Evidence for partial melting of eclogite from the Moldanubian Zone of the Bohemian Massif, Czech Republic

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Eclogites from the Moldanubian Zone of the Bohemian Massif (Czech Republic) have experienced ultrahigh-pressure (UHP) and ultrahigh-temperature (UHT) metamorphic conditions ($P > 4.0$ GPa, $T > 1000$ °C). One eclogite sample collected from Nové Dvory, eastern part of Czech Republic, contains leucocratic pockets. The mineral assemblage of the melanocratic part of the eclogite is garnet + omphacite + rutile + later-stage minerals (biotite + amphibole + plagioclase). The leucocratic pockets mainly consist of plagioclase and include moderate amounts of garnet and clinopyroxene + small amounts of biotite and amphibole. Garnet and clinopyroxene grains in the leucocratic pockets display faceted shapes whereas those in the melanocratic part show irregular shapes. These are consistent with the idea that garnet and clinopyroxene grains in the leucocratic pockets had been surrounded by melt, as melt can provide free space for the formation of such faceted shapes. The major and trace element composition of garnet grains in the melanocratic part are the same as those in the leucocratic pockets. Clinopyroxene also shows the same major and trace element composition for irregular shape grains in the melanocratic part as faceted grains in the leucocratic pockets. If the melt had originated from the gneiss surrounding the peridotite body with eclogite lenses or layers, the composition of clinopyroxene in the leucocratic pockets would have been completely different from that in the melanocratic part. In addition, the trace element composition of melt estimated from clinopyroxene composition resembles that of Tonalite ~Trondjhemite ~Granodiorite (TTG), which can be produced by partial melting of eclogite. Thus, these observational and analytical data suggest that the leucocratic pockets were originally melt that was internally produced by partial melting of the eclogite.

Keywords: Partial melting, Eclogite, Leucocratic pockets, Bohemian Massif, Moldanubian Zone

INTRODUCTION

Tonalite–Trondjhemite–Granodiorite (TTG) and adakitic rocks can be derived from partial melting of subducting oceanic basalt or gabbro (e.g., Defant and Drummond, 1990; Rapp et al., 2003). Thus, slab melting can generate andesitic melt that can be a source of continental crust, if young and hot oceanic crust was subducted. Thereby, the study of natural partially molten eclogite can give us precious information about the mechanism of continental crust formation and is important for the elucidation of the evolution process of the Earth. However, evidence for partial melting of natural eclogite has been rarely reported, except for a few examples (e.g., Konilov et al., 2011; Chen et al., 2012; Gao et al., 2012). Konilov et al. (2011) and Chen et al. (2012) reported the presence of felsic veins in eclogite and interpreted that the felsic veins were products of partial melting of eclogite. Konilov et al. (2011) showed that the trace element compositions of the felsic veins were very similar to those of the average TTG and experimental melt of eclogite, whereas the trace-element compositions of the felsic veins reported by Chen et al. (2012) are quite different from the natural TTG compositions. Other works (e.g., Gao et al., 2012) treated the presence of multiphase solid (MS) inclusions as evidence for partial melting of eclogite, although Gao et al. (2012) did not estimate the chemical composition of
the melt from the MS inclusions.

An eclogite sample with leucocratic pockets (<2.0 cm) was collected from Nové Dvory located in the eastern part of Czech Republic. On the origin of the eclogite from Nové Dvory, two possible hypotheses have been proposed: gabbroic origin at the plagioclase fraction, and in the leucocratic pockets. In addition, we estimated trace-element compositions of clinopyroxene in the leucocratic pockets in conjunction with partition coefficients between clinopyroxene and the melt. This study will give insight into the nature of the partial melting process of eclogite.

GEOLOGICAL OUTLINE

The Bohemian Massif is situated at the eastern end of the Variscan orogenic belt, which is divided into the northern Saxothuringian Zone and the southern Moldanubian Zone. The Moldanubian Zone is further subdivided into the structurally lower Monotonous and Varied units and higher Gföhl unit (e.g., Matte et al., 1990). The latter Gföhl unit mainly consists of felsic granulite and migmatic gneiss which include sporadically distributed garnet peridotite masses or layers with and without eclogite (e.g., Medaris et al., 1990; 2005). One eclogite layer without peridotite occurs within the felsic Gföhl granulite in the central part of Czech Republic (near the village of Spáčice) (Medaris et al., 1998). Geothermo-barometric calculations suggest that several eclogite and garnet peridotite masses in the Gföhl unit experienced UHP conditions (e.g., Nakamura et al., 2004; Medaris et al., 2006; Naemura et al., 2009). On the other hand, evidence for UHP metamorphism of felsic granulite and gneiss in the Bohemian Massif is rare, but a few findings of microdiamond and coesite from such felsic rocks have been recently reported (e.g., Kobayashi et al., 2008; Kotková et al., 2011; Perraki and Faryad, 2014), indicating that some garnet peridotite masses and surrounding felsic rocks may have shared the same P-T history, although peak P-T conditions of granulite in the Gföhl unit have been estimated to be approximately 1.6–2.0 GPa, 900–1100 °C (e.g., Carswell and O’Brien, 1993).

