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# A zircon study from the Rhodope metamorphic complex, N-Greece: Time record of a multistage evolution

Christoph Bauer<sup>a,\*</sup>, Daniela Rubatto<sup>b</sup>, Kurt Krenn<sup>a</sup>,  
Alexander Proyer<sup>a</sup>, Georg Hoinkes<sup>a</sup>

<sup>a</sup> *Institute of Earth Sciences, Department of Mineralogy and Petrology, Karl-Franzens-University of Graz, Universitätsplatz 2, 8010 Graz, Austria*

<sup>b</sup> *Research School of Earth Sciences, The Australian National University, Canberra, ACT 0200, Australia*

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## Abstract

Zircons from an eclogite and a diamond-bearing metapelite near the Kimi village (north-eastern Rhodope Metamorphic Complex, Greece) have been investigated by Micro Raman Spectroscopy, SEM, SHRIMP and LA-ICPMS to define their inclusion mineralogy, ages and trace element contents. In addition, the host rocks metamorphic evolution was reconstructed and linked to the zircon growth domains.

The eclogite contains relicts of a high pressure stage (ca. 700 °C and >17.5 kbar) characterised by matrix omphacite with Jd<sub>40–35</sub>. This assemblage was overprinted by a lower pressure, higher temperature metamorphic event (ca. 820 °C and 15.5–17.5 kbar), as indicated by the presence of clinopyroxene (Jd<sub>35–20</sub>) and plagioclase. Biotite and pargasitic amphibole represent a later stage, probably related to an influx of fluids. Zircons separated from the eclogite contain magmatic relicts indicating Permian crystallization of a quartz-bearing gabbroic protolith. Inclusions diagnostic of the high temperature, post-eclogitic overprint are found in metamorphic zircon domain Z2 which ages spread over a long period (160–95 Ma). Based on zircon textures, zoning and chemistry, we suggest that the high-temperature peak occurred at or before ca. 160 Ma and the zircons were disturbed by a later event possibly at around 115 Ma. Small metamorphic zircon overgrowths with a different composition yield an age of 79±3 Ma, which is related to a distinct amphibolite-facies metamorphic event.

The metapelite host rock consists of a mesosome with garnet, mica and kyanite, and a quartz- and plagioclase-bearing leucosome, which formed at granulite-facies conditions. Based on previously reported micro-diamond inclusions in garnet, the mesosome is assumed to have experienced UHP conditions. Nevertheless, (U)HP mineral inclusions were not found in the zircons separated from the diamond-bearing metapelite. Inclusions of melt, kyanite and high-Ti biotite in a first metamorphic zircon domain suggest that zircon formation occurred during pervasive granulite-facies metamorphism. An age of 171±1 Ma measured on this zircon domain constrains the high-temperature metamorphic event. A second, inclusion-free metamorphic domain yielded an age of 160±1 Ma that is related to decompression and melt crystallization.

The similar age data obtained from the samples indicate that both rock types recorded a high-T metamorphic overprint at granulite-facies conditions at ca. 170–160 Ma. This age implies that any high pressure or even ultra-high pressure metamorphism in the Kimi Complex occurred before that time. Our findings define new constraints for the geodynamic evolution for the Alpine orogenic cycle within the northernmost Greek part of the Rhodope Metamorphic Complex. It is proposed that the rocks of the Kimi

\* Corresponding author. Tel.: +43 316 380 8717; fax: +43 316 380 9865.

E-mail address: [chrbauer@gmx.at](mailto:chrbauer@gmx.at) (C. Bauer).

Complex belong to a suture zone squeezed between two continental blocks and result from a Paleo-ocean basin, which should be located further north of the Jurassic Vardar Ocean.

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## 1. Introduction

The Rhodope Metamorphic Complex (RMC) in northern Greece is considered to be a nappe stack of metamorphic units derived from continental and oceanic crust (e.g. Burg et al., 1996; Ricou et al., 1998). Existence of Variscan (Carboniferous–Permian) and Alpine (Late Cretaceous–Tertiary) metamorphism is supported by radiometric data (Jones et al., 1994; Peytcheva and von Quadt, 1995). Since UHP metamorphism was reported by Mposkos and Kostopoulos (2001), the RMC became object of several geochronological studies (Liati et al., 2002; Liati 2005; Turpaud and Reischmann, 2005). Despite controversial discussions about diamond and other UHP indicators like multicrystalline polygonal quartz (Mposkos and Kostopoulos, 2001; Beyssac and Chopin, 2003), a number of different UHP metamorphic ages were recently reported for the RMC (e.g. Liati, 2005 and ref. therein). Perraki et al. (2006) reported micro-diamond inclusions in metapelitic garnet from Kimi Complex, north-eastern Rhodope and confirmed the UHP metamorphic event in the RMC, already proposed by Mposkos and Kostopoulos (2001).

The Rhodope UHP Metamorphic Complex, similarly to other UHP terranes (see a review in Carswell and Compagnoni, 2003), likely had a complex metamorphic evolution characterised by multiple stages and strong re-equilibration. This has been suggested by a number of petrological and geochronological studies of the massif (e.g. Mposkos and Krohe, 2000; Liati et al., 2002). In order to add further time constraints to this complex high-grade evolution, ages need to be linked to metamorphism. To achieve this goal we use a combination of petrography, mineral chemistry, and detail investigation of the trace elements and U–Pb composition of zircons. Due to the composite nature of the zircon, ages have been measured by SHRIMP (Sensitive High Resolution Ion MicroProbe), which combines high spatial resolution with analytical precision (e.g. Williams, 1998). This approach has been successful in the past in establishing timing and conditions of prograde and retrograde metamorphic histories even in highly reworked samples (e.g. Hermann et al., 2001; Wu et al., 2006).

The link between absolute zircon ages and metamorphic events is difficult because zircon formation can be

induced by various processes within a wide range of pressure ( $P$ ) and temperature ( $T$ ) conditions. Zircon crystals may record a prograde as well as a retrograde stage of the  $P$ – $T$  path (e.g. Hermann et al., 2001; Wu et al., 2006), but reversely zircon does not necessarily record all the metamorphic events that a rock underwent (e.g. Hoskin and Black, 2000).

One possibility to correlate zircon ages with metamorphic events is to consider the trace element composition of the zircon and surrounding minerals (e.g. Rubatto, 2002). Trace element characteristics of zircon can reflect coeval growth of some mineral phases like plagioclase, which is a sink for Eu, garnet which sequesters the HREE, or rutile because of its affinity for Nb or Ta (Li et al., 2005). Another direct link between metamorphic history and the formation of zircon is provided by its mineral inclusions. Their diagnosis is restricted to the surface when using standard secondary electron microscopy and electron microprobe technique. Raman micro-spectroscopy however has the capability to below-surface investigation and thus is a powerful complementary tool to determine inclusions on a micrometer scale. In addition, phase identification based on structural information of polymorphs ( $\text{Al}_2\text{SiO}_5$ , diamond/graphite, quartz/coesite) is possible (e.g. Nasdala et al., 2004).

In this paper, we present new geochronological data, trace element chemistry and a detailed investigation of zircon inclusion mineralogy of a diamond-bearing garnet micaschist and an eclogite. We link petrological data of the host rocks with zircon inclusion mineralogy and trace element characteristics to correlate metamorphic events with age data from metamorphic zircon domains. The aim of this study is to decipher the  $PT$ -time history of the RMC by investigating zircon from one eclogite and a recently established, diamond-bearing UHP metapelite.

## 2. Geological setting

The tectonic units of the RMC represent the northern part of an Alpine nappe stack in the Aegean region that formed during the convergence of Africa and Europe since the Middle Jurassic (e.g. van Hinsbergen et al., 2005). The Complex extends over large areas of Northern Greece and Bulgaria and contains mainly continental

material with intercalated oceanic slices (Burg et al., 1996; Ricou et al., 1998). The Rhodope Massif was classically subdivided in a lower and an upper terrane by Burg et al. (1996). A recent study by Turpaud (2006) subdivided the Central Rhodope into the Thracia Terrane, dominated by Permo-Carboniferous orthogneisses and Triassic marbles, and the Rhodope Terrane, consisting of Late-Jurassic orthogneisses (Fig. 1). The Thracia Terrane and the Rhodope Terrane can be interpreted as lower and upper continental plates, respectively, which were tectonically superimposed during Alpine N–S directed continent–continent collision and subsequent SW directed nappe stacking (Ricou et al., 1998). The two terranes are separated by the Nestos Suture Zone, which is well exposed north of the SW-directed thrust fault (Nestos Thrust, Fig. 1) within the Central Domain of the RMC (Burg et al., 1996; Barr et al., 1999). Within this suture zone, HP to UHP metamorphism is recorded in meta-sediments (Mposkos and Kostopoulos, 2001; Perraki et al., 2006), mafic rocks (Kolcheva et al., 1986; Liati and Seidel, 1996) and possibly carbonates (Mposkos et al., 2006). The entire Rhodope nappe stack is transgressively overlain by Lutetian/Priabonian (48–42 Ma) sediments, consisting of turbiditic clastics, conglomerates and limestones (Mposkos and Krohe, 2000; Krohe and Mposkos, 2002). In addition, the Rhodope Terrane and the suture zone were intruded by large-scale Tertiary granitoids, which led to local migmatization of the host rocks (e.g. Peytcheva et al., 2004; Liati, 2005). Miocene extensional tectonics led to the formation of extensional basins, forced by the activation of orogen-parallel to orogen-normal detachment faults as a result of the activity of the North

Anatolian Fault System (Dinter and Royden, 1993; Krohe and Mposkos, 2002).

The subject of this study is the Kimi Complex (after Krohe and Mposkos, 2002 and ref. therein), a highly deformed and metamorphosed part of this suture zone that is well exposed SE of the Kimi village (Fig. 2) and which contains diamond-bearing metapelites (Perraki et al., 2006). The Kimi Complex is composed of quartzitic gneisses, Grt–Ky–gneisses, amphibolites/eclogites, marbles and serpentinites. The mafic rocks occur mainly as lenses within the orthogneisses, whereas the metapelites and the serpentinites strike NE–SW (Fig. 2). Local partial melting occurred after eclogite-facies metamorphism, and a penetrative amphibolite-facies fabric points to ductile shearing and folding during regional metamorphism (Fig. 2; Burg et al. 1990, 1996; Dinter and Royden, 1993).

Previous petrological studies from the Kimi Complex revealed peak pressures of around 13–14 kbar and temperatures of 735–765 °C from retrogressed eclogites (Mposkos and Perdikatsis, 1989) and around 16 kbar and 800 °C from an ultramafic boudin (Mposkos and Krohe, 2000). Peak conditions were followed by amphibolite-facies (ca. 10 kbar and 600 °C) and later greenschist-facies metamorphism (Mposkos and Krohe, 2000). Sm–Nd whole rock data obtained from a garnet–pyroxenite (Warwzenitz and Mposkos, 1997) returned an age of  $119 \pm 3.5$  Ma, which was interpreted as the age for HP metamorphism. Two U–Pb SHRIMP ages from a garnet-rich mafic rock were reported by Liati et al. (2002): the first zircon age of  $117.4 \pm 1.9$  Ma was interpreted as the age of protolith crystallization and the second age of  $73.5 \pm 3.4$  Ma was assigned to the (U)HP metamorphic stage.

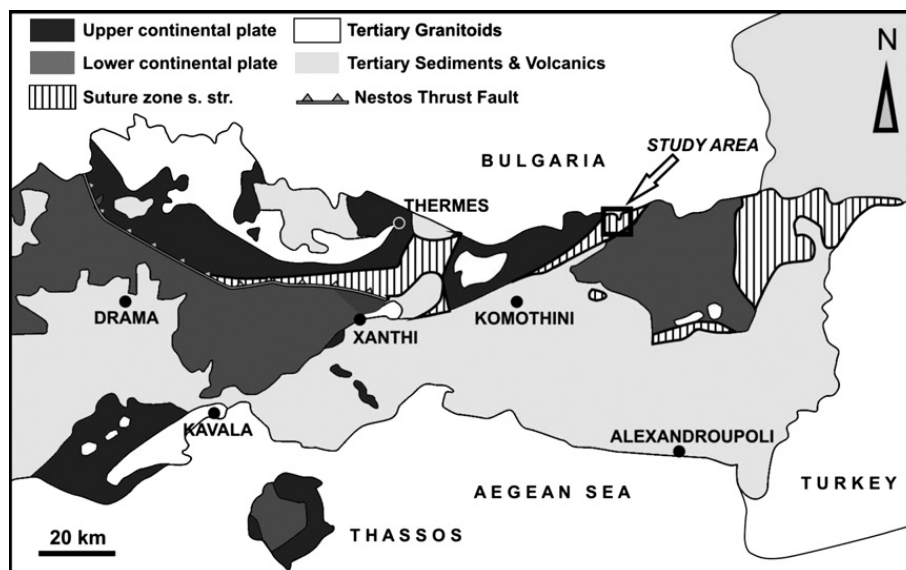


Fig. 1. Schematic geological map of the Rhodope Metamorphic Complex modified after Mposkos and Krohe (2000).

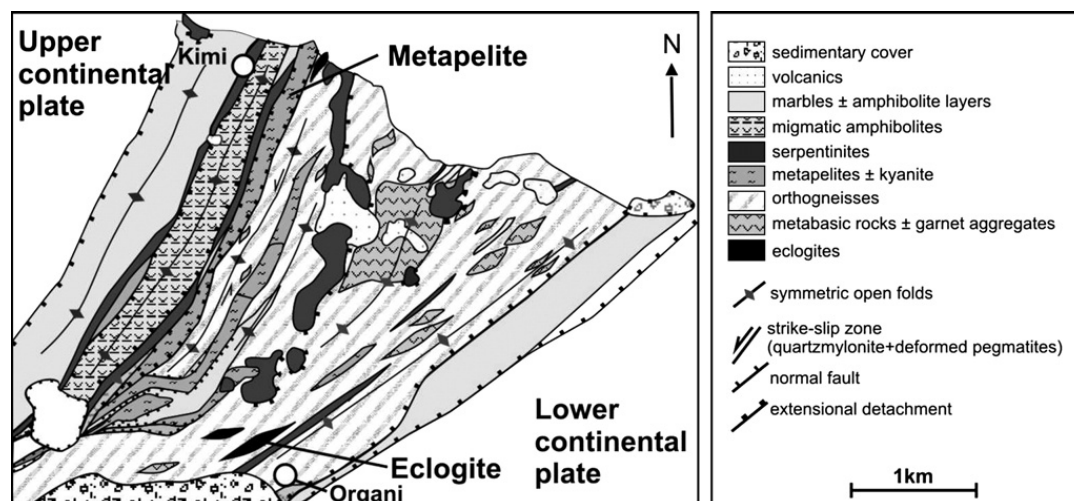


Fig. 2. Simplified geological map of the Kimi area (own mapping) with the locations of the investigated samples.

