Multiple origins of UHP eclogites in a garnet peridotite block (Nové Dvory, Czech Republic) and short duration of heating

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The origins of eclogite associated with garnet peridotite in continent–continent collision belts are still debated. We performed petrological studies of eclogites collected from a garnet peridotite block from Nové Dvory in the Gföhl Unit of the Moldanubian Zone in the Variscan orogenic belt, Czech Republic. The eclogite was divided into three types: one kyanite (Ky)–bearing and two Ky–free types. Garnet and omphacite in the Ky–bearing eclogite have lower Fe contents than those in the Ky–free eclogite. Furthermore, the Ky–free eclogite was divided into two types on the basis of Ca content in garnet: Ca–rich (Xgrs > 0.32) and Ca–poor (Xgrs < 0.32) types, except for Ca–poor rim compositions. Application of conventional geothermobarometers to the Ky–bearing type and the Ky–free type with Ca–rich garnet yielded similar pressure–temperature (P–T) conditions (3.2–4.8 GPa and 920–1160 °C) to those of previous studies, whereas the Ky–free type with Ca–poor garnet yielded slightly lower P–T conditions (3.1–3.4 GPa and 950–990 °C) than the other two types. The observed chemical variation of garnet is probably due to the difference in origins, whereby, according to our new results and previous findings, the Ky–bearing eclogite was derived from plagioclase–bearing crustal gabbro, whereas the Ky–free eclogite from Ca–rich garnet was derived from a crystal cumulate possibly in the mantle wedge. In the Ky–free eclogite samples with Ca–poor garnet, chemical compositions of garnet and omphacite are different from those in the other Ky–free samples, and those samples with Ca–poor garnet would have a different origin from the others. One of the Ky–free type with Ca–poor garnet retains garnet grains with chemical zonings probably created during the prograde history, although the eclogite underwent the extremely high temperature (~ 1000 °C) metamorphism. Calculated diffusion distances in garnet reach 0.5 mm during 2 million years, even if we adopted a low value of diffusion coefficient data. Thus, the residence time of the eclogite at the peak metamorphic conditions would have been shorter than at least 2 million years. The subsequent decompression and cooling after the peak metamorphism were also probably very fast to avoid the chemical homogenization of garnet.

Keywords: Bohemian Massif, Eclogite, P–T conditions, Garnet, Peridotite

INTRODUCTION

Since the first discoveries of coesite in metamorphic rocks originating from crustal material (Chopin 1984; Smith 1984), there have been numerous studies of ultra-high-pressure (UHP) metamorphic rocks. Occurrences of UHP eclogites have been recognized mainly from continent–continent collision belts, and UHP eclogite lenses or blocks directly enclosed within gneiss may be derived from mafic igneous rocks in granitic rocks located in shallow levels, as proposed by the in situ model (e.g., Hirajima and Nakamura, 2003). However, the origins of eclogite lenses or layers enclosed in peridotite blocks are not easy to determine because they are surrounded by mantle material (peridotite). In the Gföhl Unit of the Moldanubian Zone in the Variscan orogenic belt, many garnet peridotite blocks occur in country felsic granulate and migmatitic gneiss (crustal material), and several include eclogite as lenses or layers (e.g., Medaris et al., 1990; Medaris et al., 2005). Occurrences of eclogite lenses or blocks directly enclosed in country felsic rocks are very rare in the Gföhl Unit (Medaris et al., 1998). Thus, how and when these peridotite blocks with or without eclogite were entrapped into or juxtaposed with the felsic crustal material remains enigmatic. To elucidate the tec-
tonic processes of their entrapment or juxtaposition, a combination of petrological, geochemical, chronological, and geological studies is required. The petrological study can provide fundamental information on the history of the rock, the pressure-temperature ($P$-$T$) path, and the duration (and/or rate) of metamorphism.

At least two different ideas have been proposed for the origin of eclogite in the Gföhl Unit. One is the high-pressure crystal cumulate origin, in which garnet and clinopyroxene were directly formed from the melt at mantle depths (e.g., Medaris et al., 1995a). The other is the plagioclase-bearing gabbro origin, in which the protolith was formed at plagioclase-stable low-$P$ conditions (Obata et al., 2006). In the study of Obata et al. (2006), three eclogite samples that were collected from one peridotite block (Nové Dvory, Czech Republic) showed positive Sr and Eu anomalies in bulk rock chemical compositions. The peak metamorphic $P$-$T$ conditions of kyanite (Ky)-bearing and Ky-free eclogite samples collected from the same peridotite block (Nové Dvory) have been estimated as 4.5–4.9 GPa and 1050–1150 °C (Nakamura et al., 2004) and 4.3 GPa and 1050 °C (Miyazaki et al., 2016), respectively, with both results showing UH$P$ conditions. However, petrological studies of the three samples analyzed by Obata et al. (2006) have not yet been performed, nor have the metamorphic $P$-$T$ conditions of these samples been determined. Muriuki et al. (2020) classified garnet peridotite from Nové Dvory into three types (A, B, and C) on the basis of chemical and textural features and reported different peak metamorphic $P$-$T$ conditions (ranging from 4.4 GPa and 1035 °C for type A through 5.4 GPa and 1273 °C for type B to 6.3 GPa and 1230 °C type C) through the application of conventional geothermobarometers. Thus, eclogite samples collected from the studied block as well as the garnet peridotite did not necessarily share the same $P$-$T$ path.

In the study of Nakamura et al. (2013), a chemical heterogeneity measuring a few centimeters was found in an eclogite sample (sample ND120), where three types of garnet concerning chemical zoning were recognized: the first type has an Mg-rich core with decreasing Mg content toward the rim; the second type has an Fe-rich core with decreasing Fe content toward the rim; and the third type is nearly homogeneous or shows complex and irregular zoning. Thus, core compositions of garnet differ between the three types of garnet, whereas rim compositions are essentially the same. The differences in garnet core compositions were interpreted to be due to differences in the local chemical composition, and the duration of heating would have been very short (<1 million years) because this small-scale chemical heterogeneity was not erased by element diffusion, even at UHT (~1000 °C) conditions.

Given the above, in this paper we report a comprehensive study of the petrological characteristics of the eclogite samples (including sample ND120) from the Nové Dvory peridotite block to reveal their $P$-$T$ conditions and briefly discuss their origins and tectonic implications.

