P-T CONDITIONS OF GRANULITE-FACIES ROCKS FROM THE HIDAKA METAMORPHIC BELT, HOKKAIDO, JAPAN

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Abstract The Hidaka metamorphic belt consists of the Western and Main Zones, the latter being thrust over the former along the Hidaka Main Thrust. The Main Zone can be subdivided into the Upper sequence in the east and the Lower sequence in the west, and divided into five metamorphic zones from the east to the west. The Upper sequence corresponds to zone I and to low-grade part of zone II, while the Lower one corresponds to high-grade part of zone II and to zones III, IV and V. The metamorphic grade increases progressively westward from the greenschist facies up to the granulite facies.

The garnet-hypersthene-cordierite granulite and the garnet-cordierite-biotite granulite, which are high-grade metamorphic rocks of the Main Zone, occur in zones IV₁ and V₁ in the western part of the Main Zone. The P-T conditions of the granulite-facies rocks reach ca. 730°C and 6.5 kb on the basis of the geothermo-barometers. These values correspond to the conditions of the lower crust at about 23 km in depth. The geothermal gradient of the Lower sequence of the Main Zone is estimated to be about 33°C/km.

Introduction

The Hidaka metamorphic belt stretches longitudinally for a distance of about 140 km with a width of 10~20 km, and constitutes an axial zone of Hokkaido Island, Japan. The metamorphic belt represents a zonal arrangement of metamorphic rocks, intrusive plutonic rocks and migmatites. The migmatites were considered to be core complexes which are surrounded by successive zones from gneiss to hornfels through crystalline schist (MINATO *et al.*, 1965). A number of thrust faults and shear planes, which suggest a west-directed tectonic polarity, are observed in the western side of the metamorphic belt. The zonal ar-

rangement has been interpreted to be a product of the Alpine phase orogeny in Hokkaido (the *Hidaka orogenesis*: HUNAHASHI & HASHIMOTO, 1951; HUNAHASHI, 1975; MINATO *et al.*, 1965). KIZAKI (1964) proposed that the maximum metamorphic grade may have reached up to the amphibolite facies at the center of the metamorphic belt characterized by the occurrence of migmatites, because the migmatites had been considered to be generated by anatexis of the gneiss *in situ*.

Whereas, the rocks showing higher grade than the amphibolite facies have been reported in the Hidaka metamorphic belt. Such rocks having mineral parageneses of the granulite facies have been sporadically found in the Horoman region at the southern end of the belt, but their origin has been attributed to the contact metamorphism of peridotite of the Horoman ultramafic complex (HUNAHASHI, 1948).

Recently, in the southern part of the Hidaka metamorphic belt, ARITA *et al.* (1978) reported hypersthene-bearing gneisses and garnet-cordierite gneisses of the granulite facies

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Fig. 1. Simplified geological map of the Hidaka metamorphic belt. W.B.T.: Western Boundary Thrust, H.M.T.: Hidaka Main Thrust, W.Z.: Western Zone.

from the plagioclase porphyroblastic gneiss zone on the west of the migmatite core. They suggested that these granulite-facies rocks have been formed possibly prior to the formation of the migmatites and associated metamorphic rocks in the east.

Subsequently further occurrences of the granulite-facies rocks have been recognized in the western part of the Main Zone (MOTOYOSHI, 1979; KOMATSU, 1980; OSANAI, 1981, 1985; TOYOSHIMA & UDA, 1981; SHIBA & MAEDA, 1981; BAMBA, 1982; AONO, 1982; OWADA, 1984). These studies have shed a new light on the geology of the Hidaka metamorphic belt. KOMATSU *et al.* (1979, 1982, 1983) pointed out that the Hidaka metamorphic belt consists of the Western Zone of an

imbricated oceanic crustal slab and the Main Zone of a continental or island-arc type crustal slab. The Main Zone has been thrust over the Western Zone as a result of the westward collision of the Kurile arc in Late Miocene to Pliocene (KIMURA, 1981, 1982; KIMURA *et al.*, 1982). OSANAI (1985) investigated the detailed mineral parageneses of the metamorphic rocks from the Main Zone in the Shizunai River region, and confirmed that the metamorphic grade increases progressively westward from the greenschist facies to the granulite facies. The aim of this paper is to present the regional distribution of the granulite-facies rocks in the Main Zone of the Hidaka metamorphic belt and to estimate the P-T conditions of the granulite-facies metamor-

Fig. 2. Schematic geologic cross section of the Hidaka metamorphic belt in the Sasshibichari River-Satsunai River district (modified from OSANAI, 1985).

1-11 : Main Zone, 1 : mylonite zone, 2 : granulite, 3 : brown hornblende amphibolite, 4 : biotite gneiss, 5 : hornblende-biotite gneiss, 6 : gneissose biotite migmatite, 7 : biotite tonalitic migmatite, 8 : banded biotite gneiss, 9 : tonalite, 10 : biotite-muscovite gneiss, 11 : muscovite-chlorite (-biotite) hornfels, 12 : Western Zone, 13 : Hidaka Supergroup. 1-2 : granulite unit, 4-5 : hornblende-biotite gneiss unit, 8 and 10 : biotite-muscovite gneiss to schist unit. W.B.T., H.M.T. and W. Z. are the same as in Fig. 1.

phism based on geothermo-barometers.