The rocks of the Kimi Complex were intensely disrupted by E-directed detachment tectonics (Krohe and Mposkos, 2002) and exhumed to shallow crustal levels at around 62 Ma, based on magmatic zircon domains in discordant pegmatoids (Liati et al., 2002). Lutetian transgressive conglomerates (ca. 48 Ma) postdate extensional tectonics in the Central Rhodope (Krohe and Mposkos, 2002).

### 3. Methods

Circa 250 zircon grains from the eclogite and about 1800 grains from the metapelite were separated by crushing the samples in a mill and then using magnetic and heavy liquid separation. From the heavy fraction, the zircons were handpicked and put on glass plates as loose grain mounts. This preparation is totally non-destructive and allows microscopic investigation of the inclusions in the entire volume of the grains. Furthermore, fluorescence effects caused by the embedding material are avoided during investigations with Micro Raman Spectrometry. For Scanning Electron Microscopy (SEM), Laser Ablation–ICP–MS and Sensitive High Resolution Ion MicroProbe (SHRIMP) analysis the grains were embedded in a Struers epoxy resin and polished down to expose the grain centres.

Mineral inclusions were identified by Raman spectroscopy and, whenever possible analysed by SEM. Raman analysis was performed with a Jobin-Yvon LabRam-HR 800 Raman micro-spectrometer at the Institute of Earth Sciences, University of Graz, Austria. A He-Ne laser with 633 nm excitation line and 5.9 mW at the sample was used with an Olympus 100x objective. The laser focus was ca. 1  $\mu$ m.

CL imaging was performed with a JEOL JSM 6310 SEM with 15 kV acceleration voltage at the Institute of Earth Sciences, University of Graz. Additional imaging was carried out at the Electron Microscopy Unit, The Australian National University, with a HITACHI S2250-N Scanning Electron Microscope working at 15 kV,  $\sim 60 \mu$ A and  $\sim 20$  mm working distance.

Major element composition of inclusions and matrix minerals was measured with a JEOL JSM 6310 SEM equipped with a LINK ISIS energy dispersive system and a MICROSPEC wavelength dispersive system (for Na) at the Institute of Earth Sciences, University of Graz. Analytical conditions were an acceleration voltage of 15 kV and a probe current of 5 nA. Detection limits are 0.1–0.2 wt.% for EDS and 0.03 wt.% for WDS analysis.

Bulk-rock analyses were performed on a Siemens Pioneer S4 WD-XRF at the Institute of Earth Sciences, University of Graz. Additional analyses of trace elements and REE were obtained with a Perkin Elmer SCIEX ELAN 6000 ICP-MS at ActLabs, Ancaster, Ontario.

Trace element composition of minerals was measured with Laser Ablation–ICP–MS at the Research School of Earth Sciences (RSES) at The Australian National University, using a pulsed 193 nm ArF Excimer laser with 100 mJ energy at a repetition rate of 5 Hz (Eggins et al., 1998) coupled to an Agilent 7500 quadrupole ICP-MS. Pit size varied between 19 and 86  $\mu$ m. External calibration was performed relative to NIST 612 glass using the concentrations given in Pearce et al. (1997). Internal standards were stoichiometric Si for zircon and Ca and Si for all other minerals. Reproducibility and accuracy were assessed by repeated

Table 1  
Representative analyses of matrix minerals and inclusions in zircons

| Eclogite       |             |            |             |            |       |        |       |            |                |           |            |              |         | Metapelite |        |       |       |       |           |                |
|----------------|-------------|------------|-------------|------------|-------|--------|-------|------------|----------------|-----------|------------|--------------|---------|------------|--------|-------|-------|-------|-----------|----------------|
|                | Matrix      |            |             |            |       |        |       |            | Zrn Inclusions |           |            |              |         | Matrix     |        |       |       |       |           | Zrn Inclusions |
|                |             |            |             |            |       |        |       |            |                |           |            |              |         |            |        |       |       |       |           |                |
| Grt1 (core)    | Grt2 (poic) | Grt3 (rim) | Omp1 (core) | Omp2 (rim) | Pl    | Bt     | Hbl   | GrtZrn inc | OmpZrn inc     | BtZrn inc | HblZrn inc | Hbl ?Zrn inc | Grtcore | Grtrim     | Pl     | Ms1   | Ms2   | Bt    | BtZrn inc |                |
| <i>Mineral</i> |             |            |             |            |       |        |       |            |                |           |            |              |         |            |        |       |       |       |           |                |
| SiO2           | 39.43       | 39.16      | 39.19       | 54.83      | 52.42 | 65.19  | 38.03 | 41.71      | 40.34          | 52.34     | 38.42      | 45.29        | 46.40   | 38.98      | 38.00  | 62.24 | 46.08 | 46.93 | 37.41     | 37.55          |
| TiO2           | <0.2        | <0.2       | <0.2        | 0.22       | 0.60  | <0.2   | 4.07  | 1.51       | <0.2           | 0.36      | 4.57       | 1.64         | 2.52    | <0.2       | <0.2   | <0.2  | 0.49  | 0.91  | 2.29      | 4.15           |
| Al2O3          | 21.42       | 21.24      | 21.39       | 9.98       | 8.29  | 21.40  | 14.50 | 13.80      | 22.10          | 5.99      | 13.92      | 10.43        | 12.47   | 21.52      | 21.06  | 23.04 | 33.99 | 32.68 | 19.26     | 18.03          |
| FeOtot         | 21.73       | 22.63      | 24.16       | 5.33       | 6.04  | <0.1   | 12.36 | 11.53      | 21.27          | 6.12      | 12.20      | 11.14        | 9.33    | 28.88      | 32.20  | 0.47  | 1.40  | 1.03  | 13.24     | 13.26          |
| MgO            | 10.37       | 10.22      | 9.33        | 9.32       | 11.33 | <0.2   | 17.54 | 12.88      | 9.85           | 12.16     | 16.19      | 13.06        | 14.16   | 8.89       | 6.39   | <0.2  | 1.44  | 1.68  | 14.19     | 11.91          |
| MnO            | 0.46        | 0.60       | 0.59        | <0.2       | <0.2  | <0.2   | <0.2  | <0.2       | 0.45           | <0.2      | <0.2       | <0.2         | <0.2    | 0.54       | 1.04   | <0.2  | <0.2  | <0.2  | <0.2      | <0.2           |
| CaO            | 6.35        | 5.16       | 5.55        | 13.69      | 16.67 | 2.52   | <0.1  | 9.81       | 5.92           | 18.57     | <0.1       | 10.06        | 7.17    | 1.81       | 1.63   | 4.31  | <0.1  | <0.1  | <0.1      | <0.1           |
| Na2O           | <0.01       | <0.01      | <0.01       | 5.91       | 3.86  | 10.69  | 0.49  | 3.49       | <0.01          | 2.86      | 0.45       | 3.06         | 2.22    | <0.01      | <0.01  | 9.49  | 0.51  | 0.60  | 0.23      | 0.23           |
| K2O            | <0.1        | <0.1       | <0.1        | <0.1       | <0.1  | 0.24   | 9.27  | 1.10       | <0.1           | <0.1      | 9.24       | 0.57         | 5.55    | <0.1       | <0.1   | 0.19  | 9.05  | 9.71  | 8.58      | 9.87           |
| BaO            | <0.2        | <0.2       | <0.2        | <0.2       | <0.2  | <0.2   | <0.2  | <0.2       | <0.2           | <0.2      | <0.2       | <0.2         | <0.2    | <0.2       | <0.2   | <0.2  | 0.95  | <0.2  | <0.2      | <0.2           |
| Σ              | 99.76       | 99.01      | 100.21      | 99.28      | 99.21 | 100.04 | 96.26 | 95.83      | 99.93          | 98.40     | 94.99      | 95.25        | 99.82   | 100.62     | 100.32 | 99.74 | 93.91 | 93.54 | 95.20     | 95.00          |
| <i>Cations</i> |             |            |             |            |       |        |       |            |                |           |            |              |         |            |        |       |       |       |           |                |
| Si             | 2.99        | 3.00       | 2.99        | 1.97       | 1.91  | 2.87   | 2.78  | 6.18       | 3.05           | 1.93      | 2.84       | 6.71         | 6.63    | 2.99       | 2.98   | 2.77  | 3.11  | 3.16  | 2.74      | 2.78           |
| Ti             | 0.00        | 0.00       | 0.00        | 0.01       | 0.02  | 0.00   | 0.22  | 0.17       | 0.00           | 0.01      | 0.25       | 0.18         | 0.27    | 0.00       | 0.00   | 0.00  | 0.03  | 0.05  | 0.13      | 0.23           |
| Al             | 1.91        | 1.92       | 1.92        | 0.42       | 0.36  | 1.11   | 1.25  | 2.41       | 1.97           | 0.26      | 1.21       | 1.82         | 2.10    | 1.95       | 1.95   | 1.21  | 2.70  | 2.60  | 1.66      | 1.57           |
| Fe2+           | 1.27        | 1.37       | 1.44        | 0.13       | 0.11  | 0.00   | 0.75  | 0.95       | 1.34           | 0.13      | 0.75       | 1.11         | 1.12    | 1.79       | 2.03   | 0.00  | 0.08  | 0.06  | 0.81      | 0.82           |
| Fe3+           | 0.11        | 0.08       | 0.10        | 0.03       | 0.07  | 0.00   | 0.00  | 0.48       | 0.00           | 0.06      | 0.00       | 0.27         | 0.00    | 0.06       | 0.09   | 0.02  | 0.00  | 0.00  | 0.00      | 0.00           |
| Mg             | 1.17        | 1.17       | 1.06        | 0.50       | 0.62  | 0.00   | 1.91  | 2.85       | 1.11           | 0.67      | 1.78       | 2.88         | 3.02    | 1.02       | 0.75   | 0.00  | 0.15  | 0.17  | 1.55      | 1.32           |
| Mn             | 0.03        | 0.04       | 0.04        | 0.00       | 0.00  | 0.00   | 0.00  | 0.00       | 0.03           | 0.00      | 0.00       | 0.00         | 0.00    | 0.04       | 0.07   | 0.00  | 0.00  | 0.00  | 0.00      | 0.00           |
| Ca             | 0.52        | 0.42       | 0.45        | 0.53       | 0.65  | 0.12   | 0.00  | 1.56       | 0.48           | 0.73      | 0.00       | 1.60         | 1.10    | 0.15       | 0.14   | 0.21  | 0.00  | 0.00  | 0.00      | 0.00           |
| Na             | 0.00        | 0.00       | 0.00        | 0.41       | 0.27  | 0.91   | 0.07  | 1.00       | 0.00           | 0.21      | 0.06       | 0.88         | 0.61    | 0.00       | 0.00   | 0.82  | 0.07  | 0.08  | 0.03      | 0.03           |
| K              | 0.00        | 0.00       | 0.00        | 0.00       | 0.00  | 0.01   | 0.86  | 0.21       | 0.00           | 0.00      | 0.87       | 0.11         | 1.01    | 0.00       | 0.00   | 0.01  | 0.78  | 0.84  | 0.80      | 0.93           |
| Ba             | 0.00        | 0.00       | 0.00        | 0.00       | 0.00  | 0.00   | 0.00  | 0.00       | 0.00           | 0.00      | 0.00       | 0.00         | 0.00    | 0.00       | 0.00   | 0.00  | 0.03  | 0.00  | 0.00      | 0.00           |
| Σ              | 8.00        | 8.00       | 8.00        | 4.00       | 4.00  | 5.02   | 7.84  | 15.81      | 7.98           | 4.00      | 7.76       | 15.56        | 15.86   | 8.00       | 8.01   | 5.04  | 6.94  | 6.96  | 7.72      | 7.68           |

Zrn inc=inclusion in zircon.

analyses of a BCR glass and resulted between 1–6% and mostly within 10%, respectively.

U–Th–Pb analyses were performed using a Sensitive, High-Resolution Ion MicroProbe (SHRIMP II) at the RSES. Instrumental conditions and data acquisition for zircon analysis were generally as described by Compston et al. (1984). The data were collected in sets of six scans throughout the masses. The measured  $^{206}\text{Pb}/^{238}\text{U}$  ratio was corrected using reference zircon from a Temora granodiorite (417 Ma, Black et al., 2003). A zircon of known composition (SL 13) was used to determine the U content. The data were corrected for common Pb on the basis of the measured  $^{204}\text{Pb}$ ,  $^{207}\text{Pb}/^{206}\text{Pb}$  or  $^{208}\text{Pb}/^{206}\text{Pb}$  (Williams, 1998) according to age range and Th–U composition. The common Pb composition was according to the model of Stacey and Kramers (1975). Age calculation was done using the software Isoplot/Ex (Ludwig, 2003). Isotopic ratios and single ages are reported with 1 $\sigma$  error, whereas mean ages are given at the 95% confidence level.

#### 4. Sample description

This study concentrates on two samples from the Kimi Complex, an eclogite and a metapelite for which field relations, petrography and mineral chemistry are reported below. Representative major mineral compositions for the eclogite and the metapelite are listed in Table 1; trace element compositions are given in Table 2. Throughout text, figures and tables mineral abbreviations are according to Kretz (1983).

