

***P–T–t* evolution and textural evidence for decompression of Pan-African high-pressure granulites, Lurio Belt, north-eastern Mozambique**

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ABSTRACT Pan-African high-pressure granulites occur as boudins and layers in the Lurio Belt in north-eastern Mozambique, eastern Africa. Mafic granulites contain the mineral assemblage garnet + clinopyroxene + plagioclase + quartz ± magnesiohastingsite. Garnet porphyroblasts are zoned with increasing almandine and spessartine contents and decreasing grossular and pyrope contents from core (Alm₄₆Prp₃₂Grs₂₁Sps₂) to rim (Alm₅₂Prp₂₆Grs₁₉Sps₃). This pattern is interpreted as a retrograde diffusion zoning with the preserved core chemistry representing the peak metamorphic composition. Mineral reaction textures occur in the form of monomineralic and composite plagioclase ± orthopyroxene ± amphibole ± biotite ± magnetite coronas around garnet porphyroblasts. Thermobarometry indicates peak metamorphic conditions of up to 1.57 ± 0.14 GPa and 949 ± 92 °C (stage I), corresponding to crustal depths of ~55 km. Zircon yielded an U–Pb age of 557 ± 16 Ma, inferred to date crystallization of zircon during peak or immediately post-peak metamorphism. Formation of plagioclase + orthopyroxene-bearing coronas surrounding garnet indicates a near-isothermal decompression of the high-pressure granulites to lower pressure granulite facies conditions (stage II). Development of plagioclase + amphibole-coronas enclosing the same garnet porphyroblasts shows subsequent cooling into amphibolite facies conditions (stage III). Symplectitic textures of the corona assemblages indicate rapid decompression. The high-pressure granulite facies metamorphism of the Lurio Belt, followed by near-isothermal decompression and subsequent cooling, is in accordance with a long-lived tectonic history accompanied by high magmatic activity in the Lurio Belt during the late Neoproterozoic–early Palaeozoic East-African–Antarctic orogeny.

Key words: corona textures; high-pressure granulites; isothermal decompression; Lurio Belt; Pan-African.

INTRODUCTION

Granulite facies rocks are common in most ancient orogenic belts, ranging from Archean to Phanerozoic in age. Granulites attest to high-temperature metamorphic conditions during orogeny. The granulite facies *P–T* domain is commonly subdivided into low-, intermediate- and high-pressure sub-fields based on the coexistence of orthopyroxene, clinopyroxene and garnet in mafic lithologies (e.g. Spear, 1993). High-pressure granulites are defined by the mineral assemblage Grt + Cpx + Pl ± Hbl ± Qtz (Pattison, 2003; abbreviations follow Kretz, 1983). Opx coexists with this paragenesis in the intermediate-*P* field, while garnet disappears in the low-*P* field (Spear, 1993). These three metamorphic fields can be diagnostic of different orogenic or tectonic processes, and the reconstruction of the *P–T* path followed by a rock while crossing the metamorphic fields is thus of particular interest for the unravelling of tectonic

processes and the interpretation of metamorphic terranes.

A single sample showing an equilibrated mineral assemblage can constrain one individual point along the *P–T* path followed by a metamorphic rock. Samples showing microtextural and mineral chemical disequilibrium are, however, even more informative, because they can provide information on segments of evolutionary *P–T* paths (Harley, 1989; Williams *et al.*, 2000; Brown, 2002). Relict metastable phases are found in geometrically simple features such as coronas and symplectites (Griffin, 1971; Mørk, 1986; Hensen *et al.*, 1995; Engvik *et al.*, 2001). Plagioclase coronas around garnet are, for example, a typical disequilibrium feature of granulites (e.g. Harley, 1989; Elvevold *et al.*, 2003; Shervais *et al.*, 2003). The coexistence of plagioclase with other minerals, such as orthopyroxene, amphibole or biotite, in the corona, points to a sequence of reactions that documents a *P–T* evolution. Mineral-chemical zoning provides additional

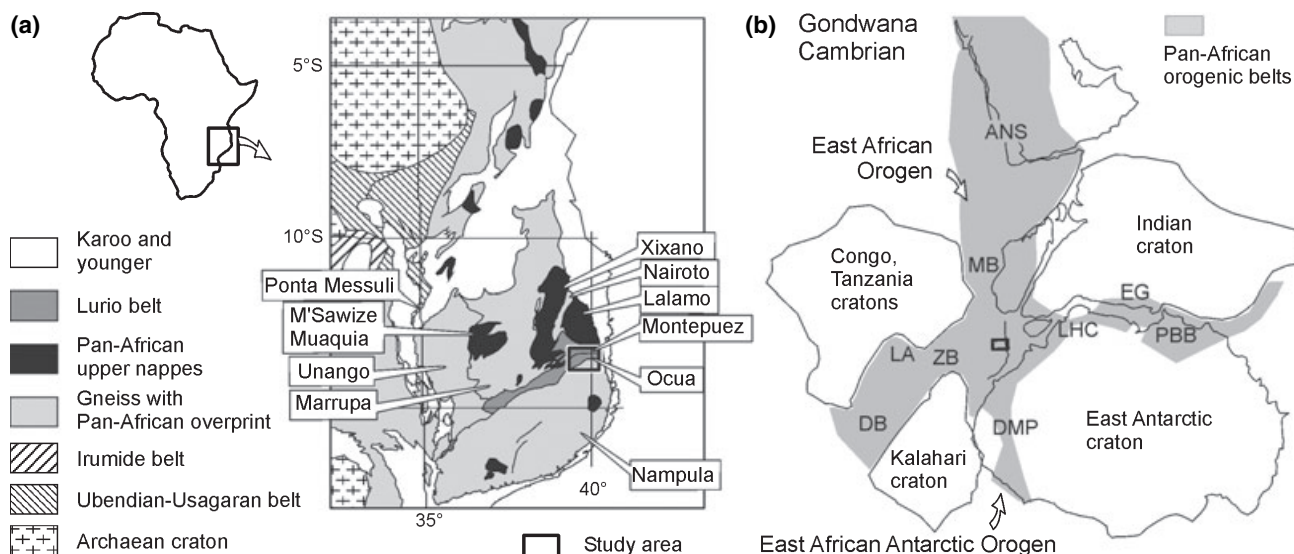


Fig. 1. (a) Sketch map of north-eastern Mozambique and adjacent areas showing the location of the main tectonostratigraphic complexes (Norconsult Consortium, 2007). (b) Reconstruction of Gondwana at the end of the Pan-African orogeny, following Meert (2003), with location of the East-African-Antarctic orogen (EAAO). Shaded areas denote Pan-African orogenic belts. ANS, Arabian-Nubian Shield; DB, Damara Belt; DMP, Dronning Maud Province; EG, Eastern Ghats; LA, Lufilian Arc; LHC, Lützow-Holm Complex; MB, Mozambique Belt; PBB, Prydz Bay Belt; ZB, Zambezi Belt. The EAAO covers ANS, MB and DMP.

information on the post-peak evolution of granulites (e.g. Elvevold *et al.*, 2003; Indares, 2003).

This contribution emphasizes the importance of textural relationships for deducing the decompressional evolution of high-pressure granulites, taking the specific example of Pan-African granulites from the Lurio Belt in north-eastern Mozambique (Fig. 1a; Pinna *et al.*, 1993). We describe the mineralogy, report new mineral chemical data and zircon U–Pb geochronological data, and deduce the peak-metamorphic conditions for the Lurio Belt granulites. The typical post-peak microtextural evolution of the granulites is documented. In particular, the composite coronas surrounding garnet porphyroblasts are described and used to deduce the retrograde part of the *P–T* path. The information contributes to a better understanding of exhumation mechanisms in orogens in general, and in particular to insight into the evolution of the Lurio Belt granulites.

GEOLOGICAL SETTING

The geology of north-eastern Mozambique belongs to the Mozambique Belt, which is a part of the East African Orogen (Stern, 1994; Meert, 2003) or, at larger scale, of the East-African-Antarctic orogen (Fig. 1b; EAAO; Jacobs & Thomas, 2004). The EAAO is up to 1000 km wide and stretches for more than 8000 km along the eastern margin of Africa and into East Antarctica and resulted from a multi-plate collision of various parts of East and West Gondwana during Late Neoproterozoic/Early Palaeozoic times. The bedrock geology of north-eastern Mozambique has recently been re-mapped as part of an infrastructure develop-

ment programme (Norconsult Consortium, 2007). Based on the results of these investigations, a new tectonostratigraphy has been proposed, whereby the region is subdivided into a number of distinct lithological complexes (Fig. 1). The northernmost part of the area is dominated by a nappe stack comprising the Unango, Marrupa and Xixano Complexes, which in turn overlie a Paleoproterozoic basement exposed in the Ponta Messuli Complex (Fig. 1a; Bingen *et al.*, 2006; Viola *et al.*, 2006). The Unango and Marrupa Complexes are made up of 1.1–1.0 Ga granitoids and metasedimentary rocks, whereas the Xixano Complex is dominated by Neoproterozoic rocks. The Xixano Complex includes mafic granulites dated at 735 ± 4 Ma (metamorphic age; Bingen *et al.*, 2006). The Unango and Marrupa Complexes are overprinted by granulite and upper amphibolite facies metamorphism and deformation, due to their tectonic juxtaposition and reworking between 580 and 520 Ma (Bingen *et al.*, 2006; Viola *et al.*, 2006). Farther to the south, the Nampula Complex shows similar lithological, age and metamorphic characteristics as the Unango and Marrupa Complex, but is separated from the northern nappe stack by the prominent Lurio Belt.

The Lurio Belt is a repeatedly reactivated Pan-African high-strain zone (Viola *et al.*, 2006), forming a linear ENE–WSW-trending structure in the Mozambique Belt of East Africa. It extends through north-eastern Mozambique from the Mesozoic–Cenozoic Rovuma Basin in the east to Malawi in the west (Fig. 1a). It is a 25–30 km wide belt that comprises strongly deformed, often mylonitic rock types. The Lurio Belt is cored by the newly defined Ocuia Complex (Norconsult Consortium, 2007), which contains mafic

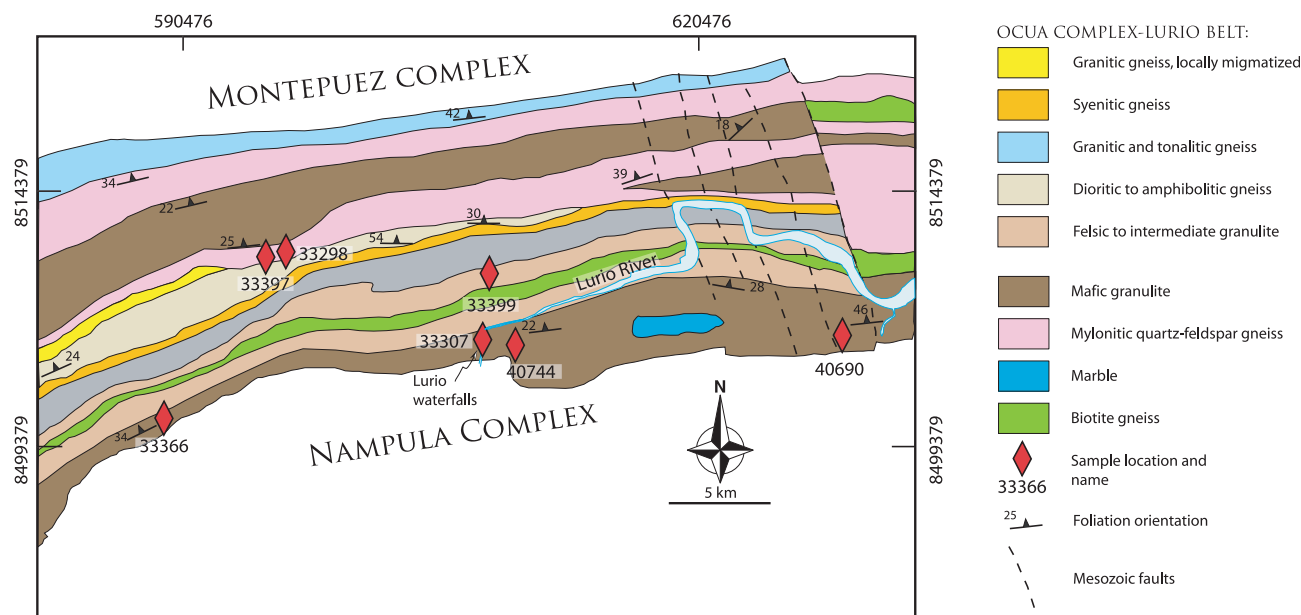


Fig. 2. Detailed geological map of eastern part of the Lurio Belt with sample locations. Map based on Bjerkgård *et al.* (2006a,b).