**GEOLOGICAL SETTING**

The Bohemian Massif is located at the eastern end of the Variscan orogenic belt in Europe (Fig. 1a) and has been divided into four major tectonic zones; i.e., the Teplá-Barrandian, Saxothuringian, Moldanubian, and Moravo-Silesian Zones. The Moldanubian Zone comprises mainly amphibolite–granulite–facies metamorphic rocks, including peridotite and eclogite blocks, and later-intruded granitoid bodies. The Moldanubian Zone consists of three major tectonic units: the basal Monotonous and Varied Units and the overlying Gföhl Unit (e.g., Franke, 1989). Quartz-feldspathic paragneiss is predominant in the Monotonous Unit, and the Varied Unit contains the same rock type together with subordinate quartzite, crystalline limestone, calc-silicate gneiss, and amphibolite. The Gföhl Unit contains garnet-, kyanite-, and biotite-bearing felsic granulate and migmatic gneiss, with minor amounts of pyroxene-bearing granulate (e.g., Carswell and O’Brien, 1993), and these have recently been interpreted as orogenic lower-crustal material (e.g., Schumann et al., 2008). The metamorphic grade is generally higher in the Gföhl Unit than in the Monotonous and Varied Units (e.g., Medaris et al., 1995b). In the Gföhl Unit, peridotite blocks occur sporadically in both the granulite and migmatic gneiss (e.g., Cháh et al., 2007; Janoušek et al., 2020; Fig. 1b), and most of the eclogites are spatially associated with the peridotite blocks (e.g., Medaris et al., 1998). Peridotite in the Gföhl Unit has been classified into three types on the basis of geological, petrological, and geochemical data (Medaris et al., 2005). Type I is spinel and garnet peridotite and is devoid of garnet pyroxenite or eclogite, with estimated $P$-$T$ conditions assigning it to a low-$P$/$T$ regime. Type II peridotite has relatively high Fe contents and abundant garnet pyroxenite layers. Type III is garnet peridotite, including eclogite and garnet pyroxenite layers, and was formed under a moderate $P$/$T$ regime (Medaris et al., 2005).

Eclogite in the Moldanubian Zone has been classified according to geological and petrological data into four groups (M, G, P, and P′; Medaris et al., 1995b). Group M is eclogite that occurs as a large body of metamorphosed mafic rock, group G is enclosed in gneiss, group P is enclosed in peridotite, and group P′ is in...
gneiss but close to ultramafic rocks. Furthermore, the Moldanubian eclogite has been subdivided into high-temperature (>750 °C) and medium-temperature (<750 °C) varieties (Medaris et al., 1995b). The Nové Dvory eclogite studied here is classified into the high-temperature group P eclogite and included by the Type III peridotite in the Gföhl Unit.

The age of high-pressure granulite metamorphism is dated at ~ 340 Ma from U-Pb zircon dating (e.g., Aftalion et al., 1989; Kröner et al., 2000; Sláma et al., 2008) in the southern Bohemian Massif, but older zircon ages of ~ 360 Ma have also been reported and interpreted as protolith formation ages (e.g., Janoušek et al., 2006). U-Th-Pb ages obtained from garnet peridotite in the Gföhl Unit have yielded a weighted mean age of 333.8 ± 4.5 Ma (Naemura et al., 2008). Eclogites from Nové Dvory (the study area) have yielded Sm-Nd ages for garnet-omphacite pairs of ~ 340 Ma, which is very similar to the metamorphic age of the granulites, although eclogites from other areas, such as Biskupice and Bečváry, have yielded different Sm-Nd ages of around 320 and 380 Ma, respectively (Beard et al., 1992; Medaris et al., 1995a).

The peak P-T conditions of the Gföhl Unit have been estimated at around 1.6-2.0 GPa and 900–1100 °C (e.g., Carswell and O’Brien, 1993; Cooke and O’Brien, 2001; Usuki et al., 2017) for granulite and 2-5 GPa and 800–
1100 °C for eclogite (e.g., Nakamura et al., 2004; Medaris et al., 2006; Faryad, 2009; Miyazaki et al., 2016), with some peridotite blocks showing peak $P$ conditions of 3–7 GPa (e.g., Medaris et al., 2006; Faryad, 2009; Naemura et al., 2009, 2011; Muriuki et al., 2020). These data indicate that the estimated $P$–$T$ conditions even within the Gföhl Unit are highly variable depending on differences in both the locality and lithological type. The peridotite block at Nové Dvory (measuring a few kilometers in length) is surrounded by migmatitic gneiss of the Gföhl Unit (Fig. 1) and includes eclogite layers and lenses and minor amounts of garnet pyroxenite. Muriuki et al. (2020) classified the garnet peridotite of this block into three types (A, B, and C) with different textural and chemical features. Type A is garnet peridotite with Cr-rich spinel inclusions hosted by Cr-rich garnet and shows relatively low–$P$–$T$ conditions (4.4–4.5 GPa and 1000–1070 °C). Type B is the most abundant and is a spinel-free garnet peridotite formed under $P$–$T$ conditions of 5.0–5.7 GPa and 1220–1325 °C. Type C is garnet peridotite with Cr-rich spinel in the matrix and Cr-poor spinel in Cr-rich garnet and is chemically heterogeneous, especially in the Cr content of garnet. Orthopyroxene in type C is very low in Al$_2$O$_3$ (~0.4 wt%), and extremely high–$P$ conditions (5.6–7.0 GPa and 1190–1270 °C) have been estimated for this type. Thus, the peak $P$–$T$ conditions vary even within the same peridotite block, suggesting that the origins of the three types of peridotite may have differed. Eclogite included in this block may not have been derived from a single protolith. The locations of the eclogite and garnet peridotite samples studied here and by previous investigations (Nakamura et al., 2004; Miyazaki et al., 2016; Muriuki et al., 2020) are summarized in a geological sketch map in Figure 2.

PETROGRAPHY

The studied samples collected from Nové Dvory are black-colored eclogite containing abundant dark–reddish garnet. Compositional banding created by differences in modal abundances of garnet and clinopyroxene is recognized (Fig. 3). The eclogite samples can be classified by the presence and absence of kyanite into two types. Eight samples were analyzed: four samples are Ky–bearing eclogite (samples ND5, ND128c, ND141, and ND142–1, all of which are boulders), and the other four samples are Ky–free eclogite (samples ND114, ND118, ND120, and ND120–1).

Figure 2. Location map of the studied eclogite samples in the Nové Dvory peridotite block. Locations of eclogite and garnet peridotite samples studied in previous investigations (ND6, Nakamura et al., 2004; ND110, Miyazaki et al., 2016; peridotite, Muriuki et al., 2020) are also shown as gray characters. The peridotite samples were classified into three types (types A, B, and C) by Muriuki et al. (2020). Possible coesite relics were identified from migmatitic gneiss near the peridotite block (Kobayashi et al., 2008). The outline of the peridotite block is based on a diagram by Faryad et al. (2013).

Figure 3. Scanned images of the studied eclogite thin-sections. (a) Kyanite-bearing eclogite (sample ND141). Relatively large oval grains are garnet. (b) Kyanite-free eclogite (sample ND118). Large slightly reddish grains are garnet. Pale–greenish grains are omphacite.
of these samples, two Ky-bearing eclogites (ND141 and ND142–1) were collected from the northern part of the peridotite block (49°05.49′N, 16°04.36′E) and their bulk-rock chemical compositions were analyzed by Obata et al. (2006), and the others were obtained from the southeastern part of this block (49°04.65′N, 16°04.96′E). At the latter locality, samples ND114, ND118, ND120, and ND124 were collected from a 10–m-high cliff of the outcrop, and ND5 and ND128c were boulders from below the cliff (Fig. 2). Mineral abbreviations used in this study follow those of Whitney and Evans (2010).