Geological setting

1. General geology

The Hidaka metamorphic belt is divided into the Main and Western Zones by the Hidaka Main Thrust (KOMATSU *et al.*, 1979, 1983). Rock foliations of the Main Zone strike generally parallel to the general trend of the Hidaka metamorphic belt, and dip steeply east, showing a homoclinal structure. Graded beddings suggesting east upward are found in the hornfels unit in the east. The evidence suggests an upward stratigraphic polarity from the Hidaka Main Thrust eastward (OSANAI, 1985). The metamorphic rocks of the Main Zone vary in metamorphic grade from the granulite facies in the west to the greenschist facies in the east. The Main Zone can be divided into two lithologic sequences: the lower metamorphic sequence (Lower sequence) rich in basic rocks and the upper metamorphic sequence (Upper sequence) consisting of pelitic to psammitic rocks with lesser amounts of basic rocks (KOMATSU *et al.*, 1983; OSANAI, 1985) (Fig. 1). Mig-

matites are intruded into the metamorphic rocks between the Lower and Upper sequences and those of the Lower sequence as mentioned later (OSANAI *et al.*, 1982).

In the northern part of the Shunbetsu River-Menashunbetsu River area, a typical cross section of the Main Zone is obtained (Fig. 2). The Lower sequence in the area is further divided into three units, *i.e.* granulite, brown hornblende amphibolite and hornblende-biotite gneiss units, and the Upper sequence into two units, *i.e.* biotite-muscovite gneiss to schist and hornfels units. Intrusive bodies of granite, diorite and gabbro occur in places mainly in the eastern part of the Main Zone (Fig. 3). The intrusive bodies of migmatites in this area can be classified into three types in terms of their characteristic features such as differences in emplacement position, lithofacies and kind of their inclusions as follows:

1) Biotite tonalitic migmatite which is intruded as large masses between the Lower and Upper sequences, and is characteristically surrounded by banded injection gneisses. The inclusions in the migmatite are biotite-muscovite gneiss, schist and hornfels;

Table 1. Equilibrium mineral assemblages of pelitic and psammitic metamorphic rocks in the Main Zone of the Hidaka metamorphic belt. Opaque minerals, apatite and zircon are also included in all assemblages. The Roman numerals represent numbers of metamorphic zone.

	Pelitic rocks						Psammitic rocks					
	Up. sequ.		Low. sequence				Up. sequ.		Low. sequence			
	I	II	II	III	IV	V	I	II	II	III	IV	V
Chl	++	+	-	-	-	-	++	+	-	-	-	-
Phe	++	-	-	-	-	-	++	-	-	-	-	-
Mus	-	++	+	-	-	-	-	++	+	-	-	-
Bt	-	++	++	++	++	+	-	++	++	++	+	+
And	-	+	+	-	-	-	-	-	-	-	-	-
Sil	-	-	-	+	-	-	-	-	-	-	-	-
Gt	-	+	+	++	++	++	-	-	+	+	++	++
Cd	-	-	+	+	++	++	-	-	-	+	++	++
Oamp	-	-	-	-	-	-	-	-	-	+	+	-
Opx	-	-	-	-	-	+	-	-	-	-	+	++
Pl	++	++	++	++	++	++	++	++	++	++	++	++
Kfs	-	-	-	+	+	+	-	-	-	-	+	+
Qz	++	++	++	++	++	++	++	++	++	++	++	++

++ : present, + : present or absent, - : absent; Chl : chlorite, Phe : phengite, Mus : muscovite, Bt : biotite, And : andalusite, Sil : sillimanite, Gt : garnet, Cd : cordierite, Oamp : orthoamphibole, Opx : hypersthene, Pl : plagioclase, Kfs : potash feldspar, Qz : quartz.

2) Hypersthene-biotite-garnet enderbitic migmatite which occurs in the brown hornblende amphibolite unit of the Lower sequence, and contains inclusions of garnet-cordierite-biotite granulite, garnet-biotite gneiss, and brown hornblende amphibolite;

3) Garnet-hypersthene-biotite enderbitic migmatite which is found in the granulite unit of the Lower sequence, and includes garnet-hypersthene granulite, hypersthene-plagioclase granulite, hypersthene amphibolite, brown hornblende amphibolite, and meta-harzburgite.

These three types of migmatites are named the upper, the middle and the lower migmatites, respectively.

The westernmost part of the granulite unit is strongly mylonitized to form a mylonite zone along the Hidaka Main Thrust (Fig. 3).

The pelitic and psammitic metamorphic rocks in the Main Zone have various mineral assemblages (Table 1). Bulk chemical compositions of both rocks are rich in FeO, MgO and Na₂O and poor in K₂O (OSANAI, 1985). Especially, psammitic rocks have the least content of K₂O. The hypersthene-bearing assemblages occur only in psammitic rocks.

Among these pelitic and psammitic assemblages, the garnet+hypersthene+cordierite assemblage and most of the garnet+cordierite+biotite assemblage can be referred to the granulite facies as mentioned later. The latter assemblage, however, is also found in the amphibolite-facies rocks on the east of the granulite unit. The granulite-facies rocks bearing above two assemblages are hereafter called garnet-hypersthene-cordierite granulite (GO granulite) and garnet-cordierite-biotite granulite (GC granulite), respectively, and the amphibolite-facies rocks bearing the latter assemblage is called garnet-cordierite-biotite gneiss (GC gneiss).

