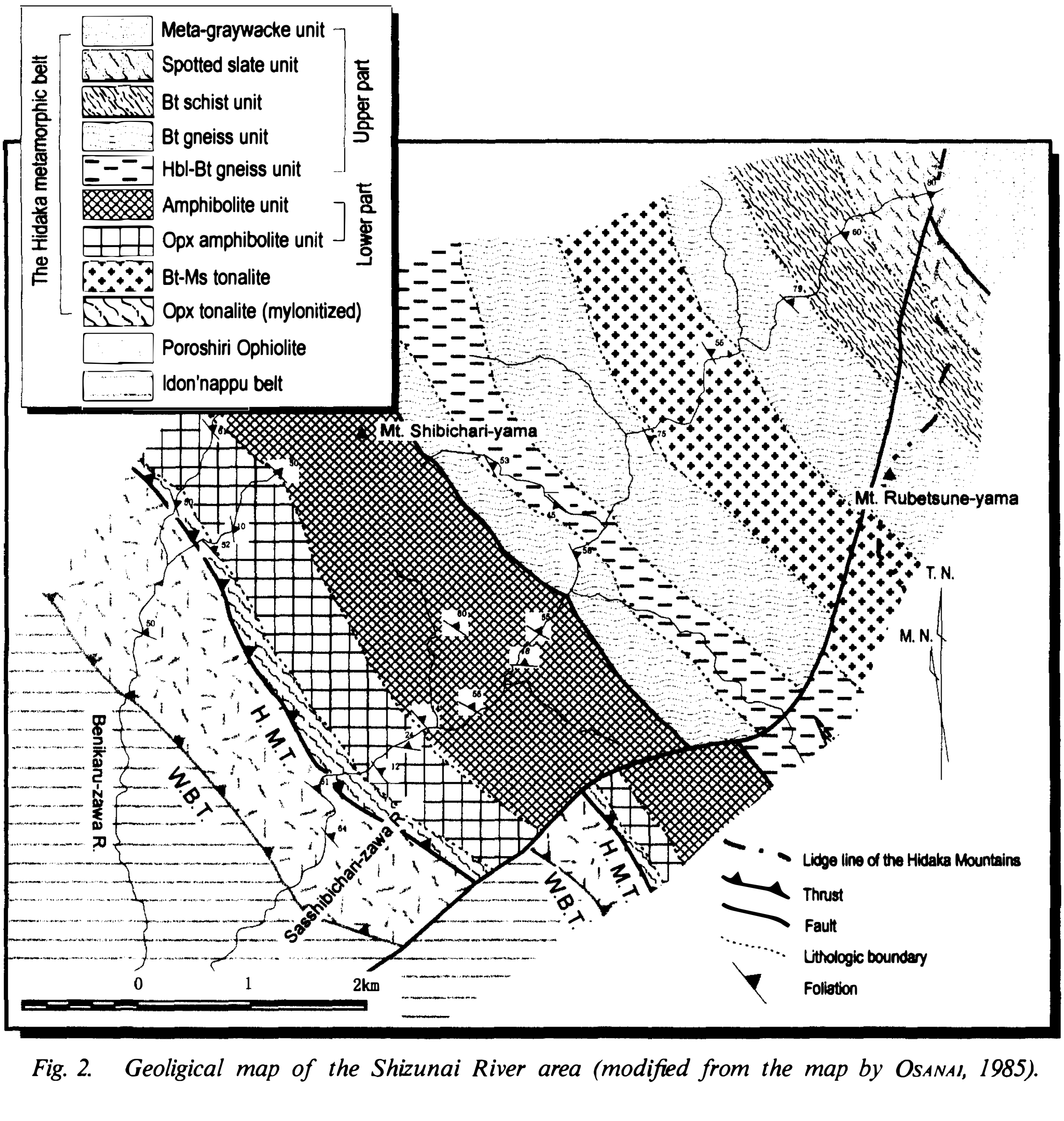

Fig. 2. Geoligical map of the Shizunai River area (modified from the map by Osanai, *1985).*

5) Hornblende-biotite gneiss unit: characterized by hornblende-biotite gneiss and biotite gneiss, which are generally well-foliated in layers 1-5 mm thick.

Units in the lower part are:

1) Amphibolite unit: predominantly green- and brown-hornblende amphibolites, which are generally weakly foliated. Layers or lenses of garnet-cordierite-biotite gneiss, garnet amphibolites and orthoamphibole-bearing gneisses are intercalated within the amphibolite layers.

2) Orthopyroxene-amphibolite unit: predominantly orthopyroxene-amphibolite and brown hornblende amphibolite. Toward the HMT, a gradation from weakly-foliated amphibolite with a minor amount of thin leucocratic veins to lenticular amphibolite surrounded by tonalite is observed. Garnet-cordierite-biotite gneiss, orthoamphibole-bearing gneisses and garnet amphibolites are also occasionally exposed as thin layers (1-500 cm thick) in amphibolites. These gneisses occasionally contain thick leucosome layers composed of coarse grained quartz, plagioclase and cordierite. The unit, characteristically in its western margin, is intruded by orthopyroxene tonalite (Fig. 2).