and felsic granulites in addition to orthogneisses of granitic to amphibolitic composition, and heterogeneous paragneisses, including biotite- and quartz-feldspar gneisses and marbles (Fig. 2). The Lurio Belt is interpreted as containing a tectonic melange (the Ocua Complex) formed by slices of the adjoining complexes, which were deformed, transposed and dismembered during the Pan-African tectonic evolution (Viola *et al.*, 2006). The WSW–ENE-trending lithological banding, mylonitic foliation and the associated megascopic isoclinal folds with moderately reclined axial surfaces dip moderately to the NW (Henderson *et al.*, 2006). The eastern part of the Lurio Belt is, with its E–W orientation, slightly misoriented relative to the overall regional WSW–ENE orientation but is structurally well defined. The belt structural grain tends to become progressively less obvious to the WSW, where the Ocua Complex is tightly interfolded with the neighbouring complexes. Moreover, lateral segmentation of the Ocua Complex in response to significant flattening, results in a series of individual, lensoidal granulite bodies, which are concentrated along the tectonic contact that separates the Nampula and Unango Complexes (Thomas *et al.*, 2005; Hollick *et al.*, 2006; Viola *et al.*, 2006). In this study, we focus on the eastern part of the belt, where, due to better exposure, well-preserved high-*P* granulites are easily accessible and the structural relationships are clear.

SAMPLING AND ANALYTICAL METHODS

This study reports data on seven granulite samples, selected from a representative regional sampling of lithotypes (Fig. 2). The samples were selected on the

basis of preservation of a granulite facies assemblage, including garnet and pyroxenes, and lack of pervasive, low-grade retrogression of pyroxene. Four mafic granulites (samples 40744, 33366, 40690 & 33307) and three felsic granulites (samples 33298, 33397 & 33399) were chosen (Table 1). Two of the samples (40737 & 33307) were collected from a prominent outcrop situated at the waterfalls of the Lurio river.

The petrography of the samples was studied on polished thin sections with both optical (Figs 3–5) and scanning electron microscopy (SEM) using the LEO 1450 VP instrument at the Geological Survey of Norway. Semi-quantitative X-ray mineral chemical maps of selected garnet crystals were obtained using an energy-dispersive spectrometer mounted on the SEM (Figs 6 & 7). Quantitative mineral chemical data collected along selected linear profiles through the same garnet crystals were obtained using the same equipment (Fig. 8). These analyses were performed at 10 nA sample current and 15 kV acceleration voltage. Counting times were 120 s live time.

For the purpose of thermobarometry (Fig. 9), quantitative microanalyses of minerals were performed using a Cameca SX100 electron microprobe equipped with five wavelength-dispersive spectrometers at the Institute of Geosciences, University of Oslo (Tables 2–6). The accelerating voltage was 15 kV and the counting time 10 s on peak. Garnet, pyroxene and amphibole were analysed at 15 nA with a focused beam, and biotite with a defocused beam (10 µm in diameter). Detection limit varies between 0.02 and 0.06 wt%. Feldspar was analysed with a defocused beam (10 µm) at 10 nA; Na and K were analysed first. Detection limit varies between 0.03 and 0.10 wt%. A

Table 1. List of the studied mafic and felsic granulite samples.

Sample no.	UTM E	UTM N	Zone	Lithology
40744	609956	8505284	37	Mafic granulite
33366	589268	8501098	37	Mafic granulite
40690	629006	8505766	37	Mafic granulite
33307	608008	8506110	37	Mafic granulite
33298	596463	8510768	37	Felsic granulite
33397	595897	8510654	37	Felsic granulite
33399	608426	8509552	37	Felsic granulite

selection of synthetic and natural minerals and oxides was standardized. Data reduction was carried out using the PAP program (Pouchou & Pichoir, 1984).

Geochronological data were collected on zircon, separated from the sample after crushing. A selection of zircon grains was cast in epoxy, polished and imaged with a cathodoluminescence detector in the SEM (Fig. 10). Another selection of grains was mounted on

double-sided tape and analysed for U–Pb using laser ablation–inductively coupled plasma mass spectrometry (LA–ICPMS) (Fig. 10; Table 7). The data were collected at the Geological Survey of Norway using a Finnigan Element1 single collector sector ICPMS, alimanted by a Finnigan 266 nm laser micro-sampler. The analytical protocol and assessment of the results followed methods outlined in Bingen *et al.* (2005). After a pre-analysis cleaning ablation, two or three analyses were performed with a 10–15 μm laser beam rastered over an area of $\sim 40 \times 60 \mu\text{m}$ of the grain, each of them representing progressively deeper parts of the grain. With this instrumentation and analytical method, the $^{207}\text{Pb}/^{206}\text{Pb}$ age proves to be the best estimate for the timing of crystallization of a zircon, after correction for common Pb using the ^{204}Pb analysis and a modern common Pb isotopic composition. A weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of $605 \pm 10 \text{ Ma}$ (30 analyses, MSWD = 0.76) was obtained for reference

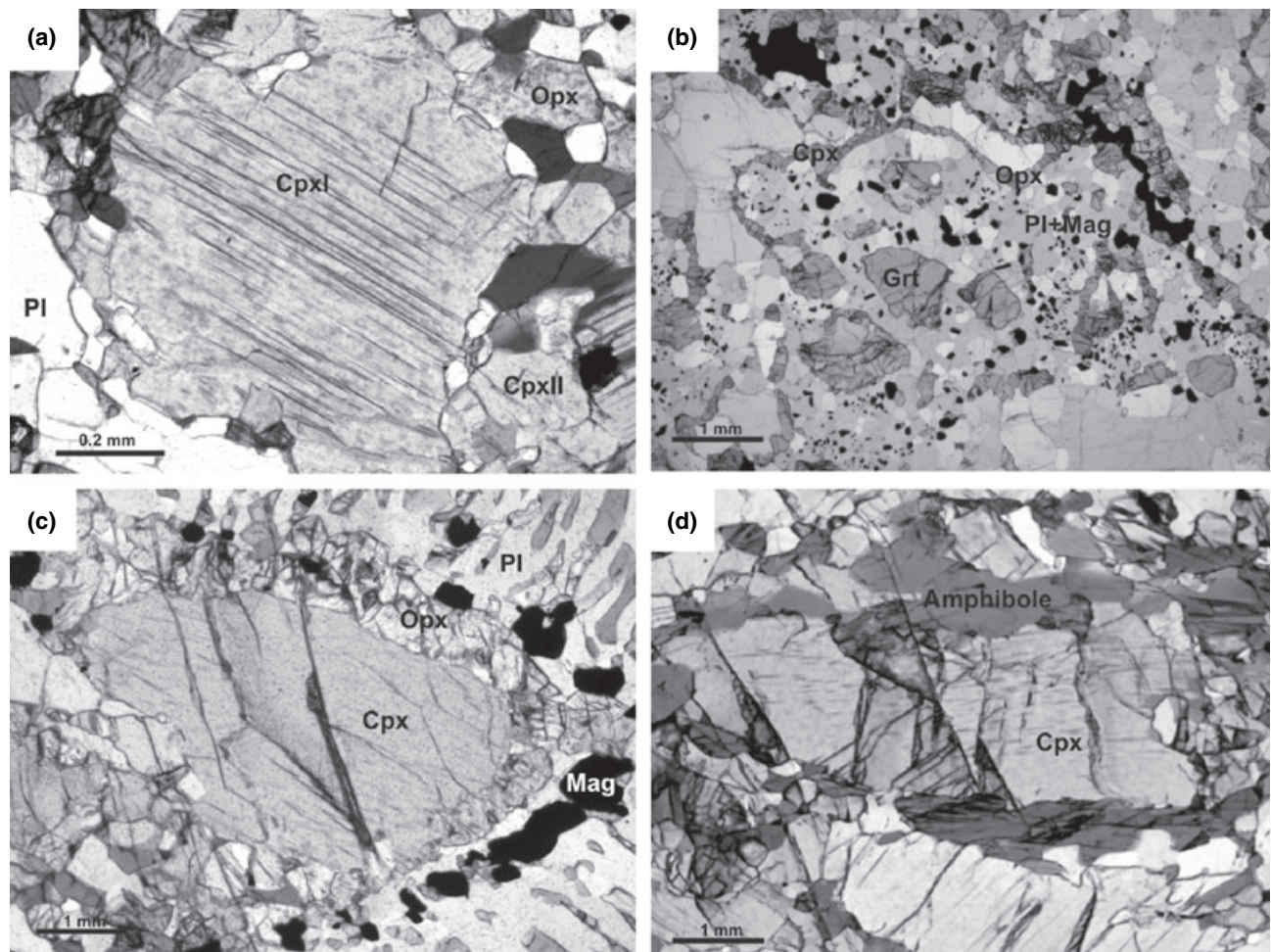


Fig. 3. Optical photomicrographs of characteristic textures from mafic granulites from the Ocu Complex: (a) Twinned clinopyroxene porphyroblast (CpxI) in mafic granulite (sample 40690) preserved in medium-grained matrix of Opx + CpxII + Pl + magnetiohastingsite. (b) Medium-grained Cpx + Opx in corona textures around former garnet porphyroblasts. Garnet porphyroblasts are partly replaced by Pl + Mag-symplectite (sample 40690). (c) Fine-grained orthopyroxene occurring as corona on clinopyroxene porphyroblast (sample 40744). (d) Replacement textures of magnetiohastingsite on clinopyroxene porphyroblast (sample 40744).

