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15

16 **Short title:** Strain-dependent evolution of garnet

17

18 **Abstract**

19 Reaction and deformation microfabrics provide key information to understand the
20 thermodynamic and kinetic controls of tectono-metamorphic processes, however they are
21 usually analysed in two dimensions, omitting important information regarding the third
22 spatial dimension. We applied Synchrotron-based x-ray microtomography to document
23 the evolution of a pristine olivine gabbro into a deformed omphacite-garnet eclogite in
24 four dimensions, where the 4th dimension is represented by the degree of strain. In the
25 investigated samples, which cover a strain gradient into a shear zone from the Western
26 Gneiss Region (Norway), we focused on the spatial transformation of garnet coronas into
27 elongated clusters of garnets with increasing strain. Our microtomographic data allowed
28 quantification of garnet volume, shape and spatial arrangement evolution with increasing
29 strain. We combined microtomographic observations with light microscope- and
30 backscatter electron images as well as electron microprobe- (EMPA) and electron
31 backscatter diffraction (EBSD) analysis to correlate mineral composition and orientation
32 data with the x-ray absorption signal of the same mineral grains.

33 With increasing deformation, the garnet volume almost triples. In the low strain domain,
34 garnets form a well interconnected large garnet aggregate that develops throughout the
35 entire sample. We also observed that garnet coronas in the gabbros never completely
36 encapsulate olivine grains. In the most highly deformed eclogites, the oblate shapes of
37 garnets reflect a deformational origin of the microfabrics. We interpret the aligned garnet
38 aggregates to direct synkinematic fluid flow and consequently influence the transport of
39 dissolved chemical components. EBSD analyses reveal that garnet show a near-random
40 crystal preferred orientation that testifies no evidence for crystal plasticity. There is,

41 however evidence for minor fracturing, neo-nucleation and overgrowth. Microprobe
42 chemical analysis revealed that garnet compositions progressively equilibrate to eclogite
43 facies, becoming more almandine-rich. We interpret these observations as pointing to a
44 mechanical disintegration of the garnet coronas during strain localisation, and their
45 rearrangement into individual garnet clusters through a combination of garnet
46 coalescence and overgrowth while the rock was deforming.

47

48 **Key words:**

49 Synchrotron x-ray microtomography; garnet; high-pressure shear zone; Western Gneiss
50 Region; strain localisation;

51

52 **INTRODUCTION**

53 Synkinematic reaction microfabrics carry important information on the kinetics, timing,
54 and mechanics of tectono-metamorphic processes. The spatial arrangement of reaction
55 products reflects directions and magnitudes of mass and element transport. An
56 assessment of the geometry of reaction microfabrics is therefore a critical component in
57 reconstructing the tectono-metamorphic evolution of a rock. Despite being routinely
58 interpreted in metamorphic and structural studies, reaction and deformation
59 microfabrics are usually described in two dimensions, which can lead to incorrect
60 petrographic and structural interpretations. In this study, we use garnet to explore the
61 significance of a 3-dimensional (3D) approach to the description of synkinematic
62 reactions and deformation microfabrics.

63 In nature, garnet represents an extremely versatile recorder of metamorphism (Baxter &
64 Scherer, 2013) and in particular garnet coronas capture metamorphic processes "in
65 flagranti" (Carlson & Johnson, 1991; Carlson, 2011; Ague & Carlson, 2013).
66 Consequently, garnet coronas and their metamorphic significance have been intensely
67 studied over the past decades (Mørk, 1985; Johnson & Carlson, 1990; Johnson, 1993;
68 Spiess *et al.*, 2001; Prior *et al.*, 2002; Konrad-Schmolke *et al.*, 2005; Massey *et al.*,
69 2011; Goergen & Whitney, 2012).

70 Garnet porphyroblasts often hold the key to unravel the synkinematic PTtd conditions.
71 The origin of these garnet porphyroblasts has been controversially discussed as either
72 being evidence of rotational strains ("*Snowball garnets*", Johnson, 1993; Jiang &
73 Williams, 2004), as documenting strain partitioning (Bell & Johnson, 1989; Aerden,
74 2005) or, where polycrystalline, as forming from the coalescence of nuclei (Spiess *et*

75 *al.*, 2001, Dobbs *et al.* 2003).

76 Garnet also readily partakes in mylonitic deformation: crystal plastic deformation of
77 garnets at lower crustal conditions was documented by, e.g., Ji & Martignole (1994), Ji
78 & Martignole (1996), Prior *et al.*, (2002), Storey & Prior (2005), Massey, Prior &
79 Moecher (2011), Martelat *et al.*, (2012). Garnets in mylonitic eclogites from SW
80 Norway were shown to have deformed by grain-boundary diffusion creep and by
81 pressure-solution (Smit *et al.*, 2011). However, garnet in eclogitic mylonitized
82 micaschists was also shown to have deformed by cataclasis and frictional sliding
83 (Trepmann & Stöckhert, 2002).

84 Conclusions derived in these studies often invoke an extrapolation from the second to
85 the third spatial dimension, which is naturally speculative. With the advent of x-ray
86 microtomography, garnet became the focus of a number of microstructural studies that
87 explored the third spatial dimension (Denison & Carlson, 1997; Ketcham, 2005a;
88 Whitney *et al.*, 2008; Goergen & Whitney, 2012).

89 These pioneering 3-dimensional studies outlined the possibilities that the combination of
90 x-ray microtomographic data with other microanalytical techniques holds in regards to
91 the interrogation of tectono-metamorphic processes. In this present contribution, we
92 apply this approach to analyse the distribution of garnet in rock samples from
93 Kråkeneset, a tectonic domain within the well-studied Western Gneiss Region (Norway)
94 (Mørk, 1985; Mørk, 1986; Austrheim, 1987; Boundy *et al.*, 1992; Austrheim *et al.*, 1997;
95 Krabbendam & Dewey, 1998; Cuthbert *et al.*, 2000; Engvik *et al.*, 2000; Krabbendam *et*
96 *al.*, 2000; Engvik *et al.*, 2001; Wain *et al.*, 2001; Labrousse *et al.*, 2004; Terry &
97 Heidelberg, 2006; John *et al.*, 2009; Hacker & Andersen, 2010; Labrousse *et al.*, 2010).