**Kyanite-bearing eclogite**

Samples ND5, ND128c, ND141, and ND142–1 were classified as kyanite-bearing eclogite. Their main constituent minerals are garnet (Grt), kyanite (Ky), omphacite (Omp), and quartz (Qz) (Figs. 4a–4d), with minor amounts of rutile, biotite, amphibole, and plagioclase. Apatite is also present as an accessory mineral. Many garnet grains are anhedral and measure 1–2 mm in diameter, but larger grains with diameters of >2 mm are also present locally. Most garnet grains in the Ky-bearing eclogite have been partially replaced by fine-grained kelyphite (symplectite replacing garnet) along margins and cracks. Kyanite and omphacite are present both as inclusions in garnet and matrix grains, but kyanite grains in the matrix are almost completely replaced by very fine-grained symplectite composed mainly of spinel and plagioclase (Figs. 4c and 4d). Such replacement of kyanite can be observed in Ky-bearing eclogite that underwent granulite-facies overprinting (e.g., Nakamura and Hira-jima, 2000). Omphacite grains in the matrix are also par-

![Figure 4. Photomicrographs of the studied eclogite thin-sections.](image-url)
tially replaced by symplectite, and their grain sizes range from ~0.1 to 0.5 mm. The sizes of kyanite inclusions in garnet are ~0.1 mm, and those of omphacite inclusions from ~0.1 to 0.5 mm. The sizes of kyanite inclusions in initially replaced by symplectite, and their grain sizes range from ~0.1 to 0.5 mm. The sizes of kyanite inclusions in garnet are also present, and their grain sizes range from ~0.1 to 1.2 mm (Figs. 4e and 4f). Several garnet grains are replaced by thin films of kelyphite, but such replacement of garnet by kelyphite in the Ky-free eclogite is rare compared with the Ky-bearing eclogite. Omphacite grains in the matrix are smaller, many with sizes of <1 mm. They are partially replaced by symplectite composed of Na-poor clinopyroxene and plagioclase and are irregular in shape. Omphacite inclusions in garnet are also present, and their grain sizes range from ~0.1 to 1.2 mm (Figs. 4e and 4f). In sample ND114, garnet grains are relatively small, with many having sizes of 1-2 mm. Some garnet grains in sample ND114 are surrounded by relatively large amphibole grains measuring about 2.5 mm in diameter (Figs. 4g and 4h). Apatite is also present in these eclogite samples but does not appear in sample ND114.

**MINERAL COMPOSITIONS**

Mineral compositions of sample ND120 were determined primarily by the use of a Hitachi S550 scanning electron microscope with an energy-dispersive X-ray analytical system (Kevex 8000 + Kevex Quantum detector) at Kyoto University, Kyoto, Japan. The analytical procedure used followed that of Mori and Kanehira (1984) and Hirajima and Banno (1991). A 20 kV accelerating potential and a 500 pA beam current were employed, with 250 s of live time for counting. The other quantitative analyses were performed using an electron probe micro-analyzer with wavelength-dispersive X-ray spectrometry (JEOL JXA-8230) at Okayama University, Okayama, Japan. Operating conditions of a 15 kV accelerating potential, 20 nA beam current, and 3 μm beam diameter were employed for analyses. Peak and background counting times were set as 10 s and 5 s, respectively, and the Bence and Albee correction procedure was utilized to obtain the elemental compositions of each mineral. The analyzed chemical compositions of garnet and omphacite are listed in Table 1, and the listed compositions were used for P-T estimations with geothermobarometers. In this study, total iron was treated as Fe\(^{2+}\) for both garnet and clinopyroxene. The assumption of Fe\(^{2+}\) = Fe\(^{total}\) in clinopyroxene may cause high deviations from the ‘actual’ values in high oxygen fugacity environments. This assumption in the application of Grt-Cpx Fe-Mg exchange geothermometry may overestimate the temperature, because the presence of Fe\(^{3+}\) in clinopyroxene makes the amounts of Fe\(^{2+}\) and the calculated temperatures be lower than those in the case assuming Fe\(^{2+}\) = Fe\(^{total}\). Yet, we can still obtain information on the maximum temperature limits at the equilibrium stage.

**Garnet**

Garnet in the studied eclogite from Nové Dvory consists primarily of pyrope, grossular, and almandine components with very small amounts of the spessartine component \(X_{\text{grs}} = (\text{Mg} + \text{Fe} + \text{Mn} + \text{Mg} + \text{Ca}) / (\text{Fe} + \text{Mn} + \text{Mg} + \text{Ca}) < 0.03\) in both the Ky-bearing and Ky-free eclogites, and hence the analyzed compositions were plotted onto a Ca-Fe-Mg triangle diagram (Fig. 5). Garnet in the Ky-bearing samples (ND5, ND128c, ND141, and ND142-1) tends to be poor in the almandine component \(X_{\text{alm}} = (\text{Fe} + \text{Mn} + \text{Mg} + \text{Ca}) / (\text{Fe} + \text{Mn} + \text{Mg} + \text{Ca}) = 0.15-0.40\) compared with the Ky-free samples (ND118, ND124, and ND114) \(X_{\text{alm}} = 0.30-0.43\), excluding sample ND120, in which garnet shows clearly Ca-poor compositions \(X_{\text{grs}} = \text{Ca}/(\text{Fe} + \text{Mn} + \text{Mg} + \text{Ca}) = 0.17-0.25\). Garnet in Ky-bearing sample ND128c is slightly richer in Fe \(X_{\text{alm}} = 0.25-0.40\) relative to the other Ky-bearing samples \(X_{\text{alm}} = 0.15-0.35\), and kyanite inclusions in garnet were not observed in ND128c. Except for the two Ky-free samples ND114 and ND120, garnets in both the Ky-bearing and Ky-free types are rich in the grossular component \(X_{\text{grs}} > 0.30\). In a previous study of Ky-bearing eclogite from Nové Dvory (sample ND6; Nakamura et al., 2004), garnet shows Fe-poor and Ca-rich compositions, and the garnet richest in Ca in sample ND6 has a similar composition to that in sample ND141. In another previous study of Ky-free eclogite from Nové Dvory (sample ND110; Miyazaki et al., 2016), garnet has relatively Fe- and Ca-rich compositions that are similar to those of garnet in Ky-free samples ND118 and ND124 studied here. Although samples ND114 and ND120 were classified as Ky-free eclogite, garnets in these samples are distinctly poorer in Ca \(X_{\text{grs}} < 0.32\) in comparison with the other samples. Thus, the Ky-free eclogite can be further subdivided into two subgroups: Ca-rich and Ca-poor subgroups.