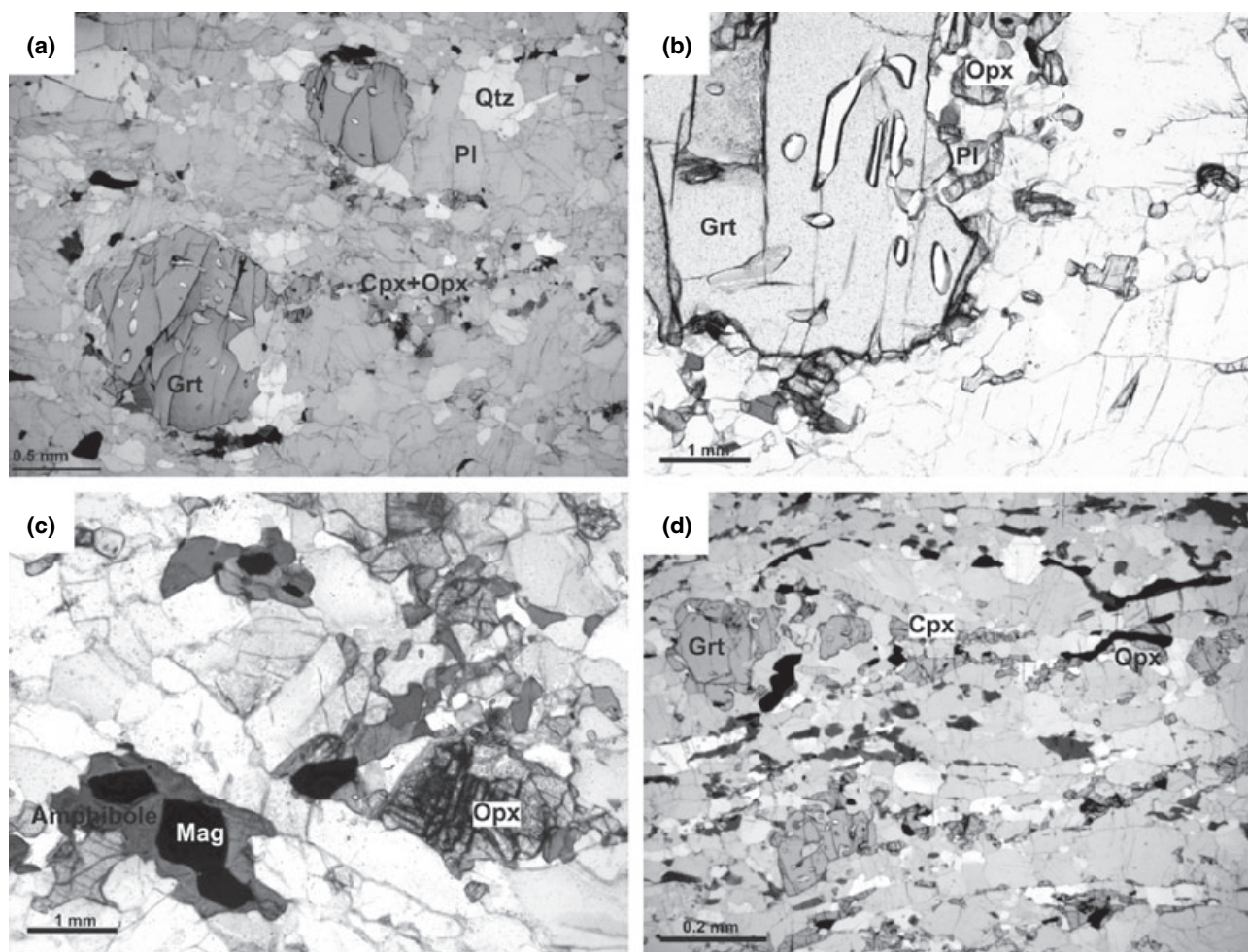


Fig. 4. Optical photomicrographs of characteristic textures from felsic granulites from the Ocuca Complex: (a) Subhedral garnet porphyroblasts in felsic granulite. Clinopyroxene and orthopyroxene occur as fine grains in the medium-grained matrix of plagioclase and quartz (sample 33298). (b) Opx + Pl growing as corona on garnet porphyroblasts (sample 33298). (c) Calcic amphibole growing as corona on magnetite and around orthopyroxene (sample 33298). (d) Felsic mylonitic granulite with sheared and disrupted garnet associated with clinopyroxene and orthopyroxene (sample 33397).

zircon GJ1 (609 ± 2 Ma, Jackson *et al.*, 2004) during the course of analytical work reported in this study.

THE LURIO BELT GRANULITES

Petrography and mineral chemistry

The granulite facies gneisses of the Ocuca Complex vary from felsic to mafic in composition. Felsic granulite are commonly interbedded and folded together with the mafic granulite. The granulites generally have a strongly developed proto-mylonitic to mylonitic fabric, and mafic rock types occur commonly as boudins parallel to the regional fabric.

Mafic granulite

The mafic granulite contains a high-pressure granulite facies paragenesis formed by garnet, clinopyroxene,

plagioclase, quartz, ilmenite and commonly magnetite, calcic amphibole and biotite. Mafic granulites are usually texturally heterogranular, typically with anhedral to subhedral grains. Garnet and clinopyroxene occur as coarse-grained porphyroblasts with a grain size up to 5 mm (Figs 3a–d & 5a). Garnet generally shows evidence of breakdown at the rim, and is replaced by plagioclase-bearing coronas. It contains inclusions, mainly of quartz, but also of plagioclase and Fe-oxides. Garnet is zoned with an Fe/(Fe + Mg) ratio increasing from the core to the rim (0.59–0.70). Its chemistry shows, in general, increasing almandine and spessartine contents and decreasing grossular and pyrope contents from the core ($\text{Alm}_{46}\text{Prp}_{32}\text{Grs}_{21}\text{Sps}_2$) to the rim ($\text{Alm}_{52}\text{Prp}_{26}\text{Grs}_{19}\text{Sps}_3$). Representative analyses are presented in Table 2. The chemical zoning of garnet porphyroblasts is described in detail below.

In samples 33366, 40690 and 40744, clinopyroxene porphyroblast (Cpx I) shows a composition of

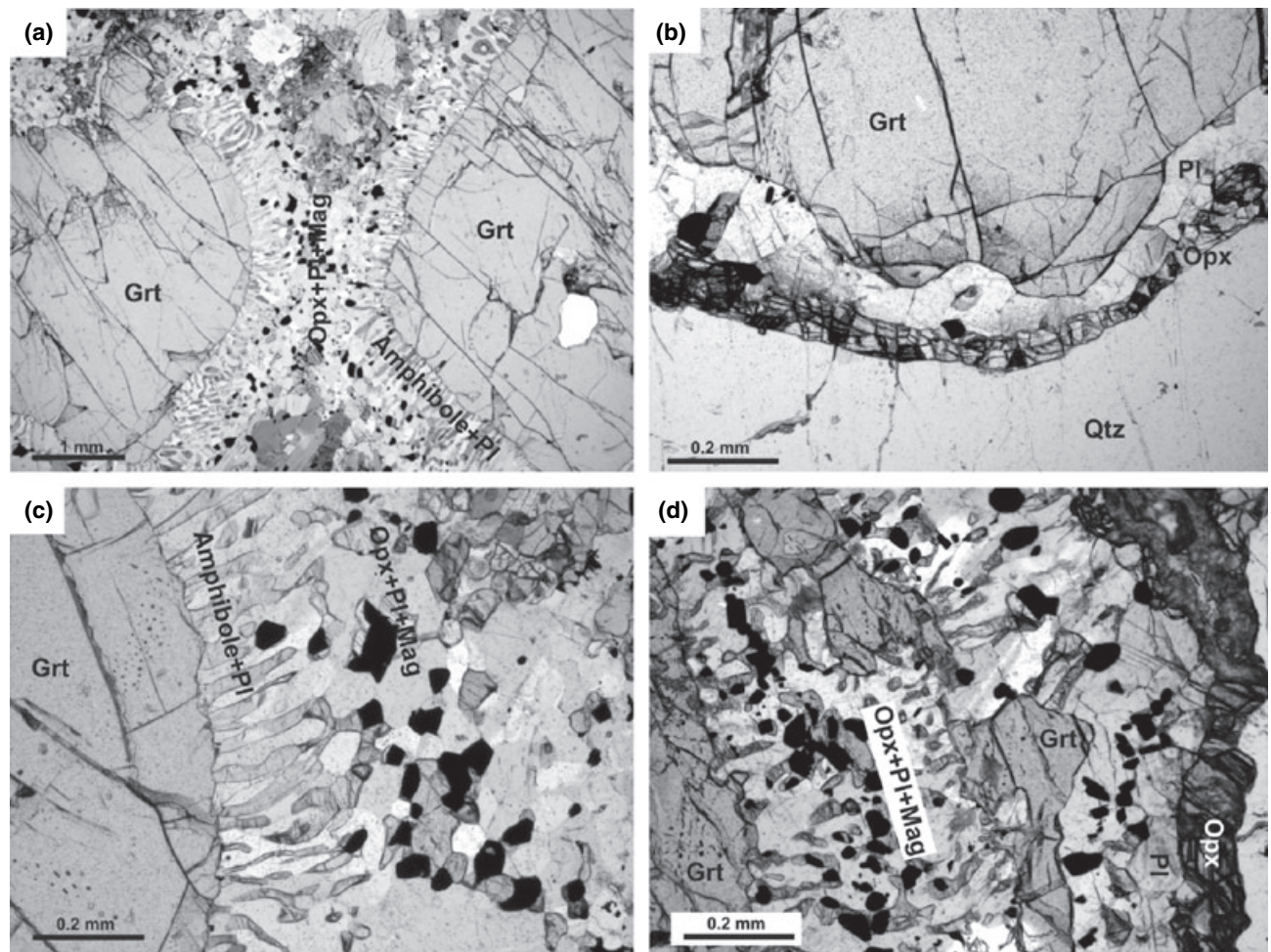


Fig. 5. Photomicrographs of coronas surrounding garnet in mafic granulite (sample 40744): (a) Garnet porphyroblasts in matrix of Cpx + amphibole + Pl + Qtz. Garnet is surrounded by an inner corona of green amphibole + Pl, and an outer corona of Opx + Pl + Mag. (b) Garnet porphyroblast surrounded by an inner corona of Pl and an outer corona of Opx at the contact to quartz. (c) Detail of the two symplectitic coronas surrounding garnet porphyroblast, with amphibole + Pl and Opx + Pl + Mag respectively. (d) Detail of three coronas around garnet of (i) Opx + Pl + Mag symplectite (inner corona) including a relict from the former garnet porphyroblast, (ii) Pl and (iii) Opx (outer corona).

En_{38–39}Fs_{11–12}Wo_{49–51} with an Fe/(Fe + Mg) ratio of 0.21–0.24. In places, they are twinned (Fig. 3a), and are interpreted as the most pristine clinopyroxene. Medium-grained matrix clinopyroxene (Cpx II, see Fig. 3a) shows a small variation in mineral chemistry to En_{38–40}Fs₁₅Wo_{46–47} and with a higher Fe/(Fe + Mg) ratio of 0.27–0.28 compared to the porphyroblasts. Na-content of the clinopyroxenes is below 0.05 p.f.u., while Al^(IV) and Al^(VI) are below 0.12 and 0.07 respectively. Orthopyroxene is not found as a stable matrix mineral in the mafic granulites, but occurs within coronitic textures (Fig. 3c), with a composition of En_{57–65}Fs_{34–42}Wo₁ and Al-content below 0.07 and 0.05 for Al^(IV) and Al^(VI) respectively. In sample 40690, medium-grained orthopyroxene forms corona together with clinopyroxene, around garnet and clinopyroxene porphyroblasts (Fig. 3a,b).

The growth of orthopyroxene in this sample is interpreted as belonging to a secondary stage, replacing clinopyroxene after a primary Grt + Cpx-bearing assemblage.

Plagioclase with metamorphic triple-point textures occurs in the matrix of the mafic granulite together with medium-grained clinopyroxene. The matrix plagioclase has a composition of An_{30–44}Ab_{55–68}Kfs_{2–3}, and has a lower An-content relative to the plagioclase-inclusions in garnet (An_{39–49}Ab_{50–59}Kfs₂) or secondary plagioclase in the coronas around garnet (An_{42–73}Ab_{27–57}Kfs_{1–2}). Quartz is commonly found as coarse ribbons or as single grains associated with plagioclase in the matrix. Green, calcic amphibole, classified as magnesiohastingsite (after Leake *et al.*, 1997), is common in the matrix assemblage of the mafic granulites. It occurs as medium-grained