98 There, fluid infiltration along precursory fractures led to the eclogitization and coeval
99 mylonitic overprint of gabbroic rocks (Mørk, 1985; Austrheim *et al.*, 1997; Krabbendam
100 *et al.*, 2000; Engvik *et al.*, 2001; Lund & Austrheim, 2003; John *et al.*, 2009; Müller,
101 2013). Our field location is a gabbroic body in which hydrous eclogite-facies shear
102 zones cross cut the almost pristine magmatic rock. There, reaction textures indicate that
103 the eclogite-facies overprint is caused by the ingress of reactive fluids that helped to
104 overcome sluggish reaction kinetics (Austrheim, 1987; Krabbendam *et al.*, 2000; Lund &
105 Austrheim, 2003; John *et al.*, 2009; Müller, 2013). The rock samples cover a strain
106 gradient (which we consider the 4th dimension) into a dm-scale mylonitic shear zone and
107 document the metamorphic overprint. The strain gradient along the shear zones is ideally
108 suited for such a study, in that it shows progressive deformation localization under well
109 constrained P-T-fluids conditions. Based on the assumption that the strain gradient can
110 be regarded as a proxy for time, which is a common assumption where strain softening
111 leads to progressive strain localisation (Means, 1995; Fousseis, *et al.*, 2006; Fousseis &
112 Handy, 2008), the samples allow us to characterize the spatiotemporal evolution of a
113 gabbro into a deformed eclogite. In our samples, this transition is reflected by the
114 evolving 3-dimensional distribution of garnets in the microfabric. We determine how the
115 garnet evolved from its arrangement in a primary coronitic texture to forming a key
116 component of the tectonic microfabric. To do this, we developed a methodological
117 workflow that combined classical electron-beam techniques with Synchrotron x-ray
118 microtomography. In combination, these data allow us to speculate on the mechanisms
119 that accomplished the transformation of garnet microfabrics.

120 **GEOLOGICAL SETTING**

121 The studied rock samples come from Kråkeneset in the Western Gneiss Region (WGR)
122 of the Norwegian Caledonides. As many other parts of this lowest tectonic unit in the
123 Scandinavian terrains, the outcrops in Kråkeneset preserve evidence for Caledonian high-
124 pressure metamorphism in association with the subduction of Baltica underneath
125 Laurentia after the Silurian closure of the Iapetus ocean (Engvik, *et al.*, 2000;
126 Krabbendam *et al.*, 2000; Wain *et al.*, 2001; Lund & Austrheim, 2003; Labrousse *et al.*,
127 2004; John *et al.*, 2009; Müller, 2013). It is commonly accepted that even though some
128 of the rocks in the WGR were subducted to depths beyond 100 km, large parts of the
129 complex remained metastable until fluid infiltration along brittle fractures and cleavage
130 planes overcame sluggish reaction kinetics and initiated large-scale eclogitisation
131 (Austrheim, 1987; Krabbendam *et al.*, 2000; Wain *et al.*, 2001; Labrousse *et al.*, 2010).
132 In Kråkeneset, the high-pressure metamorphic overprint takes the form of hydrous
133 eclogites that occur within shear zones cutting dry gabbroic host rocks (Krabbendam, *et*
134 *al.*, 2000; Lund & Austrheim, 2003; John *et al.*, 2009). The pristine gabbroic mineral
135 assemblage is preserved in the less deformed areas, and is characterized by an ophitic
136 texture, in which garnet and orthopyroxene coronas surround olivine cores. Previous
137 authors have interpreted these coronas as having derived from diffusion-controlled
138 reactions of olivine and plagioclase (Mørk, 1985; Johnson & Carlson, 1990). The
139 eclogite-facies mineral assemblages occur within narrow shear zones where, across their
140 margin, a gradient from a “dry” gabbroic mineral assemblage (Ol + Cpx + Grt + Pl + Ilm
141 + Bt + Am \pm Rt), to a synkinematic mostly “wet” eclogitic mineral assemblage is
142 preserved. The latter consists of Grt + Opx + Am + Ab-Czo symplectites + Bt + Opaque
143 phases (e. g Ilm) \pm phengite, as well as omphacite + garnet (Fig. 4), where the reaction

144 advanced further or local chemical domains supported this assemblage (Austrheim, 1987;
145 Lund & Austrheim, 2003; John *et al.*, 2009; Putnis & Austrheim, 2010; Müller, 2013).
146 The replacement of magmatic plagioclase by Ab-Czo symplectites (e.g., Wayte *et al.*,
147 1989), along with the widespread formation of amphiboles and of Grt-Omp assemblages,
148 occurs where transport during reactions has been enhanced (e.g., Mørk, 1985; John &
149 Schenk, 2003; Putnis & Austrheim, 2010). All these developments positively correlate
150 with the observed strain gradient, and show that eclogitization of the gabbro was driven
151 by the close interplay of infiltration of externally derived fluids and deformation (Mørk,
152 1985; Austrheim, 1987; Krabbendam *et al.*, 2000; Lund & Austrheim, 2003; Labrousse
153 *et al.*, 2010; Putnis & John, 2010).

154 **METHODS**

155 From a hand specimen that covers the margin of an eclogite shear zone, three 2-mm
156 thick rock wafers covering the strain gradient were extracted in x-z kinematic
157 orientations (Fig. 1). From these wafers, parallelepipeds with dimensions of 2x2x6 mm
158 were cut for Synchrotron x-ray microtomography (S μ CT). After S μ CT, the wafers
159 including the S μ CT samples were polished into thin sections that could be used for
160 further analyses using light microscopy, scanning electron microscopy (SEM), electron
161 microprobe analyses (EMPA) and electron backscatter diffraction (EBSD). This
162 approach allowed for a comprehensive characterisation of the metamorphic
163 microfabrics in four dimensions (Fig. 1). This study focussed on three specimens,
164 #066B2, #061751 and #0618, which sample the low-, intermediate- and high-strain
165 domain of the shear zone.