2. Granulite unit

The granulite unit is exposed in width of 300 to 1300 m in the northern part, 200 to 1000 m in the middle part and 1000 to 1500 m in the southern part of the present area. In the middle and southern parts the unit often occurs repeatedly owing to tectonic imbrication caused by a thrust movement. The granulite unit consists of GO granulite, GC granulite, hypersthene-plagioclase granulite, hypersthene-(clinopyroxene) amphibolite, brown hornblende amphibolite, and garnet-

Fig. 3. Geologic map of the central part of the Hidaka metamorphic belt (Shunbetsu River-Menashunbetsu R. area). W.B.T. : Western Boundary Thrust, H.M.T. : Hidaka Main Thrust. Sh : Shunbetsu River, Kb : Koibokushu-shibichari R., Sb : Sasshibichari R., Ni : Nishuomanai-zawa R., Ho : Horobetsu R., Nb : Niobetsu R., Me : Menashunbetsu R., Ke : Mt. Kamui-ekuuchi-kaushi, Ko : Mt. Koikakushu-satsunai, Ya : Mt. Yaoromappu, Ru : Mt. Rubetsune, Pt : Mt. Petegari, Na : Mt. Nakano-dake, Km : Mt. Kamui, Pi : Mt. Pirika-nupuri, To : Mt. Toyoni, No : Mt. Nozuka, Rk : Mt. Rakko.

hypersthene-biotite enderbitic migmatite. In the northern to middle part the granulite unit can be subdivided into three subunits of (1) garnet-hypersthene-biotite enderbitic migmatite, (2) GO granulite, and (3) GC granulite and hypersthene-plagioclase granulite from west to east (OSANAI *et al.*, 1982; BAMBIA & KOMATSU, 1983; OSANAI, 1985). The GC granulite is found also in the subunit (2) as a narrow layer of 5 to 50 m in width, and is strongly mylonitized as mentioned above. In the southern part of the present area, all the granulites are weakly to strongly mylonitized.

Petrology

In this section, petrography and mineral chemistry of the GO and GC granulites will be described.

1. Petrography of GO and GC granulites

The GC granulite is commonly medium-grained, and shows a gneissose structure with fine banding, 2 to 3 mm thick, of melanocratic and leucocratic layers, whereas the GO granulite is medium- to coarse-grained, and shows a gneissose to massive structure. The GC granulite contains garnet, cordierite, biotite, plagioclase, quartz and subordinate amounts of potash feldspar, sillimanite (fibrolite), opaque minerals, apatite and zircon. The GO granulite contains garnet, hypersthene, cordierite, plagioclase, quartz and small amounts of biotite, potash feldspar, opaque minerals, apatite and zircon.

Garnet occurs as euhedral to subhedral porphyroblasts (2~5 mm in diameter) in both rocks, and rarely includes helictic fibrolite in the GC granulite. Cordierite porphyroblasts (3~7 mm in diameter) are subhedral to irregular, and often alter to pinites. Fibrolite and symplectite composed of fibrolite and hercynite are found only in the GC granulite, which occur as inclusions in some cordierite and garnet porphyroblasts of GC granulite. Biotite in the GC granulite occurs both as granular grains (0.5~1 mm in diameter) in garnet and cordierite and as tabular grains (2~3 mm) arranged parallel to the rock foliation in the matrix. Hypersthene is subhedral to euhedral porphyroblasts 0.3~8 mm in diameter, which include poikiloblasts

of garnet and biotite. These minerals are replaced retrogressively by such minerals as biotite, muscovite, chlorite, gedrite, cumingtonite and zoisite. Plagioclase occurs as subhedral porphyroblasts (2~3 mm) with albite twin but without a zonal structure. Potash feldspar is found as small interstitial patches. Quartz shows an amoeboidal or ribboned shape. Opaque minerals are irregularly shaped ilmenite, pyrrhotite and graphite.

The modal amounts of these minerals are as follows; garnet 8.7~12.0 percent, cordierite 7.0~11.2, biotite 5.7~22.6, plagioclase 47.7~52.2, quartz 12.3~17.7 and small amounts of potash feldspar, and accessory minerals in the GC granulite; garnet 2.1~7.3, hypersthene 10.3~18.5, cordierite 1.0~21.2, biotite 3.4~3.6, plagioclase 40.1~63.4, quartz 9.0~17.8, opaque minerals 1.4~2.3, and small amounts of potash feldspar and accessory minerals in the GO granulite.

2. Mineral chemistry

Chemical compositions of the representative minerals in the GC and GO granulites have been determined by a microprobe analyzer (JEOL JXA-5A in Niigata University and Geological Survey of Japan; JEOL JXA-50A in Hokkaido University).

