LETTER

Finding of prehnite-pumpellyite facies metabasites from the Kurosegawa belt in Yatsushiro area, Kyushu, Japan

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Common occurrence of prehnite and pumpellyite is newly identified from metabasites of Tobiishi sub-unit in the Kurosegawa belt, Yatsushiro area, Kyushu, where Ueta (1961) had mapped as a greenschist facies area. Prehnite and pumpellyite are closely associated with chlorite, calcite and quartz, and they mainly occur in white colored veins or in amygdules in metabasites of the relevant area, but actinolite and epidote are rare in them. Pumpellyite is characterized by iron-rich composition (7.2–20.0 wt% as total iron as FeO) and its range almost overlaps with those in prehnite-pumpellyite facies metabasites of Ishizuka (1991). These facts suggest that the metabasites of the Tobiishi sub-unit suffered the prehnite-pumpellyite facies metamorphism, instead of the greenschist facies.

Keywords: Prehnite–pumpellyite facies, Lawsonite–blueschist facies, Kurosegawa belt

INTRODUCTION

The subduction zone has an essential role for the global circulation of solid, fluid and volatile materials between the surface and inside of the Earth at present. Recent progress of thermal modeling has helped to interpret the thermal structures of the descending plate in various types of subduction zone (e.g., Peacock and Wang, 1999; Gerya et al., 2002; Miyazaki and Okumura, 2002). Linking these results with the metamorphic phase petrology can make it possible to predict what type of metamorphism is going on in the present day subduction system, e.g., the lawsonite–blueschist (LBS) can be formed from mid-ocean ridge basalt (MORB) at around 30 km depths in the cold subduction environment and pumpellyite–actinolite (PA), prehnite–pumpellyite (PrP) or prehnite–actinolite (PrA) facies metabasites can be formed in shallower parts than that of the LBS formation (e.g., Peacock and Wang, 1999).

In Japanese Islands, the LBS is mainly reported from the lower grade part of the Kamuikotan belt (e.g., Shibakusa, 1989) and in tectonic blocks or small coherent units from the Kurosegawa belt and Renge belt (e.g., Ueta, 1961; Kato et al., 1984; Maruyama et al., 1984; Tsujimori and Itaya, 1999; Tomiyoshi and Takasu, 2009). Until now, there is neither clear geological nor petrological evidence suggesting what type of metamorphic rocks occupied the lower grade part of the LBS in above mentioned areas, except for the Kamuikotan belt (Ishizuka et al., 1983). In other words, this fact means that the thermal structure in the shallower level of the cold subduction system predicted by the thermal modeling was not certified in nature.

Our recent petrological study in the Kurosegawa belt in Yatsushiro area, Kyushu, have newly identified metabasites that suffered the PrP facies metamorphism to the east of the LBS area, which was originally reported by Ueta (1961). This paper concisely describes the areal extent of PrP zone, and the mode of occurrence and chemical compositions of prehnite and associated metamorphic minerals.

GEOLOGICAL SETTING

The Kurosegawa and Chichibu belts lie between the Usuki-Yatsushiro Tectonic Line, a western extension of the Median Tectonic Line, and the Butsuzo Tectonic Line in central Kyushu (Fig. 1). Ueta (1961) divided the Tobiishi and Shimotake Formations of Kanmera (1952) in the Yatsushiro area into two metamorphic zones based on the...
mode of occurrence of lawsonite (Table 1); zone 1, characterized by the occurrence of LBS, is mostly exposed in the western half of the Tobiishi Formation, and zone 2, characterized by the occurrence of greenstones without lawsonite, is mostly in the Shimotake Formation and the eastern half of Tobiishi Formation. He proposed that the metamorphic grade had increased from the zone 1 to zone 2 and that these metamorphic rocks are the western extension of the Sanbagawa belt.

Although any modern geological and petrological study has not been carried out in this area until the end of 20th century after Ueta (1961), recently Saito et al. (2005) published a detail geologic map. They proposed that serpentinite mélange with metamorphic and plutonic rocks, Paleozoic-Mesozoic strata, and Permian and Jurassic sedimentary complexes belong to the Kurosegawa belt (Fig. 1 and Table 1).

In this area, metabasites are mainly exposed in the Tobiishi Formation of Kanmera (1952), or Hakoishi serpentinite mélange unit and basaltic lava and volcaniclastic rocks of Otao unit belonging to Jurassic sedimentary complex of Saito et al. (2005). We tentatively propose new unit names based on the areal extent of occurrence of metabasites, as Hakoishi and Tobiishi sub-units, from the viewpoint of metamorphic petrology as described below (Fig. 1 and Table 1).