166 **Analytical Techniques**

167 Mineral assemblage and chemical zoning were analysed on the carbon-coated thin
168 sections using a Zeiss SIGMA HD VP Field Emission SEM equipped with an Oxford
169 Instruments SD EDS detector and AZtec software for acquisition and processing of
170 EDS spectra, at the School of Geoscience in Edinburgh. Working conditions during
171 acquisition of SEM backscatter images and during EDS analysis were 20 KV
172 acceleration voltage and a working distance of 6.9 mm. Chemical compositions, to be
173 correlated with the x-ray absorption coefficients, were measured on a Cameca SX100
174 electron microprobe at 20 kV acceleration voltage and a beam diameter of 3 μm , at the
175 University of Edinburgh. The microprobe is composed by 5 vertical crystal
176 spectrometers and a PGT Spirit energy dispersive analyser. Natural standards were
177 used. Further microprobe analyses were acquired at the EMPA at the University of
178 Munster, using a JEOL 8530F electron microprobe. The standard microprobe
179 conditions were 15 nA and 20 keV for quantitative analysis and 50 nA and 15 keV for
180 the element mapping. Standards used for quantitative measurement were jadeite (Na),
181 kyanite (Al), sanidine (K), olivine (Mg), hypersthene (Si), diopside (Ca), rhodocrosite
182 (Mn), rutile (Ti), fayalite (Fe), and chromite (Cr). Compositional maps were obtained
183 using XMapTools v. 2.3.1 (Lanari *et al.*, 2014).

184 Crystallographic orientations were measured on a Jeol 6610 SEM equipped with a
185 NordlysNano EBSD detector (Oxford Instruments) at the Plymouth University Electron
186 Microscopy Centre. Working conditions during acquisition of the EBSD patterns were
187 20 kV acceleration voltage, 70° sample tilt, high vacuum (in case of the carbon-coated
188 samples 0617 and 066B2), and low vacuum (30 Pa, in case of the uncoated sample
189 0618). EBSD patterns were acquired on rectangular grids with step sizes varying from

190 0.8 to 4.8 μm . All the thin sections were chemically polished with colloidal silica prior
191 to EBSD analysis. EBSD patterns were indexed with the AZtec software (Oxford
192 Instruments) and processed with Channel 5 software (Oxford Instruments). Raw EBSD
193 data were processed to reduce data noise following the procedure proposed by Prior *et*
194 *al.*, (2002) and Bestmann & Prior (2003). Crystallographic data were plotted on pole
195 figures as one point per grain. Pole figures are oriented with their horizontal diameter
196 corresponding to the trace of the mylonitic foliation (E-W). Crystallographic maps were
197 produced to highlight phase distribution (phase map), the internal misorientation of
198 grains (local misorientation map) and the crystallographic orientation of grains with
199 respect to specific direction of the kinematic reference frame (Inverse Pole Figure Map,
200 IPF).

201 **Synchrotron x-ray microtomography**

202 X-ray absorption microtomographic data were collected at the beamline 2-BM at the
203 Advanced Photon Source (USA) using a monochromatic beam of 27 KeV and a low
204 sample-detector distance to minimise phase contrast. 1500 projections per dataset were
205 reconstructed into 3-dimensional image stacks using the gridrec algorithm (Rivers &
206 Wang, 2006). The voxel (i.e. a 3-dimensional pixel) side length of the reconstructed
207 data is 1.3 μm , which is sufficient to resolve the necessary petrographic details on the
208 μm -scale.

209 **Image Processing and Analysis**

210 The reconstructed x-ray absorption microtomographic datasets were filtered using an
211 Anisotropic Diffusion Filter 2D to reduce image noise (Tschumperlé & Deriche, 2005;
212 Schlüter *et al.*, 2014). Using the image processing software Fiji (Schindelin *et al.*,

213 2012), garnet was then segmented (i.e. numerically isolated) from the 3-dimensional
214 data using Statistical Region Merging followed by Global Thresholding (Nock &
215 Nielsen, 2004). Analysis of the resulting segmented images included the quantification
216 of garnet volumes and grain sizes, as well as a garnet interconnectivity analysis, all of
217 which were performed in Avizo Fire (v.8) (<http://www.fei.com/software/avizo3d/>)
218 using its Labelling and Label Analysis operators. Label analysis is a process that
219 identifies and evaluates face-connected clusters of voxels belonging to a specific class
220 (i.e. garnet) in segmented data. Face-connected voxel clusters do not represent
221 individual garnet grains but rather volumes occupied by garnet. Since X-ray absorption
222 microtomography does not detect grain boundaries in the garnet coronas, numerical
223 separation of the voxel clusters into individual grains is impossible in our data and we
224 are restricted to interpreting voxel clusters. To avoid introducing numerical shape
225 artefacts during the analyses of garnet, isolated voxel clusters with a volume smaller
226 than 125 cubic voxels (5x5x5 voxels, $\sim 275 \mu\text{m}^3$) were removed using the Analysis
227 Filter operator (see Füsseis *et al.*, 2012 for details).

228 In microtomographic data, volume calculations are affected by errors introduced by
229 the segmentation method (Arns *et al.*, 2002). To estimate the errors, we applied the
230 method described in Füsseis *et al.* (2012). Each segmented volume was both
231 numerically eroded and dilated by 1 voxel, and the resulting changes to the volume
232 and label analysis were quantified. The resulting quantifications are considered as
233 maximum possible errors.

234 Besides providing errors bars, binary data that have been eroded or dilated have the
235 potential to reveal details on the shape and spatial arrangement of voxel clusters, as

236 each morphological operation will cause voxel clusters to join, break up or disappear
237 altogether (see inset in Fig. 8). We analysed a version of the segmented garnet data
238 that underwent a single morphological erosion step. Morphological erosion removes
239 each voxel classified as garnet that is not completely surrounded by other voxels
240 classified the same. The erosion operator responds to the size and shape of the voxel
241 clusters, and the shortest diameter defines this response. The smallest unit that would
242 survive a morphological erosion step is a cubic array consisting of 3^3 voxels. A much
243 larger, spherical voxel cluster would retain its spherical shape through multiple erosion
244 steps. Oblate voxel clusters, which are characterised by one radius being substantially
245 shorter than others, will respond differently to erosion. Where cluster shapes are
246 irregular, morphological erosion will stragulate clusters at the shortest diameters (i.e.
247 the weakest links) and break them apart into several smaller ones, which is reflected
248 by a corresponding change in the cluster size distribution.

