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METAMORPHIC CONDITIONS OF HIGH–GRADE MARBLES FROM MOGOK–KYATPYIN AREA OF THE MIDDLE SEGMENT OF THE MOGOK METAMORPHIC BELT, CENTRAL MYANMAR*

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Abstract

The Mogok-Kyatpyin area forming a mountainous region with two distinct valleys of Mogok valley and Kyatpyin valley is well known for its gem minerals. A variety of marbles, calc-silicate rocks, gneisses, migmatites and locally granulites are well exposed with the emplacement of various types of granitoid rocks. The high-grade assemblages of marble samples are characterized by calcite + dolomite + diopside + spinel + graphite with forsterite and clinohumite in some samples. Based on the mineral assemblages and textural relationship, temperature and fluid (T-X_{CO2}) diagrams indicate temperature and X_{CO2} conditions of > 800 °C and > 0.5 at an isobaric pressure of 0.8 GPa for the clinohumite-bearing and forsterite-bearing marble samples for the peak stage. Re-equilibrium texture of clinohumite + tremolite + dolomite indicates a decrease in temperature and X_{CO2} condition, and yields <540 °C and <0.02 at an isobaric pressure of 0.4 GPa. The present study combining with other high-grade areas along the Mogok metamorphic belt suggest widespread distribution of upper amphibolite to granulite facies metamorphism in the middle segment including Mogok-Kyatpyin area. During peak metamorphic stages, the fluid conditions had higher X_{CO2} value. In contrast, decreasing X_{CO2} values with decreasing temperature and pressure might indicate that infiltration of H_2O-rich fluid occurred during retrograde metamorphism.

Keywords: clinohumite, granulite, metamorphic fluid, retrograde

Introduction

The Cenozoic Mogok metamorphic belt, extending for about 1500 km, is exposed at the western margin of the Shan-Thai Block, and forms a prominent part for understanding the continental evolution of Southeast Asia. It consists of meta-igneous rocks and meta-sedimentary rocks with subduction-related granitoid intrusions. Geochronological studies indicate that an assemblage of the Mogok high-grade metamorphic rocks formed during the Paleogene to early Neogene in association with the India–Eurasia continental collision (Bertrand et al., 1999; 2001; Barley et al., 2003; Searle et al., 2007).

Peak metamorphic conditions appear to vary between different parts of the elongated belt, such as the amphibolite facies in the Kyanigan and Kyauske areas (e.g., Searle et al., 2007) and the granulite facies in the northern Mogok region (Yonemura et al., 2013) and the Sagaing ridge (Maw Maw Win et al., 2016). Ye Kyaw Thu et al. (2016) reported a paragneiss with a spinel + quartz assemblage coexisting with Ti-rich biotite (up to 6.9 wt% TiO_2) that formed under granulite facies conditions. These results imply that high-grade metamorphic rocks occur extensively in the western Shan-Thai Block.

However, mineralogical and petrological characteristics of the Mogok metamorphic rocks and their conditions including pressure, temperature and metamorphic fluid have been poorly

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constrained. The present study combining with other reported areas attempts to deduce the metamorphic conditions during the peak and retrograde stages of the marbles rocks, which may provide understanding the metamorphism of the Mogok metamorphic belt.

Geological Setting

The Mogok metamorphic belt occurs along the western margin of the Shan Plateau extending up to about 1500 km from the Gulf of Mantaban through Mogok to eastern Himalayan Syntaxis (Mitchell et al., 2007; Searle et al., 2007). This belt consists of schist, gneiss, quartzite, marble, calc-silicate rock, locally granulite and migmatite with various granitoid intrusions. These metamorphic rocks were regionally metamorphosed under medium- to high-grade amphibolite facies and localized granulite facies conditions (e.g., Barley et al., 2003; Mitchell et al., 2007; Searle et al., 2007; Yonemura et al., 2013; Ye Kyaw Thu et al., 2016; 2017).