In this study, chemical zoning patterns of garnet were carefully examined for several grains in each sample by
Table 1. Representative chemical compositions of garnet and omphacite of the studied samples from Nové Dvory

| Garnet | ND5 | ND128c | ND141 | ND142-1 | ND118 | ND124 | ND114 | ND120 |
|--------|-----|--------|-------|---------|-------|-------|-------|-------|
| SiO₂   | 40.79 | 40.03 | 41.22 | 41.25 | 39.90 | 40.24 | 40.69 | 40.21 |
| TiO₂   | 0.13  | 0.10  | 0.09  | 0.09  | 0.13 | 0.21  | 0.10  | 0.09  |
| Al₂O₃  | 23.59 | 22.93 | 23.15 | 23.57 | 22.25 | 22.47 | 22.79 | 22.14 |
| Cr₂O₃  | 0.00  | 0.03  | 0.05  | 0.09  | 0.02 | 0.07  | 0.03  | 0.00  |
| FeO    | 9.35  | 13.48 | 7.94  | 6.77  | 16.14 | 15.37 | 14.97 | 17.59 |
| MnO    | 0.19  | 0.27  | 0.24  | 0.17  | 0.30 | 0.29  | 0.29  | 0.37  |
| MgO    | 10.89 | 8.80  | 10.63 | 12.58 | 7.94 | 15.38 | 11.91 | 9.19  |
| CaO    | 15.68 | 14.29 | 16.79 | 15.39 | 13.73 | 15.38 | 10.51 | 10.57 |
| Na₂O   | 0.02  | 0.03  | 0.02  | 0.18  | 0.06 | 0.07  | 0.02  | 0.00  |
| K₂O    | 0.00  | 0.00  | 0.02  | 0.06  | 0.00 | 0.00  | 0.00  | 0.00  |
| Total  | 100.64 | 99.96 | 100.15 | 100.15 | 100.47 | 101.63 | 101.31 | 100.16 |

| Omphacite | ND5 | ND128c | ND141 | ND142-1 | ND118 | ND124 | ND114 | ND120 |
|-----------|-----|--------|-------|---------|-------|-------|-------|-------|
| SiO₂      | 54.54 | 55.69 | 54.23 | 54.58 | 55.90 | 55.70 | 55.36 | 54.53 |
| TiO₂      | 0.26 | 0.18  | 0.20  | 0.16  | 0.17  | 0.18  | 0.16  | 0.21  |
| Al₂O₃     | 12.34 | 13.05 | 12.22 | 10.58 | 13.10 | 15.08 | 9.40  | 7.37  |
| Cr₂O₃     | 0.00 | 0.04  | 0.04  | 0.11  | 0.01  | 0.01  | 0.04  | 0.00  |
| FeO       | 2.27 | 2.59  | 1.44  | 1.17  | 4.12  | 3.23  | 3.73  | 5.18  |
| MnO       | 0.00 | 0.00  | 0.04  | 0.07  | 0.04  | 0.06  | 0.06  | 0.00  |
| MgO       | 9.72 | 8.69  | 9.93  | 11.45 | 7.79  | 6.72  | 11.10 | 11.35 |
| CaO       | 15.70 | 13.93 | 16.41 | 17.90 | 12.47 | 11.27 | 16.72 | 17.30 |
| Na₂O      | 5.48 | 6.49  | 5.20  | 4.22  | 7.87  | 8.71  | 5.05  | 4.41  |
| K₂O       | 0.01 | 0.02  | 0.02  | 0.01  | 0.01  | 0.00  | 0.00  | 0.00  |
| Total     | 100.32 | 100.68 | 99.73 | 100.25 | 101.45 | 100.94 | 101.62 | 100.35 |

Formulae of garnet and omphacite were calculated based on total oxygen = 12 and 6, respectively.
For Ky-bearing samples, many garnet grains are nearly homogeneous or have homogeneous cores, with marked decreases in Ca content being observed toward the margins of the grains and near omphacite inclusions (Fig. 6a). However, one large garnet grain with a size of >2 mm in sample ND142-1 shows a slight increase in Ca content from the core ($X_{\text{grs}} = \sim 0.35$) to the rim ($X_{\text{grs}} = \sim 0.40$) (Fig. 6b). Such an increase in Ca content of garnet from core to rim has been already reported for Ky-bearing sample ND6 (Nakamura et al., 2004).

In Ky-free samples ND118, ND124, and ND120 (but not sample ND114), garnet grains have relatively large sizes ranging from ~1 to 6 mm in diameter but have nearly homogeneous cores with decreases in Ca content toward the rims and near omphacite inclusions (Fig. 6c). However, in sample ND124, a large garnet grain with a size exceeding 5 mm, which includes a composite omphacite inclusion (Figs. 4e and 4f), has an asymmetric and complex chemical zoning pattern, and Ca contents vary markedly across this grain (Fig. 6d). In Ky-free samples ND118, ND124, and ND114, Fe/Mg ratios of garnet are relatively constant within each sample, but those of garnet from sample ND120 vary spatially in thin-section and even within single grains. Therefore, we describe chemical structures of sample ND120 and garnet compositions and zoning in the following section.

**Figure 5.** Compositions of garnet from the studied eclogite samples plotted on a Ca-Fe-Mg ternary diagram. Garnet in the kyanite-bearing samples (ND5, ND128c, ND141, and ND142-1) is relatively poor in the almandine component in comparison with the kyanite-free samples (ND118, ND124, ND114, and ND120). Except for samples ND114 and ND120, garnets in both types are rich in the grossular component ($X_{\text{ca}} = \sim \text{Ca/(Fe + Mg + Ca)} > 0.30$).

Macroscopic chemical structures of sample ND120

In sample ND120, garnet and Na-rich clinopyroxene are the main constituents in the matrix, and abundant rutile and minor amounts of apatite are also present as accessory minerals. Both garnet and clinopyroxene grains are anhedral and oval-shaped. The sizes of clinopyroxene are mostly <1.0 mm, and those of garnet range from ~1 to 10 mm. Replacement of garnet by kelyphite is rare. The development of symplectite after Na-rich clinopyroxene is also rare, but biotite, plagioclase, and brown amphibole are present as secondary low- to medium-pressure phases. The presence of biotite and amphibole in eclogite generally indicates the influx of fluid into eclogite during the exhumation stage (e.g., Heinrich, 1982).

Compositional banding is unclear under the naked eye but is revealed by wide-range X-ray mapping. The X-ray mapping analysis was conducted on a thin slab with a size of approximately 8 cm × 5 cm using a wave-length-dispersive X-ray spectrometer (JEOL JXA-8105) at Kyoto University, Kyoto, Japan. The obtained X-ray maps are shown in Figure 7 and display clear compositional banding primarily with respect to Ti content. Fe-poor garnet grains, which are abundant in the area bounded by the broken white line in Figure 7, tend to be in Ti-poor regions (Figs. 7a and 7c). Several large garnet grains with high Mg contents are recognized within the Ti-poor region on the presented plane (Fig. 7b). The Ca contents are essentially uniform throughout this plane (Fig. 7d), although several garnet grains show slight zoning in Ca content. The formation mechanisms of this banded structure and the variations in Ti, Fe, and Mg contents are discussed below in the section entitled ‘Origins of the banded structure in Ky-free eclogite (ND120).