3. Metamorphic Zonation

Detailed structural and petrological studies in the Shizunai River area were carried out by OSANAI (1985), who firstly divided the area into five metamorphic zones. His report of granulite along the western margin of the HMB is first description of regional occurrence of granulite in Japan. Later, OSANAI *et al.* (1991) re-examined the zonation, and recognized four metamorphic zones after reconsideration of granulite facies rocks. Osanai and coworkers estimated the *P-T* conditions as: Zone I (<400°C, 1.8-2.7 kbar), zone II (400-500°C, 2.6-3.5 kbar), zone III (530-670°C, 5.0-6.0 kbar), zone IV (720-870°C, 5.7-7.3 kbar).

On the basis of mineral assemblages of mainly pelitic rocks along the Sasshibichari-sawa River and Benikaru-sawa River, upper stream of the Shizunai River, we propose a detailed metamorphic zonation (Fig. 3). From east to west, six metamorphic zones are distinguishable; lower-biotite, upper-biotite, garnet, sillimanite-muscovite, garnet-cordierite and orthopyroxene. The upper- and lower-biotite, garnet, and sillimanite-muscovite zones correspond to the upper part of the sequence, whereas the garnet-cordierite and orthopyroxene zones correspond to the lower lithologic sequence. Quartz, apatite and opaque minerals such as ilmenite and sulphide occur in all analyzed rocks as excess phases. Carbonaceous materials occur in the lower grade rocks

We also estimate the progressive metamorphic reactions listed below, based on petrography and mineral chemistry.

Lower-biotite zone

Biotite occurs sporadically with chlorite+phengite in Fe-rich pelitic rocks (Fig. 4A). A peristerite gap between $X_{an}=0.02$-0.05 and 0.17-0.21 occurs in plagioclase. The chlorite zone as characterized by the chlorite+phengite assemblages is distributed on the eastern side of the zone, outside the mapped area, with a width of *ca.* 5 km (*e.g.* OSANAI *et al.*, 1991).