249 Using Avizo Fire, the 2-dimensional BSE images together with the EDS and EBSD
250 image data were reintroduced into 3-dimensional space to combine observations from
251 various sources with the microtomographic data into multidimensional datasets (Fig.
252 2). This allowed correlating x-ray absorption signals with chemical compositions and
253 crystallographic information and, as a result, extrapolating observations made by
254 electron microscopy to the third dimension.

255 **RESULTS**

256 **Petrological characterization**

257 In the *low strain domain*, at larger distance to the shear zone centre (sample #066B2),
258 although the magmatic gabbroic assemblage is still preserved, all mineral phases show

259 reaction textures (Fig. 3A). These reactions, related to sluggish kinetics, were triggered
260 by fluid-rock interactions: the amount of the reacted rock volume decreases with the
261 distance to the hydrous shear zone (Lund & Austrheim, 2003; John *et al.*, 2009).

262 Olivine cores ($\text{Fo}_{54}\text{Fa}_{45.6}\text{Tep}_{0.3}$) are surrounded by innermost coronas of fibrous
263 orthopyroxene followed by a $\sim 50 \mu\text{m}$ wide poikiloblastic corona of garnet
264 ($\text{Alm}_{63.3}\text{Grs}_{19.8}\text{Py}_{14.9}$, Fig. 3A) and fibrous amphibole (Hornblende) at the contact with
265 plagioclase. The grain size of olivine cores is variable, generally of the order of a few
266 hundred micrometers. Olivine grains exhibit cleavage planes in different orientations.
267 While orthopyroxene coronas seem to have a constant width around olivine grains,
268 garnet coronas vary in thickness. These microfabrics are similar to the ones previously
269 described by Mørk, (1985), Krabbendam *et al.*, (2000), Lund & Austrheim (2003),
270 Müller (2013). According to Mørk (1985), the coronas between olivine and plagioclase
271 form through reaction: $\text{Ol} + \text{Pl} (\text{An}) + \text{Cpx} + \text{H}_2\text{O} \Rightarrow \text{Opx} + \text{Grt} + \text{Am} + \text{Pl} (\text{Ab})$. It is
272 unclear whether these coronas formed as products of synkinematic fluid infiltration
273 (Krabbendam *et al.*, 2000; Lund & Austrheim, 2003), or as results of late-magmatic
274 processes (Mørk, 1986). However, we speculate that amphibole is indicative of the
275 external influx of hydrous fluids upon shear zone formation, as shown later by CPO of
276 hornblende in the high strain zone (Austrheim, 1987; Austrheim, *et al.*, 1997; Engvik *et*
277 *al.*, 2000; Labrousse *et al.*, 2004; Putnis & Austrheim, 2010).

278 Truly eclogite-facies assemblages are only observed at fluid pathways terminations or
279 where fluid availability and/or deformation enhanced the size of the reacted domains
280 allowing for sufficient material transport and thus bulk equilibration resulting in the
281 formation of an omphacite-garnet assemblage (Fig. 4) (Lund & Austrheim, 2003; John

282 *et al.*, 2009; Putnis & Austrheim, 2010). However, the overall dominance of amphibole
283 over omphacite in the samples indicates that the chemical equilibrium of the system was
284 local, and in favour of garnet-amphibole assemblage, instead of garnet and omphacite.
285 In those cases where plagioclase reacted in rather isochemical systems, the high-
286 pressure assemblage is dominated by the Ab-Czo symplectites \pm amphibole \pm garnet
287 (Lund & Austrheim, 2003; John *et al.*, 2009).

288

289 In the *intermediate strain domain* (sample #061751), the texture changes (Fig. 3C-3D).
290 Olivine grains are pseudomorphically replaced by orthopyroxene and orthoamphibole
291 intergrowth, which is surrounded by a thin (a few μm wide) rim of omphacite (Fig. 4B,
292 see also Lund & Austrheim, 2003). Mørk (1985) interprets the discontinuous growth of
293 thin omphacite layers between orthopyroxene and garnet coronas to have formed
294 through: $(\text{Ol}) + \text{Grt} + \text{Opx} + \text{Am} + \text{Pl} \Rightarrow \text{Omp} + \text{Spin}$. However, the fact that, in contrast
295 to Mørk (1985), we did not observe spinel inclusions, points to this reaction being
296 incomplete in our samples, and mineral growth limited by material supply (see also
297 Mørk, 1985; John *et al.*, 2009). Clinopyroxene grains in this domain appear less regular
298 and altered by cloudy patches of Fe-Ti oxides as a result of destabilization through the
299 reaction: $\text{Cpx} (\text{Aug}) + \text{Na} \Rightarrow \text{Na-Aug} + \text{Fe-Ti oxides}$, in which Na-Aug constitutes a
300 second generation of more altered clinopyroxene with increase Jd-component but
301 reduced Ti and Fe contents (Cpx_2) (Mørk, 1985). Garnet and amphibole are still present,
302 but they do not form clear corona structures anymore (see also Fig. 3B). The 3-
303 dimensional distribution of garnets still resemble coronas where decaying olivine grains
304 are more completely replaced by orthopyroxene, but generally garnet grains develop

305 euhedral crystals and form disconnected and more elongated aggregates (Fig. 7B).
306 Towards the shear zone, all plagioclase is replaced by clinozoisite and albite symplectites
307 through the reaction (Fig. 4B, C): $Pl(An) + H_2O \Rightarrow Czo + Ab$ symplectites (Wayte *et al.*,
308 1989; Lund & Austrheim, 2003; John *et al.*, 2009; Müller, 2013) (Fig. 4). The Czo+Ab
309 symplectites are preserved without evidence of any later overprint, and we consider them
310 to have formed as prograde replacement of plagioclase in a fluid-mediated system,
311 indicating a metastable prograde reaction (Wayte *et al.*, 1989). Therefore, in the presence
312 of amphibole, omphacite associated with these delicate symplectite textures indicates a
313 prograde conversion of the gabbro to an eclogite in which fluid infiltration was
314 synkinematic and linked to the progress of reaction and deformation (Fig. 4B).