Garnet

Garnet shows a typical reverse zoning: the core being almandine content (Alm) 64.2~71.9, spessartine (Spe) 0.9~3.4, pyrope (Pyr) 22.2~30.0, grossular (Gro) 1.2~3.5 (mol. percent) in the GC granulite and Alm 58.1~67.6, Spe 1.1~4.8, Pyr 23.5~35.2, Gro 2.6~8.5 in the GO granulite: the rim being Alm 69.6~77.5, Spe 1.2~8.5, Pyr 13.8~26.5, Gro 1.2~5.1 in both rocks. The zonal structure is characterized by a broad core part with almost the same composition and a narrow rim part (10~100 μ m thick) showing rapid decrease in Mg content and increase in Fe, Mn and Ca contents from the interior to rim (Fig. 4). The zoning pattern varies clearly according to the kind of adjacent mineral phases. For example, an abrupt Fe-Mg cation exchange is observed in the case of the contact with biotite, orthopyroxene and cordierite, but such a tendency is not observed

Fig. 4. Composition maps of garnet in granulite. Dots indicate analysed points. The figures in Fe and Mg maps represent values of $100 \times \text{Fe}/(\text{Fe} + \text{Mn} + \text{Mg} + \text{Ca})$ and $100 \times \text{Mg}/(\text{Fe} + \text{Mn} + \text{Mg} + \text{Ca})$, respectively.

at points of contact with plagioclase and quartz. Garnets in the mylonitized granulites show lower content of Mg and higher contents of Ca and Mn at the core (Alm 68.5~73.2, Spe 5.2~10.4, Pyr 12.5~21.3, Gro 2.7~8.1) than those in the non-mylonitized ones. Such garnets are excluded from the P-T estimates, because they are presumed to be out of primary equilibrium due to a post metamorphic event.

Cordierite

The X_{Fe} value of cordierite ranges from 0.16 to 0.36 in the core, but a weak compositional zoning from core to rim is observed in each grain. Cordierite has X_{Fe} value of 0.16~0.29 in the GO granulite and 0.26~0.31 in the GC granulite, whereas cordierite in the GC granulite inclusion in the middle migmatite has higher X_{Fe} value (0.30~0.32) than those in above mentioned rocks. The mylonitized GC granulite contains cordierite of high X_{Fe} value (0.33~0.36) due to the retrograde metamorphism caused by mylonitization.

Biotite

There is a distinct disparity in chemical composition between the two types of biotite in the GC granulite. Biotite included in garnet represents lower value of X_{Fe} (0.35~0.40) than that in the matrix (0.42~0.45), though Ti contents of both biotites are almost the same ($\text{TiO}_2 = 1.3 \sim 5.2$ wt.%). The lower X_{Fe} value of biotite included in garnet may be ascribed to exchange of Mg and Fe cations between garnet and biotite during retrogression. This interpretation is supported by the fact

that biotite in contact with garnet increases in Mg content from core to rim. Therefore, biotite in garnet is excluded from the garnet-biotite geothermometry.

Hypersthene

Hypersthene ranges in En% from 52 to 65 with a predominance in 55~58, and contains Al_2O_3 of 2.5~7.0 wt.% and CaO of 0.02~0.25 wt.%. A weak compositional zonation is recognized by a difference in X_{Mg} value between the core (0.53) and the rim (0.60).

Plagioclase and potash feldspar

Plagioclase ranges in An% from 12 to 36 with a predominance in 22~26 in the GC granulite and from 25 to 45 in the GO granulite. Potash feldspar varies within a limited range of Or 85~89 and Ab 9~12 (mol.%).

Regional metamorphic zonation

In the Main Zone of the Hidaka metamorphic belt, the metamorphic zonation has been made mainly based on the changes in mineral parageneses (Table 1) of pelitic and psammitic metamorphic rocks, which widely occur in the Upper to the Lower sequences (OSANAI, 1985). The changes in mineral parageneses of pelitic and psammitic rocks have been discussed using AFM (THOMPSON, 1957) and A'FM (REINHARDT, 1968) diagrams. However, the mineral parageneses vary depending upon the K_2O content of rocks. Therefore, AKFM tetrahedrons (Fig. 5) are used to clarify the changes in mineral parageneses.

The Main Zone can be divided into five metamorphic zones (zone I-V). The Upper

Fig. 5. AKFM diagrams showing critical mineral parageneses of pelitic to psammitic rocks from zone I to V. Mineral abbreviations are shown in Table 1.

sequence is assigned to zone I and the low-grade part of zone II, while the Lower sequence refers to the high-grade part of zone II, zone III, zone IV, and zone V. Zones III and IV show notable differences in mineral parageneses between pelitic and psammitic rocks owing to the occurrence of orthopyroxene and orthoamphibole (Fig. 5). According to MIYASHIRO (1973) and TURNER (1980), zone I, zone III, and zones IV and V are equivalent to the greenschist, amphibolite, and granulite facies, respectively. Zone II shows a transitional feature from the greenschist facies to the amphibolite facies. Metamorphic reactions separating the zones are as follows (mineral abbreviations are shown in Table 1);

Pelitic rocks

Psammitic rocks

The GO and GC granulites dealt with in the present paper are found in zones IV and V. Reactions forming the granulite-facies assemblages are supported by the facts that garnet is replaced on its rim by hypersthene in the GO granulite (reaction 7) and that garnet and cordierite often contain inclusions of relict biotite and sillimanite (fibrolite) in the GC granulite (reaction 4). A regional metamorphic zonation map in the central part of the Main Zone of the Hidaka metamorphic belt is shown in Fig. 6. The boundaries between each zone are parallel to the general trend of the lithologic boundaries of the Hidaka metamorphic belt, and around the migmatite bodies these are not even locally disturbed (Fig. 6).