##### 4.1. Eclogite

The occurrence of eclogites in the Kimi area is restricted to small outcrops within folded amphibolite lenses surrounded by leucocratic orthogneisses (Fig. 2). These lenses vary in size from tens to hundreds of meters in length, and are discordantly cut by cm-sized pegmatitic veins. The amphibolites are strongly foliated

Table 2  
Representative trace element analyses of minerals, determined by LA-ICPMS

| Mineral | Eclogite                |                         |                        |                       |                         | Metapelite          |                     |                    |                    |                       |                      |
|---------|-------------------------|-------------------------|------------------------|-----------------------|-------------------------|---------------------|---------------------|--------------------|--------------------|-----------------------|----------------------|
|         | Grt <sub>1</sub> (core) | Grt <sub>2</sub> (poic) | Grt <sub>3</sub> (rim) | Rt <sub>in</sub> Omp1 | Rt <sub>in</sub> others | Grt <sub>Core</sub> | Grt <sub>Core</sub> | Grt <sub>Rim</sub> | Grt <sub>Rim</sub> | Rt <sub>in</sub> Plag | Rt <sub>in</sub> Grt |
| Ti      | 302                     | 1090                    | 432                    | 597,000               | 597,000                 | 266                 | 269                 | 263                | 261                | 597,000               | 597,000              |
| V       | 48.51                   | 119.30                  | 42.77                  | 1057                  | 1027                    | 226.5               | 232.1               | 162.8              | 246.8              | 4203                  | 7563                 |
| Cr      | 16.06                   | 7.09                    | 159.2                  | 526.7                 | 489.6                   | 81.05               | 91.92               | 99.95              | 113.9              | 758.8                 | 725.5                |
| Rb      | Bdl                     | 0.06                    | 0.22                   | Bdl                   | Bdl                     | Bdl                 | 0.15                | 0.12               | Bdl                | Bdl                   | Bdl                  |
| Sr      | 0.16                    | 24.16                   | 0.19                   | 3.67                  | 4.13                    | 0.02                | 0.04                | 0.01               | 0.01               | 3.90                  | 3.58                 |
| Y       | 162.8                   | 95.34                   | 146.2                  | 0.25                  | 1.51                    | 121.3               | 187.3               | 89.54              | 105.8              | 0.37                  | 0.27                 |
| Zr      | 4.77                    | 11.02                   | 3.35                   | 459.6                 | 1041                    | 9.17                | 16.02               | 18.60              | 13.16              | 429.6                 | 375.8                |
| La      | Bdl                     | 0.32                    | 0.00                   | Bdl                   | 0.04                    | Bdl                 | 0.01                | 0.02               | Bdl                | 0.12                  | Bdl                  |
| Ce      | 0.13                    | 2.06                    | 0.05                   | Bdl                   | 0.07                    | 0.03                | 0.03                | 0.09               | Bdl                | 0.20                  | Bdl                  |
| Pr      | 0.13                    | 0.55                    | 0.04                   | Bdl                   | 0.01                    | Bdl                 | 0.01                | Bdl                | Bdl                | 0.02                  | Bdl                  |
| Nd      | 2.72                    | 4.41                    | 1.01                   | Bdl                   | 0.06                    | 0.11                | 0.28                | 0.21               | 0.48               | 0.11                  | Bdl                  |
| Sm      | 5.03                    | 3.88                    | 3.32                   | Bdl                   | 0.02                    | 2.94                | 3.43                | 3.19               | 2.47               | 0.03                  | Bdl                  |
| Eu      | 1.89                    | 1.36                    | 1.54                   | Bdl                   | 0.01                    | 0.73                | 1.22                | 0.61               | 0.59               | 0.01                  | Bdl                  |
| Gd      | 17.21                   | 10.17                   | 13.91                  | Bdl                   | 0.04                    | 20.37               | 18.96               | 10.58              | 9.63               | Bdl                   | Bdl                  |
| Tb      | 4.65                    | 2.34                    | 3.55                   | Bdl                   | 0.02                    | 4.59                | 5.32                | 2.31               | 2.65               | Bdl                   | Bdl                  |
| Dy      | 34.85                   | 18.04                   | 26.88                  | Bdl                   | 0.18                    | 29.00               | 41.65               | 16.72              | 21.37              | 0.03                  | Bdl                  |
| Ho      | 6.47                    | 3.83                    | 5.72                   | Bdl                   | 0.05                    | 4.67                | 8.41                | 3.64               | 4.35               | 0.00                  | Bdl                  |
| Er      | 15.22                   | 10.79                   | 16.52                  | Bdl                   | 0.15                    | 10.74               | 21.41               | 10.29              | 11.18              | 0.02                  | Bdl                  |
| Tm      | 1.67                    | 1.42                    | 2.25                   | Bdl                   | 0.02                    | 1.32                | 2.66                | 1.47               | 1.36               | 0.00                  | Bdl                  |
| Yb      | 8.47                    | 8.57                    | 14.27                  | 0.10                  | 0.36                    | 8.21                | 15.97               | 9.85               | 8.06               | 0.14                  | 0.12                 |
| Lu      | 0.93                    | 1.10                    | 1.89                   | Bdl                   | 0.02                    | 1.12                | 2.19                | 1.58               | 1.18               | Bdl                   | Bdl                  |
| Nb      | Bdl                     | 0.01                    | 0.19                   | 664.8                 | 682.0                   | 0.06                | 0.14                | Bdl                | 0.01               | 1224                  | 3242                 |
| Ta      | Bdl                     | Bdl                     | Bdl                    | 26.58                 | 17.72                   | 0.01                | Bdl                 | Bdl                | Bdl                | 108.9                 | 227.5                |
| Hf      | 0.17                    | 0.58                    | 0.05                   | 22.78                 | 34.49                   | 0.26                | 0.34                | 0.43               | 0.28               | 27.40                 | 24.41                |
| Pb      | 0.03                    | 1.16                    | 0.23                   | 0.09                  | 1.47                    | 0.19                | 0.11                | Bdl                | 0.02               | 0.40                  | 0.34                 |
| Th      | Bdl                     | 0.05                    | 0.01                   | Bdl                   | Bdl                     | Bdl                 | 0.01                | Bdl                | Bdl                | 0.09                  | Bdl                  |
| U       | Bdl                     | 0.01                    | 0.01                   | 13.48                 | 18.42                   | 0.03                | 0.03                | 0.02               | 0.02               | 11.18                 | 26.35                |
| Dy/Yb   | 2.69                    | 1.38                    | 1.23                   | –                     | –                       | 1.71                | 1.31                | 1.11               | 1.73               | –                     | –                    |
| Dy/Gd   | 1.64                    | 1.43                    | 1.56                   | –                     | –                       | 1.78                | 1.42                | 1.28               | 1.79               | –                     | –                    |
| Lu/Sm   | 1.11                    | 1.71                    | 3.44                   | –                     | –                       | 3.85                | 3.68                | 2.99               | 2.87               | –                     | –                    |
| Eu/Eu*  | 0.56                    | 0.63                    | 0.59                   | –                     | –                       | 0.36                | 0.35                | 0.29               | 0.32               | –                     | –                    |

Eu/Eu\* = 2Eu/(Sm + Gd). Bdl = below detection limit.

and contain remnants of retrogressed eclogites. Fresh eclogites within the amphibolite lenses are scarce and show no mineral preferred orientation. The sample was collected ca. 500 m northwest of Organi village (Fig. 2) from the core of an amphibolite lens. Omphacite and garnet amount to ca. 90% of the volume of the massive eclogite. Minor minerals (ca. 10% in volume) are plagioclase, hornblende, biotite, rutile, apatite and zircon. The mineral distribution appears inhomogeneous, enforced by the large grain size of garnet and omphacite.

Garnet grains (1–10 mm in diameter) are poikiloblastic and show straight grain boundaries with hornblende and plagioclase (Fig. 3a). Three zones are distinguished: an inclusion-free core (Grt1, mm-sized), a dominant poikiloblastic mantle (Grt2, mm-sized), and an inclusion-free rim (Grt3,  $\leq 500 \mu\text{m}$  in size) (Fig. 4a). Inclusions in Grt2 are omphacite ( $\text{Jd}_{37}\text{--Jd}_{20}$ , Fig. 5a), biotite, hornblende and rutile, with rare polyphase inclusions of omphacite ( $\text{Jd}_{37}\text{--Jd}_{20}$ ) plus plagioclase ( $\text{Ab}_{90}$ ). Inclusions of omphacite, plagioclase and rutile are considered to be primary, whereas biotite and hornblende inclusions are always associated with cracks and therefore probably secondary. Garnet grains are virtually homogeneous in major elements ( $\text{Alm}_{43} \text{Grs}_{15} \text{Prp}_{38} \text{Sps}_1$ ) with only a slight increase in  $X_{\text{Fe}}$  and decrease in  $X_{\text{Mg}}$  towards the rim ( $\text{Alm}_{46} \text{Prp}_{33}$ ), and a slight

increase in Ca in Grt1 ( $\text{Grs}_{17}$ , Fig. 4b). However, the three garnet zones have different trace element contents (Fig. 4c). Grt1 is characterised by slightly higher MREE and lower HREE contents ( $\text{Lu/Gd}$  0.27) and is also the poorest in most other trace elements. Grt2 has the highest content in Li, B, Ti, V, Sr, Zr and LREE. Consistently high values were obtained for all the seven analyses, which showed a constant ablation pattern through time. This suggests that the high concentration of these elements is not caused by micro-inclusions. The M-HREE pattern of the poikiloblastic Grt2 is nearly flat ( $\text{Lu/Gd}$  0.81). Grt3 is particularly rich in Cr and Sc, poor in LREE and shows a flat M-HREE pattern ( $\text{Lu/Gd}$  0.94). All three zones display a similar negative Eu anomaly ( $\text{Eu/Eu}^*$  ca. 0.60).

Matrix omphacite is mostly isometric, up to 1 mm in size and surrounded by plagioclase ribbons (Fig. 3a–c). Rutile inclusions are common throughout omphacite. The composition of the omphacite core is  $\text{Jd}_{35\text{--}40} \text{Ae}_{0\text{--}5} \text{Di}_{55\text{--}60}$  (Omp1, Fig. 5a). The outermost rim, when in contact with plagioclase, has a retrograde composition of  $\text{Jd}_{20\text{--}35} \text{Ae}_{0\text{--}5} \text{Di}_{75\text{--}80}$  (Omp2; the BSE-brighter rims in Fig. 3a). Plagioclase ( $\text{Ab}_{90}$ ) occurs at the border between omphacite and garnet and forms small rims (tens of microns) around omphacite grains (Fig. 3a–c). Symplectitic intergrowth between omphacite and plagioclase

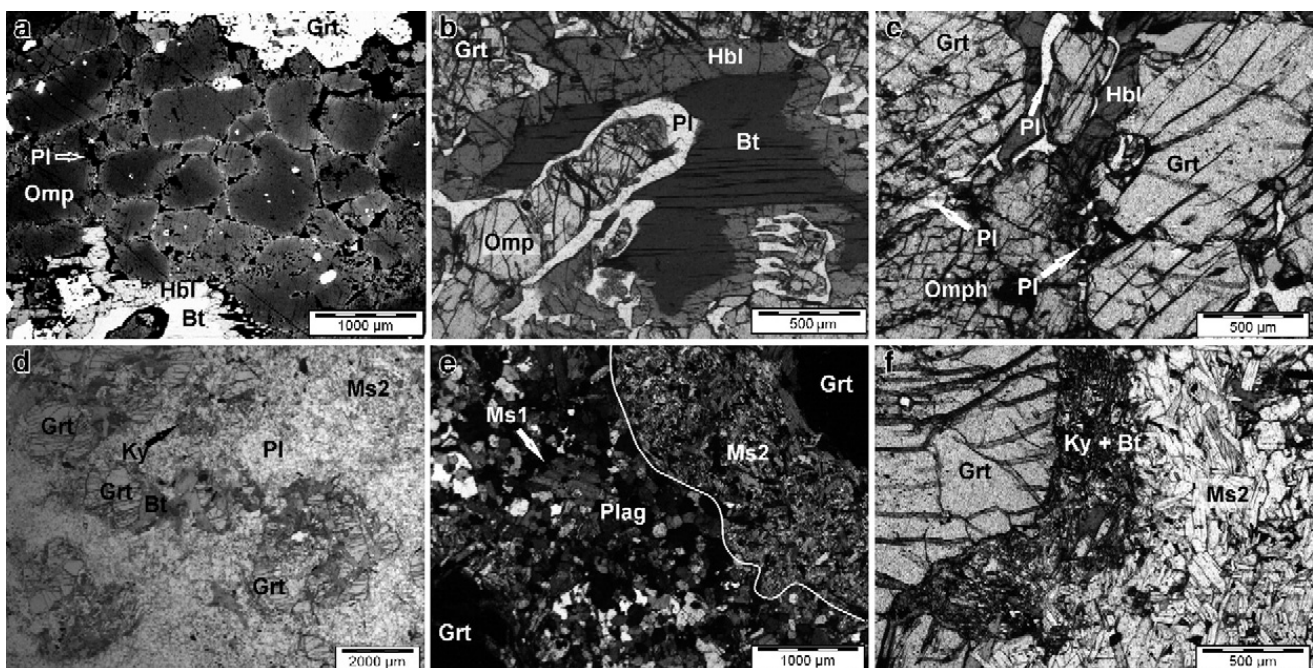


Fig. 3. Photomicrographs (except a) of eclogite (a–c) and metapelite (d–f). a) BSE image of omphacite grains with dark cores reflecting a higher Jd content compared to the rims. The omphacite grains are surrounded by interstitial plagioclase (black). b) Biotite surrounded by hornblende. c) Garnet, plagioclase, hornblende and biotite show straight grain boundaries, while omphacite is always surrounded by a plagioclase seam. d) Metapelite matrix with biotite developing around garnet. e) The two mineral assemblages present in the metapelite: the mesosome is composed of garnet and muscovite and the leucosome consists of plagioclase and muscovite (crossed polars). The boundary is marked by the white line. f) Biotite + Ky2 corona between garnet and muscovite.

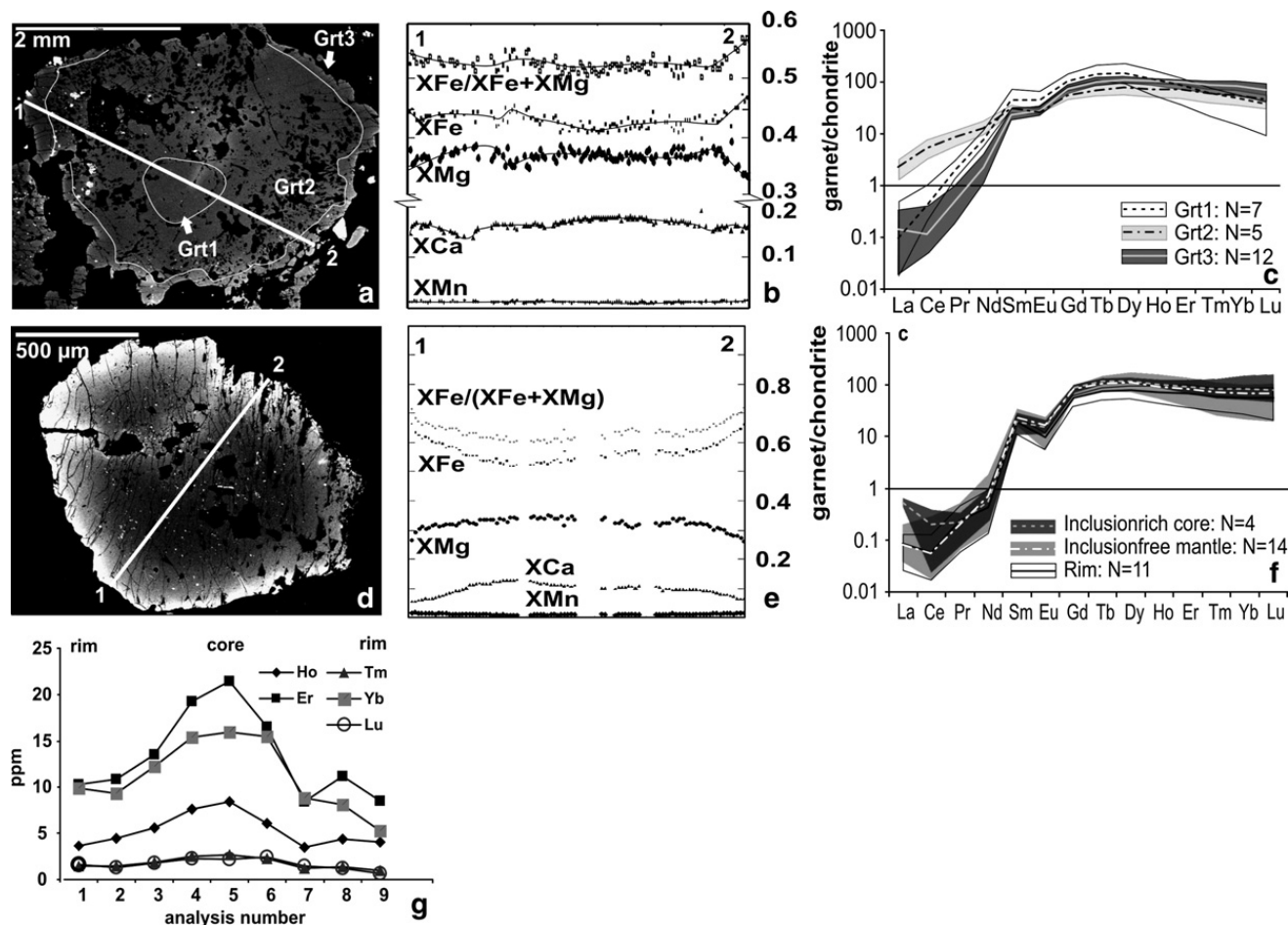


Fig. 4. Composition of garnet in eclogite (a–c) and metapelite (d–g). a) BSE image of a garnet grain with a core (Grt1) surrounded by an inclusion-rich domain (Grt2) and a thin rim (Grt3). Inclusions are omphacite and omphacite + plagioclase. The thin white lines mark the boundaries of the three garnet domains. b) Major elements profile across the garnet shown in a). c) REE patterns of the three garnet domains normalised to C1 chondrite (McDonough and Sun, 1995). d) BSE image of a garnet grain from the metapelite. e) Major elements composition across the garnet grain showing Fe increase and Mg and Ca decrease toward the rim. f) Chondrite-normalised garnet REE patterns for the different domains. High LREE in garnet core are due to microinclusions. g) HREE traverse over a garnet with enrichment in the core. See text for details.