The study area, Nové Dvory, is located in the eastern part of the Bohemian Massif, where a garnet peridotite mass, including several eclogite layers, with a size of approximately 2 km² occurs and is surrounded by migmatic gneiss (Medaris et al., 1990). The Nové Dvory peridotite has been interpreted as part of former mantle wedge material, and eclogite layers are believed to represent high-P cumulates from silicate melt (Medaris et al., 2005). Obata et al. (2006) have proposed that kyanite-quartz eclogite was originally low-P cumulus gabbro and then subjected to an increase in pressure up to mantle depths. The studied eclogite sample including leucocratic pockets was collected from the southeastern part of this peridotite mass (49°04′39″N, 16°05′E). Three samples of eclogites from Nové Dvory yield Sm-Nd Grt-Cpx-WR isochron ages of 332–342 Ma (Beard et al., 1992), which is approximately the same as the metamorphic age (~ 340 Ma) of the Gföhl granulites (e.g., Sláma et al., 2008), although eclogites from other areas, such as Biskupice and Bečváře, have yielded different Sm-Nd ages of around 320 and 380 Ma, respectively (Beard et al., 1992).

PETROGRAPHY

Eclogite from the study area can be divided into kyanite-bearing and kyanite-free types. Most of the kyanite-bearing eclogite samples include quartz (probably transformed from coesite), whereas many of kyanite-free samples lack quartz and consist mainly of garnet and clinopyroxene with small amounts of rutile, apatite and opaque minerals as well as later-stage phases such as plagioclase, amphibole and biotite. Hydrous minerals of the UHP stage such as epidote and phengite are absent from both types of eclogite, which is probably due to the extremely high-temperature conditions that these eclogites have experienced. Detailed petrological characteristics of kyanite-bearing eclogite from this locality are described in Nakamura et al. (2004).

The sample selected for this study (ND110) is kyanite-free and quartz-free dark-green bi-mineralic eclogite with leucocratic pockets that mainly comprise large
plagioclase crystals (Fig. 1). The leucocratic pockets lack quartz as well as in their host (the remnant melanocratic part), but contain garnet and clinopyroxene crystals. Other constituent minerals are rutile and later-stage biotite and dark-green or brown amphibole occurring mainly in the melanocratic part (Fig. 1). However, small amounts of biotite and amphibole are also present in the leucocratic pockets (Fig. 2). The chemical composition of garnet grains varies depending on their locations and sizes. We classify them into three types: (1) a garnet megacryst with a diameter of approximately 15 mm in the melanocratic part (Fig. 1b) (Grt I), (2) garnet grains in the melanocratic part (Grt II), and (3) garnet grains in the leucocratic pockets (Grt III). Except for Grt I, sizes of garnet grains are generally less than 3 mm. Some garnet grains are partially replaced by kelyphite. Clinopyroxene is present in both garnet (Grt II and III) and the matrix. Grt I also include clinopyroxene near its margin. We classified clinopyroxene into three types: clinopyroxene in the melanocratic part (Cpx II), clinopyroxene in the leucocratic pockets (Cpx III), and small omphacite inclusions (50–200 µm in diameter) within the garnet grains (Cpx I) located both in the leucocratic pockets and the melanocratic part. Some Cpx I included in Grt II and III show negative crystal or euhedral shapes. Cpx II is partially replaced by augite + plagioclase symplectite in some places, whereas Cpx III contains many inclusions of plagioclase and shows relatively coarse-grained symplectite-like texture (Fig. 2). The plagioclase inclusions in Cpx III show different extinction angles from the surrounding large plagioclase grains (Fig. 2d).

The shapes of garnet and clinopyroxene differ depending on the locations. Grt II and Cpx II in the melanocratic part show irregular shapes, whereas some Grt III and almost all Cpx III in the leucocratic pockets show faceted shapes (Fig. 2). These observations are consistent with the idea that the leucocratic pockets were originally melts, which allowed garnet and clinopyroxene to grow as faceted grains.