315

316 In the *most deformed sample* (#0618), all mineral phases are aligned parallel to a
317 mylonitic foliation. The foliation is defined by a compositional layering of elongated
318 orthopyroxene-amphibole symplectites, and garnet, forming isolated elongated clusters
319 >100 μm wide and several hundred μm long (Fig. 3E-3F). Some of garnet grains still
320 exhibit faceted crystals (Fig. 7C).

321 Omphacite is present at the margins of relict magmatic clinopyroxene grains and of
322 orthopyroxene-amphibole symplectites (Fig. 4C).

323

324 **Garnet chemical composition**

325 Garnet compositions in the three samples were measured using electron microprobe
326 analyses in order to confirm the chemical evolution of garnet with respect to the
327 deformation history (Fig. 5, 6; Tab. S3). With increasing deformation, garnet

328 compositions become more Alm-rich (Fig. 5), an expected trend for a gabbro that is
329 gradually equilibrating under eclogite-facies P-T conditions. Within the low-strain
330 domain, high CaO concentrations (X_{Grs}) are represented by garnet in the proximity of
331 Ca-rich phases (e.g. plagioclase). In the high strain domain the compositional maps
332 show that some garnet displays CaO zoning (5-12 wt. %) and zoning pattern similar to
333 those observed in low strain domain (Fig. 6). It seems that locally these garnets
334 represent collapsed former coronas (a', b' in Fig. 6C).
335 Furthermore, fine-grained garnets (Fig. 6C to the left) represent highly fragmented and
336 collapsed former coronas.

337

338 **4D spatial evolution of garnet grains**

339 A subvolume with dimensions of 600^3 voxels ($\sim 0.5 \text{ mm}^3$) was extracted from each of the
340 three microtomographic datasets to visualize the 3-dimensional distribution of garnet
341 (Fig. 7). In the subsequent label analysis, garnet distribution was evaluated and
342 quantified in the original, statistically representative 7 mm^3 subvolumes (Fig. 3, 9). In the
343 label analysis, we considered all garnet clusters that consist of face-connected voxels and
344 are larger than 125 cubic voxels ($\sim 275 \mu\text{m}^3$). This allowed us to relate the following
345 observations to the 3-dimensional petrography presented above.

346 The volumetric quantification of the segmented garnet data shows that the garnet volume
347 increases into the shear zone, from 6 % (± 2.5 %) in the low-strain sample, to 11 % (± 3
348 %) in the intermediate strain sample, and 20 % (± 4 %) in the high-strain sample.

349

350 The visualisation confirms that in the *low strain domain*, garnet forms voluminous

351 interconnected coronas around orthopyroxene and decaying olivine grains (Fig. 7). It also
352 becomes apparent that different olivine cores have garnet rims with different thicknesses.
353 Measurements of garnet corona thicknesses around five different olivine grains show an
354 average thickness of 60 μm with standard deviations that vary from 10 to 35 μm in the
355 most complex coronas. Where two olivine grains neighbour each other, garnet coronas
356 become almost twice as thick. There seems to be no correlation between the thickness of
357 the garnet- and the amphibole rims, which should have evolved in unison (Mørk, 1985;
358 Mørk, 1986; Johnson & Carlson, 1990). Despite their considerable spatial extent, garnet
359 coronas do not enclose olivine grains entirely, which leaves dormant reactants in direct
360 contact with each other (Figure S9). The resulting baseball-glove shaped domains also do
361 not show any preferential spatial orientation with respect to the kinematic framework of
362 the shear zone (Figure S9). The total garnet volume in the analysed subvolume is
363 accommodated by 1116 garnet voxel clusters (Table S3).

364 The label analysis shows that the garnet population is dominated by one large
365 interconnected garnet voxel cluster that percolates across the entire subvolume (Fig. 9A).
366 This cluster accounts for 83 % of the entire garnet volume in the sample (Fig. 8A, B).
367 Garnet voxel clusters between $2.2 \cdot 10^6$ and $3.08 \cdot 10^7 \mu\text{m}^3$ account for 11%, whereas voxel
368 clusters $< 2.2 \cdot 10^6 \mu\text{m}^3$ do not contribute substantially to the total garnet volume (Fig.
369 8B).

370 We submitted the segmented data to a numerical volume erosion process to learn more
371 about the spatial arrangement of garnet (see supplementary data for details on the
372 procedure and Table S4 for the results). Garnet interconnectivity persists through the
373 volume erosion, which evidences how tightly individual garnets grains are linked in the

374 coronas (see suppl. material for details). In the eroded data, the garnet volume forms
375 2796 voxel clusters (Table S4). The largest interconnected voxel cluster dramatically
376 decreases in volume from $4 \cdot 10^8 \mu\text{m}^3$ to $10^8 \mu\text{m}^3$, now accounting for only 35 % of the
377 total volume. The eight largest interconnected voxel clusters ($> 2.2 \cdot 10^6 \mu\text{m}^3$) account for
378 89 % of the total garnet volume as seen in the cumulative frequency diagram (Fig. 8B).
379 The erosion process also leads to a substantial increase in frequency for sizes smaller
380 than 10^4 cubic μm^3 (Fig. 8A), which is in contrast to the intermediate and high-strain
381 datasets.

382

383 The visualisation of garnet in the *intermediate strain domain* shows that the larger garnet
384 voxel clusters form complexly-shaped rims around orthopyroxene aggregates that likely
385 have their origin in former coronas (Fig. 9B). In this sample, the garnet volume is made
386 up of 12068 garnet voxel clusters. This almost ten-fold increase over the low strain
387 sample is essentially being accommodated by the smallest ($< 10^5 \mu\text{m}^3$) and largest ($>$
388 $6 \cdot 10^8 \mu\text{m}^3$) voxel cluster size fractions (Table S3). A similar number of voxel clusters in
389 the size region of $10^5 \mu\text{m}^3$ was detected, whilst a particularly large number of voxel
390 clusters with volumes between 10^3 and $10^4 \mu\text{m}^3$ were found. Again, the largest 10 voxel
391 clusters ($> 2.2 \cdot 10^6 \mu\text{m}^3$) account for over 90 % of the total garnet volume. The largest
392 interconnected voxel cluster, which is larger than in the low-strain sample (from $4 \cdot 10^8$
393 μm^3 to $6.5 \cdot 10^8 \mu\text{m}^3$) develops through the subvolume and accounts for 80 % of the total
394 garnet volume. The garnet voxel clusters in the range of $2.6 \cdot 10^5$ to $4 \cdot 10^6 \mu\text{m}^3$ are often
395 formed by isolated, euhedral and potentially newly formed garnet grains (Fig. 7, 9B; see
396 Discussion). Voxel clusters smaller than $10^5 \mu\text{m}^3$ are arranged in patchy clouds

397 surrounding bigger interconnected voxel clusters.