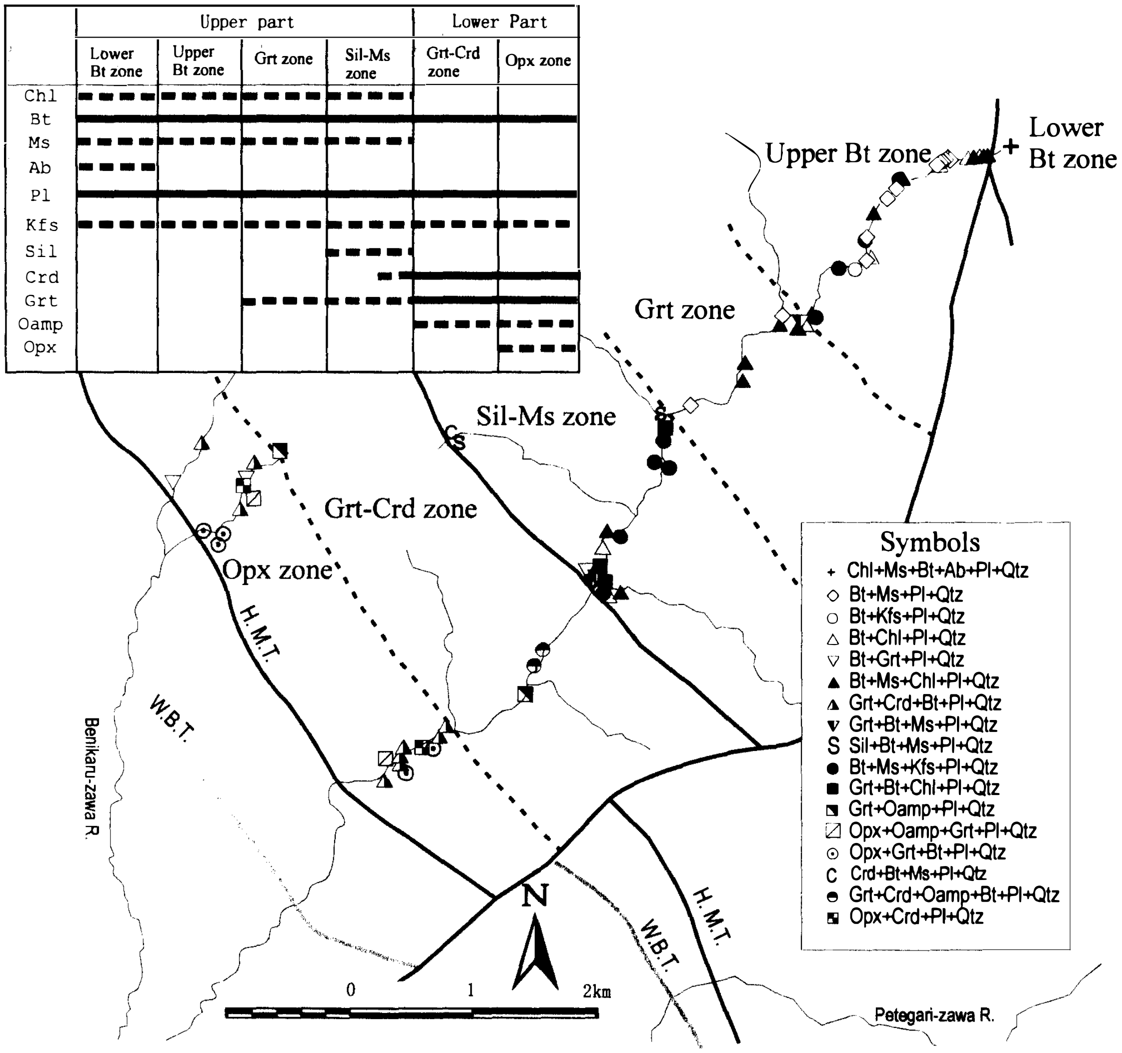

Fig. 3. Map showing distribution of mineral assemblages in pelitic and orthoamphibole-bearing rocks in the Shizunai River area. Stabilities of minerals in each zone are shown in the inset. Solid line: major constituent; dashed line: minor consistuent. Abbreviation of minerals after Kretz *(1983), except Oamp (orthoamphibole).*

Upper-biotite zone

This zone is characterized by ubiquitous occurrence of biotite. White mica becomes much less phengitic and we here use the term of muscovite in this zone, and in the upper metamorphic grade rocks. Biotite + chlorite + muscovite + plagioclase and biotite + muscovite + K-feldspar + plagioclase assemblages (Fig. 4B) are observed. Chlorite + K-feldspar is not recognized. The peristerite gap in plagioclase disappears; X_{an} of plagioclase is 0.27-0.33. The lower grade side of this zone is fault-bounded. The phase relations are illustrated on an AFM diagram projected from muscovite, ilmenite, quartz and H_2O (Fig. 5). The reactions from the lower-biotite zone are inferred to be:

$$\mathrm{Chl + Kfs = Ms + Bt + Qtz + H_2O,}$$
$$\mathrm{Phe + Chl = Ms + Bt + Qtz + H_2O.}$$