Further observations on garnet zoning patterns of sample ND120 allow four types of garnet to be recognized. The first type is Fe type, which preserves an Fe-rich core with increasing pyrope content toward the rim. The Fe-rich core has Mg$^\#$ [$= 100 \times \text{Mg/(Fe + Mg)}$] values of 30-40, and the Fe-poor rim has Mg$^\#$ values of ~50 (Fig. 8). The grossular content ($X_{\text{grs}}$) of this type of garnet is nearly constant at approximately 0.20-0.25. The second type is Mg type, which preserves an Mg-rich core with increasing almandine content toward the rim. The Mg-rich core has Mg$^\#$ = 60-70, and the Fe-rich rim has Mg$^\#$ = ~50 (Fig. 8). The grossular content of this type increases slightly from core ($X_{\text{grs}} = 0.19-0.23$) to rim ($X_{\text{grs}} = 0.20-0.25$). The rim compositions of these two types of garnet coincide with each other. The diameters of the Fe-type garnet grains are approximately 1-2 mm, whereas those of the Mg-type grains are approximately 1.5-10 mm. The third type is nearly homogeneous garnet.
Figure 6. Compositional profiles of representative garnet grains. (a) Garnet including an omphacite (Omp) inclusion in a kyanite-bearing sample (ND5). (b) Garnet with a relatively Ca-poor core in a kyanite-bearing sample (ND142-1). (c) Garnet including an omphacite inclusion in a kyanite-free sample (ND124). (d) Garnet including a composite omphacite inclusion in a kyanite-free sample (ND124). Mg, Mg/(Fe + Mn + Mg + Ca); Ca, Ca/(Fe + Mn + Mg + Ca); Fe, Fe/(Fe + Mn + Mg + Ca); Mn, Mn/(Fe + Mn + Mg + Ca); 2-Si, 2-Si a.p.f.u. (O = 6).

Figure 7. X-ray element mapping images of an eclogite slab from sample ND120. Banding structures are not clear in the Fe content map (a), but Fe-poor garnet grains (pale-green areas) are recognized in the left-upper-side portion bounded roughly by the broken white line. Blue-colored areas are primarily clinopyroxene. (b) Mg content map of the slab. Several greenish areas located in the left-upper-side portion are garnet with Mg-rich compositions. (c) Ti content map of the slab. Small white Ti-rich particles create a banding structure, with a few layers being enriched in these Ti-rich particles. (d) Ca content map of the slab. Several garnet grains display slight zoning in Ca content.
with compositions similar to those of rims of the Fe– and Mg–type garnets, but it is necessary to consider the possibility that we are looking at a plane cutting the rim of an Fe– or Mg–type garnet grain. The fourth type is the Ca–type, which has complex characteristics and shows wide variation in Ca content. The Ca contents in the core and mantle of this type are slightly higher ($X_{\text{grs}} = 0.25–0.30$) than those of the other types of garnet, but rims of this type show similar compositions to the rims of other types.

Figure 8 shows the distribution of the four types of garnet grain in a thin–section. The garnet zoning patterns were checked by back–scattered electron (BSE) images. This thin–section can be divided into two parts according to the distributions of Fe– and Mg–type garnets: one is an Fe–rich part, in which Fe–type garnets are present, and the other is an Fe–poor part, in which Mg–type garnets are present (Fig. 8). The BSE images and compositional profiles of representative Fe– and Mg–type garnets are also shown in Figure 8. Core compositions are quite different, but rim compositions are similar to each other. Near–homogeneous and Ca–type garnet grains are distributed in both of the two aforementioned parts of the studied thin–section.

**Clinopyroxene**

Clinopyroxene in the studied samples is primarily omphacite with compositions of $\text{Na}/(\text{Ca} + \text{Na}) > 0.20$. There are distinct differences in chemical composition between omphacite inclusions in garnet and matrix grains (Fig. 9). In Ky–bearing samples, omphacite inclusions have higher jadeite contents [maximum Na/(Ca + Na) value of 0.46] than those of matrix grains [Na/(Ca + Na) < 0.32]. The Ca–Tschermak (defined as CaAl$_2$SiO$_6$) contents of omphacite inclusions tend to be lower (maximum Si value is 1.98 a.p.f.u. based on O = 6) than those of matrix grains (Si < 1.92 a.p.f.u., excluding one low–Na datum). A positive relationship is observed between Si content and Na/(Ca + Na) ratio. In addition, omphacite inclusions tend to show higher Mg# values than those of matrix grains in each sample (Fig. 9). These chemical differences between inclusions in garnet and matrix grains are also recognized in Ky–free samples but are not as distinct compared with the chemical differences in Ky–bearing samples (Fig. 9).

In Ky–free samples with relatively Ca–poor garnet (ND114 and ND120), the Na contents of omphacite are clearly lower $\text{Na}/(\text{Ca} + \text{Na}) = \approx 0.3$ than those in the
other Ky–free samples [Na/(Ca + Na) > 0.4, except for some data from grain margins]. Mg# values of omphacite in sample ND114 are high (~84) compared with other Ky–free samples ND118 and ND124 (Mg# < 82). In contrast, the Mg# values of omphacite in sample ND120 are widely scattered and range from ~70 to 85. In this sample, omphacite inclusions in Fe–type garnet show low Mg# values (~70–77), and those in Mg–type garnet display high Mg# values (~85). Clinopyroxene in the matrix and omphacite inclusions in homogeneous garnet show intermediate Mg# values of ~80 in ND120. Mg# values of omphacite inclusions in these samples likely reflect those of the host garnet grains, namely, omphacite inclusions with high Mg# are hosted in high-Mg# garnet grains (Figs. 5 and 9), and Mg# values of omphacite grains in the Ky–bearing eclogite are generally higher than those in the Ky–free eclogite (samples ND118 and ND124), excluding eclogite with Ca–poor garnet and Na–poor omphacite (samples ND114 and ND120). Furthermore, omphacite grains in the Ky–bearing eclogites show clearly lower Na contents [Na/(Ca + Na) < 0.46] than those in the Ky–free eclogites with Ca–rich garnet (samples ND118 and ND124) [Na/(Ca + Na) = 0.44 to 0.58, excluding several data from grain margins]. A weak negative relationship between Mg# and Na/(Ca + Na) of omphacite can be recognized, whereby omphacite with high Mg# shows low Na/(Ca + Na) (e.g., sample ND142–1), and that with low Mg# is high in Na/(Ca + Na) (samples ND118 and ND124; Fig. 9). All studied omphacite inclusions in garnet in both the Ky–bearing and Ky–free eclogites show zoning, with decreasing Na and Si contents from core to rim (Fig. 6a), whereas the
ESTIMATIONS OF P–T