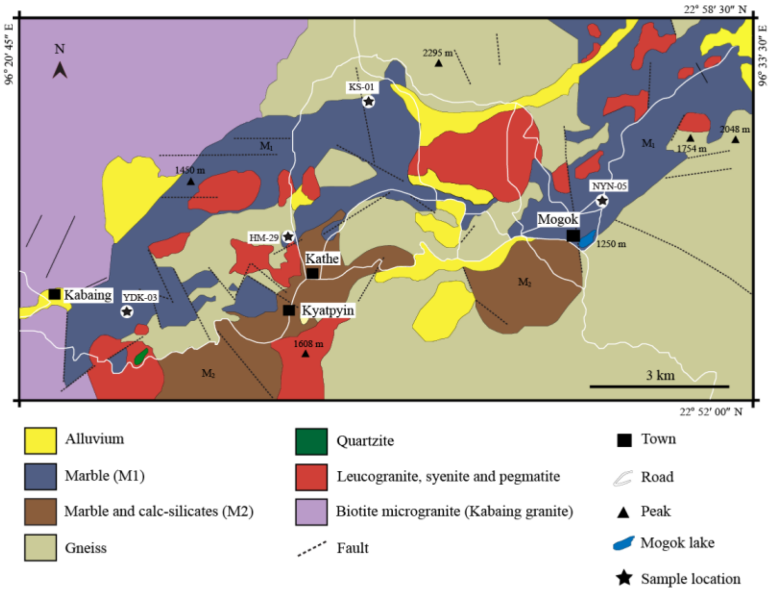

Figure 1 Geological map of the Mogok-Kyatpyin area (simplified from geological maps of Kyaw Thu, 2007; and Themelis, 2008).

A wide variety of marbles are divided into two groups; M1 marbles (gem-bearing marbles) and M2 marbles (non-gem bearing marbles) based on composition, texture and mode of occurrence (Themelis, 2008). The marbles form massive or commonly interbedded with calc-silicate rocks, and show fine to coarse-grained granoblastic texture. Bothe M1 and M2 marble units are widespread in the Mogok-Kyatpyin area and its environs without distinctive configuration.

Diopside marbles are fine to medium grained and frequently associated with calc-silicate rocks. Forsterite-bearing marbles occur as thick-bedded to massive and show medium- to coarse-grained granobastic texture. Clinohumite-bearing marbles are exposed locally and form in massive cliffs and show medium grained granoblastic texture. Among the collected samples clinohumite-bearing marble (KS01 sample), forsterite-bearing marbles (HM29 and NYN05 samples) and diopside-bearing marble (YDK03 sample) are made for detailed studies, and the common constituent minerals of the analyzed marble samples are listed in table 1.

Table 1 Constituent mineral assemblage of marble samples from the Mogok-Kyatpyin area.

Sample	Cal	Dol	Chu	Fo	Spl	Di	Amp	Qz	Phl	Other
KS01	+, i	+	+	+, i	+		r			Gr
HM 29	+,i	+, sym		+			r	+	+	Gr, Pl
NYN05	+, i	+, sym		+	+					Gr, Srp
YDK03	+	+			+	+	r	+		Gr, Ttn

+, present as a primary phase; i, inclusion phase; sym, symplectitic phase; r, retrograde phase.

Petrography of Marble Samples (KS01, HM29, NYN05 and YDK03)

Clinohumite-bearing marble (KS01 sample)

The sample is colleceted from Kyauksin village (latitude 22° 57' 25" N and longitude 96° 25' 36" E), and is characterized by the assemblages of Cal + Dol + Chu + Fo + Spl + Gr.

Calcite grains occur as subhedral to anhedral grains in matrix and as elongated and irregular inclusions in forsterite, spinel and clinohumite grains (Figs. 2a – d). The calcite inclusions range in size fro 0.2 to 1 mm in diameter. Dolomite grains occur as subhedral grains in matrix and intergrown phase with calcite inclusion. The intergrowth phase is rarely observed in matrix dolomite. Forsterite grains occur as irregular or rounded-grains ranging from 0.5 – 1.5 mm in diameter (Fig. 2b). Some forsterite grains occur as inclusion (0.2 mm in diameter) in clinohumite grains. Spinel forms as prismatic porphyroblast or smaller grains (about 0.2 – 2.5 mm in diameter) (Figs. 2a and b). Clinohumite occur as granular to irregular grains and range in size from 1 – 3 mm in diameters (Figs. 2a – d). Some grains contain inclusions of rounded calcite and granular forsterite grains, which is considered to form at a retrograde stage after forsterite. Some grains also form as a corona around dolomite and forsterite (Fig. 2b). The rims of the clinohumite grains are mostly replaced by symplectitic amphibole and dolomite (Figs. 2c and d). Amphibole occurs as elongated grain intergrowing with dolomite around clinohumite grains (Figs. 2c and d). Graphite occurs as minor amount.