398 In the numerically eroded data, the number of garnet voxel cluster reduces to 4995. Since
399 a numerical erosion cannot lead to voxel cluster coalescence, this decrease reflects a
400 sensitivity to the disappearance of volumetrically small voxel clusters in the procedure
401 (Fig. 8C, Table S4). In the erosion process, the largest voxel cluster breaks apart to form
402 two smaller voxel clusters, which together account for 70 % of total garnet volume (Fig.
403 8D, Fig. S10).

404

405 The visualization of the microtomographic data shows that in the most deformed sample,
406 the garnet voxel clusters define a mylonitic foliation. In this subvolume, garnets
407 contribute to a deformation microfabric; the garnet voxel clusters define the
408 compositional layering observed in the SEM analysis (Fig. 9C). Additional analyses that
409 we conducted (using the software package Quant3D, Ketcham & Ryan (2004)) revealed
410 that most of the garnet voxel clusters in this sample have an oblate shape (Fig. S11).
411 Garnet in the subvolume is organized in 9297 voxel clusters (Table S3). A total of 46
412 voxel clusters have a volume larger than $2.2 \cdot 10^6 \mu\text{m}^3$, and they account for 86 % of the
413 total garnet volume (Fig. 8F). The absolute frequency-size distribution is self-similar,
414 with no major local variations between the size classes. This trend is confirmed by the
415 cumulative plot (Fig. 8F), which shows that all size classes contribute progressively
416 towards the total garnet volume, and is in contrast to the other two samples.

417 Numerical erosion reduces the number of garnet voxel clusters to 8014, of which 62 are
418 larger than $2.2 \cdot 10^6 \mu\text{m}^3$ and accommodate 81 % of garnet total volume (Table S4). The
419 reduction in total voxel cluster number is accommodated by all size fractions, which

420 indicates that the voxel clusters have shapes that withstand a numerical erosion process
421 (Fig. 8E, F).

422 **EBSD analysis: Misorientation of garnet grains in the shear zone**

423 We analysed predominantly garnet in the three samples using EBSD to investigate the
424 dominant deformation mechanisms that contributed towards the evolution of the
425 microfabric in garnets.

426 Garnet and orthopyroxene in the *low strain sample* exhibit frequent low angle
427 boundaries (misorientation between 3° and 10°). The phase map of a coronitic domain
428 around magmatic olivine shows that orthopyroxene and hornblende grows as fibrous
429 crystals: the long axis of orthopyroxene and hornblende are perpendicular to the
430 reaction interface (Fig. S3A). In the case of hornblende, the elongation is parallel to the
431 <001> axis (Fig. S4F). The inverse pole figure map (IPF) of garnet, shown with respect
432 to the E-W direction (i.e. approximately equivalent to the normal to the reaction
433 interface and parallel to the elongation direction of hornblende) (Fig. 10A), highlights
434 the presence of low-angle boundaries, which correspond, in the local misorientation
435 map (Fig. S3C), to internal misorientation zones with up to 9° of misorientation in
436 garnet. A misorientation profile across them does not show any progressive distortion
437 of the crystal lattice, but rather a sudden jump in misorientation (Fig. 10B). The
438 average local internal misorientation of grains is very low, on the order of 1°, i.e. within
439 the error of measurement. The misorientation axes for misorientation angles of 3-10°
440 do not show clear maxima in crystal coordinates (Fig. 10C). Pole figures show that
441 coronitic garnet grains are not elongated parallel to specific crystallographic directions
442 (Fig. S3B, S4E).

443 In the *intermediate strain sample* the spatial density of low angle boundaries is highly
444 variable. A local misorientation map shows that the interiors of garnet grains are
445 virtually undeformed (average local misorientation on the order of 1°), and that there
446 are bands with high misorientation up to 9° (Fig. 10D). A misorientation profile across
447 one of the bands shows a rather abrupt misorientation jump (of up to 8°) (Figure 10E).
448 Similar to the low strain domain, the misorientation axes for misorientation angles of 3-
449 10° do not show clear maxima in crystal coordinates (Figure 10F). The IPF map and
450 the associated pole figures show a weak preferred orientation of garnet, with voxel
451 clusters of grains preferentially oriented with their $\langle 111 \rangle$ parallel to the stretching
452 lineation of the shear zone (Fig. S5A, S5E). The IPF map shows that garnet grains
453 range in size between 10-20 μm and 200 μm .

454 In the *high strain sample*, the density of low angle boundaries in garnet is very low, and
455 they are typically present only in grains larger than 50 μm (Figure 10G). The phase
456 map indicates that individual garnet grains range in size from ca. 10 μm to ca. 150-200
457 μm and are dispersed in a matrix of hornblende, orthopyroxene and minor biotite (Fig.
458 S6A). Garnet grains are internally strain-free (average local misorientation is $< 1^\circ$), and
459 again, there is no progressive accumulation of misorientation towards the few internal
460 high misorientation bands (as indicated by the local misorientation map in Fig. S6B).
461 Less frequently, a progressive accumulation of lattice distortion (of up to 4°) towards
462 the low angle boundaries was observed (Fig. 10H). The misorientation axes for
463 misorientation angles of 3- 10° do not show clear maxima in crystal coordinates (Fig.
464 10I). Pole figures of garnet show only weak maxima of $\langle 100 \rangle$, one of which is oriented
465 subparallel to the stretching lineation (Fig. S6C, S7A, S7B). Neighbouring grains are

466 typically characterized by large misorientations ($>30^\circ$, Fig. S6F).

467 In contrast, hornblende shows a crystal preferred orientation (CPO) with the c-axis
468 oriented subparallel to the stretching lineation. This CPO of hornblende has been
469 commonly observed in lower crustal shear zones where hornblende grew
470 synkinematically to deformation (Berger & Stünitz, 1996; Getsinger & Hirth, 2014;
471 Menegon *et al.*, 2015).