P-T conditions of amphibolite- to granulite-facies metamorphism

Metamorphic temperatures have been calculated on GC granulites in terms of garnet-biotite and garnet-cordierite geothermometers,

Fig. 6. Regional metamorphic zonation map of the central part of the Hidaka metamorphic belt. Abbreviations are the same as in Fig. 3.

Table 2. Calculated temperatures based on garnet-biotite geothermometer of garnet-cordierite-biotite (GC) granulite in zones IV and V.

Sample No.	Loc.	X_{Mg}^{Gt}	X_{Mg}^{Bt}	$X_{Al^{VI}}^{Bt}$	X_{Ti}^{Bt}	T1	T2	T3	T4
SBT-81	S	0.269	0.530	0.096	0.074	757	716	859	725
7807	S	0.306	0.599	0.077	0.077	721	690	802	673
7809	S	0.319	0.610	0.102	0.047	726	694	809	776
P-8415	S	0.312	0.613	0.106	0.072	710	682	786	665
HS-80	H	0.297	0.592	0.065	0.078	716	687	794	667
SS-18	H	0.290	0.565	0.062	0.042	742	706	835	770
H-26	H	0.265	0.563	0.107	0.074	702	677	773	658
HS-604	H	0.279	0.570	0.125	0.049	717	687	796	710
TH-01	H	0.251	0.541	0.094	0.075	706	679	779	654
GB-21	H	0.240	0.535	0.069	0.066	695	671	763	661
72309	M	0.253	0.553	0.115	0.049	689	667	753	677
9306*	M	0.206	0.553	0.148	0.046	659	645	708	633
93021*	M	0.180	0.532	0.196	0.013	591	593	611	586

*: mylonitized samples

T1: THOMPSON (1976) ($^{\circ}\text{C}$),
T2: PERCHUK (1977), T3: FERRY
& SPEAR (1978) ($P=6.5$ kb),
T4: INDARES & MARTIGNOLE
(1985) ($P=6.5$ kb). Pressure of
6.5 kb is an average pressure of
GO granulite.
 X_{Mg}^i : $\text{Mg}/(\text{Fe}+\text{Mg})$ of mineral
"i", $X_{Al^{VI}}^{Bt}$: $\text{Al}^{VI}/(\text{Al}^{VI}+\text{Ti}+\text{Fe}$
 $+\text{Mn}+\text{Mg})$ of biotite, X_{Ti}^{Bt} :
 $\text{Ti}/(\text{Al}^{VI}+\text{Ti}+\text{Fe}+\text{Mn}+\text{Mg})$ of
biotite; S: Shizunai River, H:
Horobetsu R., M: Menashun-
betsu R.

and on GO granulites in terms of garnet-orthopyroxene and garnet-cordierite geothermometers. Metamorphic pressures have been calculated on GO granulites by the method of garnet-orthopyroxene-plagioclase-quartz geobarometer. As mentioned before both GC and GO granulites are associated with each other. To estimate the geothermal gradient in the Lower sequence of the Hidaka metamorphic belt, P-T conditions of zone III are also calculated by the method of garnet-biotite geothermometer and garnet-cordierite- Al_2SiO_5 -quartz geobarometer for the GC gneiss.

Coexisting garnet+biotite+cordierite and garnet+hypersthene+plagioclase+quartz are in contact with one another in thin sections. As mentioned above garnet shows an intense reverse zoning. The garnet core, however, may indicate an equilibrium condition at the metamorphic peak, since the core represents a broad and flat compositional profile (Fig. 4). On the other hand, the compositions of the narrow rim of garnet may correspond to the retrograde metamorphism. A slight zoning due to retrograde metamorphism is observed in cordierite, hypersthene and biotite. Therefore, the P-T estimates of the metamorphic peak condition are performed using the

core composition of each mineral.

Temperature estimation

Temperature estimates are made using garnet-biotite geothermometer (THOMPSON, 1976; PERCHUK, 1977; FERRY & SPEAR, 1978; INDARES & MARTIGNOLE, 1985) and garnet-cordierite geothermometer (PERCHUK & LAVRENT'eva, 1983) for GC granulite, and garnet-orthopyroxene geothermometer (HARLEY, 1984) and garnet-cordierite geothermometer for GO granulite.

Fe-Mg distribution between coexisting garnet and biotite is essentially a function of their equilibrium temperature (THOMPSON, 1976; PERCHUK, 1977). However, Fe and Mg are partially replaced by Al and Ti in natural biotite. A positive correlation between Ti in biotite and metamorphic grade, and a correlation between Al^{VI} in biotite and bulk chemical composition of rocks have been discussed (MEHNERT, 1972; DALLMEYER, 1974; DYMEK, 1983; INDARES & MARTIGNOLE, 1984). According to FERRY & SPEAR (1978), their garnet-biotite geothermometer is useful for $(\text{Ca}+\text{Mn})/(\text{Ca}+\text{Mn}+\text{Fe}+\text{Mg}) < 0.2$ in garnet and $(\text{Al}^{VI}+\text{Ti})/(\text{Al}^{VI}+\text{Ti}+\text{Fe}+\text{Mg}) < 0.15$ in biotite. All garnets in the present study are within the limit (0.03~0.11), but the biotites

Table 3. Calculated temperatures based on garnet-cordierite geothermometer of GC and GO granulites in zones IV and V.