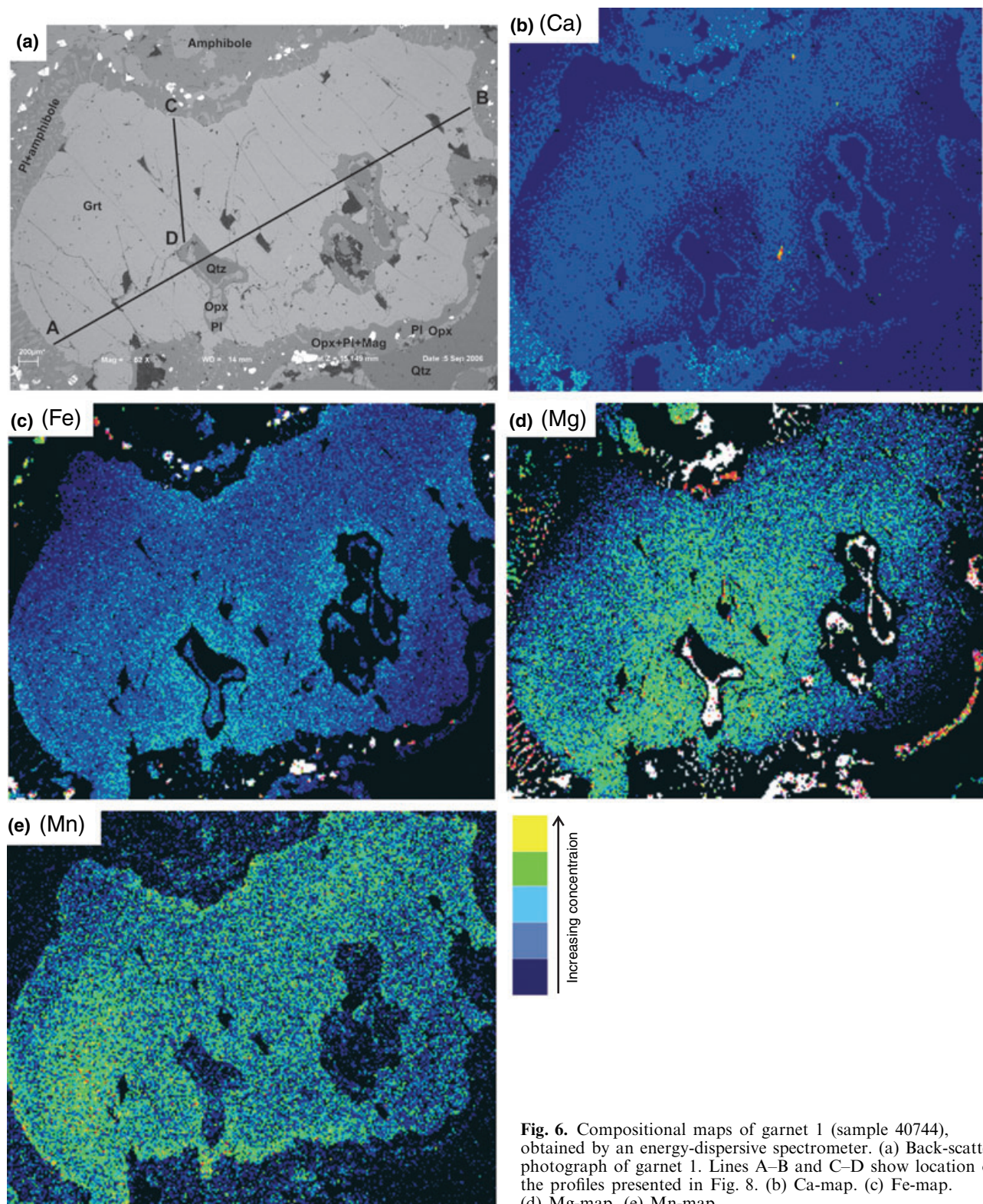


Fig. 6. Compositional maps of garnet 1 (sample 40744), obtained by an energy-dispersive spectrometer. (a) Back-scatter photograph of garnet 1. Lines A–B and C–D show location of the profiles presented in Fig. 8. (b) Ca-map. (c) Fe-map. (d) Mg-map. (e) Mn-map.

crystals, often within textures indicating replacement of the high-pressure assemblage. This is evident where amphibole surrounds and replaces clinopyroxene

(Fig. 3d). Biotite is less common, and occurs only as retrograde replacement. Biotite shows a high Ti-content of up to 0.67 p.f.u.

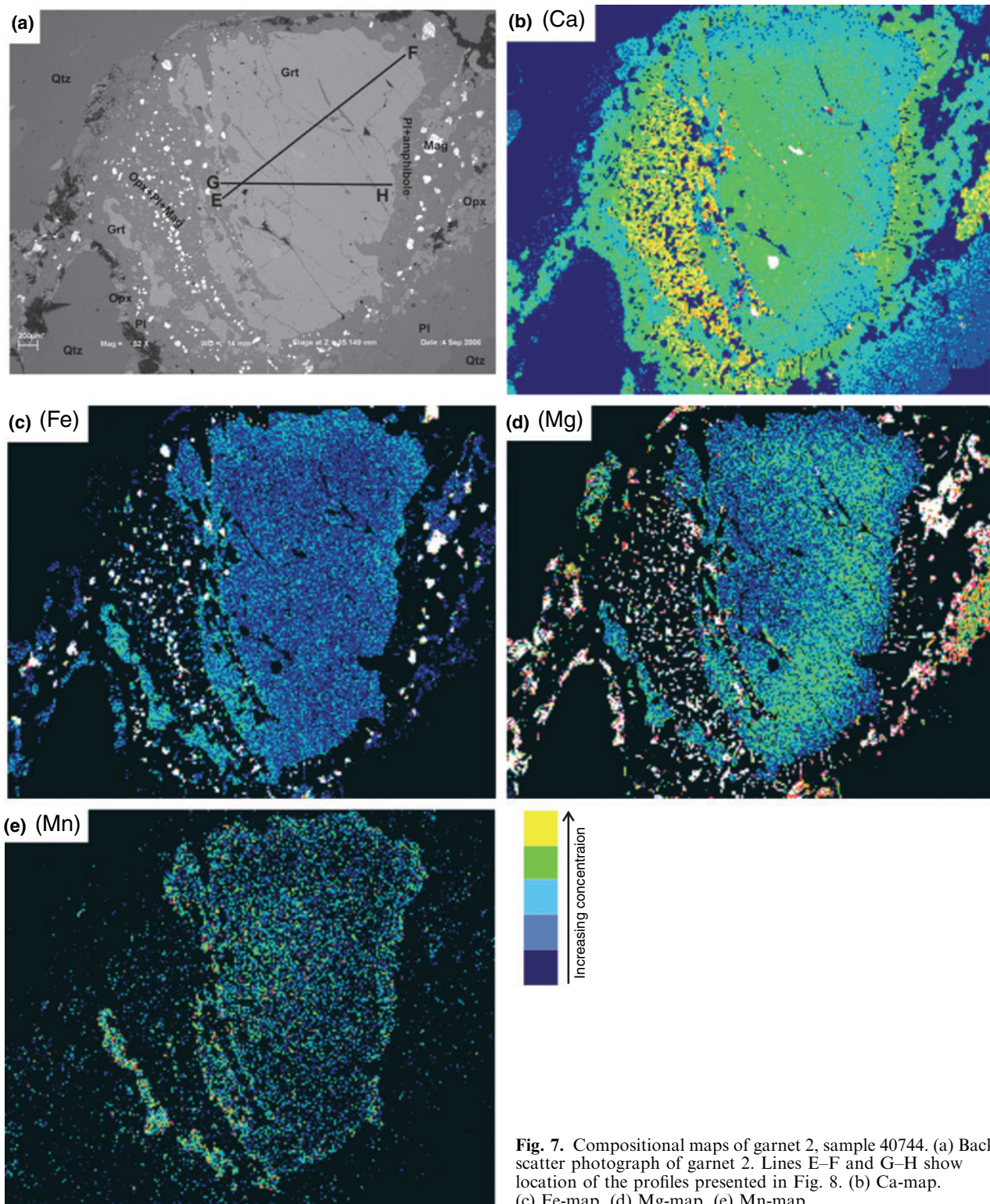


Fig. 7. Compositional maps of garnet 2, sample 40744. (a) Back-scatter photograph of garnet 2. Lines E–F and G–H show location of the profiles presented in Fig. 8. (b) Ca-map. (c) Fe-map. (d) Mg-map. (e) Mn-map.

Felsic granulite

Felsic granulites are heterogranular quartzofeldspathic gneisses with garnet, pyroxene, calcic amphibole,

biotite, magnetite and ilmenite. Garnet occurs as subhedral porphyroblasts in a medium-grained matrix (Fig. 4a). It has a core composition of $\text{Alm}_{56-61}\text{Prp}_{16-23}\text{Grs}_{18-19}\text{Sps}_{1-5}$ and shows increase in Fe and

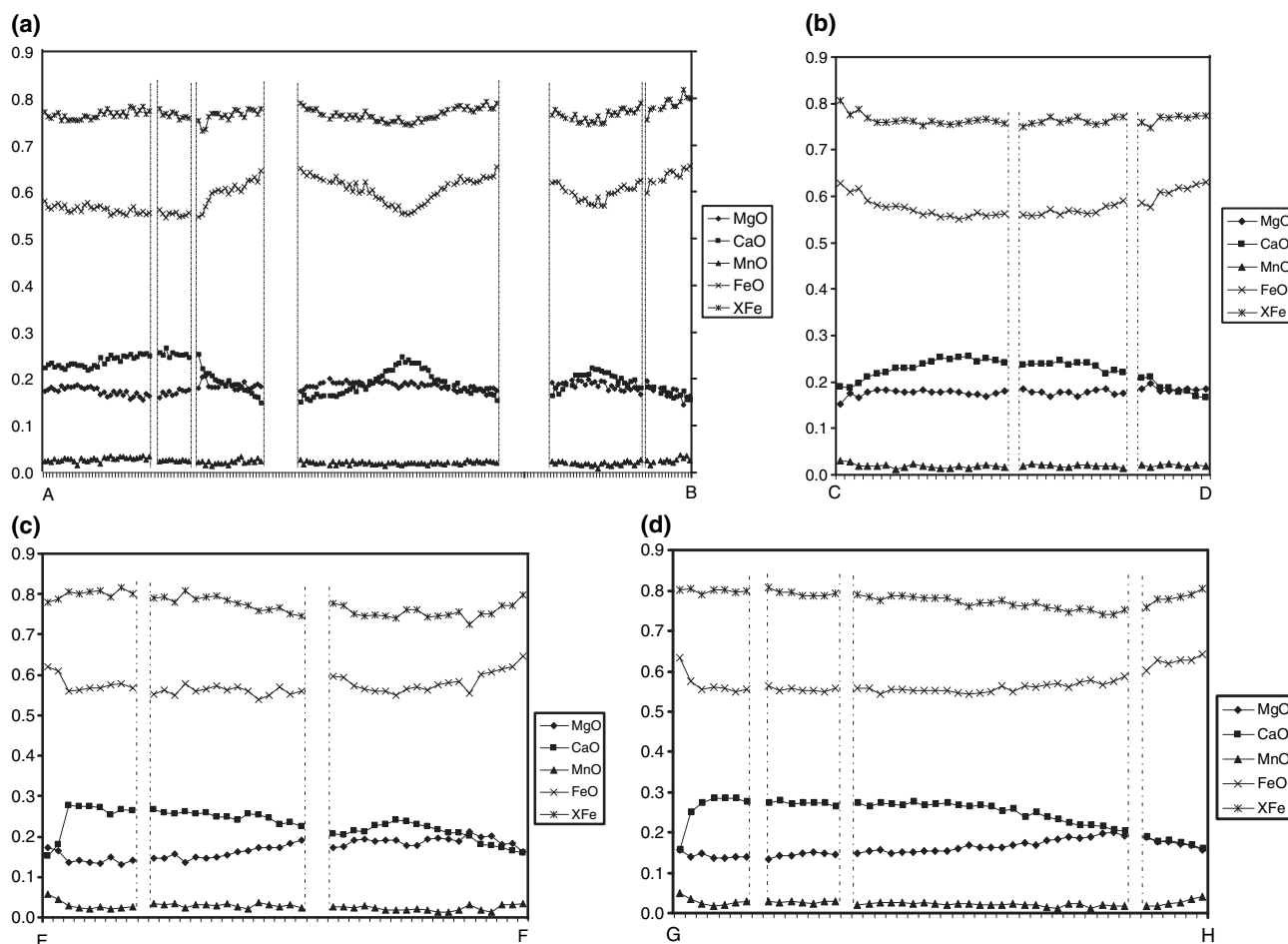


Fig. 8. Chemical profiles through garnet obtained with an energy-dispersive spectrometer. Plots of the compounds FeO, CaO, MgO and MnO show normalized values. X_{Fe} represents the ratio $FeO/(FeO + MgO)$. Open gaps in the plot represent deleted analytical points of inclusions. (a) Profile A–B through garnet 1 (see Fig. 6a), sample 40744; 198 analytical points over a total length of 6 mm. (b) Profile C–D through garnet 1 (see Fig. 6a), sample 40744; 41 analytical points over a total length of 1.3 mm. (c) Profile E–F through garnet 2 (see Fig. 7a), sample 40744; 46 analytical points over a total length of 2.5 mm. (d) Profile G–H through garnet 2 (see Fig. 7a), sample 40744; 48 analytical points over a total length of 1.9 mm.