MINERALOGY

Analytical procedures

Mineral compositions in five thin sections (ND110A, ND110C, ND110D, ND110E, and ND110F) made from one fist-sized sample (ND110) were analyzed with the Electron Probe Micro Analyzer (EPMA), primarily at Okayama University. Trace element mineral compositions in two thin sections (ND110A and ND110C) were analyzed with the Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS) at Kanazawa University and the Czech Academy of Sciences. Quantitative analyses of major elements were performed with wavelength-dispersive X-ray spectrometry at Okayama University (JEOL JXA-8230) and at Kyoto University (JEOL JXA-8105). A 15-kV accelerating potential and a 20-nA beam current were employed in the analyses at Okayama University. Choice of standards is as follows: quartz (SiO₂) for Si, rutile (TiO₂) for Ti, corundum (Al₂O₃) for Al, eskolaite (Cr₂O₃) for Cr, hematite (Fe₂O₃) for Fe, manganosite (MnO) for Mn, periclase
Figure 2. Photomicrographs of the studied eclogite from Nové Dvory. Abbreviations: Grt, garnet; Pl, plagioclase; Cpx, clinopyroxene; Bt, biotite; Amp, amphibole; Ap, apatite. (a) Irregular shape garnet grain in the melanocratic part (ND110A). Plane-polarized light. (b) Faceted shape garnet grain surrounded by plagioclase in the leucocratic pocket (ND110A). Plane-polarized light. (c) Irregular shape clinopyroxene grains containing several plagioclase inclusions in the melanocratic part (ND110A). Crossed polars view. (d) Faceted shape clinopyroxene grains in the leucocratic pocket (ND110C). These grains contain many small plagioclase inclusions and are partially replaced by fine-grained symplectites. Crossed polars view. (e) Faceted shape clinopyroxene grains in the leucocratic pocket (ND110A). Small biotite and amphibole grains are present in this area. Plane-polarized light. (f) Crossed polars view of (e). The clinopyroxene grains are surrounded by single plagioclase grain. (g) Faceted shape clinopyroxene grains in the leucocratic pocket (ND110C). Plane-polarized light. (h) Crossed polars view of (g). Also in this area, several clinopyroxene grains are surrounded by single plagioclase grain.
(MgO) for Mg, wollastonite (CaSiO₃) for Ca, jadeite (NaAlSi₂O₆) for Na, and potassium titanyl phosphate (KTiOPO₄) for K. Representative compositions of the constituent minerals in the thin section ND110A are listed in Table 1.

Trace element (Ti, Rb, Sr, Y, Zr, Nb, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Th, Yb, Lu, Ta, Th, and U) compositions of garnet, clinopyroxene, amphibole, and biotite were determined by LA-ICP-MS at Kanazawa University (Morishita et al., 2005). Each analysis of minerals was performed by single-spot ablation, 50 µm in diameter, at a repetition rate of 6 Hz with an energy density of 8–10 J/cm². NIST 612 glass was used as external reference material for calibration, and its reference values were selected from data by Pearce et al. (1997). Data reduction was facilitated using Si as an internal standard element, based on SiO₂ content determined by EPMA, following a protocol essentially outlined by Longerich et al. (1996). NIST 614 glass was measured for quality control of each measurement session. The precision of analyses estimated from NIST 614 data is better than 4% (1-sigma relative standard deviation: RSD) for all elements (Table 2).

Representative major element compositions of constituent minerals in the thin section ND110A are listed in Table 1.

Trace element (Ti, Rh, Sr, Y, Zr, Nb, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tb, Yb, Lu, Ta, Th, and U) compositions of garnet, clinopyroxene, amphibole, and biotite were determined by LA-ICP-MS at Kanazawa University (Morishita et al., 2005). Each analysis of minerals was performed by single-spot ablation, 50 µm in diameter, at a repetition rate of 6 Hz with an energy density of 8 J/cm². NIST 612 glass was used as external reference material for calibration, and its reference values were selected from data by Pearce et al. (1997). Data reduction was facilitated using Si as an internal standard element, based on SiO₂ content determined by EPMA, following a protocol essentially outlined by Longerich et al. (1996). NIST 614 glass was measured for quality control of each measurement session. The precision of analyses estimated from NIST 614 data is better than 4% (1-sigma relative standard deviation: RSD) for all elements (Table 2).

Compositions of plagioclase in the leucocratic pocket and a garnet megacryst were analyzed by LA-ICP-MS at Institute of Geology of the Czech Academy of Sciences (New Wave Research UP-213 and Thermo-Finnigan Element 2). The laser was fired at a repetition rate of 20 Hz with a beam size of 55 µm in diameter and an energy density of 8–10 J/cm². The data were calibrated against NIST 612 glass using the recommended values from Jochum et al. (2011), and the internal standardization with Ca was used. The precision of the laser ablation analyses ranges between 2 and 6% (as RSD) for most of the detected elements. The accuracy was monitored by analyzing soda-lime float glass NIST 1830 and was compared with the values published by Flem and Bédard (2002), varying between 5 and 20% for most of elements. Representative mineral trace element data are listed in Table 2.