is scarce. Plagioclase with the same composition also forms polyphase inclusions in garnet (Plag + Omp2). *Pargasitic hornblende* commonly forms around garnet and has straight grain boundaries with plagioclase, garnet and biotite (Fig. 3b). Hornblende is absent in omphacite-rich domains (Fig. 3a) and was not observed as primary inclusion in garnet. *Biotite* occurs as large flakes in the matrix and is mostly surrounded by hornblende (Fig. 3b). Its  $X_{Mg}$  varies between 0.71–0.78 (Fig. 5a). Biotite shows a high Ba content between 3700 and 4400 ppm. *Rutile* is a common inclusion within all major minerals and shows variable sizes up to hundreds of microns. Trace element contents are V: 760–1200 ppm, Cr: 320–650 ppm, Nb: 620–1020 ppm and Ta: 14–50 ppm. Zr content is lower in rutile included in Omp1 (Zr: 460–620 ppm) than in rutile included in Omp2, garnet, amphibole, plagioclase and biotite (Zr: 780–1040 ppm).

#### 4.2. Metapelite

Metapelites in the study area are kyanite-bearing garnet micaschists, which are bordered by serpentinites and leucocratic orthogneisses (Fig. 2). These rocks show a well-developed foliation and intense weathering. The investigated sample was collected 500 m southeast of the Kimi village, from the same outcrop where micro-diamond inclusions in garnet were described (Perraki et al., 2006).

The metapelite sample consists of garnet, biotite, plagioclase, muscovite, kyanite and quartz, with accessory rutile, monazite and zircon. Two distinct mineral assemblages define the mesosome and leucosome and characterize the inhomogeneous mineral distribution of the sample (Fig. 3d–f). The mesosome is defined by mm-sized, elongated lenses of garnet, biotite, kyanite, muscovite,  $\pm$ quartz,  $\pm$ plagioclase and  $\pm$ graphite. The

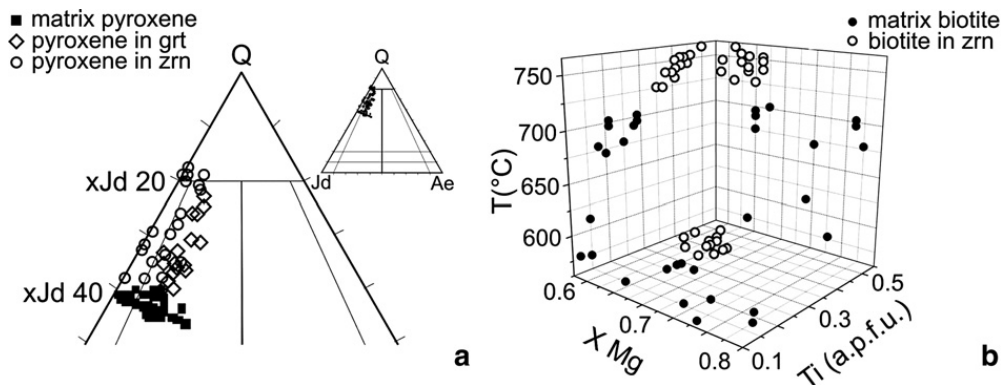


Fig. 5. a) Comparison of pyroxene chemistry in eclogite (Classification after Morimoto 1988). Q is Quad pyroxene. The small triangles show the standard plot. Filled squares represent cores of matrix pyroxene with XJd ~40; diamonds are pyroxene inclusions in garnet, XJd ~37–20, circles are pyroxene included in zircon with similar XJd ~37–17 to pyroxene in garnet. b) Difference in composition between the biotite included in zircon and that in the metapelite matrix. Temperature estimates are after the thermometer of Henry et al. (2005).

mesosome lenses are surrounded by a leucosome composed of slightly zoned plagioclase grains, together with quartz and inclusion-rich muscovite (Fig. 3d–f).

Garnet grains are 1–4 mm in diameter and show extensive replacement by biotite (Fig. 3d, f). Core domains, which show minor biotite overprinting, have higher Ca and Mg contents and a lower Fe content compared to the rims (Fig. 4d–e). The garnet core contains clusters of dark,  $\mu\text{m}$ -sized and cuboid-shaped inclusions consisting of  $\text{CO}_2$ , ordered/disordered graphite, apatite and carbonates. Both, single phases and polyphase inclusions of C-phases occur. Perraki et al. (2006) reported diamonds from within similar cuboid inclusions in garnet cores of the same rock, however, in our sections no diamond was found. Garnet cores are also characterized by rounded rutile inclusions, whereas fine-grained, crystallographically oriented rutile needles occur across the entire garnet grains. The inclusion-free mantle domain shows the same composition as the core, but lacks the cuboid inclusions. The garnet core has a composition of  $\text{Alm}_{58} \text{Grs}_7 \text{Prp}_{36} \text{Spes}_1$ , while the rim is  $\text{Alm}_{69} \text{Grs}_5 \text{Prp}_{23} \text{Spes}_3$ . The chondrite-normalized REE patterns (Fig. 4f) show minor differences between the inclusion-rich garnet core, the inclusion-free mantle and the rim. Some core analyses show higher LREE, probably due to LREE-bearing microinclusions. HREE are enriched by a factor of 2 in the core when compared to the rim (Fig. 4g and Table 2). A negative Eu anomaly ( $\text{Eu}/\text{Eu}^* = 0.26–0.31$ ) is observed in all domains and the HREE pattern has a flat to negative trend ( $\text{Lu}/\text{Gd} = 0.66–0.98$ ).

Two generations of kyanite are observed; a first generation of mm sized kyanite grains (Ky1), and a second generation (Ky2) of about 10–100  $\mu\text{m}$  in size. Ky1 occurs in the mesosome as well as in the leucosome, where it is surrounded by small, recrystallized grains of Ky2. Furthermore, Ky2 is situated in areas where garnet is

consumed by biotite (Fig. 3f). Three types of plagioclase occur: Pl1 forms a fine-grained matrix (100–200  $\mu\text{m}$ ) with well-developed triple junctions. This plagioclase is slightly zoned (core:  $\text{An}_{15}$ , rim:  $\text{An}_{20}$ ). Pl2 occurs as inclusions in Ms1 and quartz, with a composition of ca.  $\text{An}_{20}$ . Pl3 are large (0.5–1 mm) grains in the matrix with a composition of  $\text{An}_{20}$ . Muscovite is only slightly phengitic (3.1–3.15 Si a.p.f.u.) and two types are distinguished. Large grains (Ms1, ca. 500  $\mu\text{m}$ ) within the leucosome have inclusions of quartz and plagioclase ( $\text{An}_{20}$ ) and are characterized by a patchy Ba zoning (up to 1 wt.% BaO) and embayments along their outlines. Fine-grained muscovite (Ms2, <50  $\mu\text{m}$ ) occurs in the mesosome and Ba is below detection limit. Biotite is restricted to the mesosome and forms around garnet. Its  $X_{\text{Mg}}$  varies between 0.63 and 0.80, and Ti varies between 0.1 and 0.3 a.p.f.u. (Fig. 5b).

## 5. Zircon inclusions, composition and ages

Zircon is the sole U–Pb mineral in the eclogite and the main U–Pb mineral in the metapelite. It has been investigated for its internal structure and inclusions and was analysed for U–Pb isotopes and trace elements.

### 5.1. Eclogite Zircons

Zircons are present within garnet, plagioclase, hornblende and biotite, but absent within omphacite. The grains are colourless, prismatic, with rounded outlines and 100 to 250  $\mu\text{m}$  in length (length/width = 1.5:1). Isometric grains are subordinated. CL investigation (Fig. 6) generally reveals a large core with variable CL emission and mostly a broad, polygonal oscillatory zoning that occasionally looks faint. The cores can be surrounded and/or transected by unzoned areas showing strong to intermediate CL emission (Fig. 6a, c and e). Embayments of

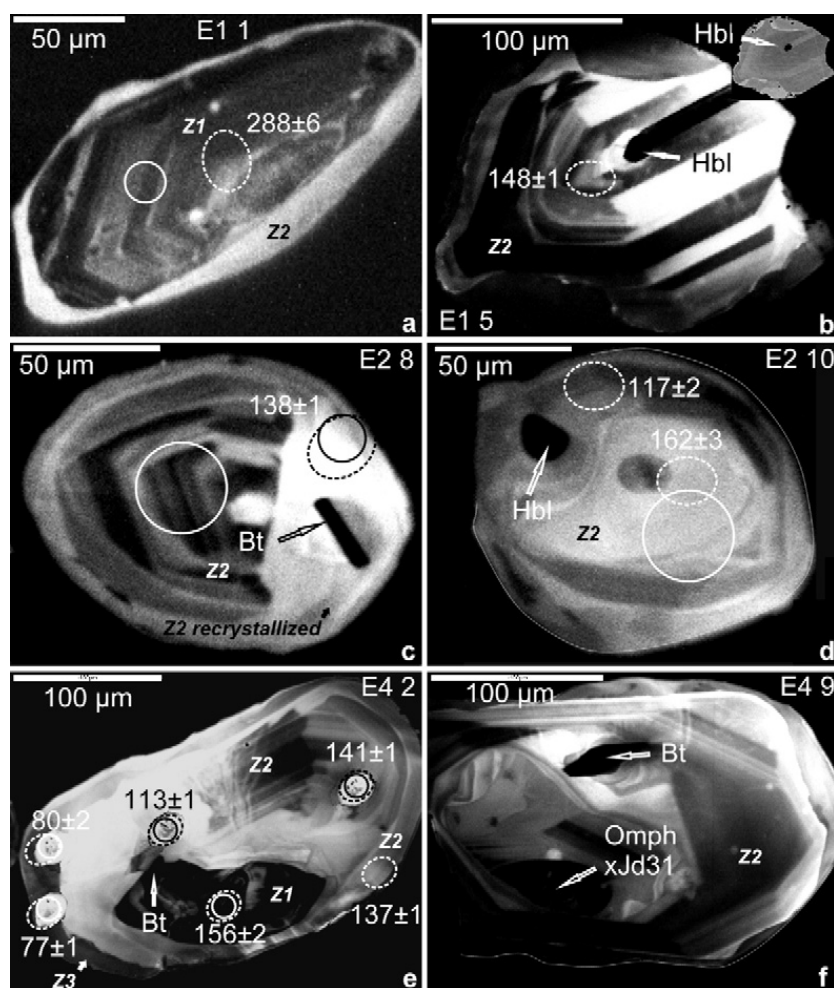


Fig. 6. Cathodoluminescence images of zircon crystals from the eclogite. Dashed ellipses correspond to SHRIMP analyses and circles to LA-ICPMS analyses. Numbers are  $^{206}\text{Pb}/^{238}\text{U}$  ages ( $\text{Ma} \pm 1\sigma$ ). The inset in b) shows the BSE-image of the same crystal with a K-rich Hbl inclusion. Note the embayments of the zoning around inclusions in c, d and f.

zoning around mineral inclusions are commonly observed (Fig. 6d and f).

Three distinct zircon domains can be recognised only when all information from internal CL zoning (not always diagnostic), inclusion mineralogy, and trace element composition are combined. Z1 domains are zircon cores with either oscillatory zoning patterns and/or low CL emission partly masking any zoning (Fig. 6a, e). The inclusions in domain Z1 are restricted to quartz and apatite. As suggested by their low CL emission, Z1 domains generally have the highest trace element content of the three domains (for example U: 533–1251 ppm, Th: 276–1037 ppm, Table 4) and an elevated Th/U ratio in the range of 0.5–0.8. The REE pattern of Z1 (Fig. 7a) shows a pronounced positive Ce anomaly, a well developed negative Eu anomaly ( $\text{Eu}/\text{Eu}^* = 0.03$ ) and an increasing enrichment in HREE with respect to MREE ( $\text{Lu}/\text{Gd} = 20$ ). Seven SHRIMP analyses (Table 4) on the U-rich Z1 domains yielded  $^{206}\text{Pb}/^{238}\text{U}$  ages scattering between

288±6 and 156±2 Ma, without any statistically consistent group (Fig. 7b).