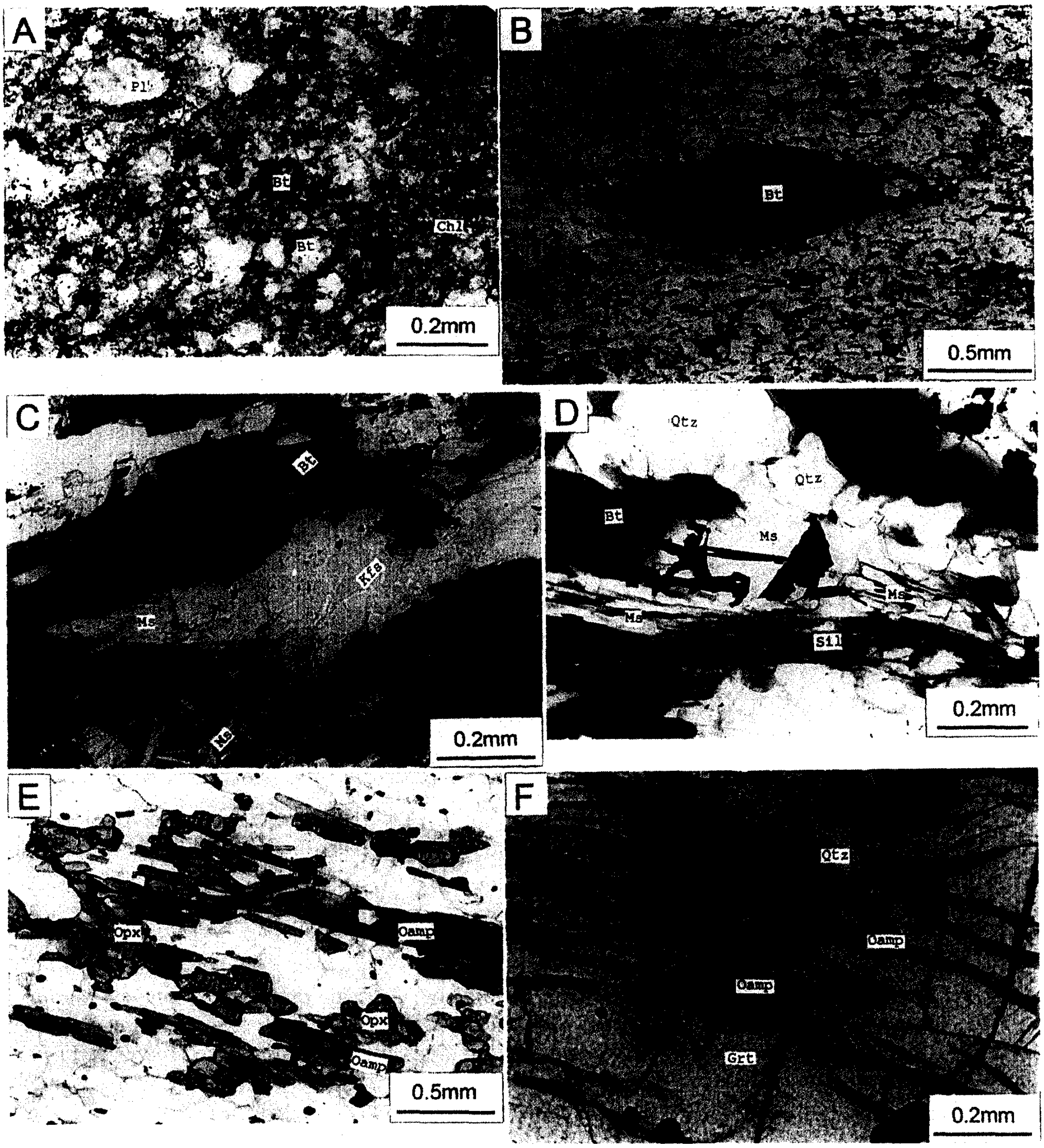

Fig. 4. *Photomicrographs of metamorphic rocks in the study area.*
A: Meta-graywacke from the lower biotite zone.
B: Spotted slate from the upper biotite zone.
C: Biotite-muscovite schist from the upper biotite zone.
D: Biotite-muscovite-fibrolite gneiss from the sillimanite-muscovite zone.
E: Orthoamphibole-bearing rock from the orthopyroxene zone.
F: Orthoamphibole inclusions in garnet in the same sample as E.

Garnet zone

The zone is defined by almandine-rich garnet ($prp_{11}alm_{62}grs_3sps_{24}$). Garnet+biotite+muscovite and biotite+chlorite+muscovite assemblages are observed in this zone. X_{an} in plagioclase is 0.28–0.29. The progressive reaction producing garnet from the upper-biotite zone is:

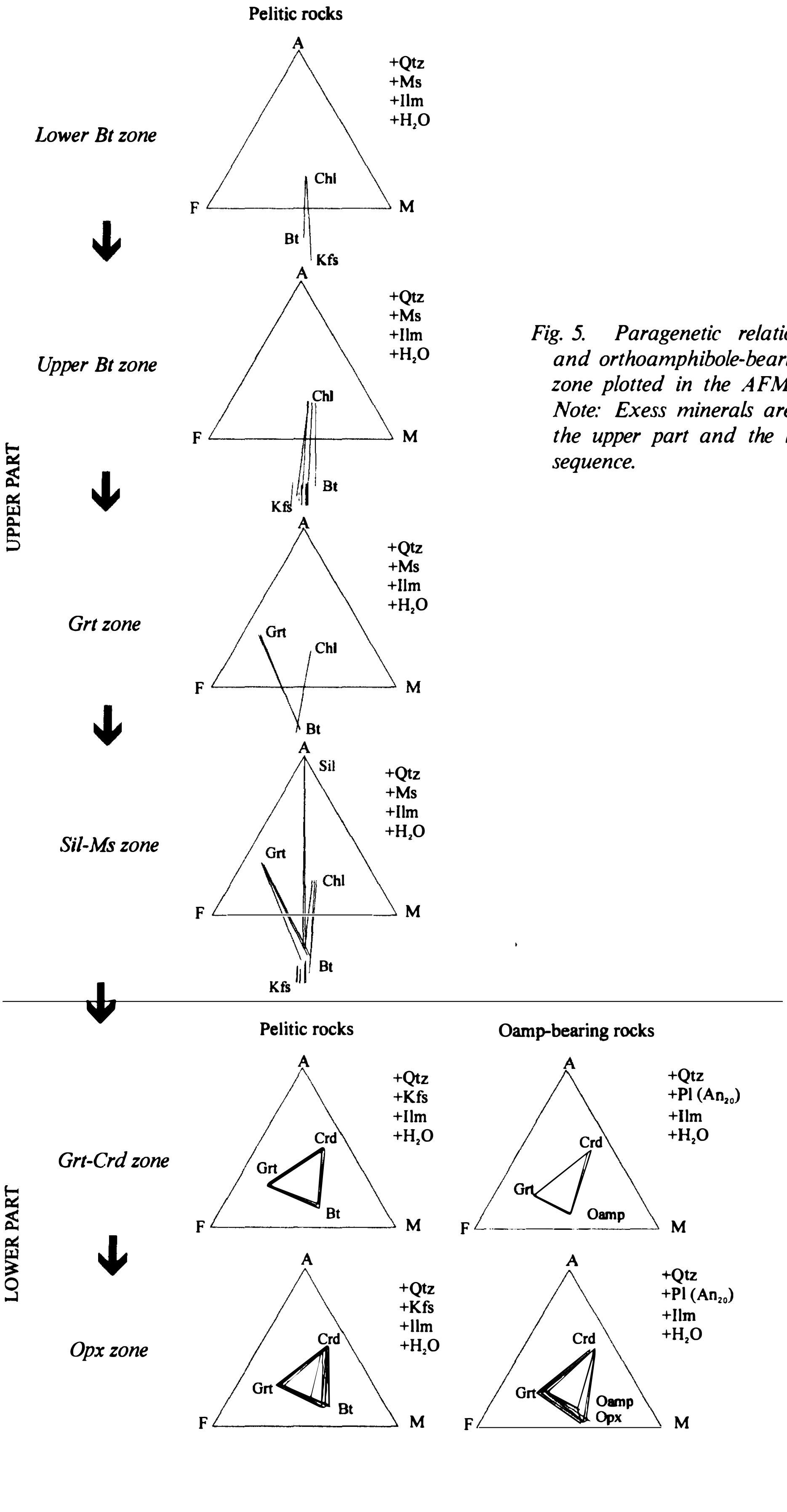

Fig. 5. Paragenetic relationships in pelitic and orthoamphibole-bearing rocks of each zone plotted in the AFM diagram. Note: Exess minerals are not the same in the upper part and the lower part of the sequence.

$$Chl\ (low\text{-}X_{Mg}) + Ms + Qtz = Grt + Bt + H_2O.$$

The *P-T* conditions of the zone are estimated to be *ca.* 3.5 kbar, *ca.* 600°C from a garnet + plagioclase + biotite + muscovite + quartz assemblage, using HOISCH (1990) and HODGES and SPEAR (1982) calibrations with the garnet solution model by BERMAN (1990).