**Major elements compositions**

Garnet in the studied sample mainly comprises almandine \(X_{\text{alm}} = [\text{Fe}/(\text{Fe} + \text{Mg} + \text{Mn} + \text{Ca})] \approx 0.4\), pyrope \(X_{\text{prp}} = [\text{Mg}/(\text{Fe} + \text{Mg} + \text{Mn} + \text{Ca})] \approx 0.3\), and grossular \(X_{\text{grs}} = [\text{Ca}/(\text{Fe} + \text{Mg} + \text{Mn} + \text{Ca})] \approx 0.3\) components with small amounts of spessartine \(X_{\text{sps}} = [\text{Mn}/(\text{Fe} + \text{Mg} + \text{Mn} + \text{Ca})] < 0.02\). Three types of garnet were
recognized, as described in the previous chapter. The first type (Grt I) has a relatively homogeneous core composition of $X_{\text{aln}} \approx 0.45$, $X_{\text{prp}} \approx 0.37$, $X_{\text{grs}} \approx 0.16$, and $X_{\text{sps}} \approx 0.02$ and shows a significant increase in Ca content, decreasing in Fe and Mg content toward the margin of the grain, where the composition is $X_{\text{aln}} \approx 0.40$, $X_{\text{prp}} \approx 0.30$, and $X_{\text{grs}} \approx 0.30$ (Fig. 3a). The second type of garnet in the melanocratic part (Grt II) is homogeneous and shows similar composition to the margin of Grt I (Fig. 3b). This Ca-rich composition probably reflects the equilibrated states at the peak-P stage of this eclogite. The third type of garnet in the melanocratic part (Grt II) is homogeneous and shows similar composition to the margin of Grt I (Fig. 3b). This Ca-rich composition probably reflects the equilibrated states at the peak-P stage of this eclogite. The third type of garnet in the melanocratic part (Grt II) is homogeneous and shows similar composition to the margin of Grt I (Fig. 3b). This Ca-rich composition probably reflects the equilibrated states at the peak-P stage of this eclogite. The third type of garnet (Grt III) has a core composition identical to that of Grt II (peak-P composition) but shows a distinct decrease in Ca content at the rim ($X_{\text{grs}} \approx 0.20$, Fig. 3c). Grt III is present within the leucocratic pockets, but some garnet grains in the melanocratic part also show a slight decrease in Ca content at their rims. This Ca-poor composition at the rims of Grt III probably corresponds to the overgrowth (and/or chemical modification) of garnet during the later decompression stage. The chemical compositions of garnet are summarized in Figure 4. As shown in this figure, garnet composition significantly changes depending on location, even within the same sample; i.e., it varies according to thin section. For example, garnet in the ND110C thin section is poorer in Ca ($X_{\text{grs}} = 0.23-0.29$) and richer in Mg ($X_{\text{prp}} = 0.30-0.36$) than garnet in the thin sections of ND110A and ND110D, which exhibits the composition of $X_{\text{grs}} = 0.25-0.33$ and $X_{\text{prp}} = 0.27-0.32$ (Fig. 4). In addition, the compositional range of garnet in the ND110F thin section is wider, with the pyrope content ($X_{\text{prp}}$) changing from 0.36 to 0.43. This difference in garnet composition is probably due to variation in local (on a thin-section scale) bulk composition, as complete equilibrium states were not achieved in the first-sized sample scale. Nevertheless, the composition of Grt III overlap that of Grt II within each thin section, except for the rim of Grt III in the leucocratic pockets (Fig. 4), suggesting that chemical equilibrium was probably attained on a thin-section scale.

The compositional range of clinopyroxene is also wide, and three types of clinopyroxene are present: inclusions both in Grt II and Grt III (Cpx I), matrix grains in the melanocratic part (Cpx II), and those in the leucocratic pockets (Cpx III). The jadeite content ($X_{\text{jd}} = \frac{\text{Al} - 2(2 - \text{Si} - \text{Ti})}{\text{total cations} = 4}$) varies from approximately 0.45 to 0.00, depending on these types. For example, Cpx I grains show a higher jadeite content of 0.20–0.45 than Cpx II and III with jadeite contents below 0.25 (Fig. 5). Each clinopyroxene grain tends to show chemical zoning that exhibits a decrease in jadeite content from the core toward the rim (Fig. 6). The Ca-tschermak content and the Fe/(Fe + Mg) ratio increases with decreasing jadeite content (Fig. 5). Total Fe in clinopyroxene is treated as Fe$^{2+}$ here. Cpx II is partially replaced by symplectite of augite + plagioclase, and Cpx III contains tiny (<0.1 mm) plagioclase inclusions (Fig. 6c). These textural and chemical features suggest that omphacite inclusions in garnet (Cpx I) preserve the peak-P composition in their cores, whereas matrix grains in both the leucocratic pockets and the melanocratic part (Cpx II and III) have undergone chemical modification and/or crystallization under plagioclase-stable low-P conditions. The Fe/(Fe + Mg) ratios of Cpx I vary with thin section (Fig. 5). For example, Cpx I in ND110A and ND110D is higher in Fe/(Fe + Mg) ratio (~ 0.25) than Cpx I in ND110C (~ 0.21), which is consistent with the variation of Fe/(Fe + Mg) ratio in garnet composition (Fig. 4). Thus, the Cpx I composition is also controlled by the local (on a thin-section scale) bulk composition. On the other hand, Cpx II and III show approximately the same Fe/(Fe + Mg) ratio of 0.25–0.35 (Fig. 5). The Si content of Cpx II and III is also approximately the same [1.8–1.9 a.p.f.u. (atoms per formula unit) based on total cations = 4] (Fig. 5). Thus, chemical equilibrium was approximate.
ly achieved, at least on a thin-section scale, during the decompression stage.