Z2 domain is volumetrically dominant and occurs either as cores or rims around Z1 cores. Domain Z2 shows a variety of zoning patterns from oscillatory (Fig. 6b, c, e, f) to homogeneous (e.g. rim in Fig. 6a, c and d), with a number of domains showing a faint zoning, often transecting the oscillatory bands (Fig. 6a, c). This zircon domain is particularly rich in inclusions of metamorphic minerals like biotite, omphacite, clinopyroxene, hornblende, garnet, quartz, carbonates, apatite and rutile, as well as polyphase inclusions of biotite and quartz (Table 1). Inclusions that displayed weak Raman bands of plagioclase or albite, but did not have plagioclase composition when analysed with SEM were interpreted as former melt. Carbonate inclusions showed Raman bands of ankerite, calcite, dolomite and magnesite, but were mostly too small for SEM analysis (except calcite) and were thus classified as generic “carbonate”. Biotite

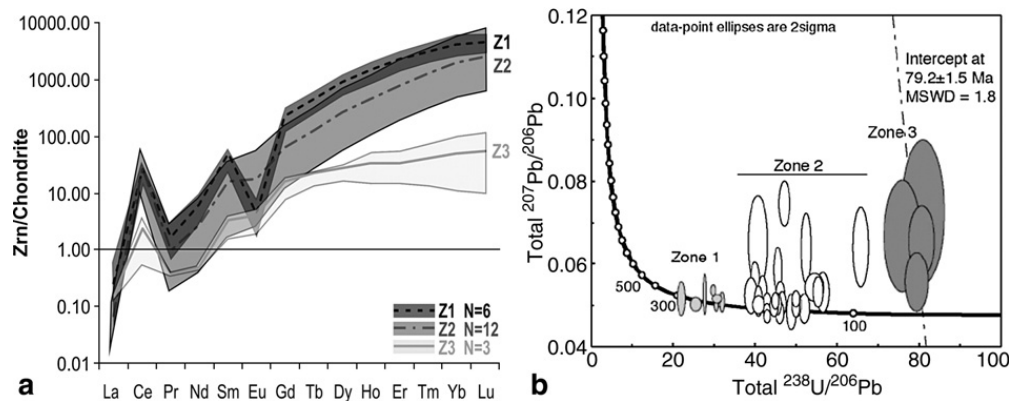


Fig. 7. a) Chondrite-normalised REE patterns of the three zircon domains from the eclogite. Thick lines are the average values of analyses contained in the polygon (data from Table 3). b) Tera–Wasserburg diagram for SHRIMP analyses of the eclogite zircons showing an age scatter for core domains (Z1, light grey ellipses) and Z2 domains (white ellipses), and a weighted mean age for Z3 (dark grey ellipses) of  $79.2 \pm 1.5$  Ma.

inclusions in domain Z2 show slightly lower  $X_{\text{Mg}}$  values and higher Ti content compared to matrix biotite (inclusions:  $X_{\text{Mg}}$  0.68–0.71 and 0.45–0.50 Ti a.p.f.u. vs. matrix biotite:  $X_{\text{Mg}}$  0.71–0.78 and 0.37–0.48 Ti a.p.f.u.). The jadeite component in omphacite varies between  $X_{\text{Jd}17}$  and

$X_{\text{Jd}17}$ , and is similar to the composition of Omp2 in the matrix (Fig. 5a). Z2 domains have lower U and Th contents than Z1 domains, but similar Th/U (0.2–0.7). They show similar REE patterns (Lu/Gd=41), but with lower amounts of trace elements and a less pronounced negative Eu

Table 3  
Representative trace element analyses of zircon domains

| Domain | Eclogite |         |          |          |          |          | Metapelite |          |         |          |
|--------|----------|---------|----------|----------|----------|----------|------------|----------|---------|----------|
|        | Z1       | Z1      | Z2oscill | Z2faint  | Z3       | Z3       | R1         | R1       | R2      | R2       |
| P      | 1259.80  | 786.12  | 424.25   | 204.91   | 73.36    | 58.95    | 401.56     | 613.69   | 286.77  | 264.84   |
| Ti     | 17.05    | 34.21   | 9.55     | 4.48     | 5.28     | 3.38     | 12.91      | 8.63     | 18.68   | 18.18    |
| Sr     | 0.64     | 0.47    | 0.27     | 0.40     | 0.23     | 0.18     | 0.39       | 0.40     | 0.10    | 0.09     |
| Y      | 2704.38  | 2309.47 | 971.58   | 270.53   | 41.52    | 28.72    | 386.06     | 409.33   | 136.24  | 184.52   |
| Nb     | 6.53     | 5.46    | 2.82     | 1.05     | 0.19     | 0.15     | 0.91       | 1.29     | 0.29    | 0.21     |
| La     | 0.03     | bdl     | 0.01     | bdl      | 0.04     | bdl      | 0.07       | bdl      | bdl     | bdl      |
| Ce     | 20.76    | 22.05   | 18.70    | 8.57     | 1.40     | 0.38     | 0.75       | 0.61     | 1.52    | 1.87     |
| Pr     | 0.11     | 0.12    | 0.07     | bdl      | bdl      | bdl      | 0.05       | bdl      | 0.10    | 0.14     |
| Nd     | 2.61     | 2.57    | 1.40     | 0.21     | 0.23     | bdl      | 0.76       | 0.30     | 2.33    | 2.55     |
| Sm     | 8.01     | 6.97    | 2.85     | 0.44     | 0.63     | 0.26     | 1.32       | 1.08     | 6.10    | 7.41     |
| Eu     | 0.25     | 0.13    | 0.97     | 0.14     | 0.34     | 0.12     | 0.45       | 0.65     | 0.15    | 0.20     |
| Gd     | 52.65    | 44.20   | 16.37    | 3.17     | 4.10     | 1.76     | 7.07       | 8.00     | 15.92   | 20.95    |
| Tb     | 19.32    | 16.91   | 5.85     | 1.34     | 0.97     | 0.56     | 2.81       | 2.69     | 2.96    | 3.69     |
| Dy     | 261.51   | 222.33  | 78.57    | 19.77    | 6.88     | 4.60     | 34.56      | 28.41    | 21.67   | 26.51    |
| Ho     | 93.23    | 82.22   | 30.69    | 8.42     | 1.32     | 0.93     | 12.79      | 11.95    | 4.46    | 6.19     |
| Er     | 412.84   | 373.68  | 155.86   | 45.97    | 3.57     | 2.70     | 60.91      | 78.20    | 14.73   | 20.03    |
| Tm     | 87.29    | 77.81   | 37.05    | 12.12    | 0.57     | 0.37     | 18.83      | 27.50    | 2.52    | 3.35     |
| Yb     | 746.34   | 669.34  | 372.33   | 128.42   | 3.52     | 2.04     | 232.10     | 342.18   | 17.63   | 24.12    |
| Lu     | 121.20   | 111.11  | 67.37    | 25.55    | 0.50     | 0.28     | 39.05      | 66.49    | 2.52    | 3.43     |
| Hf     | 9177.62  | 9823.77 | 9712.52  | 11227.39 | 22485.22 | 22935.00 | 12821.78   | 12881.27 | 9722.27 | 10141.24 |
| Ta     | 2.83     | 2.69    | 1.37     | 0.60     | 0.06     | 0.05     | 0.42       | 0.46     | 0.07    | 0.04     |
| Pb     | 16.15    | 17.17   | 2.24     | 1.19     | 0.24     | bdl      | 0.64       | 0.56     | 0.56    | 0.51     |
| Th     | 1036.85  | 707.33  | 181.35   | 58.88    | 3.53     | 0.49     | 27.11      | 20.90    | 41.83   | 36.10    |
| U      | 1242.05  | 1027.78 | 387.28   | 126.56   | 50.42    | 16.32    | 2169.30    | 1757.18  | 426.56  | 428.84   |
| Th/U   | 0.83     | 0.69    | 0.47     | 0.47     | 0.07     | 0.03     | 0.01       | 0.01     | 0.10    | 0.08     |
| Dy/Yb  | 0.23     | 0.22    | 0.14     | 0.10     | 1.28     | 1.47     | 0.10       | 0.05     | 0.80    | 0.72     |
| Dy/Gd  | 4.02     | 4.07    | 3.88     | 5.05     | 1.36     | 2.12     | 3.95       | 2.87     | 1.10    | 1.02     |
| Lu/Gd  | 18.62    | 20.34   | 33.29    | 65.20    | 0.98     | 1.29     | 44.65      | 67.27    | 1.28    | 1.32     |
| Eu/Eu* | 0.03     | 0.02    | 0.34     | 0.26     | 0.48     | 0.41     | 0.36       | 0.49     | 0.04    | 0.05     |

Table 4  
Th-UPb data of the zircons

| Spot name         | U (ppm) | Th (ppm) | Th/U | %Pb c | $^{206}\text{Pb}/^{238}\text{U}$ | 1 $\sigma$ % | Total<br>$^{238}\text{U}/^{206}\text{Pb}$ | 1 $\sigma$ % | Total<br>$^{207}\text{Pb}/^{206}\text{Pb}$ | 1 $\sigma$ % | Age<br>$^{206}\text{Pb}/^{238}\text{U}$ | $\pm 1\sigma$ | CL<br>domain |
|-------------------|---------|----------|------|-------|----------------------------------|--------------|-------------------------------------------|--------------|--------------------------------------------|--------------|-----------------------------------------|---------------|--------------|
| <b>Eclogite</b>   |         |          |      |       |                                  |              |                                           |              |                                            |              |                                         |               |              |
| E4-5.1(a)         | 19      | 1        | 0.03 | 7.2   | 0.0120                           | 2.81         | 80.88                                     | 2.65         | 0.0728                                     | 9.67         | 76.7                                    | 2.1           | Z3           |
| E4-2.3(a)         | 70      | 5        | 0.07 | 3.4   | 0.0121                           | 1.65         | 80.58                                     | 1.59         | 0.0659                                     | 5.27         | 77.7                                    | 1.3           | Z3           |
| E4-6.1(a)         | 67      | 4        | 0.06 | 2.4   | 0.0125                           | 1.51         | 79.38                                     | 1.46         | 0.0560                                     | 5.20         | 79.8                                    | 1.2           | Z3           |
| E4-2.1(a)         | 21      | 1        | 0.05 | 5.9   | 0.0129                           | 2.50         | 75.87                                     | 2.39         | 0.0670                                     | 8.19         | 82.4                                    | 2.0           | Z3           |
| E2-6.1            | 106     | 57       | 0.54 | 2.0   | 0.0149                           | 1.53         | 65.78                                     | 1.16         | 0.0644                                     | 6.13         | 95.3                                    | 1.5           | Z2           |
| E4-2.5            | 110     | 46       | 0.42 | 0.3   | 0.0176                           | 1.27         | 56.57                                     | 1.15         | 0.0535                                     | 3.66         | 112.6                                   | 1.4           | Z2           |
| E2-5.2            | 199     | 43       | 0.22 | 0.6   | 0.0180                           | 0.96         | 55.31                                     | 0.90         | 0.0536                                     | 2.75         | 114.8                                   | 1.1           | Z2           |
| E2-10.1           | 210     | 114      | 0.54 | 0.3   | 0.0183                           | 1.91         | 54.40                                     | 1.71         | 0.0547                                     | 2.51         | 117.1                                   | 2.2           | Z2           |
| E2-7.1            | 157     | 72       | 0.46 | 2.9   | 0.0185                           | 1.79         | 52.46                                     | 0.95         | 0.0641                                     | 5.38         | 118.2                                   | 2.1           | Z2           |
| E4-1.2            | 174     | 91       | 0.52 | 0.9   | 0.0191                           | 1.14         | 51.98                                     | 0.98         | 0.0496                                     | 2.92         | 121.8                                   | 1.4           | Z2           |
| E1-2.1            | 261     | 116      | 0.44 | 0.8   | 0.0197                           | 0.91         | 50.29                                     | 0.81         | 0.0505                                     | 2.19         | 125.9                                   | 1.1           | Z2           |
| E2-6.1A           | 426     | 213      | 0.50 | 0.9   | 0.0198                           | 0.81         | 49.95                                     | 0.72         | 0.0519                                     | 1.57         | 126.6                                   | 1.0           | Z2           |
| E2-9.1            | 345     | 172      | 0.50 | 0.1   | 0.0200                           | 0.82         | 49.92                                     | 0.73         | 0.0500                                     | 2.00         | 127.8                                   | 1.0           | Z2           |
| E4-4.1            | 127     | 55       | 0.44 | 0.5   | 0.0204                           | 1.13         | 48.81                                     | 1.01         | 0.0489                                     | 3.55         | 130.1                                   | 1.5           | Z2           |
| E4-8.1            | 153     | 39       | 0.26 | 3.1   | 0.0206                           | 1.30         | 47.13                                     | 1.16         | 0.0748                                     | 2.95         | 131.2                                   | 1.7           | Z2           |
| E1-4.1            | 249     | 123      | 0.49 | 0.5   | 0.0214                           | 0.92         | 46.62                                     | 0.80         | 0.0508                                     | 2.34         | 136.2                                   | 1.2           | Z2           |
| E4-2.2            | 173     | 96       | 0.55 | 0.9   | 0.0215                           | 1.02         | 46.17                                     | 0.89         | 0.0531                                     | 2.30         | 136.9                                   | 1.4           | Z2           |
| E2-8.1            | 163     | 68       | 0.42 | 1.9   | 0.0216                           | 1.05         | 45.50                                     | 0.91         | 0.0589                                     | 3.82         | 137.6                                   | 1.4           | Z2           |
| E4-12.1           | 260     | 122      | 0.47 | 0.3   | 0.0217                           | 0.95         | 46.03                                     | 0.85         | 0.0486                                     | 2.22         | 138.2                                   | 1.3           | Z2           |
| E4-2.4            | 276     | 153      | 0.55 | 0.0   | 0.0221                           | 0.93         | 45.41                                     | 0.83         | 0.0507                                     | 2.10         | 140.6                                   | 1.3           | Z2           |
| E2-8.2            | 455     | 202      | 0.44 | 0.4   | 0.0222                           | 0.91         | 44.92                                     | 0.83         | 0.0514                                     | 1.60         | 141.4                                   | 1.3           | Z2           |
| E4-10.1           | 339     | 245      | 0.72 | 0.2   | 0.0224                           | 1.12         | 44.57                                     | 0.97         | 0.0500                                     | 1.84         | 142.8                                   | 1.6           | Z2           |
| E4-7.1            | 17      | 3        | 0.16 | 5.7   | 0.0232                           | 2.71         | 40.68                                     | 2.37         | 0.0655                                     | 7.05         | 147.8                                   | 4.0           | Z2           |
| E4-15.2           | 180     | 94       | 0.52 | 0.2   | 0.0233                           | 1.05         | 42.94                                     | 0.93         | 0.0502                                     | 2.60         | 148.2                                   | 1.5           | Z2           |
| E1-5.1            | 720     | 278      | 0.39 | 0.1   | 0.0233                           | 0.82         | 42.92                                     | 0.76         | 0.0477                                     | 1.35         | 148.3                                   | 1.2           | Z2           |
| E4-13.1           | 378     | 167      | 0.44 | 0.0   | 0.0233                           | 0.84         | 42.90                                     | 0.77         | 0.0487                                     | 1.76         | 148.6                                   | 1.2           | Z2           |
| E3-1              | 85      | 56       | 0.65 | 0.0   | 0.0241                           | 1.33         | 41.77                                     | 1.14         | 0.0531                                     | 3.41         | 153.3                                   | 2.0           | Z2           |
| E1-3.1            | 119     | 64       | 0.54 | 0.4   | 0.0244                           | 1.11         | 40.78                                     | 0.95         | 0.0514                                     | 2.86         | 155.5                                   | 1.7           | Z2           |
| E4-2.6            | 1041    | 43       | 0.04 | 0.2   | 0.0245                           | 1.42         | 40.80                                     | 1.41         | 0.0505                                     | 1.73         | 155.7                                   | 2.2           | Z2           |
| E2-4.1            | 91      | 53       | 0.57 | 0.7   | 0.0249                           | 1.32         | 39.88                                     | 1.11         | 0.0561                                     | 3.38         | 158.6                                   | 2.1           | Z2           |
| E2-10.2           | 98      | 52       | 0.53 | 0.8   | 0.0254                           | 1.85         | 39.00                                     | 1.61         | 0.0527                                     | 3.36         | 161.9                                   | 3.0           | Z2           |
| E4-1.1            | 1052    | 767      | 0.73 | 0.0   | 0.0313                           | 0.92         | 31.95                                     | 0.80         | 0.0512                                     | 1.89         | 199.0                                   | 1.8           | Z1           |
| E4-11.1           | 1125    | 696      | 0.62 | 0.0   | 0.0326                           | 1.66         | 30.69                                     | 1.49         | 0.0519                                     | 0.82         | 206.8                                   | 3.4           | Z1           |
| E4-15.1           | 2817    | 1610     | 0.57 | 0.0   | 0.0328                           | 0.84         | 30.48                                     | 0.76         | 0.0505                                     | 1.32         | 208.3                                   | 1.7           | Z1           |
| E2-1.2            | 755     | 393      | 0.52 | 0.5   | 0.0335                           | 0.89         | 29.68                                     | 0.81         | 0.0539                                     | 1.01         | 212.6                                   | 1.9           | Z1           |
| E4-3.1            | 697     | 848      | 1.22 | 0.3   | 0.0360                           | 0.92         | 27.70                                     | 0.69         | 0.0530                                     | 3.78         | 228.1                                   | 2.1           | Z1           |
| E4-14.1           | 514     | 279      | 0.54 | 0.0   | 0.0393                           | 2.35         | 25.48                                     | 2.15         | 0.0506                                     | 1.37         | 248.5                                   | 5.7           | Z1           |
| E1-1.1            | 780     | 413      | 0.53 | 0.0   | 0.0456                           | 1.96         | 21.92                                     | 1.79         | 0.0520                                     | 3.21         | 287.5                                   | 5.5           | Z1           |
| <b>Metapelite</b> |         |          |      |       |                                  |              |                                           |              |                                            |              |                                         |               |              |
| Metapelite        | U (ppm) | Th (ppm) | Th/U | %Pb c | $^{206}\text{Pb}/^{238}\text{U}$ | 1 $\sigma$ % | $^{207}\text{Pb}/^{235}\text{U}$          | 1 $\sigma$ % | $^{207}\text{Pb}/^{206}\text{Pb}$          | 1 $\sigma$ % | Age<br>$^{206}\text{Pb}/^{238}\text{U}$ | $\pm 1\sigma$ | CL<br>domain |
| M1-1.1            | 290     | 48       | 0.17 | 0.18  | 0.0239                           | 1.17         | 0.1615                                    | 3.16         | 0.0490                                     | 2.65         | 152.3                                   | 1.7           | R2           |
| M3-20.1           | 482     | 47       | 0.10 | 0.29  | 0.0242                           | 0.65         | 0.1698                                    | 2.10         | 0.0510                                     | 1.89         | 153.5                                   | 1.0           | R2           |
| M1-8.1            | 392     | 94       | 0.24 | 0.24  | 0.0242                           | 1.39         | 0.1669                                    | 4.62         | 0.0501                                     | 4.01         | 153.8                                   | 2.0           | R2           |
| M3-15.1           | 595     | 65       | 0.11 | 0.06  | 0.0243                           | 0.63         | 0.1642                                    | 2.01         | 0.0489                                     | 1.81         | 155.1                                   | 1.0           | R2           |
| M3-17.1           | 270     | 50       | 0.18 | 0.68  | 0.0244                           | 0.78         | 0.1627                                    | 3.60         | 0.0483                                     | 3.30         | 155.9                                   | 1.2           | R2           |
| M1-2.1            | 669     | 74       | 0.11 | 0.00  | 0.0247                           | 1.08         | 0.1662                                    | 2.10         | 0.0489                                     | 1.59         | 157.1                                   | 1.7           | R2           |
| M1-10.1           | 1430    | 77       | 0.05 | 0.06  | 0.0247                           | 1.05         | 0.1653                                    | 1.67         | 0.0485                                     | 1.16         | 157.6                                   | 1.6           | R2           |
| M1-14.1           | 438     | 72       | 0.16 | 0.08  | 0.0247                           | 1.17         | 0.1660                                    | 2.87         | 0.0487                                     | 2.34         | 157.7                                   | 1.8           | R2           |
| M1-4.1            | 310     | 29       | 0.09 | 0.68  | 0.0249                           | 1.15         | 0.1705                                    | 3.52         | 0.0497                                     | 3.13         | 158.4                                   | 1.8           | R2           |
| M3-6.1            | 422     | 43       | 0.10 | 0.33  | 0.0250                           | 0.68         | 0.1625                                    | 2.48         | 0.0472                                     | 2.26         | 159.3                                   | 1.1           | R2           |
| M3-19.1           | 484     | 35       | 0.07 | 0.14  | 0.0250                           | 0.65         | 0.1699                                    | 2.16         | 0.0492                                     | 1.99         | 159.4                                   | 1.0           | R2           |
| M3-8.1            | 572     | 36       | 0.06 | 0.98  | 0.0251                           | 0.64         | 0.1679                                    | 2.35         | 0.0486                                     | 2.14         | 159.8                                   | 1.0           | R2           |
| M1-12.1           | 364     | 49       | 0.13 | 0.42  | 0.0251                           | 1.16         | 0.1700                                    | 3.03         | 0.0491                                     | 2.54         | 159.7                                   | 1.8           | R2           |
| M3-11.1           | 394     | 59       | 0.15 | 0.09  | 0.0254                           | 0.70         | 0.1689                                    | 2.71         | 0.0482                                     | 2.48         | 162.0                                   | 1.1           | R2           |