Here we examine the peak metamorphic P–T conditions of the studied eclogite samples. We used a conventional garnet and clinopyroxene Fe–Mg exchange geothermometer for the temperature calculation. The formulation of this geothermometer of Nakamura (2009) was adopted for the calculation. For the pressure calculation, conventional geobarometers, a garnet–clinopyroxene–kyanite–SiO₂ phase (GCKS) geobarometer and a garnet–clinopyroxene geobarometer, were utilized. The former is based on the equilibrium reaction of Mg₂Al₃Si₅O₁₂ (pyrope) + Ca₃Al₂Si₃O₁₂ (grossular) + 2SiO₂ (coesite or quartz) = 2Al₂SiO₅ (kyanite) + 3CaMgSi₂O₆ (diopside), and the latter on the reaction of 2Ca₃Al₂Si₅O₁₂ (grossular) + Mg₃Al₂Si₃O₁₂ (pyrope) = 3CaMgSi₂O₆ (diopside) + 3CaAl₂Si₃O₆ (Ca–Tschermak). The thermodynamic dataset of Holland and Powell (1998) was adopted to calculate the Gibbs free energy of each mineral endmember (enthalpy, entropy, volume, and their correction parameters), and the activity models of pyrope, grossular, and diopside proposed by Nakamura and Banno (1997) were used for the GCKS geobarometer, which is the same method as that utilized by Nakamura et al. (2004) and was also applied to the Ky-bearing eclogites studied here. Beyer et al. (2015) proposed a new formulation of the garnet-clinopyroxene geobarometer designed for eclogite, and we adopted their model and applied it to both the Ky-bearing and Ky-free eclogites studied here.

As described above, a relatively large garnet grain in Ky-bearing sample ND142–1 shows chemical zoning with increasing Ca content from core to rim (Fig. 6b), which probably reflects the increase in pressure during the growth of this grain. At least, in kyanite–quartz–coesite-bearing eclogite, the following mass transfer reaction, 3CaMgSi₂O₆ + 2Al₂SiO₅ = 2Ca₁.₅Mg₁.₅Al₂Si₃O₁₂ + 2SiO₂, proceeds with increasing of pressure. Thus, garnet coexisting with kyanite and SiO₂ phase in eclogite should become rich in Ca at the expense of diopside component in omphacite and kyanite and make its composition approach to Ca₁.₅Mg₁.₅Al₂Si₃O₁₂. However, many garnet grains have nearly homogeneous Ca-rich cores with decreasing Ca content toward the grain margins and near omphacite inclusions (e.g., Fig. 6a and c), except for sample ND120. Such decreases in the Ca content of garnet generally reflect chemical modifications of the mineral during the decompression stage (e.g., Nakamura and Banno, 1997). In contrast, omphacite inclusions in garnet tend to have compositions that are more enriched in Na and Si relative to matrix grains (Fig. 9), and the most Na-rich composition within each grain is preserved in its core (Figs. 6a and 6c). Such Na-rich core compositions of omphacite inclusions in garnet probably preserve compositions at the peak P stage, as recognized by Nakamura et al. (2004). Therefore, we assumed the most Ca-rich core of garnet and the most Na-rich core of an omphacite inclusion in each sample as the equilibrium pair at the peak P stage and adopted it for the P–T estimation of each sample.

In this study, we analyzed four samples of Ky-bearing eclogite (ND5, ND128c, ND141, and ND142–1). Two samples (ND5 and ND128c) were collected from the southeastern part of the studied peridotite block, and two samples (ND141 and ND142–1) were collected from the northern part of the block (Fig. 2). The calculated P–T conditions of these Ky-bearing samples fall in the range of 3.2–4.8 GPa and 920–1160 °C. Values of P and T, however, differ slightly among the four samples (Fig. 10). The estimated P–T conditions for sample ND5 include especially high temperature (~ 1140 °C), and the three P–T curves for the Fe–Mg exchange thermometer, GCKS barometer, and Grt–Cpx barometer intersect at nearly identical P–T conditions (~ 4.2 GPa and 1140 °C). However, sample ND128c shows relatively low P–T conditions.
and their Ca contents are relatively constant (Fig. 8). In addition, samples ND141 and ND142–1 display wide-ranging P–T conditions of 3.2–4.8 GPa and 960–1160 °C and 3.3–4.6 GPa and 920–1100 °C, respectively. These varied P–T conditions may be due to potential uncertainties of the geothermobarometers, such as effect of clinopyroxene composition on the Fe–Mg distribution coefficient suggested by Hirajima (1996) and Nakamura et al. (2015). Although sample ND128c shows relatively low-P–T conditions, the P–T conditions of the Ky-bearing samples collected from the northern and southeastern parts of the block are fairly consistent between the two localities.

We analyzed four samples of Ky-free eclogite (ND118, ND124, ND114, and ND120). For these samples, the GCKS barometer is not available, and hence the combination of the Fe–Mg exchange thermometer and the Grt-Cpx barometer was utilized. All of these samples were collected from the southeastern part of the block. Samples ND118 and ND124 contain Ca-rich garnet (Fig. 5) and Na-rich omphacite (Fig. 9), and their calculated P–T conditions are in the range of 4.2–4.5 GPa and 1080–1110 °C (Fig. 10). In comparison, samples ND114 and ND120 with Ca-poor garnet and Na-poor omphacite showed slightly lower pressures, and the P–T conditions calculated for these samples are in the range of 3.1–3.4 GPa and 950–990 °C (Fig. 10). Garnets in sample ND120 show different zoning patterns from those in the other samples, whereby their Mg# values vary substantially within individual grains of Fe- and Mg-type garnets, and their Ca contents are relatively constant (Fig. 8). Therefore, a pair of the Na-rich core composition of an omphacite inclusion within a homogeneous garnet grain and the composition of the host garnet was used for the P–T estimation of ND120. The estimated P–T conditions for samples ND114 and ND120 (Ca-poor subgroup) are relatively low. The chemical compositions of garnet and omphacite clearly differ between the Ca-rich and Ca-poor subgroups (Figs. 5 and 9), and such differences may not have been caused by chemical modifications of garnet and omphacite during cooling, and are probably due to the difference in bulk-rock chemical composition between the two subgroups. The peak temperatures were probably different between them.