Plagioclase in this sample occurs as a main constituent of the leucocratic pockets and as a constituent of symplectites which are partially replacing clinopyroxene in the melanocratic part. The former plagioclase is approximately homogeneous oligoclase with a composition of $X_{An} \approx 0.15 - 0.25$, although anorthite content slightly increases from the core to the rim.

Biotite grains occur mainly in the matrix of the melanocratic part (Fig. 1), and small amounts of biotite are also present in the leucocratic pockets (Fig. 2b). They display a composition of $X_{An} \approx 0.15 - 0.25$, although anorthite content slightly increases from the core to the rim. Biotite grains occur mainly in the matrix of the melanocratic part (Fig. 1), and small amounts of biotite are also present in the leucocratic pockets (Fig. 2b). They display a composition of $X_{An} \approx 0.15 - 0.25$, although anorthite content slightly increases from the core to the rim. Biotite grains occur mainly in the matrix of the melanocratic part (Fig. 1), and small amounts of biotite are also present in the leucocratic pockets (Fig. 2b). They display a composition of $X_{An} \approx 0.15 - 0.25$, although anorthite content slightly increases from the core to the rim.

Amphibole grains in this sample are also mainly present in the matrix of the melanocratic part, but only very small amounts of amphibole were recognized in the leucocratic pockets (Fig. 2e). They show a composition of $X_{An} \approx 0.15 - 0.25$, although anorthite content slightly increases from the core to the rim.

### Trace element compositions

Trace element contents in garnet, clinopyroxene, plagioclase, biotite and amphibole are normalized to the primitive mantle (PM) composition (Hofmann, 1988) and plotted as spider diagrams to show the chemical characteristics of each mineral (Figs. 7–10).

### Table 2. Representative trace element compositions (in ppm) of constituent minerals in the studied eclogite

| Mineral | Grt II in M | Grt III in L | Cpx I in Grt | Cpx II in M | Cpx III in L | Pl in CAS | Bt in M | Amp in M | NIST 614 Average |
|---------|------------|-------------|-------------|------------|-------------|----------|--------|---------|-----------------|
| Ti      | 925        | 846         | 1392        | 3186       | 2850        | nd       | 32601  | 7860    | 0.3             |
| Rb      | 0.20       | 0.08        | 2521        | 30.75      | 0.06        | 0.86     | 3%     |
| Sr      | 0.46       | 0.55        | 129.7       | 34.6       | 51.2        | 1623     | 4.0     | 54.6    | 0.005           |
| Y       | 29.35      | 37.48       | 0.74        | 3.05       | 3.82        | < 0.04   | 0.43    | 16.45   | 0.005           |
| Zr      | 6.48       | 6.66        | 12.06       | 26.49      | 30.57       | < 0.10   | 3.44    | 26.42   | 0.10            |
| Nb      | 0.01       | 0.01        | 0.03        | 1.20       | 0.48        | 0.01     | 0.07   | 2%      |
| Ba      | 0.1        | 0.4         | 1.7         | 1.4        | 243         | 5558     | 176     | 0.04    |
| La      | 0.007      | 0.169       | 0.505       | 0.439      | 0.7317      | 0.610    | 0.091  | 1.792   | 0.003           |
| Ce      | 0.244      | 0.255       | 3.058       | 3.091      | 4.629       | 1.010    | 0.078  | 9.390   | 0.004           |
| Pr      | 0.189      | 0.167       | 0.676       | 0.85       | 1.154       | nd       | 0.029  | 1.922   | 0.004           |
| Nd      | 2.79       | 2.59        | 4.15        | 6.26       | 7.82        | 0.30     | 0.13   | 11.93   | 0.01            |
| Sm      | 3.03       | 3.05        | 1.05        | 2.60       | 2.99        | 0.03     | 4.59   | 0.03    |
| Eu      | 1.238      | 1.332       | 0.251       | 0.666      | 0.705       | 0.180    | 0.067  | 1.385   | 0.005           |
| Gd      | 4.68       | 5.30        | 0.58        | 1.92       | 2.19        | 0.05     | 0.23   | 4.25    |
| Tb      | 0.872      | 0.999       | 0.062       | 0.218      | 0.249       | < 0.002  | 0.579  | 0.04    |
| Dy      | 6.01       | 7.18        | 0.24        | 0.95       | 1.19        | < 0.005  | 3.62   | 0.01    |
| Ho      | 1.146      | 1.455       | 0.026       | 0.135      | 0.162       | 0.001   | 0.671  | 0.005   |
| Er      | 3.080      | 4.131       | 0.055       | 0.258      | 0.312       | 0.003   | 1.653  | 0.004   |
| Tm      | 0.422      | 0.573       | 0.003       | 0.024      | 0.035       | nd      | 0.214  | 0.005   |
| Yb      | 2.64       | 4.22        | 0.03        | 0.12       | 0.19        | nd      | 1.40   | 0.02    |
| Lu      | 0.338      | 0.594       | 0.011       | 0.027      | 0.013       | 0.180    | 0.006  |
| Hf      | 1.02       | 0.11        | 0.57        | 1.40       | 1.80        | < 0.02   | 0.15   | 1.12    |
| Ta      | 0.02       | 0.11        | 0.03        | 0.02       | 0.11        | 0.03    |
| Th      | 0.01       | 0.14        | 0.09        | 0.10       | < 0.003     | 0.20    | 0.01   |
| U       | 0.07       | 0.07        | 0.17        | 0.16       | 0.24        | 0.21    |