Mn and decrease in Mg towards the rims (see Table 2). Fine-grained orthopyroxene and clinopyroxene occur along garnet rims (Fig. 4b) or as thin concordant layers parallel to the foliation planes (Fig. 4a). Orthopyroxene shows composition $En_{47-60}Fs_{38-52}Wo_1$ with $Al^{(IV)}$ and $Al^{(VI)}$ below 0.06 and 0.03 p.f.u. respectively. Clinopyroxene is $En_{35-38}Fs_{13-19}Wo_{46-49}$ with Na-content below 0.06 p.f.u., and $Al^{(IV)}$ and $Al^{(VI)}$ below 0.1 and 0.04 p.f.u. respectively. Amphibole of tschermakitic and pargasitic compositions is associated with pyroxene, commonly within replacement textures after pyroxene or as coronas on magnetite (Fig. 4c). Feldspar has compositional ranges of $An_{30-37}Alb_{61-67}Kfs_{2-3}$ for plagioclase and $Kfs_{96-98}Alb_{1-4}$ for K-feldspar.

The felsic granulite commonly displays a medium- to fine-grained mylonitic fabric, where the $Grt + Opx + Cpx + Pl + Qtz$ assemblage is itself strongly sheared. In the mylonite, the garnet occurs

rotated and disrupted as porphyroclasts, forming strings together with orthopyroxene and clinopyroxene (Fig. 4d). Feldspar occurs partly in ribbon textures with quartz. Biotite occurs in the mylonitic granulites with Ti-content of 0.57–0.60 p.f.u. and an $Fe/(Fe + Mg)$ ratio of 0.38–0.52.

Corona textures surrounding garnet

Garnet porphyroblasts in both mafic and felsic granulites are typically surrounded by a plagioclase rim. However, more complex reaction textures are observed around some of the garnet porphyroblasts. These include a combination of up to five different concentric, very fine-grained monomineralic or polymineralic coronas: (i) Opx, (ii) Pl, (iii) Pl + Opx $\pm$ Mag, (iv) Pl + amphibole and (v) Pl $\pm$ amphibole $\pm$ Bt $\pm$ Mag. Reaction textures are also recorded around some clinopyroxene porphyroblasts; these include coronas

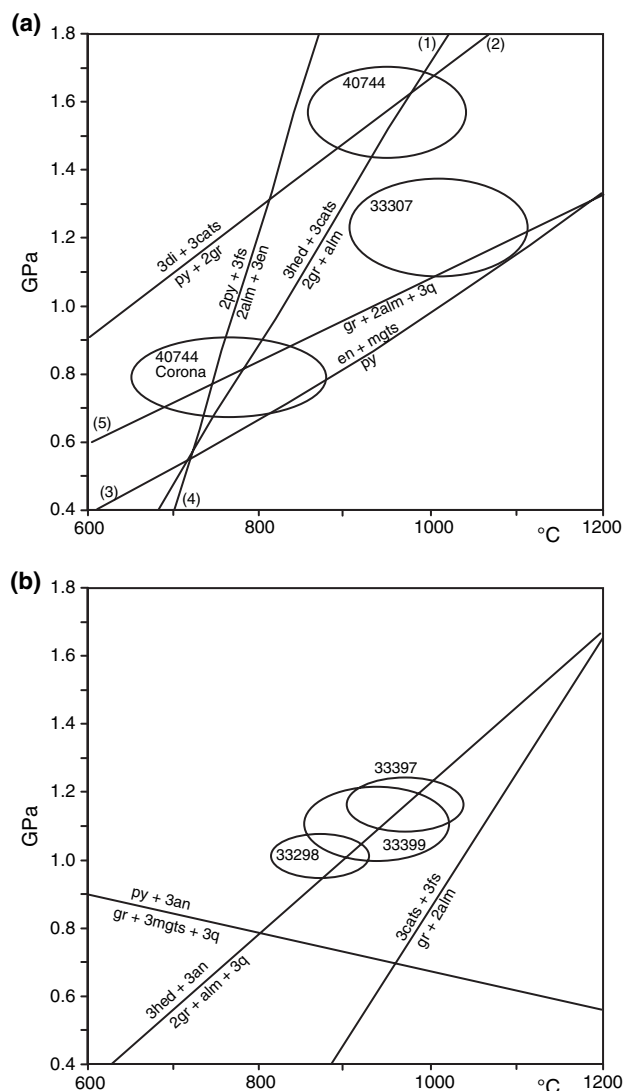
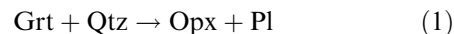


Fig. 9. Results of thermobarometric calculations (circles) and phase diagram calculations (lines) by thermocalc. (a) Results of calculations on mafic granulites. P – T calculations resulting in a maximum pressure estimated as 1.57 ± 0.14 GPa at 949 ± 92 °C (sample 40744), (representing Stage I) and a maximum temperature estimate of 1010 ± 105 °C at 1.23 ± 0.15 GPa (sample 33307). The lowest circle shows the P – T estimate of Opx + Pl-corona assemblage in equilibrium with Grt and Qtz (see Fig. 5d) achieving 766 ± 115 °C and 0.79 ± 0.12 GPa (representing Stage II). Lines represent selected phase reactions based on sample 40744; reactions (1) and (2) base on the high- P assemblage, and reactions (3–5) base on the symplectitic corona assemblage. (b) Results of calculations on felsic granulites. P – T calculations resulting in peak estimate of 891 ± 92 °C at 1.08 ± 0.12 GPa (sample 33397). Lines represent selected phase reactions based on sample 40744.

of orthopyroxene or amphibole. The formation of amphibole and biotite-bearing coronas is associated with the replacement of clinopyroxene by green amphibole and biotite in the matrix.

The most remarkable corona textures are observed in the high-pressure mafic granulite 40744 (Fig. 5a).

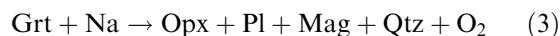
The matrix of this sample contains clinopyroxene, plagioclase, magnesiohastingsite and quartz. The simplest corona texture is made up of two layers surrounding garnet porphyroblasts in contact with matrix quartz (Fig. 5b). The inner corona is in direct contact with the garnet and constitutes very fine-grained plagioclase whereas the outer corona, in contact with quartz, is formed by orthopyroxene. In the simplest case, coronas were formed by the reaction



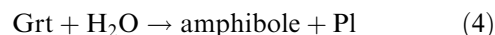
The formation of the orthopyroxene–plagioclase coronas around garnet was associated with the formation of an orthopyroxene corona around clinopyroxene (Fig. 3c):



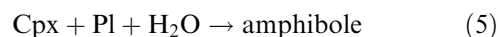
Large garnet porphyroblasts show two types of very fine-grained symplectitic corona, containing Opx + Pl + Mag and amphibole + Pl, respectively, in addition to monomineralic coronas of Opx and Pl (Fig. 5c,d). The symplectitic coronas occur on the inner side of the Opx and Pl coronas, in contact with the garnet. The symplectitic Opx + Pl + Mag coronas (Fig. 5c,d) were formed by the following reaction:



Amphibole + Pl-symplectitic coronas around garnet are produced in the following reaction (Fig. 3a,b):



Reaction 4 needs a supply of fluid and is associated with replacement of clinopyroxene by green amphibole (magnesiohastingsite) (reaction 5, Fig. 3d):



Chemical zoning of garnet porphyroblasts

Chemical zoning of two garnet porphyroblasts in sample 40744 was evaluated with element maps (Figs 6 & 7) and complemented by zoning profiles transecting the porphyroblasts (Fig. 8). The analysed porphyroblasts have a diameter of 2.0–2.5 mm, and are surrounded by four of the different corona types described in the previous section. The garnet porphyroblasts are zoned. Typically, the highest Ca and lowest Fe, Mn and X_{Fe} contents are recorded in the core. Ca content decreases and Fe and Mn content and X_{Fe} ratio increase towards the rims, and also around larger inclusions, as seen in Fig. 6. While the variations in Ca, Fe and X_{Fe} in general occur over distances of ~ 500 μm (see Fig. 8), the Mn content increases abruptly close to the rim. Magnesium shows typically smaller variations. In the garnet porphyroblast presented in Fig. 7, Mg zoning shows a more complex pattern (Figs 7d & 8c,d): Mg is low in the central part of the crystal, it increases slightly outwards before decreasing again in the outermost rim. An abnormal,

Table 2. Representative mineral-chemical data of garnet, formula calculated on the basis of 8 cations.

Lithology	Mafic granulite									Felsic granulite					
Sample no.	40744	40744	40744	40744	33366	33366	40690	33307	33307	33298	33298	33397	33397	33399	33399
Analysis no.	1	2	9	10	45	46	50	146	148	94	96	77	78	163	164
	Grt core	Grt rim	Grt core	Grt rim	Grt core	Grt rim	Grt core	Grt core	Grt rim	Grt core	Grt rim	Grt core	Grt rim	Grt core	Grt
SiO ₂	38.88	38.69	39.23	38.73	38.51	38.23	38.74	38.46	37.80	38.07	37.55	38.13	38.49	38.52	38.02
TiO ₂	0.05	0.06	0.05	0.04	0.07	0.07	0.19	0.06	0.09	0.07	0.05	0.06	0.05	0.08	0.07
Al ₂ O ₃	21.37	21.40	21.78	21.54	21.61	21.26	21.13	21.24	21.05	20.71	20.79	21.07	21.10	21.39	21.10
Cr ₂ O ₃	0.03	0.04	0.00	0.01	0.02	0.02	0.03	0.06	0.03	0.02	0.00	0.01	0.00	0.04	0.00
FeO	20.95	24.56	22.18	24.94	25.65	24.40	24.58	26.03	25.34	28.19	28.23	26.58	27.74	26.67	28.04
MnO	1.04	1.57	0.72	1.40	0.79	1.28	0.98	1.85	3.31	2.17	2.24	1.24	1.66	0.64	0.84
MgO	6.56	6.82	8.52	6.90	7.69	6.09	6.88	6.84	6.00	4.26	3.88	6.23	5.27	6.23	5.20
CaO	11.11	7.12	7.82	7.01	5.74	7.99	8.34	6.45	6.62	6.49	6.73	6.80	6.53	6.99	6.37
Total	99.99	100.27	100.42	100.57	100.09	99.32	100.87	101.01	100.23	99.97	99.51	100.14	100.85	100.57	99.64
Si	2.99	2.99	2.98	2.98	2.97	2.98	2.97	2.96	2.94	3.01	2.99	2.97	2.99	2.98	2.99
Al ^(VI)	1.93	1.95	1.95	1.95	1.96	1.96	1.91	1.92	1.93	1.93	1.95	1.93	1.93	1.95	1.96
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Cr	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
Fe ³⁺	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
Fe ²⁺	1.34	1.58	1.41	1.60	1.65	1.59	1.58	1.67	1.65	1.86	1.88	1.73	1.80	1.72	1.85
Mn	0.07	0.10	0.05	0.09	0.05	0.08	0.06	0.12	0.22	0.15	0.15	0.08	0.11	0.04	0.06
Mg	0.75	0.79	0.97	0.79	0.88	0.71	0.79	0.78	0.70	0.50	0.46	0.72	0.61	0.72	0.61
Ca	0.91	0.59	0.64	0.58	0.47	0.67	0.68	0.53	0.55	0.55	0.57	0.57	0.54	0.58	0.54
Sum oxygen	11.96	11.96	11.96	11.96	11.95	11.97	11.94	11.93	11.92	11.98	11.96	11.93	11.96	11.96	11.97
Alm	43.7	51.8	46.1	52.3	54.0	52.1	50.7	53.8	52.9	60.9	61.3	55.8	58.8	56.3	60.5
Prp	24.4	25.6	31.6	25.8	28.9	23.2	25.3	25.2	22.3	16.4	15.0	23.3	19.9	23.5	20.0
Grs	29.7	19.2	20.8	18.8	15.5	21.9	22.0	17.1	17.7	18.0	18.7	18.3	17.7	18.9	17.6
Sps	2.2	3.4	1.5	3.0	1.7	2.8	2.0	3.9	7.0	4.7	4.9	2.6	3.6	1.4	1.8
X _{Fe}	0.642	0.669	0.593	0.670	0.652	0.692	0.667	0.681	0.703	0.788	0.803	0.705	0.747	0.706	0.752

Table 3. Representative mineral-chemical data of pyroxene, formula calculated on the basis of 4 cations.