472 We emphasize that, combined, the crystallographic data point to a negligible
473 contribution of crystal plasticity to garnet deformation.

474 **DISCUSSION**

475 **Strain-dependent evolution of garnet microfabrics in the Kråkeneset shear zone**

476 The observations reported above allow to draw a detailed picture of the synkinematic
477 evolution of garnet in this deep-crustal shear zone. Our microtomographic data indicate
478 that, across the studied shear zone margin, from low to high strain, garnets evolve from
479 a highly interconnected coronitic texture to a tectonic microfabric, where they are
480 organized in oblate aggregates and define the foliation of the shear zone (Fig. 9C).
481 Simultaneously, the garnet volume in the rocks more than triples. Based on chemical
482 analyses, which revealed a partial local equilibration of garnets grains at eclogite facies
483 (Fe-rich), we interpret the oblate sheared aggregates as having formed by the
484 progressive, synkinematic disintegration and rearrangement of coronas in combination
485 with the simultaneous nucleation and coalescence of garnets grains at similar P, T, X
486 metamorphic conditions (Fig. 11).

487 We argue that the garnet coronas originally formed as the high-pressure reaction

488 products of a prograde metastable reaction between olivine and plagioclase by the
489 coalescence of nuclei. As strain localises in the shear zone, these garnet coronas are
490 broken apart and start to disintegrate (Fig. 11-1, 11-2). At this stage, the garnet voxel
491 clusters do not reflect a deformation microfabric yet, and the largest garnet cluster is
492 still interconnected through the entire sample forming complexly-shaped rims around
493 orthopyroxene porphyroclasts that have replaced olivine. New garnet grains nucleate in
494 between these large voxel clusters but are still small at this stage, while existing garnet
495 grains are overgrown and increase in volume. At the highest level of strain, the former
496 garnet coronas have been deformed and re-arranged by granular flow in a ductively
497 deforming matrix, leading to a mylonitic deformation microfabrics defined by oblate
498 garnet voxel clusters (Fig. 3, 9 C).

499 *Where does all the garnet go?*

500 The results of the label analysis, and in particular the evolution of different size classes
501 of garnet voxel clusters, reveal how the volumetric increase in garnet is accommodated
502 and what processes affect the garnet population across the shear zone margin. The
503 overall increase in the number of garnet voxel clusters into the shear zone reflects the
504 synkinematic formation of a well-dispersed garnet population (Fig. 8). This is achieved
505 by the coeval activity of three processes, the fragmentation and breakup of garnet
506 coronas, the formation of overgrowth rims, and the nucleation of new garnet crystals
507 (Fig. 11):

- 508 1. The increase in the number of garnet voxel clusters, particularly the large ones,
509 with increasing strain clearly reflects a reduction of garnet interconnectivity. The

510 largest voxel cluster in the low and intermediate strain domain accounts for ~80
511 % of the overall garnet volume, whereas a similar volume proportion is
512 accommodated by 46 voxel clusters ($> 2.2 \cdot 10^6 \mu\text{m}^3$) in the most deformed
513 sample.

514 2. The transition from the low strain- to the intermediate strain domain sees a
515 complete reorganisation in the population of the smallest garnet voxel clusters
516 (Fig. 8C). Voxel clusters $\leq 4.1 \cdot 10^3 \mu\text{m}^3$ increase in number from 698 to 11239
517 (Table S3). These clusters occur dispersed in between the larger clusters, without
518 any obvious textural link. As the total amount of garnet volume increases, they
519 cannot be fragments of initial coronitic garnet, therefore we argue that this
520 population of smallest voxel clusters is the product of nucleation and speculate
521 that these garnets may evidence pervasive fluid infiltration (see following
522 section).

523 3. In contrast, we infer the increase in the number of intermediate-sized voxel
524 clusters with volumes between $2.6 \cdot 10^5$ and $4 \cdot 10^6 \mu\text{m}^3$, which is particularly
525 apparent in the intermediate strain domain, to be related to overgrowth. The 3-
526 dimensional visualisation shows that garnet voxel clusters have euhedral or semi-
527 euhedral shapes, which is congruent with this mechanism (Padrón-Navarta *et al.*,
528 2008).

529 *What the morphological operator “Erosion” reveals about the garnet distribution*

530 The frequency diagrams reveal that the number of voxel clusters does increase as a
531 response to erosion in the *low strain domain* for smaller voxel cluster sizes ($< 10^4 \mu\text{m}^3$,

532 Fig. 8A, B) and in the *intermediate strain domain* for the largest interconnected cluster
533 (Fig. S9). This indicates that a substantial number of voxel clusters exhibit cross-
534 sectional diameters short enough to respond to a single erosion step. By acting as
535 predetermined breaking points, these weak bridges become crucial in the disintegration
536 of the garnet coronas as the rock transitions to the intermediate strain microfabrics (see
537 also Fig. 11A). We infer that the larger proportion of the garnet volume that is
538 accommodated by smaller clusters in the eroded dataset (Fig. 8B) is a consequence of
539 this break-up.

540 In the *intermediate strain domain*, the absolute frequency of voxel clusters $<5 \cdot 10^4 \mu\text{m}^3$
541 decreases significantly as a consequence of morphological erosion (Figure 8C, Tables
542 S3, S4). These are the voxel clusters that make up the patchy clouds in between the
543 larger garnet aggregates. Many of these small clusters are apparently susceptible to
544 annihilation in a single erosion step, which points towards a significant deviation from
545 sphericity in this voxel cluster population.

546 In the *high strain domain*, the garnet voxel clusters retain their self-similar frequency-
547 size distribution through the morphological erosion process in the high strain domain
548 (Fig. 8E, F). However, the changes to the frequency of voxel clusters in the different
549 bins seem to reflect a slight decrease in the fractal dimension (Fig. 8E, F). A new
550 population of voxel clusters with volumes $<10^3 \mu\text{m}^3$ is generated from larger clusters,
551 and the largest voxel cluster halves in size (from 1.1 to $2.2 \cdot 10^8 \mu\text{m}^3$).