Gr, garnet; Cpx, clinopyroxene; Pl, plagioclase; Bt, biotite; Amp, amphibole; M, melanocratic part, L, leucocratic pocket; KU, analyzed at Kanazawa University; CAS, analyzed at the Czech Academy of Sciences. Blank, data below the detection limit for the analysis at KU (DL*); nd, not determined.

NIST 614 was measured for quality control (NIST612 and 1830 were measured in CAS), and averaged values and 1σ relative standard deviations (RSD) of data at KU are shown.
example, the PM normalized amounts of Gd, Tb, Dy, Ho, Er, and Lu are 30–50 in the core, while approximately 10 near the margin (Fig. 7). The abundances of these elements at the margin of Grt I are mostly the same as those of Grt II and III (Fig. 8), which contain omphacite inclusions (Cpx I).

Comparing the trace element composition of Grt II and Grt III, there is no distinct difference between them (Fig. 8). Both display negative spikes of Sr, Zr, Hf, and Ti, and show approximately constant values of HREE. Thus, the trace element composition of Grt II resembles that of Grt III. As already described in the previous chapter, the major element composition of Grt II also resembles that of Grt III within each thin section (Fig. 4).

Figure 3. Compositional profiles of garnet (Grt). (a) Garnet megacryst in the melanocratic part of ND110A (Fig. 1b). (b) Relatively small garnet in the melanocratic (M) part of ND110A. Cpx, clinopyroxene inclusion. (c) Small garnet grain included in plagioclase of the leucocratic (L) pocket of ND110A.

Figure 4. Garnet compositions on Xgrs \([= \text{Ca/(Fe + Mn + Mg + Ca)}]\) versus Mg/(Fe + Mg) diagrams. Total Fe is treated as ferrous here. (a) Compositions of garnet (Grt) from the thin sections ND110A and ND110D including the garnet megacryst are displayed. Garnet II in the melanocratic (M) part is nearly homogeneous, whereas garnet III in the leucocratic (L) pocket shows significant decrease of grossular content toward the margin. (b) Compositions of garnet from the thin section ND110C are displayed. They are slightly richer in Mg and poorer in Ca than garnet from the thin sections ND110A and ND110D. (c) Compositions of garnet in the thin sections ND110E and ND110F.
Omphacite inclusions (Cpx I) in Grt II and Grt III show no distinct difference between them in trace element composition (Fig. 9a). The other clinopyroxene grains (Cpx II and III) also show approximately the same distribution pattern in the spider diagram between them (Figs. 9b and 9c), but both display compositions different from Cpx I (Fig. 9, Table 2), as the major element composition is different between Cpx I and matrix grains (Fig. 5). For example, Sr in Cpx I shows positive spikes in the spider diagram, and the SrN (PM normalized amount) of Cpx I is approximately 10 (Fig. 9a). On the other hand, Cpx II and III show negative spikes of Sr, and their SrN are clearly lower than 10 (Figs. 9b and 9c). Both core and rim parts within each grain were analyzed, but no systematic difference in chemical composition was recognized between them.