**DISCUSSION**

**P–T conditions**

A previous study of a Ky-bearing eclogite sample (ND6) collected from the southeastern part of the studied peridotite block estimated P–T conditions of 4.5–4.9 GPa and 1050–1150 °C (Nakamura et al., 2004), which overlap the range of P–T conditions estimated in the present study for the Ky-bearing eclogite (3.2–4.8 GPa and 920–1160 °C). This study supports the conclusion that the eclogite in this block underwent UHP metamorphism. On the other hand, two Ky-free eclogite samples (ND118 and ND124) gave P–T conditions of 4.2–4.5 GPa and 1080–1110 °C in this study. These P–T conditions are reasonably consistent with those reported for Ky-free eclogite sample ND110 from the same block (~ 4.3 GPa and 1050 °C; Miyazaki et al., 2016) and overlap with the above results for the Ky-bearing samples. As shown in Figure 10, the P–T conditions obtained from the previous studies (Nakamura et al., 2004; Miyazaki et al., 2016) and this study, except for samples ND114 and ND120, fall in the range of 3.2–4.9 GPa and 920–1160 °C, and most of the eclogite in the Nové Dvory garnet peridotite block probably shared the same P–T history at least during and after the peak P stage. In contrast, two samples of Ky-free eclogite with Ca-poor garnet (ND114 and ND120) showed slightly low-P conditions within the range of 3.1–3.4 GPa and 950–990 °C. Furthermore, garnet and omphacite in these samples are distinctly low in grossular and jadeite contents, respectively. Chemical modification of garnet and omphacite during the exhumation of eclogite can change their compositions to low-P types, such as Ca-poor garnet and Na-poor omphacite, but the development of kelyphite around garnet and symplectite after omphacite is relatively rare in samples ND114 and ND120. Some parts of eclogite in the studied block may have had a different P–T history from the majority of eclogite in the block.

P–T conditions of garnet peridotite from the studied block were recently reexamined by Muriuki et al. (2020). As mentioned above, those authors classified the garnet peridotite of this block into three types: A, B, and C. The classification was based on textural and chemical characteristics of constituent minerals, but the estimated P–T conditions of the peak metamorphic stage also differed among the three types. Type A contains spinel inclusions in garnet and displays P–T conditions of 4.4–4.5 GPa and 1000–1070 °C, which are substantially lower than those of the other types (5.0–5.7 GPa and 1220–1325 °C for type B and 5.6–7.0 GPa and 1190–1270 °C for type C). The estimated P–T conditions for type A are approximately the same as the conditions estimated here for the majority of eclogite samples (3.2–4.9 GPa and 920–1160 °C), excluding samples ND114 and ND120. The presence of spinel and Ca amphibole inclusions in garnet has been reported from type A peridotite and interpreted as precursor minerals of a relatively low-P stage (Muriuki et al., 2020). This is consistent with the presence of garnet zoning with increasing Ca content toward the rims.
in eclogite from this block (Nakamura et al., 2004; Miyazaki et al., 2016) (Fig. 6b), as such increasing Ca content in garnet also indicates increasing pressure applied onto the eclogite, as discussed in the above section entitled ‘ESTIMATIONS OF $P$–$T$’. Thus, the majority of the eclogite and some parts of the peridotite (type A) in this block underwent increasing pressure over time and reached depths of ~ 150 km, corresponding to lithostatic

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**Origins of the Ky–bearing eclogite and Ky–free eclogite with Ca-rich garnet**

A comparison of the chemical compositions of the Ky–bearing eclogite samples with those of the Ky–free eclogite samples with Ca-rich garnet (ND118 and ND124) shows that Mg# values are clearly different in both garnet and omphacite (Figs. 5 and 9). According to the bulk chemical composition data for eclogite and garnet pyroxenite from the Czech Republic reported by Medaris et al. (1995a), there is a chemical gap in Mg# between 62 and 70. Obata et al. (2006) pointed out that the Mg-rich group with Mg# > 70 originated in gabbro formed under plagioclase-stable conditions and that the Fe-rich group may have a different origin, such as high-$P$ crystal cumulate (e.g., Medaris et al., 1995a). Svojtka et al. (2016) considered that Nové Dvory garnet pyroxenite originated as high-$P$ cumulate from basaltic melts with variable proportions of recycled oceanic crust. Yasumoto et al. (2018) proposed that a Ky–free eclogite sample from Nové Dvory containing a Cr-rich band with a thickness of <1 cm originated in an intrusion of pyroxenitic melt. As shown in the present study, garnet and omphacite of Ky–bearing eclogite have higher Mg# values than those of Ky–free eclogite (ND118 and ND124; Figs. 5 and 9). Thus, the Ky–bearing eclogite could have been derived from gabbro that might have been formed in plagioclase-stable crustal depths, and the Ky–free eclogite with Ca-rich garnet (excluding ND114 and ND120 with Ca-poor garnet and Na-poor omphacite) and garnet pyroxenite were probably high-$P$ cumulate formed in the mantle wedge. Miyazaki et al. (2016) found a garnet megacryst showing a clear increase in Ca content toward the rim in a Ky–free eclogite sample (ND110) and suggested that the eclogite underwent a marked increase in pressure before the peak $P$ stage of 4.3 GPa and 1050 °C. The Ky–free eclogite samples with Ca-rich garnet and garnet pyroxenite would have originally been located in relatively shallow mantle wedge, then moved downward along the mantle convection flow and reached UHP conditions.

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**Origin of the banding structure in Ky–free eclogite (ND120)**

Sample ND120 of the Ky–free subgroup with Ca-poor garnet and Na-poor omphacite shows wide variations in Mg# both for garnet and omphacite (Figs. 5 and 9). In this sample, Fe-type garnets with Fe-rich core and Mg-type garnets with Mg-rich core are observed at a normal thin-section scale (less than a few centimeters), and their chemical compositions approach each other toward the rims which have almost identical Mg# (Fig. 8). The distribution of Fe-type garnet grains creates an Fe-rich part of the thin-section, and the Mg-type garnet grains occupy the other part of the thin-section (Fig. 8). However, banding structures are not clear in the Fe content map, although a clear banding structure consisting of Ti-rich and Ti-poor layers is recognized in the Ti content map (Fig. 7). Fe-poor garnet grains tend to be present in the Ti-poor layers, but the boundary between the Fe-poor and Fe-rich parts is obscure. In addition, the boundary between them is curved and not parallel to the banding structure of Ti content (Fig. 7). In contrast, several Mg-rich garnet grains (greenish areas in Figure 7b) are observed in a Ti-poor layer and form a band nearly parallel to the layers defined by Ti content (Fig. 7).

The parallel banding structure shown by Ti content could not have been generated by influx of fluid or melt, nor by mechanical mixing of different rocks, as such processes would be expected to form irregularly shaped boundaries. Instead, processes involved in igneous protolith formation could explain the formation of the parallel banding structure, as observed in layered mafic intrusions such as the Bushveld Complex in South Africa and the Skaergaard Intrusion on the eastern coast of Greenland (e.g., Hess, 1989). Such layered mafic intrusions are huge (>100 km$^2$), and each layer created by crystal settling would be thicker than that observed in the studied sample. However, banding structures can also be observed in smaller gabbroic intrusions (~ 200 m in thickness); for example, the Murotomisaki Gabbroic Complex, Japan (Hoshide et al., 2006). In that gabbroic complex, the modal abundances of olivine vary from 10 to 20 vol% within a thickness of ~ 2 m (Hoshide et al., 2006). The thickness of each Ti-rich layer in ND120 is, nevertheless, relatively thin, ranging from approximately 0.5–1.5 cm. Such thin layers may have been created by ductile deformation of the original banding structure during high-$P$ metamorphism. In this case, changes in the crystal settling abundances of a Ti-rich phase (probably ilmenite) on the bottom of a magma chamber could form the banding structure of Ti content. However, the Fe-poor and Mg-rich part of this sample is extremely rich in Mg, and garnet
has Mg# values of up to 70, whereas garnet in the Fe-rich part has low Mg# values of ~40 (Figs. 5 and 8). Such a wide variation in Mg# may be difficult to create within a single magma chamber, but the Mg-rich and Fe- and Ti-poor part may have been an olivine-rich domain at the protolith formation stage.