Sillimanite-muscovite zone

This zone is defined by the first appearance of fibrolite, and is characterized by occurrence of biotite + muscovite + sillimanite + plagioclase (Fig. 4C). No prismatic sillimanite is observed. Biotite + muscovite + chlorite + plagioclase and biotite + muscovite + K-feldspar + plagioclase assemblages also occur. X_{an} in plagioclase is generally 0.22–0.32. Rarely, plagioclase with $X_{an} = 0.40–0.44$ occurs with a garnet + biotite + quartz assemblage. Chlorite is not a retrogressive product, because slightly Fe-rich chlorite is included in plagioclase. The phase relations are illustrated on the AFM diagram (Fig. 5). Chlorite coexisting with biotite and muscovite in this zone is more Mg-rich than that from the garnet zone. The reaction from the garnet zone is estimated by the following reaction:

$$Chl + Ms + Qtz = Sil + Bt + H_2O.$$

Chlorite coexisting with fibrolite has not yet been found. At present recorded occurrence of sillimanite are few. Although the sillimanite-biotite-chlorite triangle is small, if more occurrences are found the paragenesis may be determined. Garnet is common, and garnet and coexisting biotite are more Mg-rich than in the garnet zone. *P-T* condition are estimated as *ca.* 4.0 kbar, *ca.* 615–650°C from a garnet + plagioclase + biotite + muscovite + quartz assemblage, using the same method as above.

Garnet-cordierite zone

This zone is distinguished by garnet + cordierite + biotite + plagioclase + quartz assemblage in pelitic rocks, although the assemblage is comparatively rare. X_{an} of plagioclase is 0.18–0.23. Orthoamphibole-bearing rocks also occur in this zone; the characteristic assemblage is garnet + cordierite + orthoamphibole (gedrite) + plagioclase + quartz. The assemblages are illustrated by AFM diagrams projected from K-feldspar, quartz ilmenite and H_2O, and projected from plagioclase (An_{20}), quartz ilmenite and H_2O (Fig. 5). In pelitic rocks, muscovite is consumed by the reaction:

$$Ms + Qtz = Sil + Kfs + H_2O.$$

Chlorite (more Fe-rich) in the sillimanite-muscovite zone reacts to sillimanite + biotite assemblage, although Mg-rich chlorite is preserved. In this zone, chlorite coexisting muscovite disappears due to the reaction:

$$Chl\ (high\text{-}X_{Mg}) + Ms + Qtz = Crd + Bt + H_2O,$$

The garnet + cordierite assemblage is formed by:

$$Bt + Sil + Qtz = Grt + Crd + Kfs + H_2O.$$

As outlined above, biotite-forming and biotite-consuming reactions occur together in this zone, suggesting the boundary between the sillimanite-muscovite and garnet-cordierite zones is not continuous. A significant gap in metamorphic condition thus occurs, as discussed later.

The following reaction accounts for the formation of the orthoamphibole-bearing assemblage;

$$Chl + Qtz = Grt + Crd + Oamp + H_2O$$

The K_D values for cordierite-garnet $((Mg/Fe)_{Crd}/(Mg/Fe)_{Grt})$ from this zone is 8.28-6.84 (corresponding to 658-721°C: THOMPSON (1976), 641-695°C: PERCHUK and LAVRENT'EVA (1983) and HOLDAWAY and LEE (1977)).

Orthopyroxene zone

The orthopyroxene zone is defined by the appearance of orthopyroxene in orthoamphibole-bearing rocks. Garnet+cordierite+biotite+plagioclase+quartz+ilmenite assemblages also commonly occur in pelitic rocks. X_{an} of plagioclase is 0.27-0.34. Phase relations are illustrated by AFM diagram (Fig. 5). The assemblage in pelitic rocks is same as that in the garnet-cordierite zone, but garnet and biotite are more Mg-rich. Moreover, garnet, cordierite and biotite from rocks in the higher grade part of the zone are more magnesian than in the lower grade part. K_D values for cordierite-garnet from the lower grade part is 6.57, and from the higher grade part is 6.34-5.81 (corresponding to 754-788°C: THOMPSON (1976); 725-753°C: PERCHUK and LAVRENT'EVA (1983); 723-750°C: HOLDAWAY and LEE (1977)).