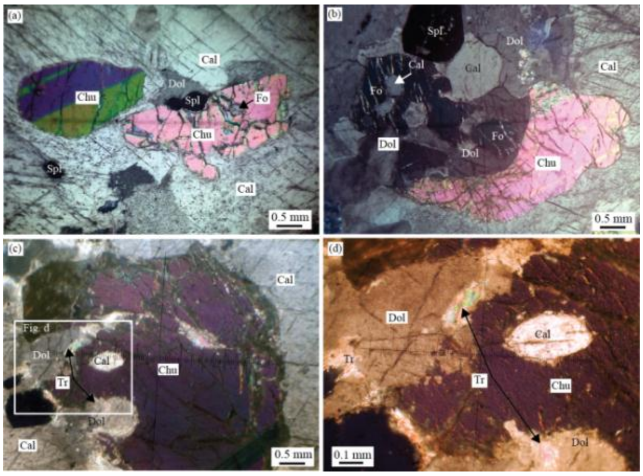

Figure 2 Photomicrographs of clinohumite-bearing marble (KS01 sample) showing (a) subhedral and irregular clinohumite grains (b) granular forsterite grain coexisting with dolomite, and clinohumite which forms corona around forsterite and dolomite (c) intergrowth of tremolite with dolomite around clinohumite grain boundary, (d) enlarged view of the intergrowth of tremolite with dolomite. All photomicrographs are under cross-polarized light.

Forsterite-bearing and diopside-bearing marbles (HM29, NYN05 and YDK03 samples)

Forsterite-bearing samples of HM29 and NYN05 are collected near Kathe (latitude 22° 54' 33" Nand longitude 96° 24' 55" E)and from Ngayantinn (latitude 22° 56' 00" N andlongitude 96° 30' 29" E), and diopside-bearing sample (YDK03) is from (latitude 22° 54′ 23″Nand longitude 96° 22′ 34″ E), respectively. These sample are characterized by Cal + Dol + Fo + Spl + Gr in NYN05 sample (Figs. 3a and b), Cal + Dol + Fo + Phl + Gr in HM29 sample (Figs. 3c and d), and Cal + Dol + Di + Spl + Gr in YDK03 sample (Figs. 3e and f).