Relatively large homogeneous garnet grains are also present in this sample (Fig. 8). It is not clear why some garnet grains preserve chemical zoning, whereas the others are chemically homogeneous. One possible reason is that heterogeneity of bulk chemical composition was present even within each part or layer, and so nucleated garnet grains, that is, cores of garnet, would have different chemical compositions depending on their locations. Then, their compositions would have changed and approached each other, as shown by the core-rim patterns in Figure 8. We cannot fully explain the mechanism for the formation of this texture, but garnet zoning observed in sample ND120 is unlikely to reflect changing \(P-T\) conditions and was instead probably created by the relaxation of an igneous banding structure owing to the enhancement of grain-boundary diffusivity associated with increasing temperature.

**Residence time at the peak metamorphic stage**

Here, simple calculations on diffusion distances in garnet were performed. We used diffusion coefficients determined by experiments at 2.8 GPa and 1057 °C (Ganguly et al., 1998). The used diffusion coefficients are self-diffusion data of Mg and Fe, but diffusion rates depend on the chemical composition of garnet, oxygen fugacity as well as pressure and temperature conditions. Thereby, we selected to use such simple diffusion data as well as a simple calculation method [i.e., \(x = (Dt)^{0.5}\)], where \(x\) is a diffusion distance (mid-concentration distance), \(D\) is a diffusion coefficient, and \(t\) is time. The calculated results showed that the diffusion distance reached 1 mm during 0.3 million years for Mg, while 2 million years were required to reach a diffusion distance of 0.5 mm for Fe (Fig. 11). Considering these results and a tendency that element diffusivities are generally enhanced by an increase of metamorphic temperature, the preservation of chemical zonings of garnet in sample ND120 (Fig. 8), probably created during the prograde history, indicate that the residence time of the sample at the peak metamorphic (probably peak \(P-T\)) stage should be shorter than at least 2 million years. Thus, the duration of heating at the peak \(P-T\) stage was geologically short, and so the descending eclogite would have quickly changed its travelling direction to upward. After that, the eclogite may have undergone a rapid decompression and cooling.

Prograde garnet zoning has also been documented in a Ky-bearing eclogite sample of the Kutná Hora Complex, northern part of the Moldanubian Zone, with peak \(P-T\) conditions estimated as 3.4 GPa and 900 °C (Faryad, 2009), although a different \(P-T\) path (isobaric heating at crustal levels after isothermal decompression from UHP conditions) has been proposed for UHP granulite from the Kutná Hora Complex of the Moldanubian Zone (Jedlicka et al., 2015). The peak temperatures estimated by Faryad (2009) are slightly lower compared with temperatures estimated for the eclogites in this study, but the preservation of prograde zoning in garnet at 900 °C also suggests a relatively short duration of heating (Faryad, 2009). Prograde garnet zoning has also been found in high-\(P\) granulite from the Gfohl Unit (e.g., Carswell and O’Brien, 1993) and in garnet-rich gneiss at Ktiš from the Lhenice shear zone of the southern Bohemian Massif (Kobayashi et al., 2011). The garnet-rich gneiss also underwent high-\(T\) metamorphism of approximately 800–900 °C. In addition, monazite grains included in the core and rim of prograde–zoned garnet and those in the matrix of the garnet-rich gneiss at Ktiš give the same Th–U–Pb ages of 336–335 Ma, suggesting extremely high exhumation rates (Kobayashi et al., 2012). These facts indicate that the duration of granulite–facies metamorphism was very short in the Moldanubian Zone of the Bohemian Massif. Besides, very rapid burial and subsequent high exhumation rates of eclogite–facies rocks are also documented by the preservation of early–stage mineral inclusions in garnet, as well as by the presence of prograde garnet zoning in granulate from the Gfohl Unit (Faryad et al., 2010).
CONCLUSIONS

We performed petrological studies of eclogites collected from a garnet peridotite block from Nové Dvory in the Gföhl Unit of the Moldanubian Zone in the Variscan orogenic belt, Czech Republic. The estimated P–T conditions of the studied eclogite, except for two samples with Ca-poor garnet (ND114 and ND120), are in the range of 3.2–4.8 GPa and 920–1160 °C, and no clear difference was recognized in P–T conditions between Ky–bearing eclogites and the Ky-free eclogites with Ca-rich garnet. The samples were collected not only from the southeastern part of the peridotite block (samples ND5, ND128c, ND118, and ND124) but also from the northern part of the block (samples ND141 and ND142–1). A distinct variation in P–T conditions depending on location in the peridotite block was not detected. However, a difference in the peak P–T conditions was detected within the southeastern part of the block, whereby two samples (ND114 and ND120) displayed slightly lower P–T conditions (3.1–3.4 GPa and 950–990 °C) than the other eclogites.

Compositional differences of garnet and omphacite in eclogites of the studied block allowed three source rocks to be identified: gabbro in lower crust (Ky–bearing eclogite), melt intrusion in mantle wedge (Ky–free eclogite with Ca-rich Grt), and possibly mafic intrusion in the continental crust (Ky–free eclogite with Ca-poor Grt).

During the Variscan orogeny, the gabbro in the lower crust and type A peridotite of Muriuki et al. (2020) were subducted to depths of 120–150 km, following which the gabbro was metamorphosed to become Ky–bearing eclogite. Simultaneously, the melt intrusion in the mantle wedge on the hangingwall side of the subducting slab was also transported along the mantle convection flow to depths of 120–150 km and formed the Ky–free eclogite with Ca-rich Grt. These two types of eclogite were probably juxtaposed during their peak P metamorphic stage. Subsequently, the mafic intrusion in the continental crust may have been subducted to a depth of ~100 km along with crustal material and was metamorphosed to become Ky–free eclogite with Ca-poor Grt. There is little evidence that the continental crust surrounding the peridotite block sank to a depth of 100 km (UHP conditions), but Kobayashi et al. (2008) reported possible coesite relics as inclusions in zircon from country gneiss collected from the northern edge of the Nové Dvory block.

The retention of compositional zoning of garnet in the eclogite (ND120) created before the peak metamorphic stage suggests that duration of heating of at least some eclogite in this block was very short (<2 million years) and its rapid decompression and cooling would be also necessary.

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