Orthoamphibole-bearing rocks of this zone are characterized by garnet+orthoamphibole (gedrite)+orthopyroxene+plagioclase+quartz (Fig. 4D, E, F) and garnet+orthoamphibole (gedrite)+cordierite+plagioclase+quartz. X_{an} of plagioclase is 0.13-0.24. The reaction producing orthopyroxene is inferred to be:

$$Oamp \text{ (more Si-rich)} = Opx + Oamp \text{ (more Al-rich)} + Qtz.$$

4. Zoning in Garnet

Garnet is a common constituent mineral in the most of the metamorphic rocks in study area. Garnets from the upper lithostratigraphic horizon are Ca- and Mn- rich and Mg-poor, and has almost no or very weak reverse zoning (Fig. 6). In contrast, garnets from the lower horizon, *i.e.*, higher metamorphic grade side, exhibit Ca- and Mn-poor and Mg-rich compositions.

Prograde zoning (Mg increasing outward) is observed in coarse grained garnets (4-12 mm in diameter) in pelites and amphibolites in the lower part, but almost no zoning is detected in finer grained garnet.

Garnet in pelites often shows Mg maximum near the rim (Fig. 6). Maximum and minimum values in zoned garnet are $X_{prp}=0.30$-0.31 and 0.23-0.25, respectively. Mn and Fe decrease from core to near the rim, while Mg increases. Ca decreases very little from core to rim, *i.e.*, from $X_{grs}=0.03$-0.05 (core) to 0.02 (rim). However, Ca maximum is slightly away from grain centers in some garnets. At the very rim, sharp increase in Fe and sharp decrease in Mg are observed, although Mn increases very little. The outermost rim (less than 5 μ wide) is considered to be formed by Fe-Mg diffusion, without resorption of garnet during the uplifting cooling process.

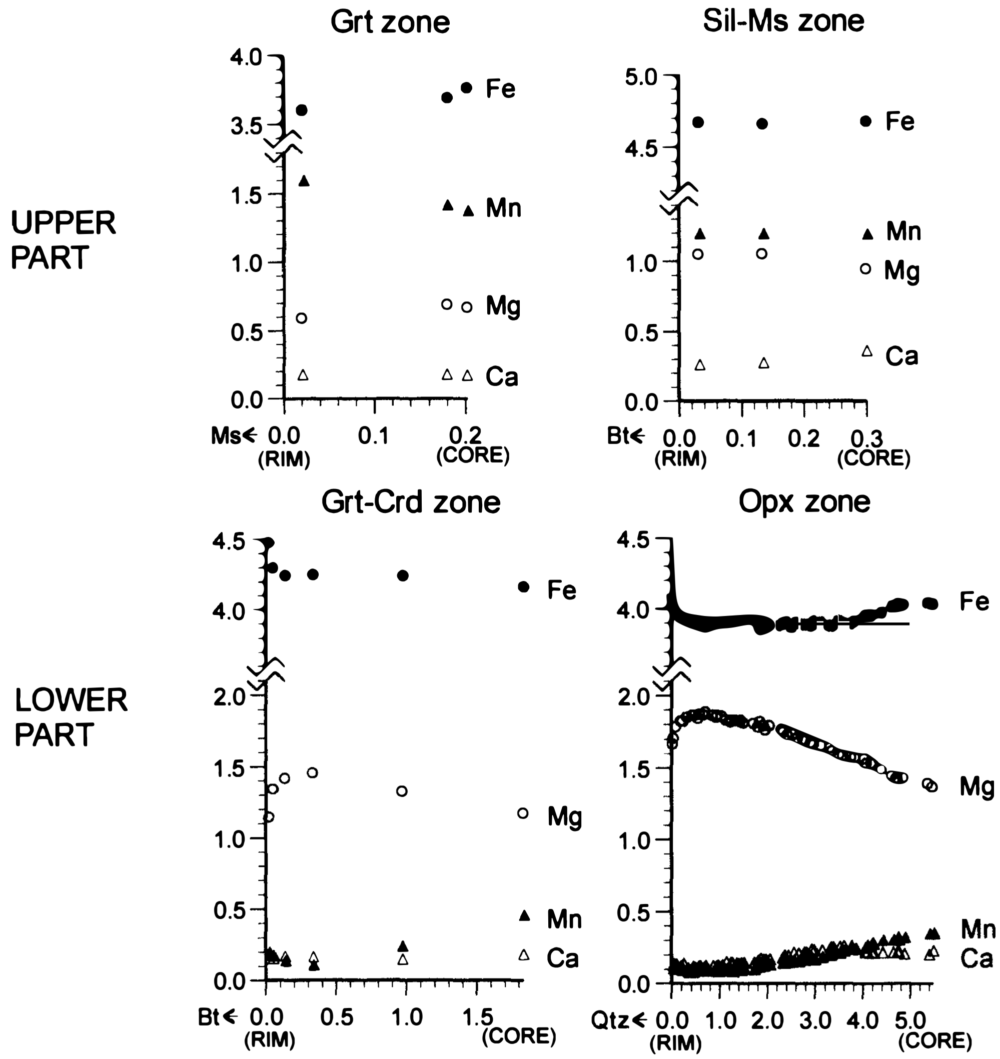

Fig. 6. Rim-core zoning profiles from garnets in pelitic rocks from each metamorphic zone. Fe, solid circles; Mg, open circles; Ca, open triangles; Mn, solid triangles. Profiles plotted in cations per formula unit based on 24 oxygens. X-axis indicates the distance from the rim in mm.. Minerals in immediate contact with garnet are also shown.