The areal extent of Hakoishi sub-unit is mostly corresponding with those of the western half of Tobiishi Formation of Kanmera (1952) and the Hakoishi serpentinite mélange unit of Saito et al. (2005). Our geologic field mapping revealed that this area is mainly composed of intercalations of LBS and meta-siliceous rocks, in a 2 × 10 km$^2$ extent, and that serpentinite is widely distributed at the southern edge of the sub-unit, but, to the best of our knowledge, it is scarce inside the sub-unit (Ibuki et al., 2008).

The areal extent of the Tobiishi sub-unit in this study is mostly corresponding with those of the eastern half of Tobiishi Formation of Kanmera (1952) and the Otao unit of Saito et al. (2005). The Tobiishi sub-unit is mainly
Prehnite-pumpellyite facies metabasites in Yatsushiro area, Kyushu

Prehnite-pumpellyite facies metabasites in Yatsushiro area, Kyushu composed of close-packed pillow lava (Fig. 2a), pillow breccia and hyaloclastite along with subordinate gabbroic and granitic rocks. Most of them still retain igneous textures and minerals in their matrix, such as ophitic texture and cavities, and they almost lack distinctive penetrative foliation. Metamorphic minerals, such as prehnite and pumpellyite, are mainly developed in veins or cavities, which are ubiquitously developed in metabasites (Figs. 2b–2d). However, neither lawsonite-sodic amphibole nor epidote–actinolite–chlorite assemblages were found from metabasites. Therefore, we tentatively call the eastern half of the Tobiishi Formation of Kanmera (1952) as Tobiishi sub-unit (Fig. 1).

PETROGRAPHY AND MINERALOGY

Petrological study based on more than 200 thin section observation revealed that the LBS and associated rocks are distributed to the west of the Mt. Yayama, i.e., Hakoi-shi sub-unit, and prehnite is a predominant metamorphic mineral in metabasites distributed to the east of Mt. Yayama (Fig. 1), i.e., Tobiishi sub-unit. As the mineral assemblage of the LBS and its areal extent are mostly identical with zone 1 of Ueta (1961), the subsequent description will concentrate on the mode of occurrence of prehnite and associated minerals in the Tobiishi sub-unit, where Ueta (1961) defined as zone 2 suffered the greenschist facies metamorphism.

The mineral identification and their chemical analysis were carried out using a Hitachi S3500H scanning electron-probe microanalyzer (EPMA) equipped with an EDAX energy dispersive X-ray analytical system at Kyoto University. The accelerating voltage and beam current were maintained at 20 kV and 500 pA, respectively.

In metabasites of the Tobiishi sub-unit, prehnite, pumpellyite, chlorite, celadonite, albite, quartz and calcite are main metamorphic minerals along with minor epidote, actinolite, adularia, and titanite in veins and amygdules (Figs. 2b–2d).

Most veins, mainly less than 1 mm and up to a few cm in width, show white color and rare ones show greenish-yellow color in hand specimens. White veins are...
mainly composed of calcite, albite, quartz and prehnite, and greenish-yellow veins are mainly composed of pumpellyite, calcite, celadonite and chlorite. Amygdules are mainly occupied by pumpellyite, chlorite, celadonite, calcite and quartz, but scarce in prehnite and actinolite.

Prehnite shows the yellowish retardation of the first order and the straight extinction (Fig. 2c), and mainly occurs in white colored veins along with quartz, pumpellyite and minor epidote and calcite. The best crystallized prehnite occurs as prisms in veins, measuring 0.1–1.0 mm long (Fig. 2c). As these optical features are almost similar with those of lawsonite, we confirmed prehnite by its chemical analysis using EPMA. Most prehnite has almost ideal composition with scarce amount of FeO (up to 5.0 wt%) of prehnite is developed as vein like form in common prehnite (Fig. 2d and Table 2).

Pumpellyite mainly occurs as aggregates of polysynthetic twining in veins and amygdules and it is pumpellyite-(Al). It generally shows an abnormal retardation represented by light gray to bright bluish gray and two types of pleochroism; X = colorless, Y = pale yellow and Z = yellow and X = pale green, Y = blue green and Z = pale yellowish green (Fig. 2b). Its chemical composition is richer in iron (~ 7–20 wt% as total iron as FeO) than those (~ 7–11 wt% of FeO) of yellowish type.

Chlorite also occurs as aggregates of polysynthetic twining. It can be distinguished from pumpellyite by its lower refractive index and lower retardation of first order bright – dark gray colors. Furthermore, pleochroism of chlorite, such as pale yellow, pale green to colorless, is generally weaker than pumpellyite. EPMA analysis suggests that chlorite is homogeneous in each grain and all analyzed chlorite are clinochlore with Mg# [= Mg/(Mg + Fe)] ranging from 0.50 to 0.65 and Si (p.f.u. on the basis of O = 14) ranging from 3.06 to 3.29.