Plagioclase in the leucocratic pockets is rich in Large–Ion–Lithophile (LIL) elements such as Rb, Ba, and Sr, and RbN, BaN, and SrN of plagioclase range from 10 to 100 (Fig. 10a). However, Eu is not so rich, and EuN values are approximately 1.

Biotite is also rich in LIL elements, and U, Nb, Ta, and Ti. Especially RbN and BaN are above 1000 (Fig. 10b). Amphibole is also rich in Rb, Ba, and U, and RbN, BaN, and UN range from 10 to 100 (Fig. 10c). On the other hand, Nb, Ta, Sr, Zr, and Hf show negative spikes in the spider diagram of amphibole. Abundances of HREE in amphibole are relatively high compared to plagioclase and biotite in the studied sample, and the PM normalized amounts of HREE range from 1 to 10.

**DISCUSSION**

**Partial melting**

The aim of this study is to examine whether the leucocratic pockets in the studied eclogite were originally melt produced by partial melting of the eclogite. Most of clinopyroxene and some garnet grains in the leucocratic pockets show faceted shapes, whereas those in the melanocratic part show irregular shapes (Fig. 2). This probably indicates that at least plagioclase in the leucocratic pockets was melt, which gave clinopyroxene (and garnet) free space to grow as faceted shaped grains. However, it
is still not clear whether the melt was created by the partial melting of the eclogite or injected from the outside. The important data necessary to answer this question are the chemical characteristics of clinopyroxene. Cpx III (Cpx in the leucocratic pockets) has approximately the same chemical characteristics as Cpx II (Cpx in the matrix of the melanocratic part) both in terms of major and trace elements (Figs. 5 and 9). Figure 11 shows the trace
element composition of representative analyzed points of Cpx II (#313, #314, #315, #316) and Cpx III (#302, #303), which are normalized to the average composition of Cpx I (omphacite inclusions in garnet). The positions of the analyzed points of those grains are shown in Figures 6b and 6c. Jadeite content is slightly higher in Cpx II than in Cpx III, but both data overlap with each other. Trace element composition is also similar between them, although some differences are recognized. For example, #314 from Cpx II shows relatively high HREE contents, whereas #313, #315, and #316 display relatively low HREE contents (Fig. 11). Thus, some differences in chemical composition exist, but the similarity in trace element composition between them probably indicates that the timing of the growth (and/or chemical modification) of Cpx III was approximately the same as that of the chemical modification of Cpx II. If the melt were injected from the outside, the chemical characteristics of Cpx III in the pockets would have become completely different from those of Cpx II. In addition, if the melt were provided from the migmatitic gneiss surrounding the eclogite and peridotite body, the melt would have been more siliceous and would have formed quartz-bearing pockets. However, quartz is free from the leucocratic pockets as well as the melanocratic part. Thus, Cpx III was likely crystallized from melt that was internally created in this eclogite.

**The melt composition**

As described above, the leucocratic pockets were probably melt produced by partial melting of the eclogite. The timing of the partial melting is unclear, but we can estimate the melt composition by using partition coefficients.
for clinopyroxene and the melt (DCpx/melt) if Cpx I and III were in chemical equilibrium with the melt during the peak–P and decompression stages, respectively. The trace element composition of the melt in equilibrium with Cpx I and III was calculated by using the average composition of Cpx I (inclusions in garnet). (a) Cpx II in the matrix of the melanocratic part. (b) Cpx III in the matrix of the leucocratic pocket. Analyzed points are shown in Figure 6.

Figure 12. Spider diagram of melt compositions estimated from the average composition of clinopyroxene in garnet (Cpx I) (a) and that in the leucocratic pocket (Cpx III) (b) by using partition coefficients between clinopyroxene and melt. The partition coefficients data are from Hart and Dunn (1993) (HD), Blundy et al. (1998) (B), Xiong (2006) (X), and Klemme et al. (2002) (K). For comparison, data of high-pressure TTG (HP–TTG) (Martin et al., 2014) are also shown in this diagram.