Sample No.	Loc.	X_{Mg}^{Gt}	X_{Mg}^{Cd}	K_D	$T(^{\circ}C)^*$
7807**	S	0.302	0.713	5.75	721
7809**	S	0.309	0.731	6.08	704
SBT-81**	S	0.266	0.700	6.34	691
P-8415**	S	0.304	0.720	5.90	713
7806***	S	0.337	0.730	5.32	733
62605***	S	0.296	0.706	5.69	724
100158***	S	0.222	0.625	5.86	716
HS-80**	H	0.290	0.714	6.11	702
TH-01**	H	0.244	0.671	6.33	691
GB-21**	H	0.229	0.636	5.87	715
HS-09***	H	0.325	0.738	5.86	716
HS-416***	H	0.332	0.734	5.56	730
72309**	M	0.245	0.679	6.51	683
9306#	M	0.193	0.641	7.46	643
93021#	M	0.166	0.658	9.69	576

*: pressure (3 - 8 kb)

** : GC granulite, *** : GO granulite

: mylonitized GC granulite

X_{Mg}^I : $Mg/(Fe+Mn+Mg)$ of mineral "i", K_D : $X_{Mg}^{Cd} (1 - X_{Mg}^{Gt}) / (1 - X_{Mg}^{Cd}) X_{Mg}^{Gt}$. T : PERCHUK & LAVRENT'eva (1983). S, H and M are the same as in Table 2.

used here generally have high values (0.14~0.21). On the other hand, INDARES & MAREIGNOLE (1985) pointed out that the validity of their garnet-biotite geothermometry is limited to case where Ti and Al substitutions take place according to reactions $2 \times (R^{2+})^{vi} = (Ti^{4+})^{vi} + ( )^{vi3}$ and $(M^{2+})^{vi} + (Si^{4+})^{iv} = (Al^{3+})^{iv} + (Al^{3+})^{iv}$. The biotites from the GC granulites satisfy these substitutional reactions.

Temperature calculations based on THOMPSON's and PERCHUK's methods show nearly the same values ranging 690°~760°C (average 725°C) with a deviation of 20°~40°C, although temperatures obtained by PERCHUK's are slightly lower than those by THOMPSON's (Table 2). However, temperatures estimated by the geothermometer of FERRY and SPEAR (1978) are high, being 750°~860°C (at P=6.5 kb). These values are conspicuously higher than other estimates. FERRY and SPEAR (1978) suggested that their geothermometer

Table 4. Calculated temperatures based on garnet-orthopyroxene geothermometer of garnet-orthopyroxene-cordierite granulite in zones IV and V.

Sample No.	Loc.	X_{Mg}^{Gt}	X_{Ca}^{Gt}	X_{Mg}^{Opx}	K_D	$T(^{\circ}C)$
7806	S	0.328	0.030	0.578	2.58	750
100158	S	0.215	0.036	0.461	2.63	755
NNC-11 II	S	0.256	0.049	0.512	2.53	770
100173	S	0.295	0.024	0.574	2.61	780
KB-33	S	0.323	0.024	0.511	2.58	750
7708	S	0.301	0.037	0.564	2.77	720
62605	S	0.289	0.027	0.532	2.75	720
81005	S	0.263	0.055	0.532	2.99	690
PT-84	U	0.264	0.030	0.513	2.73	730
NOT-01	U	0.274	0.011	0.513	2.70	720
H-4	H	0.317	0.024	0.550	2.49	775
H-6	H	0.290	0.027	0.524	2.46	780
HS-09	H	0.318	0.019	0.539	2.35	770
HS-416	H	0.317	0.046	0.562	2.53	780

K_D : $(1 - X_{Mg}^{Gt}) X_{Mg}^{Opx} / X_{Mg}^{Gt} (1 - X_{Mg}^{Opx})$, T : HARLEY (1984). S : Shizunai River, U : Moto-urakawa R., H : Horobetsu R.

should be restricted to pairs of garnet with low Ca and Mg contents and biotite with low Ti content. Because of these chemical limitation of minerals, it is not reasonable to use their geothermometer for high-grade metamorphic rocks in zones IV and V. Therefore, these values are omitted from this study. However, these high values are recalculated by INDARES and MARTIGNOLE's method to be 650° to 780°C (ave. 715°C) in temperature which are consistent with temperatures based on THOMPSON's and PERCHUK's methods.

These temperatures are obtained for the rocks from the northern to central part of the studied region. On the other hand, the garnet-biotite pairs from the southern part of the region, where the rocks are mylonitized (samples: 9306, 93021), indicate the lower temperatures (590°~630°C).

Another geothermometer is also employed here for a cross check. The garnet-cordierite geothermometer (PERCHUK & LAVRENT'eva, 1983) is applied for GC and GO granulites. In this thermometer, they suggested that the pressure effect is negligible. The results are listed in Table 3. The garnet-orthopyroxene

Fig. 7. Calculated P-T curves for the granulite-facies rocks. Curves of each calculation method show the maximum and minimum conditions. Pressure interval for the temperature estimation ranges between 4 and 8 kb, and temperature interval for the pressure estimation between 550° and 850 °C. H: HOLDAWAY (1971); RBG: RICHARDSON *et al.* (1969).

geothermometer (HARLEY, 1984) is based on the experimental study in the system $\text{FeO-MgO-Al}_2\text{O}_3\text{-SiO}_2$, in which Fe-Mg distribution between garnet and orthopyroxene largely depends on metamorphic temperatures. The results are listed in Table 4. In this case, the pressure is assumed to be 6.5 kb (see below). The results yielded 700°~780°C (ave. 740°C), which are nearly the same values obtained by the garnet-biotite and garnet-cordierite geothermometers.