Lithology	Mafic granulite									Felsic granulite					
Sample no.	40744	40744	40744	40744	33366	33366	40690	40690	40690	33307	33298	33298	33397	33397	33399
Analysis no.	4	7	14	19	50	57	62	63	68	152	99	118	69	79	166
	Opx corona	Opx corona	CpxI core	CpxI core	CpxI	CpxI	Opx corona	Cpx corona	CpxI	Cpx	Cpx core	Opx core	Opx core	Cpx core	Opx core
SiO ₂	52.22	52.25	50.28	50.79	50.36	50.64	51.52	50.92	52.00	51.79	50.97	50.63	50.98	50.82	50.28
TiO ₂	0.03	0.01	0.36	0.20	0.33	0.36	0.06	0.32	0.16	0.23	0.24	0.07	0.06	0.27	0.07
Al ₂ O ₃	2.29	1.37	4.23	3.89	3.55	3.39	1.48	3.22	2.00	2.09	2.30	0.73	1.72	3.18	0.61
Cr ₂ O ₃	0.15	0.00	0.00	0.06	0.02	0.03	0.00	0.04	0.00	0.01	0.03	0.00	0.00	0.01	0.00
FeO	21.52	24.08	9.12	8.82	9.40	9.40	25.77	11.34	9.14	10.89	12.40	31.50	28.13	10.73	32.29
MnO	0.37	0.62	0.18	0.17	0.24	0.16	0.62	0.34	0.26	0.51	0.39	0.85	0.55	0.20	0.43
MgO	22.69	20.69	12.29	12.73	12.31	12.33	19.60	12.27	12.93	12.99	11.17	15.82	18.16	12.12	15.58
CaO	0.25	0.41	22.34	22.74	22.68	23.03	0.56	21.21	22.82	20.88	21.87	0.60	0.49	21.97	0.68
Na ₂ O	0.00	0.02	0.65	0.59	0.61	0.58	0.00	0.65	0.55	0.68	0.71	0.00	0.01	0.77	0.01
Total	99.52	99.45	99.47	100.00	99.50	99.93	99.61	100.32	99.87	100.06	100.08	100.21	100.09	100.08	99.96
Si	1.94	1.97	1.88	1.89	1.89	1.89	1.96	1.90	1.94	1.94	1.92	1.97	1.95	1.90	1.97
Al ^(IV)	0.06	0.03	0.12	0.11	0.11	0.11	0.04	0.10	0.06	0.06	0.08	0.03	0.05	0.10	0.03
Al ^(VI)	0.04	0.04	0.07	0.06	0.04	0.04	0.03	0.04	0.03	0.03	0.02	0.00	0.03	0.04	0.00
Ti	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.01	0.01	0.00	0.00	0.01	0.00
Cr	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
Fe ³⁺	0.01	0.00	0.08	0.08	0.09	0.09	0.01	0.08	0.06	0.07	0.09	0.02	0.02	0.10	0.03
Fe ²⁺	0.66	0.76	0.21	0.19	0.20	0.20	0.81	0.27	0.23	0.27	0.30	1.00	0.88	0.23	1.02
Mn	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.02	0.01	0.03	0.02	0.01	0.01
Mg	1.26	1.17	0.69	0.71	0.69	0.69	1.11	0.68	0.72	0.72	0.63	0.92	1.03	0.68	0.91
Ca	0.01	0.02	0.90	0.91	0.91	0.92	0.02	0.85	0.91	0.84	0.88	0.02	0.02	0.88	0.00
Na	0.00	0.00	0.05	0.04	0.04	0.04	0.00	0.05	0.04	0.05	0.05	0.00	0.00	0.06	0.00
Sum oxygen	5.99	6.00	5.40	5.38	5.38	5.37	5.98	5.43	5.39	5.44	5.40	5.98	5.98	5.40	5.98
En	65.1	60.0	38.3	39.1	38.2	37.9	57.2	37.8	38.7	39.6	34.6	47.2	53.6	37.7	47.0
Fs	34.3	39.2	11.7	10.7	11.2	11.3	41.6	15.2	12.2	14.7	16.6	51.5	45.4	13.1	53.0
Wo	0.5	0.8	50.0	50.2	50.6	50.9	1.2	47.0	49.1	45.7	48.7	1.3	1.0	49.2	0.0
X _{Fe}	0.345	0.395	0.234	0.214	0.227	0.229	0.421	0.286	0.239	0.270	0.324	0.522	0.459	0.258	0.530

abrupt variation occurs towards the left rim in the same garnet, with an increase in Mg content and a resulting decrease in X_{Fe} ratio. This variation can be

related to later fracturing of the garnet enhanced by fluid transport of elements (e.g. Erambert & Austrheim, 1993; Engvik *et al.*, 2001).

Table 4. Representative mineral-chemical data of feldspar, formula calculated on the basis of 5 cations.

Lithology	Mafic granulite												Felsic granulite					
Sample no.	40744	40744	40744	40744	33366	33366	33366	40690	40690	33307	33307	33307	33307	33298	33298	33397	33397	33399
Analysis no.	5	12	15	16	48	53	56	58	59	151	161	162	164	106	124	1	2	11
	PI	PI	PI	PI	PI	PI	PI	PI	PI	PI	PI	PI	PI	PI	PI	Kfs	PI	Kfs
	corona	corona	core	core	corona	corona		core	core	corona	core	inclusion	inclusion	Rim	core	small	core	core
SiO ₂	50.97	49.87	58.27	58.00	51.47	55.96	56.55	58.36	57.19	57.80	60.59	55.67	58.12	59.58	60.48	63.62	59.17	63.73
Al ₂ O ₃	30.72	31.71	25.98	25.95	30.02	27.27	26.93	26.04	26.92	26.62	24.84	28.11	26.32	25.40	24.61	18.60	25.34	18.21
FeO	0.29	0.21	0.09	0.03	0.18	0.11	0.27	0.07	0.19	0.19	0.14	0.37	0.45	0.17	0.08	0.00	0.06	0.00
CaO	13.92	14.97	8.03	8.20	13.42	10.06	9.08	8.37	9.11	8.89	6.28	10.39	8.26	7.27	6.46	0.06	7.88	0.04
Na ₂ O	3.68	3.02	6.76	6.73	3.93	5.81	6.26	6.72	6.45	6.67	8.10	5.83	6.92	7.30	7.87	0.18	7.16	0.40
K ₂ O	0.15	0.14	0.49	0.44	0.14	0.23	0.29	0.50	0.46	0.29	0.49	0.26	0.39	0.47	0.53	16.40	0.46	16.16
BaO	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1.52	0.06	0.97
Total	99.75	100.02	99.61	99.38	99.22	99.52	99.40	100.10	100.35	100.49	100.47	100.66	100.50	100.26	100.03	100.42	100.13	99.51
Si	2.32	2.28	2.62	2.61	2.36	2.53	2.55	2.61	2.56	2.58	2.68	2.49	2.59	2.66	2.69	2.96	2.64	2.98
Al	1.65	1.71	1.38	1.38	1.62	1.45	1.43	1.37	1.42	1.40	1.30	1.48	1.38	1.33	1.29	1.02	1.33	1.00
Fe	0.01	0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.02	0.01	0.00	0.00	0.00	0.00
Ca	0.68	0.73	0.39	0.40	0.66	0.49	0.44	0.40	0.44	0.42	0.30	0.50	0.39	0.35	0.31	0.00	0.38	0.00
Na	0.33	0.27	0.59	0.59	0.35	0.51	0.55	0.58	0.56	0.58	0.69	0.50	0.60	0.63	0.68	0.02	0.62	0.04
K	0.01	0.01	0.03	0.03	0.01	0.01	0.02	0.03	0.03	0.02	0.03	0.02	0.02	0.03	0.03	0.97	0.03	0.96
Ba	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.03	0.00	0.02
An	67.1	72.7	38.5	39.3	64.8	48.3	43.8	39.6	42.7	41.7	29.2	48.9	38.9	34.6	30.3	0.3	36.9	0.2
Ab	32.1	26.5	58.7	58.3	34.4	50.4	54.6	57.6	54.7	56.6	68.1	49.6	58.9	62.8	66.7	1.7	60.6	3.6
Kfs	0.8	0.8	2.8	2.5	0.8	1.3	1.7	2.8	2.6	1.6	2.7	1.5	2.2	2.6	3.0	98.1	2.6	96.2

Table 5. Representative mineral-chemical data of amphibole, formula calculated on the basis of Sum-(Ca,Na,K) = 13.

	Mafic granulite								Felsic granulite		
Sample no.	40744	40744	33366	33366	40690	40690	33307	33307	33298	33397	33397
Analysis no.	11	17	47	54	52	65	134	153	100	70	82
	Magnesio-hastingsite	Magnesio-hastingsite	Magnesio-hastingsite corona	Magnesio-hastingsite	Magnesio-hastingsite	Magnesio-hastingsite	Magnesio-hastingsite	Magnesio-hastingsite	Tschermakite	Pargasite	Pargasite
SiO ₂	42.50	41.98	43.76	42.48	40.76	42.27	41.60	42.97	42.18	41.28	41.86
Al ₂ O ₃	12.07	11.77	11.03	11.04	12.43	11.78	11.98	10.79	11.61	11.99	11.65
TiO ₂	0.81	2.41	1.38	1.88	2.33	2.25	2.34	2.25	1.28	2.24	1.88
Cr ₂ O ₃	0.11	0.10	0.00	0.00	0.04	0.02	0.03	0.00	0.01	0.04	0.02
FeO	14.21	15.03	12.69	14.33	16.32	16.43	15.70	15.29	18.22	17.19	16.21
MnO	0.10	0.10	0.16	0.13	0.17	0.13	0.30	0.27	0.13	0.14	0.14
MgO	12.07	11.08	12.93	11.71	10.29	10.62	10.95	11.55	9.64	9.70	10.26
CaO	11.87	11.48	11.96	11.90	11.65	11.61	11.45	11.77	11.28	11.70	11.75
Na ₂ O	1.08	1.58	1.37	1.48	1.60	1.44	1.65	1.39	1.21	1.39	1.32
K ₂ O	1.74	1.56	1.14	1.22	1.75	1.74	1.72	1.51	1.53	1.91	1.91
Total	96.57	97.10	96.42	96.17	97.34	98.29	97.73	97.79	97.09	97.59	97.00
Si	6.32	6.28	6.48	6.39	6.14	6.28	6.20	6.38	6.34	6.23	6.33
Ti	0.09	0.27	0.15	0.21	0.26	0.25	0.26	0.25	0.15	0.25	0.21
Al	2.12	2.07	1.92	1.96	2.21	2.06	2.10	1.89	2.06	2.13	2.08
Cr	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00
Fe ³⁺	0.62	0.38	0.41	0.35	0.42	0.44	0.50	0.43	0.71	0.32	0.28
Fe ²⁺	1.15	1.50	1.16	1.45	1.63	1.60	1.46	1.47	1.58	1.85	1.77
Mn	0.01	0.01	0.02	0.02	0.02	0.02	0.04	0.03	0.02	0.02	0.02
Mg	2.68	2.47	2.85	2.63	2.31	2.35	2.43	2.56	2.16	2.18	2.31
Ca	1.89	1.84	1.90	1.92	1.88	1.85	1.83	1.87	1.81	1.89	1.90
Na	0.31	0.46	0.39	0.43	0.47	0.41	0.48	0.40	0.35	0.41	0.39
K	0.33	0.30	0.21	0.23	0.34	0.33	0.33	0.29	0.29	0.37	0.37
Sum cation	15.53	15.60	15.50	15.58	15.68	15.59	15.63	15.56	15.46	15.67	15.66
X _{Fe}	0.30	0.38	0.29	0.36	0.41	0.40	0.37	0.36	0.42	0.46	0.43

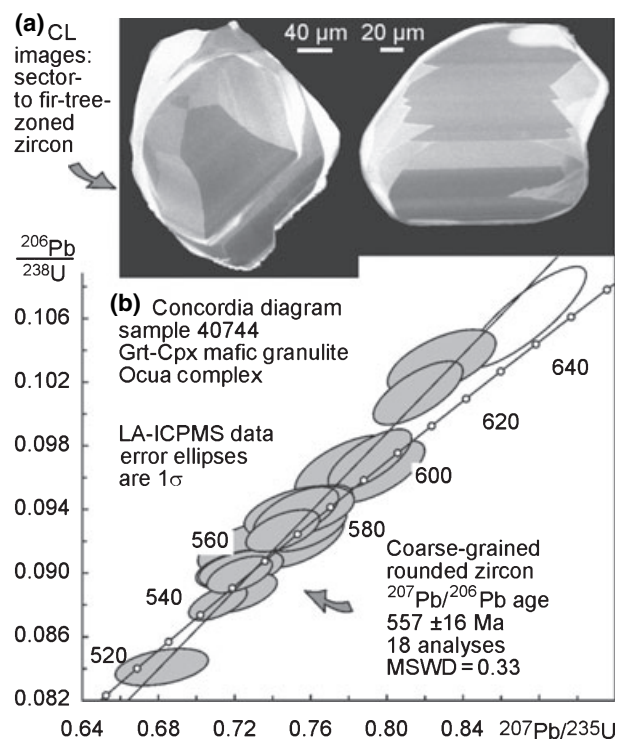
Thermobarometry

Quantitative *P-T* determinations were performed on five samples, two mafic (40744 & 33307) and three felsic granulites (33298, 33397 & 33399). The *P-T* and phase reaction calculations were made using

THERMOCALC, version 3.26 (April 2007) with thermodynamic data set and activities determined by the program A-X (Holland & Powell, 1998). Mineral chemical analyses collected in the core of large crystals are used for estimating peak conditions. As discussed below, core compositions represent the closest

Table 6. Representative mineral-chemical data of biotite, formula calculated on the basis of 22 oxygen.