Here, we describe a plausible history of this eclogite. First, the garnet megacryst (Grt I) shows a chemical zoning with an increase in Ca content (Fig. 3) and a decrease in HREE from the core toward the rim (Fig. 7), and the composition of the rim is approximately the same as those of other small and homogeneous garnet grains (Fig. 4a). The characteristics of Grt I are generally interpreted as reflecting an increase in pressure. For example, the Ca content in garnet decreases with decreasing pressure in kyanite-bearing eclogite (e.g., Nakamura and Banno, 1997). Thus, the rim composition of Grt I probably corresponds to the peak–P equilibrated states. However, this sample lacks kyanite, and hence, the reaction due to the increase in the grossular content of garnet is not clear. If kyanite was present, the diopside component in clinopyroxene would have reacted with kyanite to pro-
duce grossular-rich garnet and quartz, as was observed in kyanite-bearing eclogite from the same area (Nakamura et al., 2004). In this case, quartz must have been present as a product of this reaction. However, quartz is absent from this sample, and as such, this reaction may not have occurred. Instead, the anorthite component in plagioclase may have provided the grossular component, but the production of an Al-rich phase such as kyanite should have taken place in this case. Ca-amphibole is another candidate for supplying Ca to garnet, but there is no Ca-amphibole inclusion in the melt as far as we observed. On the other hand, another idea on the origin of eclogite from the study area (Nové Dvory) has been proposed: at least some eclogite (and pyroxenite) in the peridotite body was originally high-P cumulate of garnet and clinopyroxene at mantle depths rather than crustal mafic rocks (e.g., Beard et al., 1992; Svojtka et al., 2016). Even so, it is still mysterious why Grt I shows chemical zoning with an increase in Ca from the core to the rim. Amphibole may have been present prior to the peak-P metamorphism, as prograde stage paragentic amphibole inclusions were identified from garnet in another bi-mineralic eclogite of Nové Dvory (Yasumoto et al., 2016). The eclogite probably experienced an increase in pressure, although reactions controlling the chemical zoning are not clear, as described above.

Thus, the chemical composition equilibrated under the peak-P stage was probably preserved in the rim of the garnet megacryst (Grt I) and in the small and homogeneous grains (Grt II), which have similar compositions to the rim of Grt I. The omphacite inclusions (Cpx I) in Grt II are richer in jadeite content than the other matrix grains (Cpx II and III). Therefore, P-T conditions at the peak-P stage were estimated by applying a garnet-clinopyroxene geothermometer (Nakamura, 2009) and a garnet-clinopyroxene geobarometer (Beyer et al., 2015) to the core compositions of Grt II and Cpx I (Table 1). Total Fe was also treated as Fe2+ in this calculation. The obtained P-T conditions are approximately 1050 °C, 4.3 GPa, which are consistent with those for the kyanite-bearing eclogite from the same area (Nakamura et al., 2004) (Fig. 13). Thus, the studied kyanite-free eclogite has also undergone UHP metamorphism and the P-T conditions were much higher in temperature than the wet solidus in MORB system (Schmidt and Poli, 1998), and slightly higher than the phengite decomposition reaction line in the K2O-CaO-MgO-Al2O3-SiO2-H2O model system (Hermann and Green, 2001) (Fig. 13). Thus, the timing of the partial melting of the studied eclogite is not clear, but partial melting may have occurred at this peak-P stage.

During the decompression stage, the growth of faceted shape clinopyroxene grains (Cpx III) in the melt (the leucocratic pockets) and the chemical modification of clinopyroxene in the matrix of melanocratic part (Cpx II) should have simultaneously occurred, because Cpx II and III show approximately the same chemical characteristics between them (Figs. 5 and 9). The Ca-poor rim of garnet (Grt III), mainly observed in the leucocratic pockets (Fig. 4), was probably also created at this decompression stage by the overgrowth of relic garnet within the melt. The P-T conditions of the decompressional stage were also estimated by applying the above mentioned geothermobarometer (Nakamura, 2009; Beyer et al., 2015) to the compositions of the Grt III rim and Cpx III (Table 1). The obtained P-T conditions are around 950 °C, 1.7 GPa, when assuming that total Fe is Fe2+. Thus, the decompression to crustal depths was probably nearly isothermal (Fig. 13), and the subsequent exhumation was accompanied by significant cooling.

The mode of occurrence and the chemical compositions of biotite and amphibole grains suggest that they
were also formed during the decompression. Some of them were probably crystallized from the melt because some grains are situated within the leucocratic pockets (Fig. 2). In addition, at the final crystallization of the melt, H2O, with some alkali elements, was probably expelled from the melt to form hydrous phases, such as biotite and amphibole in the melanocratic part.

CONCLUSIONS

Judging from the chemical zonation of the garnet megacryst, this eclogite sample has undergone an increase in pressure that may have been caused by the subduction of the eclogite before the peak-P metamorphic stage. The partial melting of the eclogite probably occurred during the peak-P metamorphic stage (1050 °C, 4.3 GPa), and the degree of partial melting increased afterwards, during the decompression stage, to crustal depths (950 °C, 1.7 GPa). Thus, we conclude that the leuocratic pockets in the studied eclogite were originally melt formed by the partial melting of the eclogite. In addition, the recovered melt composition is similar to the trace element characteristics of TTG. Thus, it is concluded that the partial melting of eclogite can directly generate TTG and doric melt, which can be source of continental crust.

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