Table 4 (continued)

| Metapelite           | U (ppm) | Th (ppm) | Th/U | %Pb c | $^{206}\text{Pb}/^{238}\text{U}$ | 1 $\sigma$ % | $^{207}\text{Pb}/^{235}\text{U}$ | 1 $\sigma$ % | $^{207}\text{Pb}/^{206}\text{Pb}$ | 1 $\sigma$ % | Age<br>$^{206}\text{Pb}/^{238}\text{U}$  | $\pm 1 \sigma$ | CL<br>domain |
|----------------------|---------|----------|------|-------|----------------------------------|--------------|----------------------------------|--------------|-----------------------------------|--------------|------------------------------------------|----------------|--------------|
| M3-1.1               | 498     | 38       | 0.08 | 0.03  | 0.0255                           | 0.64         | 0.1729                           | 2.17         | 0.0491                            | 2.01         | 162.5                                    | 1.0            | R2           |
| M3-3.1               | 484     | 51       | 0.11 | 0.42  | 0.0264                           | 0.65         | 0.1701                           | 2.33         | 0.0467                            | 2.11         | 168.8                                    | 1.1            | R2           |
| M3-2.1               | 488     | 38       | 0.08 | 0.55  | 0.0262                           | 0.64         | 0.1816                           | 2.10         | 0.0503                            | 1.90         | 166.6                                    | 1.0            | R2           |
| M3-21.1              | 424     | 33       | 0.08 | 0.12  | 0.0259                           | 1.41         | 0.1762                           | 2.75         | 0.0494                            | 2.13         | 164.7                                    | 2.3            | R2           |
| M3-4.1               | 1471    | 18       | 0.01 | 0.09  | 0.0262                           | 0.54         | 0.1738                           | 1.06         | 0.0482                            | 0.90         | 166.8                                    | 0.9            | R1           |
| M3-10.1              | 1970    | 25       | 0.01 | 0.16  | 0.0263                           | 0.73         | 0.1759                           | 1.15         | 0.0486                            | 0.85         | 167.3                                    | 1.2            | R1           |
| M1-9.1               | 2399    | 13       | 0.01 | 0.05  | 0.0267                           | 1.02         | 0.1831                           | 1.27         | 0.0497                            | 0.72         | 169.9                                    | 1.7            | R1           |
| M3-7.1               | 2298    | 28       | 0.01 | 0.11  | 0.0267                           | 0.53         | 0.1812                           | 1.02         | 0.0491                            | 0.83         | 170.2                                    | 0.9            | R1           |
| M3-13.1              | 2894    | 19       | 0.01 | 0.10  | 0.0269                           | 0.52         | 0.1832                           | 0.83         | 0.0494                            | 0.63         | 171.2                                    | 0.9            | R1           |
| M3-22.1              | 744     | 35       | 0.05 | 0.24  | 0.0272                           | 0.62         | 0.1848                           | 1.96         | 0.0493                            | 1.78         | 173.1                                    | 1.1            | R1           |
| M1-6.1               | 1855    | 9        | 0.00 | 0.29  | 0.0274                           | 1.04         | 0.1869                           | 1.55         | 0.0494                            | 1.07         | 174.4                                    | 1.8            | R1           |
| M1-11.1              | 1925    | 11       | 0.01 | 0.05  | 0.0284                           | 1.03         | 0.1920                           | 1.43         | 0.0491                            | 0.97         | 180.4                                    | 1.8            | R1           |
| M3-24.1              | 1351    | 77       | 0.06 | 0.81  | 0.0286                           | 0.95         | 0.1799                           | 2.40         | 0.0456                            | 2.03         | 182.8                                    | 1.7            | R1           |
| Inherited            | U (ppm) | Th (ppm) | Th/U | %Pb c | $^{206}\text{Pb}/^{238}\text{U}$ | 1 $\sigma$ % | $^{207}\text{Pb}/^{235}\text{U}$ | 1 $\sigma$ % | $^{207}\text{Pb}/^{206}\text{Pb}$ | 1 $\sigma$ % | Age<br>$^{207}\text{Pb}/^{206}\text{Pb}$ | $\pm 1 \sigma$ | CL<br>domain |
| M3-5.1 <sup>b</sup>  | 172     | 106      | 0.62 | 1.44  | 0.0321                           | 0.97         | 0.2313                           | 7.24         | 0.0523                            | 7.17         | 298                                      | 164            | Core         |
| M3-14.1 <sup>b</sup> | 286     | 180      | 0.63 | 0.71  | 0.0480                           | 2.03         | 0.3703                           | 3.31         | 0.0560                            | 2.61         | 451                                      | 58             | Core         |
| M3-9.1 <sup>b</sup>  | 521     | 265      | 0.51 | 0.20  | 0.1877                           | 0.77         | 4.3793                           | 0.96         | 0.1692                            | 0.58         | 2550                                     | 10             | Core         |
| M1-9.2 <sup>b</sup>  | 526     | 111      | 0.21 | 0.00  | 0.2437                           | 2.20         | 5.1229                           | 4.78         | 0.1525                            | 4.24         | 2374                                     | 72             | Core         |
| M3-16.1 <sup>b</sup> | 936     | 34       | 0.04 | 0.00  | 0.3910                           | 0.89         | 11.4847                          | 1.09         | 0.2131                            | 0.62         | 2929                                     | 10             | Core         |

%Pb c=percent of common Pb.

a=Data corrected for common Pb according to the  $^{207}\text{Pb}/^{206}\text{Pb}$  and assuming concordance.

b=Data corrected for common Pb according to the measured  $^{204}\text{Pb}$ .

All other data are corrected for common Pb according to the  $^{208}\text{Pb}/^{206}\text{Pb}$  ratio.

anomaly ( $\text{Eu}/\text{Eu}^*=0.45$ ). Ti is between 6–10 ppm in the zoned part and 4.5 ppm in the unzoned areas. The large number of U–Pb analyses on Z2 domains yielded  $^{206}\text{Pb}/^{238}\text{U}$  ages scattering between 162 and 95 Ma (Table 4, Fig. 6). Within this scattered population, the unzoned or faintly zoned domain, which form rims and partly cross cut the oscillatory zoning, have a trend to younger ages (148–95 Ma), whereas the Z2 domains preserving oscillatory zoning show older ages (162–127 Ma).

Zircon domain Z3 forms rare, unzoned rims around Z2 with medium to low CL intensity. No inclusion was observed within these rare rims. Z3 domains can only be distinguished from Z2-type rims by their composition. Z3 is characterised by the lowest U and Th content (16–75 ppm and 0.5–8 ppm, respectively) and a low Th/U ratio of 0.03–0.1. Ti is also low at 4–5 ppm. These domains also have the lowest REE concentration, but Hf is enriched by a factor of two compared to the other two domains. The REE pattern shows a negative Eu anomaly ( $\text{Eu}/\text{Eu}^*=0.41$ ) and a relatively flat trend for the M-HREE ( $\text{Lu}/\text{Gd}=3$ ). Four analyses performed on Z3 domains yielded consistent ages with an average (lower intercept on a Tera-Wasserburg diagram, Fig. 7b) of  $79.2 \pm 1.5$  Ma (MSWD 1.8).

## 5.2. Metapelite zircons

Zircons of the diamond-bearing metapelite are present as inclusions in all major minerals, particularly biotite, with the notable exception of the inclusion-rich garnet core and kyanite1. The zircon grains are isometric and have a diameter of about 40 to 70  $\mu\text{m}$ . They are composed of cores and two different types of rims (Fig. 8), which are described below according to CL pattern, inclusions, composition and age.

The cores have angular shapes and are highly variable in size and zoning patterns (Fig. 8). They contain inclusions of quartz and apatite. The Th–U composition of the cores is highly variable ( $\text{Th}/\text{U}$  0.04–0.65) as are their apparent  $^{207}\text{Pb}/^{206}\text{Pb}$  ages, which are between 298 and 2129 Ma.