Garnet grains in amphibolite and orthopyroxene amphibolite show more distinct prograde zoning patterns at the rim than do those in pelitic rocks (Fig. 7). In general, garnets from the garnet-cordierite zone have comparatively homogeneous cores (X_{prp}= 0.15-0.17), whereas rims (outer 0.5 mm) X_{prp} values increase to as much as 0.23-0.24. Fe zoning shows a reciprocal pattern to Mg zoning. Mn profile shows very little decrease from core (X_{sps}=0.03-0.05) to rim (X_{sps}=0.01-0.02). Ca also shows slight decrease outward (X_{grs}=0.11-0.13 at the core, X_{grs}=0.09 rim). Garnets from the orthopyroxene zone consist of cores with gentle increase in X_{prp} (from X_{prp}=0.15 at the core to X_{prp}=0.23) outward, and rims where X_{prp} increases sharply to 0.30. The Fe profile shows the reciprocal pattern of the Mg profile. Mn decreases outward from cores, and is unchanged at rims, whereas, Ca shows very little decrease outward. A sharp upturn in Fe and downturn in Mg is also observed at the edges of rims.

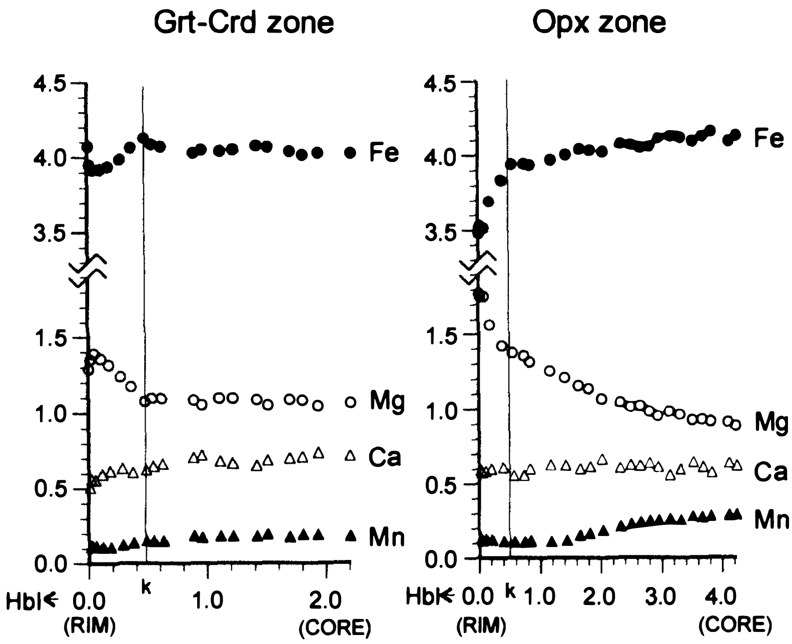

Fig. 7. *Rim-core zoning profiles from garnets in amphibolite from the Grt-Crd and Opx zones. Fe, solid circles; Mg, open circles; Ca, open triangles; Mn, solid triangles. Profiles plotted in cations per formula unit based on 24 oxygens. X-axis indicates the distance from the rim in mm. "k" indicates a kink in the profiles. Mineral in immediate contact with garnet is also shown.*

5. Discussion

5.1. Metamorphic zonation of the HMB

In this paper we report the coexistence of fibrolite and muscovite (Fig. 4D), which was not recognized in the previous zonation (*e.g.* OSANAI *et al.*, 1991). Furthermore, in the lower-grade area (upper biotite and sillimanite-muscovite zones) K-feldspar is occasionally observed with muscovite (Fig. 4C), although it was reported to occur only in the higher grade part (zone III and IV of the previous metamorphic zonation). In the orthopyroxene zone, orthoamphibole (gedrite) occurs as (1) inclusions in garnet (Fig. 4F) and (2) elongated crystals parallel to the foliation with orthopyroxene and garnet (Fig. 4E). Judging from observations (1) and (2), this type of orthoamphibole at least is not a retrograde product. The phase relations in the AFM diagram projected from plagioclase (An_{20}), quartz and ilmenite also show that orthoamphibole can coexist with garnet, orthopyroxene, and cordierite, because it is more Al-rich than associated orthopyroxene (Fig. 5). Thus we propose a new metamorphic zonation as shown in Fig. 3.

5.2. The gaps in metamorphic zonation

A wide shear zone was observed between the lower and upper part of the area as mentioned earlier (Fig. 2). The shear zone (*ca.* 250 m) separated the sillimanite-muscovite zone from the garnet-cordierite zone. Chlorite also disappears in the garnet-cordierite zone. Geothermometry indicates an abrupt temperature change. Temperature of the highest grade part of the sillimanite-muscovite zone is 610–650°C (pressure is estimated to be 4 kbar by garnet-plagioclase-biotite-muscovite assemblage) and that of the lowest part of the garnet-cordierite zone is 680–720°C from garnet-biotite pairs.

The temperature gap implies missing zones of the sillimanite-muscovite-K-feldspar and sillimanite-K-feldspar, which are reported in many other areas, *e.g.* Massachusetts, USA (TRACY, 1978; TRACY and ROBINSON, 1983). The gap is also marked by lithological contrast as mentioned before.