The results of these calculations for all samples are shown in Fig. 7; in the pressure interval between 4 and 8 kb. As mentioned above reaction (4) shows a boundary between zones III and IV. Therefore, the curve of the reaction represents the minimum temperature of zone IV (Fig. 7).

In summary, the GC and GO granulites in

zones IV and V have formed at the metamorphic temperatures between 680° and 780°C (ave. 730°C). On the contrary, the metamorphic temperature of the GC gneisses in zone III are estimated to be 540°~620°C (ave. 580°C) using garnet-biotite geothermometers (Table 5).

Pressure estimation

Since the GO granulite alternates with the GC granulite, it is reasonable that an average temperature (ca. 730°C) of the GC granulite is adopted as metamorphic temperature of the GO granulite.

Pressures of the GO granulite are calculated to be 5.8~7.2 kb (ave. 6.5 kb) on the basis of garnet-orthopyroxene-plagioclase-quartz geobarometer (NEWTON & PERKINS, 1982) (Table 6). The results for all samples are shown in Fig. 7; in the temperature interval

Table 5. Metamorphic P-T conditions of garnet-cordierite-biotite (GC) gneisses in zone III.

		$x_{\text{Mg}}^{\text{Gt}}$	$x_{\text{Mg}}^{\text{Bt}}$	$x_{\text{AlVI}}^{\text{Bt}}$	$x_{\text{Ti}}^{\text{Bt}}$	$x_{\text{Mg}}^{\text{Cd}}$	T1	T2	T3	T4	P
73021	N	0.166	0.561	0.198	0.015	0.710	538	551	537	512	5.5
80616	N	0.167	0.519	0.178	0.046	0.590	622	616	652	576	5.5
73025	N	0.142	0.526	0.179	0.031	0.624	578	583	591	544	5.1

Chemical compositions of minerals are analysed by M. MIYOSHI. T1, T2, T3 and T4 are the same as in Table 2. P: average pressure obtained from Fe and Mg end-members (WELLS, 1979). N: Nakanogawa R.

Table 6. Calculated pressures based on garnet-orthopyroxene-plagioclase-quartz geobarometer of garnet-hypersthene-cordierite (GO) granulite in zones IV and V.

		$x_{\text{An}}^{\text{Pl}}$	$x_{\text{Alm}}^{\text{Gt}}$	$x_{\text{Spe}}^{\text{Gt}}$	$x_{\text{Pyr}}^{\text{Gt}}$	$x_{\text{Gro}}^{\text{Gt}}$	$x_{\text{En}}^{\text{Op}}$	$x_{\text{Al}}^{\text{Op}}$	P*
NNC11-II	S	0.361	0.676	0.018	0.256	0.049	0.482	0.143	6.3
62801	S	0.322	0.664	0.041	0.245	0.050	0.507	0.096	6.0
7708	S	0.319	0.646	0.016	0.301	0.037	0.564	0.174	5.8
SP10-1	S	0.467	0.632	0.012	0.296	0.059	0.540	0.120	6.4
KBC	S	0.499	0.659	0.020	0.235	0.085	0.517	0.095	5.9
81003	S	0.382	0.616	0.014	0.311	0.058	0.537	0.140	7.2
7806	S	0.226	0.619	0.027	0.328	0.026	0.578	0.183	6.5
H19A-2	H	0.280	0.648	0.019	0.293	0.041	0.520	0.188	7.2
HS08A	H	0.355	0.622	0.020	0.328	0.030	0.569	0.199	5.6
HS31	H	0.293	0.651	0.011	0.309	0.029	0.566	0.188	5.7
HS391	H	0.342	0.658	0.011	0.284	0.047	0.547	0.170	6.3
HS411	H	0.462	0.581	0.020	0.352	0.048	0.611	0.154	6.2
HS412	H	0.422	0.606	0.020	0.322	0.052	0.597	0.168	6.3
HS416	H	0.423	0.622	0.016	0.317	0.046	0.549	0.177	6.4
7380801	M	0.356	0.676	0.028	0.265	0.031	0.441	0.208	5.8

P*: pressure in kb (NEWTON & PERKINS, 1982) at T=730°C. S, H and M are the same as in Table 2.

from 550° to 850°C.

Metamorphic pressures of GC gneisses in zone III are estimated by the method of garnet-cordierite- Al_2SiO_5 -quartz geobarometer (WELLS, 1979). The results are 5.8~6.4 kb for Fe end-member and 5.3~5.8 kb for Mg end-member (ave. 5.1~5.5 kb) (Table 5).

Discussion and conclusions

The granulite-facies metamorphic rocks occur in the basal part of the Main Zone in the central part of the Hidaka metamorphic belt. The granulite-facies mineral assemblages are also known to occur in other areas of the Main Zone, *e.g.* Pankenushi area (KOMATSU, 1983), Niikappu area (AONO, 1984

MS), Horoman area (HUNAHASHI, 1948; ASAI, 1956) and Nikanbetsu-Abeyaki area (MOTOYOSHI, 1979; OWADA, 1984). Thus, the granulite-facies rocks are distributed extending all over the Hidaka metamorphic belt as a narrow zone (200 to 1500 m wide). At the southern end of the Hidaka metamorphic belt, SHIBA & HARA (1983) showed that the amphibolite-facies rocks have been thermally re-metamorphosed into granulite facies by the migmatite intrusions posterior to the regional metamorphism. However, such an effect of contact metamorphism by intrusions of granite, diorite and migmatite is not recognizable in the present area.