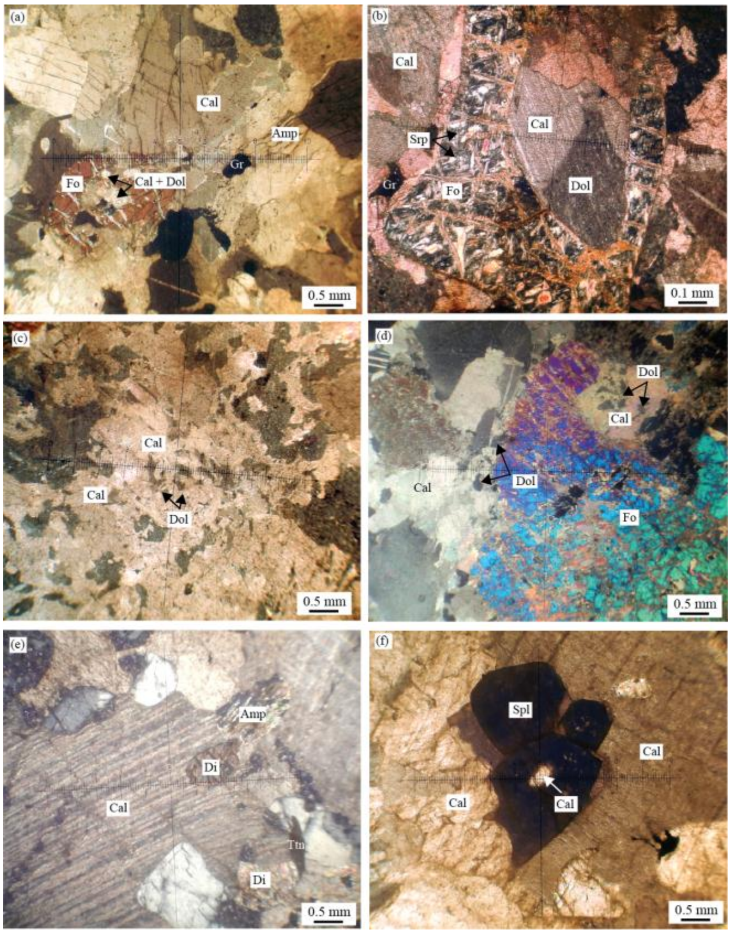

Figure 3 Photomicrographs of forsterite-bearing marble (NYN05 and HM29 samples) and diopside-bearing marble (YDK03) showing (a) granular forsterite grain with calcite inclusion which is intergrown with dolomite (b) enlarged view of the forsterite with inclusion grain of subhedral calcite grain intergrown with dolomite, (c) exsolution blebs of dolomite with different size and shape in matrix, (d) subrounded forsterite grain with calcite and dolomite intergrowths, (e) subhedral diopside grain coexisting with matrix phases and (f) prismatic spinel grain. All photomicrographs are under cross-polarized light.

Calcite grains occur as isolated grain in matrix and inclusions in forsterite and spinel grains (Figs. 3a–d and f). They form subhedral to anhedral in matrix and elliptical or irregular grains (0.5 – 1.5 mm) as inclusion. Dolomite grains occur as subhedral grains, and commonly occur as intergrown phase with calcite both in matrix and in inclusions (Figs. 3a – d). Dolomite grains intergrown with calcite are about 0.5 mm or smaller in size, and tend to form blebs of various shapes. Forsterite grains occur as irregular porphyroblastic grains ranging from 0.5 –

3 mm in diameter in NYN05 sample (Figs. 3 a and b) and up to 5 mm in HM29 sample (Fig. 3d). Some forsterite grains are commonly fractured and partly replaced by serpentine (Fig. 3b). Diopside grains occur as major phase in YDK03 sample. They form subhedral to rounded grains, and range in size from 0.4 – 0.7 mm in diameter, and some grains are replaced by secondary amphibole (Fig. 3e). Spinel forms as smaller prismatic grains with an average size of 0.5 mm in diameter (Fig. 3f). Amphibole grains occur as elongated or prismatic grain in NYN05 and HM29 samples, and as secondary pseudomorph on diopside in YDK03 sample. Phlogopite occurs as a tabular grain in sample HM29. Graphite occurs as minor amount, and serpentine only occurs as pseudomorph or replacement phase on forsterite grains.

T-X_{CO2} Estimates for Clinohumite-Bearing Sample and Forsterite-Bearing Samples

Although the chemical data of mineral are not available for the present study, based on similar mineral assemblages in metacarbonate rocks and textural relationships, T-X_{CO2} diagrams for collected metacarbonate samples were calculated using the analyzed mineral chemical data of marble samples from Onzon, Zayetkwin and Thabeikkyin areas reported by Ye Kyaw Thu and Enami (2018). THERMOCALC software (Powell and Holland, 1988) with an internally consistent thermodynamic data set (Holland and Powell, 1998) has been used to construct the temperature and X_{CO2} relations. The average peak pressure of 0.8 GPa,which was obtained from the reported gneisses from Mogok area (Yonemura et al., 2013) and those from Onzon and Thabeikkyin areas (Ye Kyaw Thu et al., 2016, 2017) was assumed here as an isobaric pressure for the present study.Based on the observed mineral assemblages and textural relationships, T–X_{CO2} grids have been constructed for the system CaO–MgO–SiO_2–H_2O–CO_2 with clinohumite, forsterite, diopside, tremolite, calcite, dolomite and magnesite for marble samples (Fig. 4) at isobaric pressure of 0.8 GPa to determine their relations, temperature conditions, fluid composition and retrogression of marble samples.