A CL-dark band marks the boundary between the core and the inner rim (R1, Fig. 8). This rim has moderate to low CL emission, displays a patchy zoning and is rich in inclusions. Carbon phases (carbonates,  $\text{CO}_2$  and more or less disordered graphite) as well as quartz, rutile, anatase, biotite, kyanite and melt are common inclusions (Table 2). Carbon phases were identified solely by Micro Raman Spectroscopy; whereas melt and other minerals were also identified by SEM. Melt inclusions show weak

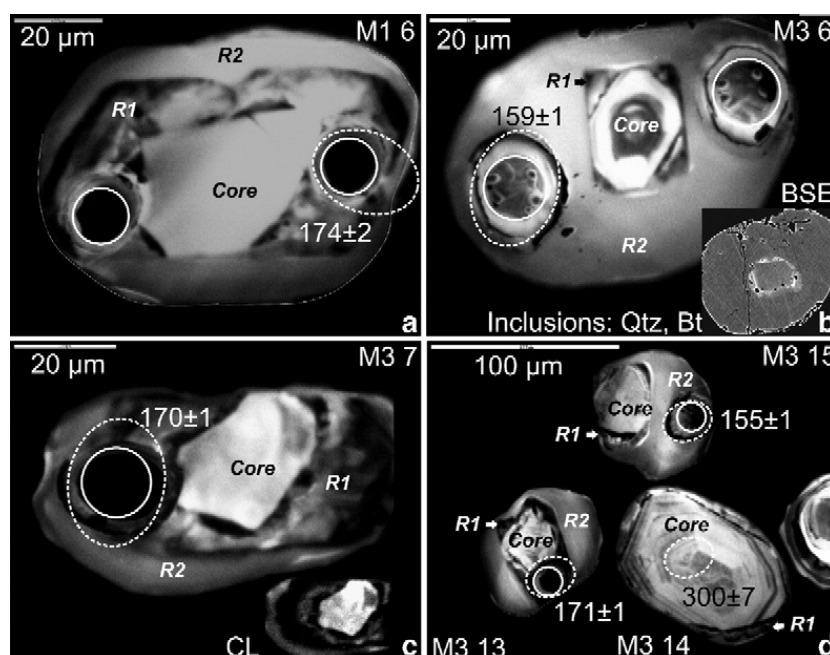


Fig. 8. a–d) Cathodoluminescence images of zircon crystals from the metapelite. Insert in b is BSE image showing the inclusions, insert in c shows the grain before LA-ICPMS analysis.

plagioclase Raman bands and have variable compositions. R1 is characterised by variably high trace element contents, as suggested by the low and patchy CL emission. The REE pattern has a weak positive Ce anomaly as well as a negative Eu anomaly ( $\text{Eu}/\text{Eu}^* = 0.41$ ). The HREE show variable enrichment with a Lu/Gd ratio between 8 and 136. Ti contents are between 9–12 ppm. This rim has high U (1400–4000 ppm) and low Th (8–27 ppm) contents resulting in a low Th/U ratio of 0.01.  $^{206}\text{Pb}/^{238}\text{U}$  ages range between 182 and 167 Ma, with a major group of five analyses averaging at  $171 \pm 1$  Ma (MSWD 1.8) (Fig. 9b). Within this group, there is no correlation between age and U content, which argues

against a resolvable matrix effect elsewhere observed in high U zircon (e.g. Butera et al., 2004). The two oldest analyses do not fit the main group possibly because of a small degree of overlapping with a detrital core. In fact, one of the analyses is reversely discordant.

The outer rim (R2) is volumetrically dominant, inclusion-free, unzoned and bright in CL. In a large number of grains, R2 is the only visible zone, while other grains display only small cores surrounded by a thin (a few microns) inner rim R1 and a large R2 domain (Fig. 8). The REE patterns of R2 (Fig. 9a) show a positive Ce anomaly and a strong negative Eu anomaly between 0.02–0.07. The HREE pattern is flat with Lu/Gd between

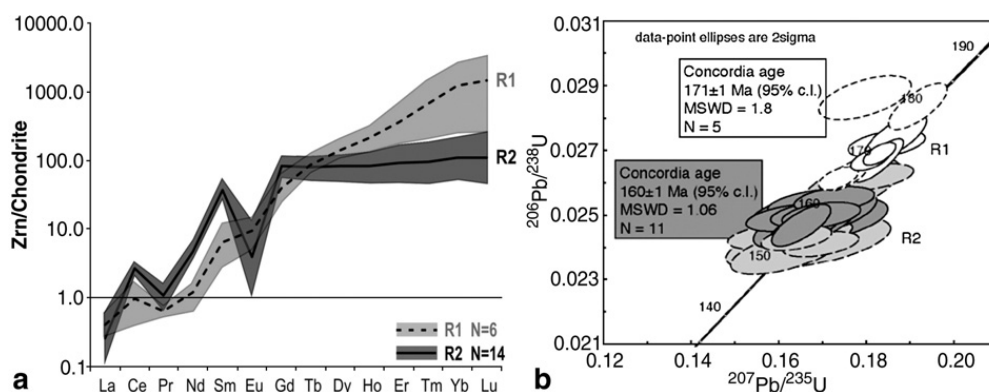


Fig. 9. a) Chondrite-normalised REE patterns of the two zircon rims from the metapelite. Thick lines are the average values of analyses contained in the polygon (data from Table 3). b) Concordia diagram for SHRIMP analyses of the metapelite zircons showing two concordia ages. Grey ellipses correspond to analyses on the inner rim R1, white ellipses correspond to the outer rim R2. Dashed ellipses were excluded for concordia age calculation.

0.6 and 1.6. Compared to R1, R2 shows higher Ti (14–20 ppm), lower U (260–550 ppm) and higher Th contents (27–66 ppm) resulting in a low Th/U ratio between 0.01 and 0.2. The  $^{206}\text{Pb}/^{238}\text{U}$  ages measured on 19 outer rims scatter between 152 and 167 Ma and do not form a statistically homogeneous population (MSWD=5.8). A major group of 11 analyses yields a concordia age of  $160 \pm 1$  Ma (MSWD 1.06) with the exclusion of the two oldest and the five youngest apparent ages (Fig. 9b).

## 6. Discussion

In the following, the metamorphic history of each rock is discussed. First, we construct the P-T evolution using the petrological data, and then we link petrology, mineral inclusions and REE composition of the distinct zircon domains with the obtained ages. Finally, we compare the results obtained from the two samples and discuss regional and tectonic implications.

### 6.1. Metamorphic evolution of the eclogite

The texturally older assemblage is represented by the cores of omphacite (Omp1), garnet (Grt1) and rutile inclusions therein. This assemblage also reflects the highest pressure conditions (stage of high pressure metamorphism, HPM). Applying the Zr-in-Rutile thermometry (Watson et al., 2006) to the rutile inclusions in Omp1, a temperature of 680–705 °C is obtained for this stage. Pressure during this stage must have been higher than the 17.5 kbar estimated for the decompressional stage (see below).

Following the pressure peak assemblage, the eclogite contains indications of decompression such as omphacite rims (Omp2), which display lower  $X_{\text{Jd}}$  ( $\text{Jd}_{20-35}$ ) than the cores. This is in line with the plagioclase ribbons around the omphacite, which formed by the reaction  $\text{Jd} + \text{Qtz} \rightarrow \text{Ab}$ , until quartz was completely consumed, resulting in a quartz-free matrix. The prior existence of quartz is proven by polyphase inclusions of quartz associated with other metamorphic minerals within zircons. This mineral assemblage occurs as inclusions in the poikiloblastic garnet domain (Grt2), which is therefore assumed to have also formed during decompression. For this stage, the Zr content of the rutile inclusions in Grt2 indicates temperatures of 730–755 °C using the thermometer after Watson et al. (2006). Cpx–grt geothermometer (Krogh Ravna, 2000) and grt–cpx–plag geobarometer (Eckert et al., 1991) applied on inclusions in garnets and Grt2 domain yield temperatures of 770–820 °C, being slightly higher than the Zr-in-rutile thermometry, and pressures of 15.5–17.5 kbar. The

higher temperature estimates for this mineral assemblage indicate that decompression was accompanied by a high-temperature metamorphic overprint and is hence termed HTM hereafter. During HTM, omphacite2, plagioclase, garnet2, biotite and hornblende formed possibly at the same time or in sequence. Primary biotite and hornblende inclusions are absent in Grt2 and indicate therefore that these two minerals might have formed after Grt2, i.e. their growth probably coincided with the formation of the latest garnet rims (Grt3). This scenario points to a sequence, where the growth of Grt2 was completed before biotite and hornblende started to grow. Textural relationships show that the latest growth stage is defined by hornblende, which formed around biotite (Fig. 3b). Biotite and hornblende show a patchy distribution within the sample. A pervasive replacement of omphacite by hornblende, as observed in other retrogressed eclogites in the RMC (e.g. Liati and Mposkos, 1990), was not observed in our sample. Biotite contains relatively high amounts of Ba (ca. 4000 ppm) despite a low Ba content in the bulk (88 ppm). A high-K hornblende inclusion (Magnesio-Katophorite, close to 1 K p.f.u., “K–Hbl” in Table 1) found in Z2 zircon is surprising given the low amount of K in the bulk rock ( $\text{K}_2\text{O}=0.19$  wt.%). These observations may point to the presence of a metapelitic or gneissic source of K- and Ba-rich, external fluid/melt, intruding into the eclogite during late HTM. This is in line with the numerous anatectic melts that are observed within the amphibolite/eclogite lenses in the Kimi area.

In summary the pressure peak during HPM is represented by the paragenesis  $\text{Omp1} (\text{Jd}_{35-40}) + \text{Grt1} + \text{Qtz} + \text{Rt}$ , which formed at *PT* conditions of ca. 700 °C and >17.5 kbar. The pressure peak was followed by the temperature peak during HTM at 15.5–17.5 kbar and up to 820 °C is documented by the assemblage  $\text{Omp2} (\text{Jd}_{20-35}) + \text{Grt2} + \text{Plag}$ . Biotite and hornblende formed at the end of HTM, probably driven by an external fluid influx.

### 6.2. Formation and age interpretation of eclogite zircons

The Z1 cores of the zircon recovered from the eclogite have CL characteristics (broad oscillatory zoning) and trace element composition (high U and Th, high Th/U ratio, negative Eu-anomaly and steep HREE pattern) that are typical for magmatic zircons, including those of gabbroic origin (e.g. Hinton and Upton, 1991; Rubatto and Gebauer, 2000; Hoskin and Schaltegger, 2003). Within Z1 zircon, inclusions are restricted to magmatic minerals like quartz and apatite. This domain is thus interpreted to have formed during the crystallization of the gabbroic protolith. The scatter of ages is indicative

for a disturbance of the U–Pb system during subsequent metamorphism and a possible indication of the minimum age of the protolith is given by the oldest apparent age measured in the Z1 cores ( $288 \pm 6$  Ma). The lack of zircon inclusions in the omphacite cores, even though magmatic zircon was present in the rock before omphacite growth, can be attributed to different mechanisms. It is possible that omphacite grew on existing magmatic pyroxene, which might not have included zircon because of the late crystallization of zircon in residual, interstitial melt. Alternatively, zircon was not observed in omphacite because of the small size and paucity of zircon crystals in the rock and the limited volume samples in thin section.

The magmatic Z1 cores are surrounded by the Z2 domain, showing oscillatory zoning and Th–U composition that could suggest a magmatic origin. However, zoned domains with relatively high Th/U have also been documented in granulites and interpreted as metamorphic (e.g. Vavra et al., 1996, 1999). The inclusions in Z2 are metamorphic minerals of similar composition to those occurring in retrogressed parts of the host rock (Fig. 5a) and represent therefore the HTM event, which is constrained in *PT* at around 730–820 °C and 15.5–17.5 kbar. Embayments of zoning around the mineral inclusions indicate their primary character (Fig. 6). Melt inclusions in Z2 domains indicate zircon crystallization in the presence of an anatectic melt. The presence of a relatively weak negative Eu anomaly ( $\text{Eu}/\text{Eu}^* = 0.45$ ) in the zircon patterns indicates the presence of feldspar during Z2 formation (e.g. Heaman et al., 1990; Schaltegger et al., 1999; Rubatto, 2002). The Ti-in-zircon thermometry (Watson et al., 2006) in the zoned zircon domains returns temperatures of 700–740 °C, which is partly overlapping the results obtained with Zr-in-Rt thermometry for the HTM stage. On the basis of these characteristics, we propose that Z2 zircon formed during the high-temperature decompressional stage HTM, possibly during melt crystallization and cooling, in the presence of feldspar and partial melt. The spread of ages in Z2 domains could be partly related to a prolonged growth, but given the long time span between 162 and 95 Ma, it is best explained by partial disturbance of the U–Pb system by subsequent metamorphism. In this case, the oldest measured age from Z2 zircon, around 160 Ma, is the best possible, even though poor, minimum time estimate for Z2 formation during the HTM stage.

The faintly zoned and unzoned parts of Z2 domain display a trend to younger ages and a decrease in trace element content. They show cross cutting relationships with the oscillatory zoning of Z2 zircon. Given these features we speculate that this is the product of leaching

and partial recrystallization (i.e. reorganization of the crystal lattice) of Z2 domains. Such leaching event was most likely induced or favoured by fluids and led to the expulsion of Pb and other trace elements from zircon. The lower Ti content of the unzoned Z2 domains (*T* ca. 675 °C, Watson et al., 2006) would suggest that the leaching occurred at lower temperature than the zircon growth. A similar process has been invoked previously: Rubatto and Gebauer (2000) referred to fluid leaching for very low U and Th zircon with faint zoning; Hoskin and Black (2000) documented recrystallization of zircon, which produced trace element purging, obliteration of the primary zoning and scattering of U–Pb ages. Following Hoskin and Black (2000), an estimate for zircon recrystallization can be tentatively calculated from the youngest group of analyses, which is at ca. 115 Ma ( $115 \pm 3$  Ma, MSWD 2.0,  $N=4$ ). This age is in line with zircon ages presented within other studies (Liati et al., 2002; Warwzenitz and Mposkos, 1997).

The most external Z3 domain yields consistent ages of  $79 \pm 3$  Ma. The lack of zoning and the low Th/U ratio are commonly reported in metamorphic zircons formed at relatively low temperatures (e.g. Rubatto, 2002; Hermann et al., 2001). The low Ti content of the Z3 rims indicate temperatures around 670–680 °C (Watson et al., 2006). The negative Eu anomaly argues for the presence of a feldspar phase sequestering Eu during zircon growth (e.g. Heaman et al., 1990; Schaltegger et al., 1999). Similarly, the flat HREE pattern suggests growth in a system where most HREE were locked up in garnet (Rubatto, 2002). It would be possible that leaching and partial age resetting of Z2 domains were caused by the same metamorphic event that is recorded in Z3. However, the HREE of strongly reset areas (i.e. youngest ages) within Z2 do not show a trend towards the low HREE compositions measured in the Z3 rims. This points to a distinct metamorphic event at ca. 115 Ma, which caused the resetting of Z2 domain, and a later one at  $79 \pm 3$  Ma, which led to the new growth of Z3.