The GO and GC granulites in the Main

Zone of the Hidaka metamorphic belt were metamorphosed under the conditions of ca. 730°C and 5.8~7.2 kb (average 6.5 kb), which correspond to those in the lower crust (19 to 24 km depth). The depth is consistent with the estimated total thickness (20~23 km) of the Main Zone and the overlying Nakano-gawa Group, the lower part of which is considered to be the original sediment of the Upper sequence of the Main Zone (KOMATSU *et al.*, 1982, 1983). The calculated P-T values may reasonably cause the partial melting *in situ* if P_{H_2O} was as high as P_{total} . However, no field evidence indicating anatexis *in situ* is observed in the granulite unit. This is probably due to low X_{H_2O} values (0.1~0.3) in the GC granulite (OSANAI *et al.*, in prep.).

Provided that the granulite unit has the metamorphic temperature of 730°C and that the Main Zone and the overlying Nakano-gawa Group reach 20~23 km in total thickness, the geothermal gradients of 32°~36°C/km are obtained. Furthermore, the geothermal gradient between zone III and zone V is 30°~35°C/km. These geothermal gradients obtained by different ways are almost consistent each other. Estimated P-T conditions of the granulite-facies rocks and the geothermal gradient of the Main Zone are shown in Fig. 8. The P-T fields of zones II, III, IV and V are obtained by the potential geothermo-barometers, reaction curves showing boundaries of each zone, and stable Al_2SiO_5 minerals. The P-T conditions of zones III, IV and V are discussed above, whereas, the conditions of zone II are inferred to be about 450°C and 3.2 kb (MIYOSHI, 1986 MS). The reaction curves are shown in view of the estimated X_{H_2O} values ($X_{H_2O}=0.1\sim0.3$ in zones IV and V, $X_{H_2O}=0.3\sim0.5$ in zone III; OSANAI, 1986). The geothermal gradient of the Main Zone of the Hidaka metamorphic belt corresponds to that of a continent (WINDLEY, 1977) or an active island-arc (SUGIMURA & UYEDA, 1973, p. 163).

The metamorphic rocks of the Lower sequence of the Main Zone indicate $16.3\pm0.6\sim17.5\pm2.2$ Ma by K-Ar dating (SHIBATA *et al.*, 1984). These ages are presumed to in-

Fig. 8. P-T conditions for the metamorphic rocks from the zones II, III, IV and V of the Main Zone. Arrows indicate the progressive P-T path of the Main Zone of Hidaka metamorphic belt.

1: HOLDAWAY (1971), 2: RICHARDSON *et al.* (1969), 3: HIRSCHBERG & WINKLER (1968), 4: KERRICK (1972), 5: HOLDAWAY & LEE (1977), 6: GRANT (1973), 7: WINDLEY (1977).

dicate the time of an upthrust movement of the Main Zone (SHIBATA *et al.*, 1984, KA No. 681, 684, 688; interpret., M. KOMATSU).

In view of above discussions, the Main Zone of the Hidaka metamorphic belt is a part of an island-arc or continental type crustal slab including the lower crust, which thrust up westward over the Western Zone in Miocene time.

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- *: in Japanese, **: in Japanese with English abstract.

〈地名〉

Horobetsu	幌 別	Nakano-dake	中ノ岳	Rakko	楽 古
Horoman	幌 満	Nakanogawa	中ノ川	Shizunai	静 内
Kamui	神 威	Niikappu	新冠	Shunbetsu	春 別
Moto-urakawa	元浦川	Nozuka	野 塚		

(要 旨)

OSANAI, Y., ARITA, K. and BAMBA, M., 1986: P-T conditions of granulite-facies rocks from the Hidaka metamorphic belt, Hokkaido, Japan. *Jour. Geol. Soc. Japan*, **92**, 793-808.

(小山内康人・在田一則・番場光隆, 1986: 日高変成帯, グラニュライト相変成岩類の温度・圧力条件. 地質雑, **92**, 793-808.)

日高変成帯は西帯と主帯から構成され, 日高主衝上断層によって, 後者が前者に衝上している. 主帯は東側の上部層と西側の下部層に区分され, 東から西へ5帯に変成分帯される. 上部層はI帯とII帯の低変成度側, 下部層はII帯の高変成度側〜V帯に相当する. これらは緑色片岩相(I・II帯)からグラニュライト相(IV・V帯)への累進的変成度上昇を示す.

主帯西縁部のIV, V帯に出現するザクロ石—シソ輝石—堇青石グラニュライトおよび, ザクロ石—堇青石—黒雲母グラニュライトは, 主帯の最高変成条件を示す. これらのグラニュライト相変成岩類から, 約 730°C, 6.5kb の変成温度・圧力条件が得られた. この変成条件は, 地下約 23 km の下部地殻の条件に相当する. さらに下部層について地温勾配を推定すると, 約 33°C/km となった.