Lithology	Mafic granulite			Felsic granulite	
Sample no.	40690	33307	33307	33397	33399
Analysis no.	64	132	172	80	173
	Bt	Bt	Bt	Bt	Bt
SiO ₂	36.07	37.05	36.73	36.94	36.08
Al ₂ O ₃	14.01	14.29	13.81	14.32	13.81
TiO ₂	5.91	6.00	5.62	5.09	5.17
Cr ₂ O ₃	0.06	0.02	0.09	0.00	0.04
FeO	17.27	15.15	16.18	15.55	20.36
MnO	0.07	0.16	0.12	0.00	0.02
MgO	12.36	13.35	13.40	13.98	10.42
CaO	0.01	0.01	0.01	0.00	0.07
Na ₂ O	0.03	0.12	0.06	0.00	0.01
K ₂ O	9.87	10.06	10.07	10.13	9.69
Total	95.66	96.20	96.08	96.00	95.67
Si	5.47	5.52	5.51	5.52	5.54
Al	2.50	2.51	2.44	2.52	2.50
Ti	0.67	0.67	0.63	0.57	0.60
Cr	0.01	0.00	0.01	0.00	0.01
Fe	2.19	1.89	2.03	1.94	2.61
Mn	0.01	0.02	0.02	0.00	0.00
Mg	2.79	2.97	3.00	3.12	2.39
Ca	0.00	0.00	0.00	0.00	0.01
Na	0.01	0.03	0.02	0.00	0.00
K	1.91	1.91	1.93	1.93	1.90
X _{Fe}	0.44	0.39	0.40	0.38	0.52

**Fig. 10.** (a) Cathodoluminescence images of zircon, and (b) concordia diagram with laser ablation–inductively coupled plasma mass spectrometry (LA–ICPMS) U–Pb zircon data from high-pressure mafic granulite sample 40744.

approximation to equilibrium compositions during peak metamorphism. Plots of the P – T estimates and calculated phase reactions are shown in Fig. 9. Based

on calculations involving the coexisting phases Grt + Cpx + Pl + Qtz, the mafic granulite show estimated P – T reaching 1.57 ± 1.4 GPa at 949 ± 92 °C and 1010 ± 105 °C at 1.23 ± 0.15 GPa. An estimate of the corona growth based on the equilibrated assemblage of Opx + Pl + Qtz + Grt gives 766 ± 115 °C and 0.79 ± 0.12 GPa for the retrograde evolution. For the felsic granulites, P – T estimates reached 1.08 ± 0.12 GPa at 891 ± 92 °C based on the coexisting phases Grt + Cpx + Opx + Pl + Qtz.

Geochronology

U–Pb geochronological data were collected on zircon in mafic granulite 40744. This sample contains comparatively abundant, clear, coarse-grained (commonly 250 μ m), rounded zircon. Cathodoluminescence images of polished grains reveal a homogeneous zircon population characterized by a sector- to fir-tree-zoning (Fig. 10a). A thin (<20 μ m) luminescent (low-U) overgrowth is generally present. A high-U core is rarely observed. A few prismatic zircon grains are present. They presumably represent inclusions in garnet. Nineteen analyses on seven zircon grains, including one prismatic zircon, yield a monomodal age distribution with a mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 557 ± 16 Ma (MSWD = 0.33, one outlying analysis discarded, Fig. 10b). The low-U overgrowth, sampled during the first of two or three ablations, did not provide a detectably distinct age. The age of 557 ± 16 Ma represents the best estimate for crystallization of the main population of zircon in sample 40744.

DISCUSSION

Garnet zoning pattern

As a result of low cation diffusivity, garnet has the property to record changes in pressure and temperature as it grows (e.g. Spear & Selverstone, 1983). However, at the high-temperature conditions typical of granulite facies, diffusion in garnet is comparatively rapid, causing chemical homogenization of porphyroblasts (Spear, 1993). During subsequent unroofing, partial thermal resetting of the garnet chemistry is common. As a result, P – T determinations generally result in estimates lower than peak granulite facies conditions (Jiang & Lasaga, 1990; Spear & Florence, 1992).

In the eastern part of the Lurio Belt, garnet porphyroblasts in mafic granulite 40744 are zoned. Zoning is characterized by lower Fe and Mn contents, and lower X_{Fe} values, and higher Ca content in the core (Figs 6–8). A lower X_{Fe} value typically represents the closest estimate to peak metamorphic conditions (e.g. Spear & Selverstone, 1983). The reported increase in X_{Fe} ratio, and Fe and Mn contents towards the rim is typically formed during cooling, while decreasing

Table 7. Zircon U–Pb data on mafic granulite 40744.

Id	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	1 σ (%)	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	1 σ (%)	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	1 σ (%)	Co	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$ Ma	1 σ	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$ Ma	1 σ	Di (%)
(1)	(2)	(3)		(3)		(3)		(4)	(5)		(5)		(6)
01	43310	0.05888	2.2	0.6818	2.4	0.08399	0.9	0.39	520	5	563	47	7.6
13	11270	0.05859	1.1	0.7114	1.4	0.08806	0.8	0.59	544	4	552	25	1.4
16	30347	0.05915	1.5	0.7233	1.8	0.08868	0.9	0.53	548	5	573	32	4.4
07	11091	0.05834	1.3	0.7228	1.6	0.08985	0.8	0.54	555	5	543	29	-2.2
02	12636	0.05812	1.9	0.7227	2.1	0.09018	0.9	0.43	557	5	534	42	-4.1
10	14889	0.05817	1.8	0.7234	2.0	0.09019	0.9	0.43	557	5	536	40	-3.8
05	5157	0.05809	2.6	0.7332	2.9	0.09155	1.3	0.45	565	7	533	57	-5.9
17	278016	0.05955	1.5	0.7551	2.0	0.09197	1.2	0.62	567	7	587	33	3.4
14	13868	0.05837	1.4	0.7455	1.7	0.09262	0.9	0.55	571	5	544	31	-5.0
08	86972	0.05927	1.5	0.7583	1.8	0.09280	1.0	0.58	572	6	577	32	0.8
11	11187	0.05823	1.6	0.7524	2.0	0.09371	1.2	0.61	577	7	539	34	-7.2
03	11343	0.05830	2.2	0.7540	2.5	0.09380	1.2	0.46	578	6	541	49	-6.8
15	22175	0.05873	1.5	0.7608	1.8	0.09396	1.1	0.59	579	6	557	32	-3.9
09	63307	0.05993	1.4	0.7962	2.0	0.09636	1.3	0.68	593	8	601	31	1.3
20	17931	0.05845	1.8	0.7784	2.3	0.09660	1.4	0.62	594	8	547	39	-8.8
18	30617	0.05909	1.3	0.7912	1.8	0.09711	1.3	0.72	597	8	570	28	-4.7
12	14546	0.05844	1.4	0.8166	1.9	0.10134	1.3	0.69	622	8	546	30	-13.9
21	8681	0.05822	1.8	0.8291	2.3	0.10328	1.3	0.58	634	8	538	40	-17.7
06x	5836	0.05969	1.3	0.8736	2.4	0.10614	2.0	0.84	650	12	592	28	-9.8

(1): Analysis identifier, x: not used for age calculation.

(2): Measured ratio.

(3): Ratio corrected for common Pb.

(4): Correlation of errors.

(5): Age corrected for common Pb.

(6): Discordance of the analysis.

Ca-content is commonly associated with decompression. Based on this, the zoning in the large garnet porphyroblasts is interpreted as a product of diffusion. Core composition is regarded as the closest preserved composition reflecting close-to-metamorphic-peak conditions. Therefore, core compositions were used to obtain quantitative P – T estimates that are inferred to record close-to-metamorphic-peak conditions (Fig. 9). The rimward increase in X_{Fe} ratio, and Fe and Mn contents, formed by diffusion, is related to decompression and cooling, simultaneously with the formation of coronas around the garnet porphyroblasts.

The rate of homogenization and formation of retrograde diffusion zoning of the garnet porphyroblast is modelled hereafter based on the diffusion coefficient and the equation for the characteristic length scale of diffusion after Spear (1993). The diffusion coefficient (D) has an Arrhenius relationship of the form

$$D = D_0 \exp\left(-\frac{E_a}{RT}\right),$$

where D_0 is a pre-exponential constant, E_a is the activation energy, R is the gas constant and T , the absolute temperature. D is therefore strongly dependent on the temperature and on the type of mineral and cation. According to Spear (1993), diffusion coefficients for major cations in garnet decrease in the following order: $D_{\text{Mn}} > D_{\text{FeMg-l}} > D_{\text{Ca}}$. The diffusion coefficient is about the same for Fe and Mg because of their similar cation size. In this modelling the diffusion coefficients proposed by Cygan & Lasaga (1985) were used. These were derived from experiments of Mg self-diffusion in

garnet at temperatures between 750 and 900 °C and pressures of 0.2 GPa. X_{Prp} in garnet has only minor dependence on pressures above 0.2 GPa (Spear *et al.*, 1990). According to Cygan & Lasaga (1985), D_{Mg} in garnet is $9.75 \times 10^{-21} \text{ m}^2 \text{ s}^{-1}$ at 750 °C, and $2.24 \times 10^{-19} \text{ m}^2 \text{ s}^{-1}$ at 900 °C.

The characteristic length scale of diffusion is:

$$x = (Dt)^{1/2},$$

where t is time. For the peak temperatures of 900 °C recorded in the high-pressure granulites of the Lurio Belt (sample 40744), calculation gives *c.* 900 000 years as the time necessary for achieving chemical homogenization of a garnet porphyroblast of 5 mm size. In a geological perspective, this is a short time interval, strongly suggesting that garnet reached equilibration at peak conditions in the Lurio Belt. Evidently, the small Mg increase in the middle part of one of the studied garnet porphyroblasts (Figs 7 & 8c,d) cannot be explained as a preserved prograde growth zoning.

Thereafter, post-peak metamorphic evolution must have been rapid in order to preserve the core chemistry of the garnet porphyroblasts. The observed diffusion zoning can be explained by chemical relaxation when the rocks cooled to amphibolite facies conditions. A penetration depth of 500 μm is typically observed in the granulitic garnet porphyroblasts (Fig. 8). Based on the formula for the characteristic length scale of diffusion and the diffusion coefficients presented above, the observed length scale of diffusion of 500 μm is achieved after *c.* 800 000 years at 750 °C. At amphibolite facies conditions, however, this requires a longer

period, from 1 to 10 Myr, indicating that cooling from granulite to amphibolite facies conditions took place within this time-scale.