### 6.3. Metamorphic evolution of the metapelite

In the metapelite, garnet shows limited variation in major and trace elements. Major element profiles across the garnets show a slight Fe increase and Mg+Ca decrease towards the rims (Fig. 4e). This type of major element zoning is common in garnet formed at relatively high temperatures and reflects elemental diffusion during cooling (e.g. Spear, 1993). REE have lower diffusion rates than Ca and their concentrations are considered to be primary. The Y and REE zoning across garnet has a “bell shape” with the core enriched in trace elements with

respect to the rim. Such a profile in high temperature garnet is commonly interpreted as due to Rayleigh fractionation during growth (e.g. Otamendi et al., 2002; Hermann and Rubatto, 2003). The fine-grained, crystallographically oriented rutile needles, which occur across the entire garnet grains, are interpreted to be rutile ex-solutions from a former Ti-rich, high temperature garnet (Keane et al., 1997; Donohue et al., 2001). High temperature, i.e. annealing or crystallization from a melt, is also suggested by the triple junctions between the plagioclase grains (e.g. Passchier and Trouw, 2005). The numerous dark cuboid inclusions are restricted to the HREE-rich garnet cores but are absent in the other domains suggesting garnet growth under evolving conditions. Assuming that the carbonaceous cuboid inclusions in the garnet core are retrogressed diamonds (as proposed by Perraki et al., 2006), the garnet growth started at UHP and progressed during decompression forming the inclusion-free garnet rim. However, the measured negative Eu anomaly in garnet suggests growth in the presence of plagioclase, which is not a stable phase at HP. Despite the numerous inclusions within garnet, plagioclase inclusions are absent. The bulk rock composition shows no Eu anomaly, which is uncommon for metapelites (e.g. Taylor and McLennen, 1985). Other samples from the study area show positive Eu anomalies, which could be explained by the infiltration of anatectic, plagioclase rich melts. We suggest that the plagioclase-rich leucosome within the studied sample at least in part entered the rock from an external source and compensated an existing negative bulk-rock Eu anomaly. This scenario would imply that the negative Eu anomaly of garnet just reflects the initial bulk composition rather than the presence of a Eu-sequestering phase like feldspar. The application of Grt-Bt geothermometer (Holdaway, 2000) and GASP geobarometer (Kozior, 1989) revealed 750–800 °C and 11–13 kbar when using compositions from inclusion-free garnet rims, matrix plagioclase and large biotite grains. The formation of the garnet rims is considered to have occurred at these conditions. Textural observations indicate that, after garnet growth, the decompression reaction  $\text{Grt} + \text{Ms}_2 \rightarrow \text{Bt} + \text{Ky}_2$  (McMullin et al., 1991) occurred in the mesosome, resulting in the formation of fine-grained biotite and Ky<sub>2</sub> around garnet grains (Fig. 3f). Outermost, inclusion-free garnet rims, biotite and muscovite<sub>2</sub> were used to calculate PT conditions for this late reaction. Temperatures of 720–740 °C and pressures of 8–10 kbar using Grt-Bt geothermometer (Holdaway, 2000) and SGAM geobarometer (McMullin et al., 1991) were obtained. Ti-in-biotite thermometry (Henry et al., 2005) gives temperatures of about 680 °C for the matrix biotite. These are considered minimum

temperatures because the Ti-in-biotite geothermometer was calibrated at 3–6 kbar and the incorporation of Ti into biotite decreases with pressure (Henry et al., 2005; Patiño Douche, 1993).

In summary, textural and compositional observations indicate that the metapelite underwent HT metamorphism at relatively high pressures ( $T=750\text{--}800\text{ }^{\circ}\text{C}$ ,  $P=11\text{--}13\text{ kbar}$ ) with extensive garnet growth. This stage was followed by retrograde decompression when the garnet rims were replaced by fine-grained biotite and kyanite<sub>2</sub> at lower pressures and temperatures ( $T=720\text{--}740\text{ }^{\circ}\text{C}$ ,  $P=8\text{--}10\text{ kbar}$ ). A similar evolution for the Kimi Complex has been previously suggested by other workers (e.g. Mposkos, 2002).

#### 6.4. Formation and ages of metapelite zircons

Five analyses from core domains yield discordant  $^{207}\text{Pb}/^{206}\text{Pb}$  ages between 300 and 2128 Ma. The rounded shape, variable zoning pattern and the age scatter indicates that the cores are detrital in origin, which is in line with the sedimentary nature of the rock.

The inner, dark overgrowths R1 contain numerous inclusions of melt, biotite and kyanite, mostly at the boundary with the detrital cores. The trace element composition of the inner zircon rim R1, particularly the HREE, is variable, possibly indicating changing chemical environment during growth. The high HREE contents and the weak negative Eu anomaly compared with the second rim suggest crystallization in a HREE-rich environment, likely garnet-poor and with limited feldspar availability (Rubatto, 2002). It can be speculated that R1 grew in the presence of melt, biotite and kyanite. The numerous biotite inclusions within R1 show a lower  $X_{\text{Mg}}$  and a higher Ti content compared to the matrix biotites. Ti-in-biotite thermometry (Henry and Guidotti, 2002; Henry et al., 2005) yields minimum temperatures of ca. 750 °C for the biotite inclusions in R1 zircons (compared to 580–700 °C for matrix biotites). This is in agreement with the Ti-in-zircon thermometry (Watson et al., 2006), which returns temperatures of 730–760 °C for this zircon domain. Inclusions of kyanite as a stable  $\text{Al}_2\text{SiO}_5$ -polymorph in R1 indicate minimum pressures of 9 kbar at these temperatures. Therefore we suggest that this zircon domain formed at around 170 Ma during metamorphism at ca. 750 °C in the presence of melt and before massive garnet growth. The age scatter within this domain could be due to the relatively long residence at HT (see below).

The outer rims (R2), which dominate in volume, are characterised by a strong negative Eu anomaly ( $\text{Eu}/\text{Eu}^*=0.06$ ) and a flat HREE pattern, which suggest

growth in a garnet-rich rock after increased feldspar crystallization. For R2, the Ti-in-zircon thermometry (Watson et al., 2006) indicates temperatures of around 800 °C, which is higher than for R1. The best age for this volumetrically dominant zircon domain is  $160 \pm 1$  Ma, with a tail of analyses down to 152 Ma. This observation suggests that this rim formed at higher temperature than R1, likely close to and after the metamorphic peak and during extensive garnet formation. At these conditions partial melt was present and the age spread could be partly due to zircon growth over an extended period of time, during cooling and melt crystallization.

The zircons in the Rhodope metapelite have striking similarities in zoning and chemical composition with the zircon described by Hermann and Rubatto (2003) in the Malenco granulite. In the case of Malenco, small, CL-dark zircon rims on detrital cores were interpreted as prograde growth on the basis of chemistry, trace element partitioning with garnet, age and mineral inclusions. On the same grounds, a second zircon overgrowth, volumetrically dominant, and with similar zoning and REE composition to R2 was interpreted as forming during melt crystallization at the peak and during cooling. Similarly to the Malenco sample, the Rhodope zircon formed over a period of time resulting in some age dispersion.

In summary, from inclusion mineralogy and REE contents it is proposed that the inner zircon rim R1 formed at around 170 Ma in the presence of high-Ti biotite, kyanite and melt, with limited garnet and feldspar; either during prograde metamorphism or decompression from UHP metamorphic conditions. Taking into consideration the overlap of ages of the two domains and their inclusion mineralogy, it is more likely that R1 and R2 formed consecutively after the pressure peak. The second zircon rim R2 dated at ca. 160 Ma formed at higher temperatures (possibly close to and after the temperature peak) when the rock was garnet rich and melt was crystallizing. The late resorption of these garnet rims by kyanite and biotite is not recorded within the zircons but observed in the matrix.

### 6.5. Regional and tectonic implications

Based on field investigations, petrological data and geochronology a similar geodynamic evolution is derived for both studied rock types.

The eclogite protolith crystallized in the Early Permian as indicated by inherited zircon cores. Magmatic activity in the Rhodope Complex has been previously reported by Liati and collaborators who dated magmatic zircon from an amphibolitized eclogite (at  $246 \pm 4$  Ma, Liati, 2005) and from orthogneisses ( $294 \pm 8$  Ma, Liati and Gebauer, 1999; lower intercept at  $294 \pm 2$  Ma, Liati, 2005). Bimodal

Permian magmatism is widespread across the entire European basement and attributed to extension and/or mafic underplating in the lower crust after the Variscan orogeny.

The eclogite recorded high-temperature metamorphic conditions in the presence of melt at around 160 Ma or earlier. Inclusions in zircons and petrographic observations indicate that high-temperature metamorphism (HTM) post-dated eclogite facies metamorphism (HPM), which therefore occurred before 160 Ma. The rock was overprinted by another metamorphic event at around 115 Ma, which caused partial resetting of the zircon U–Pb system. Liati (2005) reported similar data from zircon overgrowths on detrital cores from a paragneiss of the Central Rhodope. The ages scattered between 156 and 83 Ma, with a cluster at 149 Ma. This late Jurassic age was interpreted as dating (U)HP metamorphism on the basis of the zircon trace element composition. The zircon composition reported by Liati (2005; low HREE and weak or no Eu-anomaly) is significantly different from the composition of the Z2 zircon domain in the Kimi eclogite presented in this study. It is thus possible that the Central Rhodope paragneiss (Liati, 2005) and the Kimi rocks are several tectonic slices that were at different crustal levels during the Jurassic orogeny and thus recorded HP and HT conditions at different times, not unlike the micro-continents scenario of Liati (2005).

The scattering U–Pb ages from the Central Rhodope paragneiss were tentatively attributed by Liati (2005) to Eocene metamorphism but may also be the result of the ca. 115 Ma metamorphic event proposed here: This Early Cretaceous overprint postulated for the Kimi eclogite is in agreement with a metamorphic age of  $119 \pm 3.5$  Ma (Sm–Nd whole rock data from a garnet-pyroxenite), presented by Wawrzenitz and Mposkos (1997). A similar age of  $117 \pm 2$  Ma from a garnet-rich mafic rock (Liati et al., 2002) was interpreted as the crystallization age of the protolith based on zircon CL characteristics. Our study shows that the information obtained from mineral inclusions in zircons are crucial in determining the metamorphic nature of the zircon despite their magmatic CL characteristics. In the study area, the occurrence of silica-rich melts is common and it is thus possible that the zircon age measured by Liati et al. (2002) represents partial melting of the garnet-rich mafic rock during metamorphism rather than protolith formation. This interpretation would agree with what proposed in our study and by Wawrzenitz and Mposkos (1997). Alternatively, it is possible that both, metamorphism of the pelite (our study and Wawrzenitz and Mposkos, 1997) and crystallization of a mafic rock (Liati et al., 2002) occurred at around 115–120 Ma. In this case,

magmatic underplating and mafic intrusions within the Kimi Complex during exhumation would have produced reheating and enhanced fluid/melt mobility within the eclogite. Further investigation is needed to clarify which scenario is more likely.

In the Kimi eclogite, a late metamorphic zircon overgrowth dated at  $79 \pm 3$  Ma represents a second metamorphic overprint (probably amphibolite facies or less). This age is similar to a metamorphic age of  $73.5 \pm 3.4$  Ma presented by Liati et al. (2002) on zircon from the garnet-rich mafic rock, which was interpreted as dating HP metamorphism without any supporting evidence such as zircon chemistry or inclusions.

The two metamorphic zircon domains from the diamond-bearing metapelite record high-temperature metamorphism during two growth events at  $171 \pm 1$  Ma and  $160 \pm 1$  Ma. These ages are linked with granulite-facies metamorphism and melting based on inclusion mineralogy, Ti-in-zircon thermometry (Watson and Harrison, 2006), Ti-in-biotite thermometry (Henry et al., 2005) and REE characteristics. An earlier HP or even UHP metamorphic event recorded in the garnet cores must therefore have occurred before 171 Ma or, if the first zircon growth is considered prograde, between ca. 170 and 160 Ma.

From the results summarized above, it is thus likely that both the eclogite and the metapelite underwent (U)HP metamorphism together in the Jurassic, followed by decompression and high-temperature metamorphism at around 160 Ma. Further metamorphism is recorded in the eclogite possibly at ca. 115 Ma and at ca. 79 Ma. Given that the two rocks were coupled at 160 Ma, a common evolution is likely. The lack of age records after 160 Ma in the metapelite could be attributed to different reactivity of the two rocks during the Jurassic–Cretaceous evolution. A metapelite that underwent HT metamorphism and partial melting is a rather dry rock and any subsequent metamorphic imprint may have little effect on its mineral assemblages and even less on zircon. On the other hand, the eclogite has likely seen fluid influx with the formation of biotite and hornblende and might have been a more reactive system. This study demonstrates that zircon might not record all metamorphic events/stages that the host-rock underwent. The two different rock types selected from this area yield a complementary age record.

In relation to previous studies, our data add some important constraints: (1) We document for the first time Permian protolith ages for the mafic rocks in the Kimi Complex, which are in line with previously reported Late Carboniferous to Early Permian magmatism in other parts of the Rhodope basement. (2) The data also suggest that any HP or even UHP metamorphism in this

Complex occurred at least before 160 Ma. The Kimi Complex would thus be the part of the RMC that first underwent Alpine subduction. (3) We provide circumstantial evidence for a possible, Cretaceous overprint on the Rhodope rocks in line with what proposed by Warwzenitz and Mposkos (1997). (4) We further constrain a metamorphic event at ca. 79 Ma in the Kimi Complex, which likely reached amphibolite facies, but not HP conditions as previously proposed.

The investigated rocks preserve no zircon record of the Tertiary HP-metamorphism, fluid and melting events reported by Liati and collaborators (see a summary in Liati, 2005) across the Rhodope area. As suggested by the complex structure of the RMC, it appears that the different units represent tectonic slices that underwent metamorphism differing in grade and time. The Early Permian protolith age of the eclogite is interpreted as the result of subduction-related magmatism followed by rifting and the formation of passive margins in the Triassic. From Triassic to Mid-Jurassic, rifting led to the opening of the Vardar oceanic basin located further south, followed by subduction and continent-continent collision within the Late Cretaceous (Ricou et al., 1998; van Hinsbergen et al., 2005).

Our age data indicate that after subduction and continent-continent collision, leading to HP and possibly UHP metamorphism within the studied rocks (Perraki et al., 2006; Mposkos et al., 2006) took place before the Late Jurassic. Two continental terranes, the Thracia Terrane and the Rhodope Terrane (Turpaud, 2006) were involved into this Alpine type collision, forming the high-grade rocks of the suture zone in between, of which the Kimi Complex is part. It appears that this proposed geodynamic scenario occurred slightly before the evolution of the Vardar Zone in the south, (Ricou et al., 1998) and gives rise for the existence of an additional oceanic basin further north: the Nestos Ocean discussed by Turpaud (2006). The two oceanic basins were separated by the continental Thracia Terrane during the Triassic (Ricou et al., 1998).

The results of this study imply that the southwest-ward propagating nappe stack evolution within the Aegean region started in the north-eastern Rhodope, where the oldest metamorphic ages and UHP conditions are recorded, and continued towards southwest with decreasing ages and metamorphic conditions. Taking into account that this compressional regime lasted from the Jurassic to the Neogene (Ricou et al., 1998; van Hinsbergen et al., 2005), it is likely that the investigated rocks recorded a long-lasting (ca. 130 Ma) history of rifting, collision and exhumation. Details of this history are starting to emerge and will require further investigation.

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