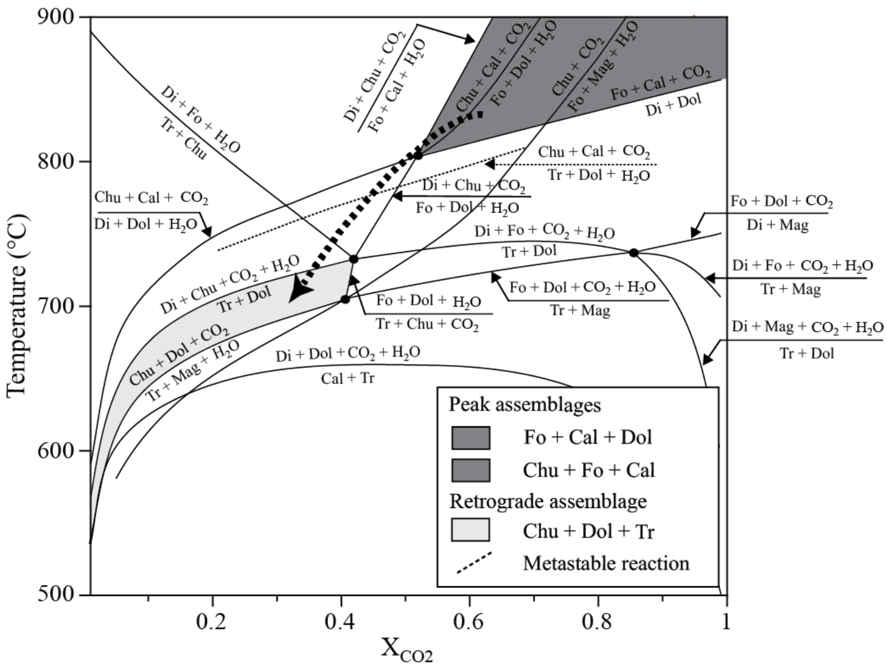

Figure 4 T–X_{CO2} diagram employed for the clinohumite-bearing sample (KS01) and forsterite-bearing samples (HM29 and NYN05) in the system CaO–MgO–SiO_2–H_2O–CO_2 at an isobaric pressure of 0.8 GPa. Dashed arrow shows possible retrogression.

The high-grade assemblage of studied marbles comprises forsterite, clinohumite, calcite and dolomite. Clinohumite grains form corona around forsterite + dolomite grains (Fig. 2b) or some grains contain minute forsterite inclusions (Fig. 2a). The textural relations indicate that forsterite, calcite and dolomite coexist before and during the formation of clinohumite grains, and clinohumite was formed from the following reaction:

4Fo + Dol + H_2O = Cal + Chu + CO_2 (1)

Its stability field displays positive slope in T-X_{CO2} diagram, and a decrease in

X_{CO2} require forming clinohumite from forsterite. The stable assemblage of Chu + Fo + Cal and Fo + Cal + Dol at isobaric pressure of 0.8 GPa yields temperature of > 800 °C andX_{CO2} value of >0.52 (Fig. 4). A further decrease in X_{CO2} results in diopside and clinohumite formation.

14Fo + Cal + $3H_2O$ = 3Chu + Di + CO_2 (2)

Although diopside occurs as a stable phase in associated marble outcrops, it is rare in sample KS01 sample. Instead, tremolite and dolomite occur between calcite and clinohumite grains as symplectite-like intergrowths observed in KS01 sample (Figs. 2c and d), forming the decarbonation reaction

2Chu + 15Cal + $11CO_2$ = Tr + 13Dol + H_2O (3)

Based on the textural relationship and T-X_{CO2} diagram, the retrograde assemblage occurs in association with decrease in pressure, and this overstepped reaction 3 begins to be stable at isobaric pressure of < 0.7 GPa in association with the decrease in temperature and X_{CO2} (Figs. 4 and 5). The temperature and fluid condition of this rectrograde assemblage indicate 530 °C and 0.02 at isobaric pressure of 0.4 GPa with decreasing pressure condition (Fig. 5). The reaction 3 continues under lower X_{CO2} conditions with infiltration of hydrous fluid during retrograde stage.

In HM29 and NYN05 samples, the peak mineral assemblage is forsterite, calcite and dolomite (Figs. 3a – d), and the stability of this assemblage is described by the combination of reaction 1 and the following reaction.

Di + 3Dol = 2Fo + 4Cal + $2CO_2$ (4)

The stable assemblage of Fo + Cal + Dol assemblage at isobaric pressure of 0.8 GPa also yields minimum temperature and X_{CO2} value of 800 °C and higher X_{CO2}value compared with clinohumite-bearing sample for the same compositional conditions (Fig. 4). In addition, based on the inferred assemblages of KS01, NYN05 and HM29 samples Di + Cal + Dol assemblage in YDK03 (Figs. 3e and f) is stable under high temperature and X_{CO2} condition.