Implications of corona textures

In addition to preservation of garnet zoning, the occurrence of corona textures gives information on the P – T evolution of a rock sample. When fluids are scarce, mineral reactions are slow due to kinetic processes (Rubie, 1990), which can cause metastability of rocks and survival of high-grade parageneses during crustal cycling (Austrheim *et al.*, 1997; Engvik *et al.*, 2000). Consequently, instead of a full reequilibration of the mineral assemblage, coronitic textures evolve around specific minerals. Based on the minerals present in the coronas, the P – T evolution of a rock sample can be traced. In particular, the occurrence of composite coronas gives valuable information of several stages of a P – T path, as discussed below for the retrogression of the high-pressure granulites of the Lurio Belt. The occurrence of plagioclase coronas around garnet is a typical feature throughout north-eastern Mozambique (Norconsult Consortium, 2007), but also extensively in the granulite facies province of the Mozambique Belt of eastern Africa (Ring *et al.*, 2002; Sommer *et al.*, 2003), and in the Maud Belt of East Antarctica (Bisnath & Frimmel, 2005; Board *et al.*, 2005). The coexistence of other minerals as symplectites with plagioclase in the coronas indicates specific stages in P – T space. The sequence of reactions as documented in this work gives the post-peak evolution of the granulites.

P – T path and textural evidence for near-isothermal decompression

For the best documented sample, which is mafic granulite 40744, mineral assemblages, microtextures, chemical zoning of garnet and thermobarometry give evidence for three metamorphic stages (stages I, II & III), indicating a P – T path (Fig. 11). Data on the other samples support the evolution inferred from sample 40744, suggesting a similar, though not necessarily coeval P – T evolution for different rock bodies in the eastern portion of the Lurio Belt. As discussed previously, no record of the prograde metamorphic evolution can be extracted from any of the samples. Stage I thus corresponds to the closest record to peak metamorphic conditions. Stages II and III reflect post-peak metamorphic evolution.

Stage I is defined by the mineral assemblage Grt + Cpx + Pl + Qtz $\pm$ Amp, a typical paragenesis in the high-pressure granulite facies (e.g. Pattison, 2003), represented by the mafic granulites including porphyroblasts of garnet and clinopyroxene (Cpx I) (Fig. 3). As described above, core compositions of the Grt + Cpx + Pl + Qtz assemblage reflect stage I and provide a P – T estimate reaching 1.57 ± 0.14 GPa at 949 ± 92 °C (Fig. 9a). This is in agreement with the

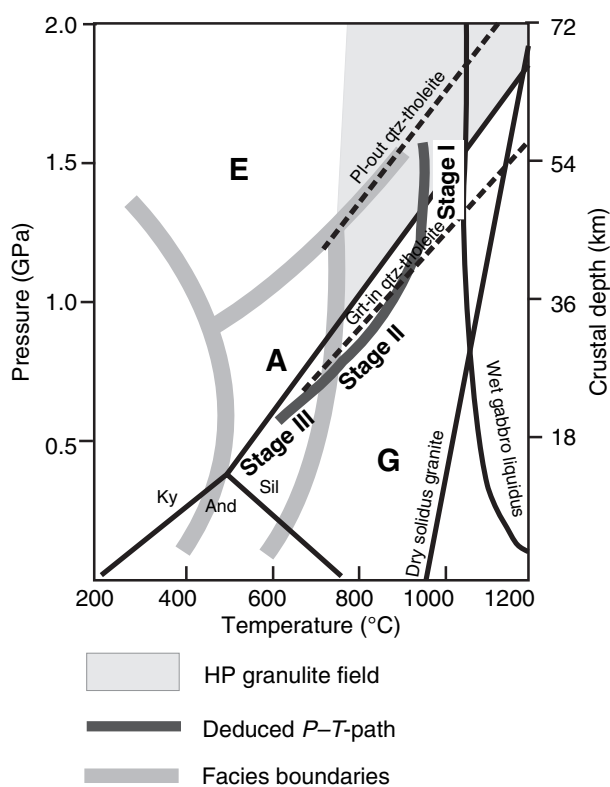


Fig. 11. P – T path as interpreted from the mafic granulite (40744) from the eastern part of the Lurio Belt. The retrograde P – T path goes through three stages from peak metamorphism in high-pressure granulite facies (I), through near-isothermal decompression to low-pressure granulite facies conditions (II), and to retrogression to amphibolite facies (III). P – T grid after O'Brien & Rötzler (2003; based on Green & Ringwood, 1967; Ito & Kennedy, 1971; Hansen, 1981; Spear, 1993; Johannes & Holtz, 1996).

high-pressure granulite facies phase diagram field as defined by Pattison (2003) and O'Brien & Rötzler (2003). A 557 ± 16 Ma zircon age was obtained for sample 40744 (Fig. 10). In view of the thorough equilibration of the Grt + Cpx + Pl + Qtz assemblage at peak metamorphism, and in view of the typical metamorphic rounded morphology and sector- to fir-tree-zoning of the zircon, the most straightforward interpretation is to link crystallization of the homogeneous 557 ± 16 Ma zircon population to stage I. Nevertheless, we cannot rule out that zircon did grow during stage II, and consequently, that the age of 557 ± 16 Ma records this stage.

Stage II corresponds to the orthopyroxene-bearing mineral assemblages. In the mafic granulites, Opx occurs exclusively in coronas around the garnet and Cpx porphyroblasts. Orthopyroxene thus belongs to a secondary stage, replacing the high-pressure mineralogy. The formation of Opx $\pm$ Pl coronas around garnet and clinopyroxene is characteristic of near-isothermal decompression at high temperatures (Harley, 1989), from the high-pressure to the medium-pressure granulite facies domains (O'Brien & Rötzler, 2003;

Pattison, 2003). Similar fine-grained symplectites formed by Opx + Pl + Spl mantling garnet and replacing a Grt + Cpx + Pl + Qtz assemblage are reported in Elvevold *et al.* (2003) and interpreted to result from decompression. In contrast to the mafic granulite, the felsic granulite include a well-equilibrated Opx + Cpx + Grt assemblage, and are thus, by definition, medium-pressure granulite. They yield pressure estimates of up to 1.08 GPa.

Stage III corresponds to the formation of amphibole + plagioclase corona texture and illustrates retrogression into amphibolite facies conditions. After the near-isothermal decompression, stage III results from a cooling of the rocks and occurs with a gentler gradient in P – T space. The fine-grained symplectitic growth of amphibole and plagioclase indicates a rapid transformation, assisted by access to fluid. The retrogression of the granulites is also evident from replacement textures, in which matrix clinopyroxene transforms to amphibole and biotite. The garnet diffusion zoning with rim-ward X_{Fe} increase, representing decreasing temperature, presumably results from cooling to stage III (see above discussion on garnet zoning).

Implications for the tectonic evolution of the Lurio Belt

Granulite facies conditions can result from a number of tectonic or geological processes in the crust. For example, low-pressure granulites are believed to reflect high heat flow and are typical of areas experiencing episodic igneous activity or magmatic underplating (e.g. Bohlen, 1991). Medium- to high-pressure granulites are, however, diagnostic of crustal thickening in collisional belts (e.g. Harley, 1989; O'Brien & Rötzler, 2003), and isothermal decompression is generally linked to tectonic exhumation during moderate-rate extension (e.g. Harley, 1989; Engvik & Elvevold, 2004).

The high-pressure granulites in the Lurio Belt, given their P – T estimates up to 1.57 ± 0.14 GPa and 949 ± 92 °C, indicate that formation of this belt is probably associated with crustal shortening processes that led to a crustal thickness in excess of 50 km. Thermobarometry shows P_{max} estimates varying between 0.87 and 1.57 GPa for different samples. The variation can be attributed to (i) the tectonic processes in which lenses and slivers of granulites formed at different crustal levels have been tectonically juxtaposed during the long-term tectonic evolution affecting the Lurio Belt. (ii) Kinetic processes on a mineral scale, such as retrograde diffusive equilibration of garnet, can also explain the lower P – T estimates. Garnet less than 1 mm in size is typically completely re-equilibrated by diffusional processes (e.g. Jiang & Lasaga, 1990). The highest pressure estimate of 1.57 GPa (sample 40744) is derived from large garnet porphyroblasts of >2 mm size, preserving the peak composition in the garnet core.

Zircon and monazite U–Pb ages obtained from various amphibolite and granulite facies rock units

distributed along the Lurio Belt range from *c.* 580 to 530 Ma (Bingen *et al.*, 2006) in age. The zircon age of 557 ± 16 Ma presented in this study records high-pressure granulite facies metamorphism in the middle of that time span. The corona microtextures, the retrograde chemical zoning of garnet and the thermobarometry suggest a 'clockwise' P – T path, including an episode of near-isothermal decompression after peak metamorphism (stage II) followed by cooling (stage III). The very fine-grained size of the symplectites, together with the preservation of peak garnet chemistry, suggest that these units underwent rapid exhumation to middle crustal level (amphibolite facies conditions) soon after peak metamorphism. Our modelling of mineral zoning requires a time frame shorter than 10 Myr for the post-peak evolution (between phases I and III). Collectively, the data suggest that the Ocua Complex (in the core of the Lurio Belt) includes slivers of rocks that reached peak metamorphism and were exhumed to middle crustal level at different times between *c.* 580 and 530 Ma. These slivers were juxtaposed, strongly deformed to a tightly banded sequence, and finally injected by granitic intrusions towards the end of that time span, to give the present-day geometry in the belt. This is in accordance with the tectonic model by Viola *et al.* (2006) who suggested that the Lurio Belt represents a major, long-lived tectonic zone resulting from repeated tectonic activity and structural reworking.

The Lurio Belt within Gondwana

The tectonic activity and high-pressure granulite facies metamorphism in the Lurio Belt relate to the Pan-African evolution of the large-scale EAAO (Stern, 1994; Meert, 2003; Jacobs & Thomas, 2004). High-grade metamorphism in the EAAO ranges from *c.* 700 to 520 Ma in East Africa and adjacent areas in the Gondwana context (Madagascar, Sri Lanka, Antarctica) (e.g. Muhongo & Lenoir, 1994; Jacobs *et al.*, 1998; de Wit *et al.*, 2001; Kröner *et al.*, 2001; Board *et al.*, 2005). Available zircon and monazite U–Pb data show two frequency maxima, one at *c.* 640 Ma and the other at *c.* 550 Ma (Meert, 2003). The first event at *c.* 640 Ma is mainly recorded in Tanzania and northwards in East Africa. It has been variably interpreted in terms of volcanic arc and microcontinent assembly at the margin of the Congo-Tanzania craton (Meert, 2003; Collins & Pisarevsky, 2005). The second event, at *c.* 550 Ma, is much more widespread and is generally linked to the final collision between East and West Gondwana. The zircon age of 557 ± 16 Ma in sample 40477 places metamorphism in the Lurio Belt as part of the second event.

Both events are characterized by high-pressure granulite facies metamorphism, indicating that both were associated with large-scale crustal thickening. In Tanzania, high-pressure granulites (Eastern and Western granulites) related to the first event at *c.* 640 Ma

show a peak metamorphism at 750–800 °C and 1.2–1.3 GPa followed by decompression (Sommer *et al.*, 2003, 2005; Fritz *et al.*, 2005). In Northern Malawi, eclogite facies metamorphism probably related to the second event at *c.* 550 Ma is locally recorded, with temperature up to 780 °C and 1.7–1.8 GPa (Ring *et al.*, 2002). However, this metamorphism is strongly overprinted, including a phase of heating to granulite facies conditions, followed by near-isothermal decompression. The Dronning Maud Province of Antarctica (Jacobs *et al.*, 1998) is characterized by granulite facies metamorphism during the second event. Conditions of 800–900 °C at intermediate pressures were followed by near-isothermal decompression during late Pan-African extension (Bucher-Nurminen & Ohta, 1993; Harley, 2003; Jacobs *et al.*, 2003; Engvik & Elvevold, 2004). Relics after Pan-African eclogite facies metamorphism are also documented in the Dronning Maud Province (Board *et al.*, 2005). However, high-temperature metamorphism seems to strongly overprint and dominate the EAAO of both Antarctica and East Africa.

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