Calcite is common in white colored veins and amygdules. Epidote rarely occurs as a tiny rounded shaped crystal closely associated with prehnite and pumpellyite in veins but it is absent from the matrix of metabasites (Fig. 2c). Actinolite is also rarely identified at the margin of relict augite. Adularia is rarely detected in white colored veins.

Following mineral assemblages can be identified in the veins and amygdules in excess of quartz:

Vein: Prehnite (Prh) + Pumpellyite (Pmp) + Chlorite (Chl) + Epidote (Ep), Prh ± Pmp ± Chl ± Calcite (Cc),
Amygdule: Mica ± Chl ± Cc,

Pmp ± Chl.

**DISCUSSION AND CONCLUSION**

Prehnite and pumpellyite are diagnostic hydros Ca–Al silicates representing sub-greenschist facies metamorphic rocks that suffered pumpellyite–actinolite (PA), prehnite–pumpellyite (PrP) or prehnite–actinolite (PrA) facies (Seki, 1961; Hashimoto, 1966; Coombs et al., 1976; Liou et al., 1985; Cho and Liou, 1987; Banno, 1998). Although the phase stability relationships among PA–PrP–PrA facies are still under the arguments (e.g., Liou et al., 1985; Beiersdorfer and Day, 1995; Banno, 1998), prehnite ( 5 wt% of H2O) and pumpellyite (~ 7.5 wt% of H2O) are important water storage phases in these metamorphic facies, instead of other hydrous Ca–Al silicates representing blueschist facies, such as lawsonite (~ 11.5 wt% of H2O) and epidote (~ 1.5 wt% of H2O).

Phase petrology of PrP and its associated rocks are mainly described in low-pressure/high-temperature metamorphic environments in nature, e.g., in the Yakuno and Horokanai ophiolites, Japan (Ishiwatari, 1985; Ishizuka, 1985), the Karmutsen contact aureole, Canada (Cho et al., 1986; Cho and Liou, 1987), and other areas referred in Beiersdorfer and Day (1995). In these areas, metabasites recorded the progressive metamorphic change from zeolite, PrP, transitional, greenschist (GS), amphibolite to granulite facies in the order of metamorphic grade. In these areas, characteristic mineral assemblages of metabasites are Prh + Pmp + Ep + Chl ± Cc for PrP, and Ep + actinolite (Act) + Chl for GS. The metabasite of the Tobiishi sub-unit contains Prh + Pmp + Chl + Ep assemblage but not Ep + Act + Chl one.

Chemical compositions of metamorphic minerals are mainly controlled by P–T and chemical environments. In the well re-crystallized system, ferric content of pumpellyite can be used as a temperature indicator based on the following continuous reaction proposed by Nakajima et al. (1977):

\[ \text{Pmp} + \text{Chl} + \text{Qtz} = \text{Ep} + \text{Act} + \text{H}_2\text{O} \]

In the lower grade metabasites, which are free from penetrative deformation, the chemical equilibrium domain is fairly limited as narrow regions, such as in veins, amygdules and small domains defined by the precursor minerals (e.g., Cho and Liou, 1987; Ishizuka, 1991; Beiersdorfer and Day, 1995). However, Ishizuka (1991) pointed out that the composition of pumpellyite is dependent upon the temperature of metamorphism. Pumpellyite composition obtained in this study overlaps with those of PrP or PA facies of Ishizuka (1991), suggesting that the Al content of pumpellyite is a function of temperature and increases as temperature rise, and that the composition of pumpellyite is dependent upon the temperature of metamorphism in low-grade metamorphic rocks. These data also suggest that the metabasite of the Tobiishi sub-unit suffered PrP facies metamorphism.

If the metabasites of the Tobiishi and Hakoishi sub-units once formed a continuous oceanic crust, the study area is a candidate of the first natural example for the proposed thermal model in the subduction zone by Peacock and Wang (1999). Petrogenetic grids applying for the lower grade metabasites predict that PA or lawsonite–actinolite (LA) facies would be stable in the P–T field between those of PrP and LBS facies (e.g., Liou et al., 1985; Beiersdorfer and Day, 1995; Banno, 1998). Furthermore, Saito et al. (2005) mapped the metabasites in Tobiishi sub-unit as an independent unit from those in the Hakoishi sub-unit (Fig. 1). Further geochronological/petrological studies should be required to unravel the subduction history in the study area.

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