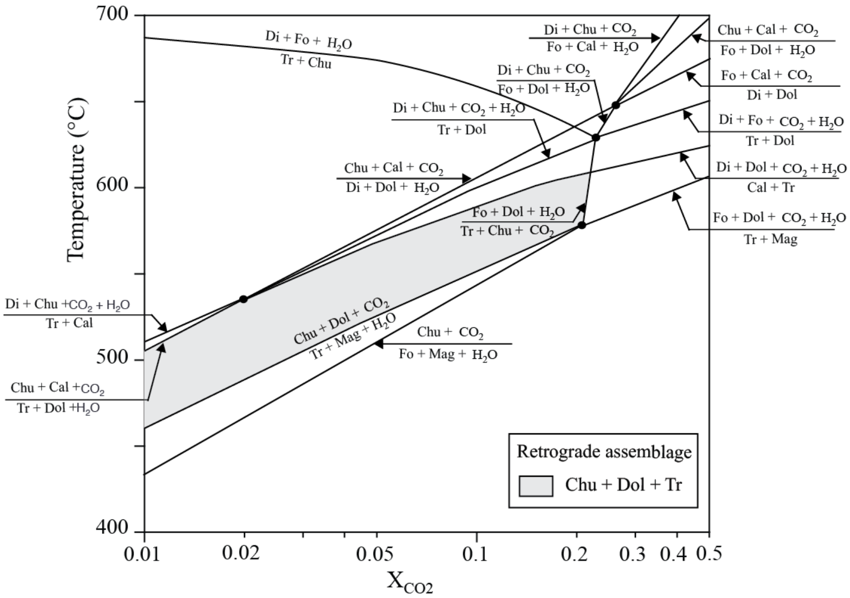

Figure 5 T–X_{CO2} diagram calculated for the retrograde assemblage in the system CaO–MgO–SiO_2–H_2O–CO_2 at isobaric pressure of 0.4 GPa.

Discussion and Conclusion

The high-grade assemblages of marble samples are characterized by Cal + Dol + Chu + Fo + Spl + Gr, Cal + Dol + Fo + Phl + Gr, Cal + Dol + Fo + Spl + Amp + Gr and Cal + Dol + Di + Spl + Ttn + Gr. The minimum temperature and X_{CO2} values suggest 800 °C and 0.52 for the stable assemblage of Chu + Fo + Cal + Dol and 800 °C and higer X_{CO2} value for the stable assemblage of Fo + Cal + Dol assemblage at isobaric pressure of 0.8 GPa. The pressure and temperature condition of 0.60–0.82 GPa/700–860 °C using the conventional geothermobarometers were reported from cordierite-bearing paragneisses and associated garnet-biotite paragneisses of Onzon and Thabeikkyin areas. From the same areas the temperature and X_{CO2} condition of > 780–800 °C and > 0.2 – 0.6 were reported from metacarbonate rock samples (Ye Kyaw Thu and Enami, 2018). Yonemura et al., 2013 reported pressure and temperature of 0.65–0.87 GPa/800–950 °C for garnet–orthopyroxene granulite in the Mogok area. Wai Yan Lai Aung (2016) also reported high-temperature granulite facies metamorphism with the *P-T* conditions of 0.62–0.93 GPa/740–810 °C for spinel and pyroxene-bearing gneiss and garnet-sillimanite gneiss from the Mount Loi-Sau and Pain Pyit areas. These pressure and temperature estimates of paragneiss and metacarbonate rocks are consistent with the present study.

During peak metamorphic stages, the fluid of the analyzed marbles samples had distinctly higher X_{CO2} value (> 0.5) in the fluid, compared with paragneisses which were free of carbonate phases. The migration of fluid phases were limited between carbonate mineral-bearing rocks and paragneisses. Homogenization of composition of metamorphic fluid has not extensively occurred during prograde metamorphic stage. In contrast, low-grade assemblages of tremolite + dolomite intergrowths at the boundary between clinohumite and calcite, and tremolite after diopside indicate significant drop in X_{CO2} (<0.02) at lower temperature. This decrease inX_{CO2} value of carbonate mineral-bearing rocks with decreasing temperature and pressure probably suggest that infiltration of H_2O-rich fluid extensively occurred beyond the lithologic boundaries during retrograde metamorphism.

These homogeneous nature of fluid composition during retrogression suggests hydrous fluid might have been liberated externally from crystallization of accompanied granitic magma. Although one potential source could be related by dehydration reaction of associated paragneisses, that might be unlikely due to homogeneous hydrous fluid composition attended during retrogression, and most of the dehydration reaction might have occurred during prograde stage. In the study area, syn- and post-tectonic granitoid rocks are commonly associated with metacarbonate rocks, and the potential fluid source might be related with the release of crystallization of syn- and post-peak granitoid rocks (late Paleogene to Neogene in age) (Searle et al., 2007; Kyaw Thu, 2007).

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