5.3. Prograde zoning of garnets: Implication to the thermal history of the Hidaka Metamorphic Belt

Zoning profiles of Fe, Mg and Mn in garnet from the lower grade part (garnet zone, sillimanite-muscovite zone) show flat or weak reverse patterns (*i.e.*, Mn slightly increases rimward) (Fig. 6). On the other hand, coarse grained garnets from the higher grade part (garnet-cordierite zone, orthopyroxene zone) shows prograde patterns (*i.e.* Mg and Mg/Mg+Fe increase outward), although finer grained garnets show homogeneous compositions, except for their rims. The finer garnet may have been homogenized by intracrystalline diffusion during peak metamorphism. Mg/(Mg+Fe) zoning profiles in garnet in amphibolites from the orthopyroxene and garnet-cordierite zones exhibit a remarkable kink ("k" in Fig. 7) at the distance of 0.5 mm from the rim. Mg/(Mg+Fe) increases very sharply between the kink and the rim, and is flat or increases gently between the kink and the core.

Temperatures of 780–790°C and 690–700°C are estimated for the marked prograde rim of garnet from the orthopyroxene and garnet-cordierite zones, respectively, using the garnet-hornblende geothermometer (PERCHUK *et al.*, 1985), whereas, estimates of 580–590°C and 570–630°C are gained from their cores. Therefore, the lower part of the Shizunai area had been metamorphosed under upper amphibolite-facies-granulite-facies conditions. Intracrystalline diffusion in garnet is very effective under these conditions (*e.g.* YARDLEY, 1977; CHAKRABORTY and GANGULY, 1990) and the kinks would be obliterated if the duration of metamorphism was sufficient. The survival of kinks thus implies that

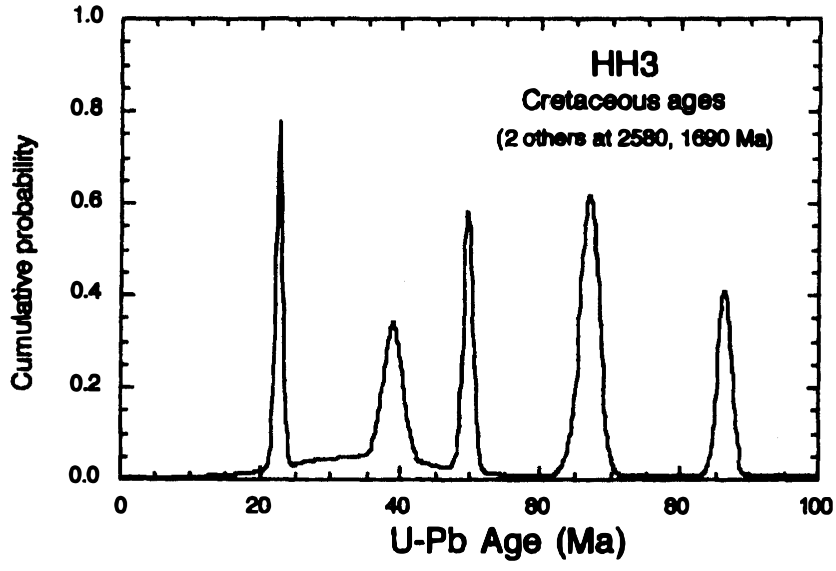

Fig. 8. Cumulative probability of SHRIMP zircon dating of pelitic granulite (HH3) from the Hidakahorobetsu River area. Data from WATANABE et al. (1997; in prep.).

duration of metamorphism was too short for diffusion to smooth out sharp differences in composition. Duration of peak metamorphism is estimated as 2–5 My from preliminary calculations based on multi-component diffusion in garnet from the orthopyroxene zone (Usuki, 1997). Arita *et al.* (1993) proposed very fast cooling (175–233°C/Ma) of the HMB based on geochronological study. Therefore, peak metamorphic age and uplift age (16–19 Ma, *e.g.* Arita *et al.*, 1993) may closely correspond. Cumulative probability of SHRIMP zircon U-Pb ages of pelitic granulite (Fig. 8) from the Hidakahorobetsu River area which locates to the south part of the study area (Watanabe *et al.*, 1997) support our estimation of youngest granulite formation, although older granulite might date back to Paleogene time. Zircon U-Pb ages obtained from tonalite intruding the gneiss in the same area also indicate the Early Miocene thermal event (Watanabe *et al.*, 1994). These geochronologic data are very consistent with our estimation of the timing of the latest phase of granulite formation in the Shizunai River area.

6. Conclusions

1) We propose a new metamorphic zonation in the Shizunai River area of the Hidaka metamorphic belt. Six metamorphic zones are recognized, i.e., Lower biotite zone, Upper-biotite zone, garnet zone, sillimanite-muscovite, garnet-cordierite and orthopyroxene zones.

2) A gap in metamorphic temperatures is observed between the sillimanite-muscovite and garnet-cordierite zones, which coincides with the lithological boundary is between the upper (east) and lower (west) lithostratigraphical horizons.

3) Coarse grained garnets in pelitic rocks show prograde zoning pattern in the garnet-cordierite and orthopyroxene zones, but flat or retrograde pattern in the lower grade zones.

4) Marked and rapid increase of Mg/(Fe+Mg) of garnet rims in amphibolite suggests that the granulite was formed by a later, superimposed, Miocene metamorphic event.

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