552 *Micromechanisms involved*

553 Our EBSD data indicate that the mechanism by which the garnet coronas are

554 disintegrated does not involve crystal plasticity by means of dislocation activity. Whilst
555 garnet was shown to deform by dislocation creep at upper amphibolite to granulite
556 facies metamorphic conditions (Ji & Martignole, 1994; Ji & Martignole, 1996), this was
557 not the case in the sampled shear zone. Misorientation maps and profiles indicate that
558 neighbouring garnet domains show only limited and relative rotations (Fig. 10). These
559 motions are accommodated by narrow, distinct bands that correspond to low-angle
560 boundaries; the grains themselves show very little internal deformation. The bands
561 coincide with sudden jumps in misorientations, testifying that they are not subgrains or
562 dislocation walls (Fig. 10B, E, H, e.g. Viegas *et al.*, (2016)). Furthermore, the plots of
563 misorientation axis in crystal coordinates show that the low-angle boundaries are not
564 tied to the host crystallography but rather show a highly dispersed distribution (Fig.
565 10C, F, I). Based on these arguments, we suggest that the low angle boundaries in the
566 low strain domain are growth features, and probably related to an early stage of
567 coalescence of nuclei. The overall lack of chemical differences amongst the newly
568 formed garnets and their seeds would be congruent with a close initial nucleation
569 spacing of garnets seeds, similar to the observations reported in Whitney & Seaton
570 (2010).

571 On the basis of an almost complete lack of evidence for crystal plasticity, we argue that
572 the progressive disintegration and rearrangement of garnet coronas was accommodated
573 by microfracturing and passive granular flow of garnets in a viscously deforming
574 matrix (cfr. Trepmann & Stöckhert, 2002). This view is supported by experimental
575 data on garnet rheology (Voegelé *et al.*, 1998; Wang & Ji, 1999; Zhang & Green,
576 2007), which establish the possibility of brittle garnet behaviour at the inferred

577 metamorphic conditions.

578 Microfracturing and passive granular flow of garnet grains could have been assisted by
579 a fluid phase (Den Brok & Kruhl, 1996; Storey & Prior, 2005; Smit *et al.*, 2011). As it
580 is well established, fluid infiltration played a critical role in triggering eclogitization and
581 strain localisation in dry and ridged precursor rocks (Austrheim, 1987; Austrheim *et al.*,
582 1997; Engvik *et al.*, 2000; John & Schenk, 2003; Miller *et al.*, 2007; Labrousse *et al.*,
583 2010; Putnis & John, 2010). The presence of fluids in the system is evident from the
584 hydrous high-pressure mineral assemblage in the shear zone. However, we found no
585 clear evidence for fluid-assisted deformation mechanisms, such as intergranular
586 pressure solution (e. g. Azor *et al.*, (1997), Smit *et al.*, (2011)), diffusion creep (Den
587 Brok & Kruhl, 1996; Storey & Prior, 2005) or grain-boundary sliding and diffusion
588 creep (Terry & Heidelbach, 2004) to have dominated garnet deformation. However, we
589 do interpret garnet to trace fluid migration pathways to some extent (see following
590 subsection).

591 **Implications for fluid flow, mass- and element transport**

592 The 3-dimensional spatial arrangement of garnets is not only the results of deformation,
593 but, in the low-strain domain, it also reflects mass transport between plagioclase and
594 olivine grains during their reaction (Austrheim, 1987; Lund & Austrheim, 2003;
595 Labrousse *et al.*, 2010; Putnis & John, 2010). Our observations show that garnet
596 coronas are highly interconnected throughout the low strain samples (Fig. 9A) and thus,
597 fluid transport must have happened on a trans-granular scale. However, the coronas do
598 not encapsulate and isolate olivine grains from plagioclase, as commonly thought when
599 observing coronas in two dimensions (Mørk, 1986; Johnson & Carlson, 1990; Keller *et*

600 *al.*, 2004). Where the coronas did not form, this happened despite the reactants being in
601 direct contact with each other, and obviously the reaction was subdued. We argue that
602 garnet formed where fluids facilitated the reaction and we therefore link the
603 heterogeneously distributed reaction products to fossilized fluid pathways.

604 In the intermediate strain domain, syn-reactive fluid-infiltration is testified by the
605 presence of cloudy patches of small garnets, along with the observation that water-
606 bearing minerals are concentrated in the shear zone centre. The abundance of these
607 minerals decreases along the lateral strain gradient away from the shear zone and are
608 absent where the gabbro is undeformed (John *et al.*, 2009). These observations are
609 congruent with those reported in earlier studies by Austrheim (1987), Wayte *et al.*,
610 (1989), Engvik *et al.* (2001), John & Schenk (2003), and Putnis & John (2010). These
611 studies established that eclogitization in the lower crust can be triggered by an external
612 input of fluids and facilitated by the presence of preferential pathways, such as
613 fractures, which controlled element mobility and defined reaction pathways. However,
614 our data also reveal that there is no systematic arrangement of the garnet coronas with
615 respect to a kinematic framework defined by the deformation microfabrics. It therefore
616 remains unclear what controlled preferential fluid pathways on the grain scale.

617 In an extension to this argument, we claim that in the high-strain samples, the oblate
618 garnet aggregates also should have channelized synkinematic fluid flow (see also
619 Austrheim (1987)). We interpret the aligned, oblate garnet aggregates, defining the
620 foliation, as having acted as fluid barriers and thereby direct synkinematic fluid flow in
621 the shear zone.

622 **CONCLUSIONS**

623 4-dimensional quantitative x-ray micro-tomography proved to be an excellent approach
624 to investigate the evolution of metamorphic reaction microfabrics in three dimensions.
625 In combination with established microanalytical methods, it allowed a comprehensive
626 characterization of the processes affecting the evolution of garnet during eclogitization
627 in a shear zone in the Western Gneiss Region, Norway. In particular, we were able to:

628 • Capture and monitor the spatial distribution of mineral phases in four dimensions:
629 the x-ray absorption contrast between individual mineral phases in our micro-
630 tomographic data is sufficient to allow the same petrographic observations than in light-
631 and electron microscopy, but extended to the 3rd and, where strain is considered a proxy
632 for time, 4th dimension.

633 • Quantify the change in garnet volume across the strain gradient: with increasing
634 deformation, the garnet volume increases from about 6 % to 20 %.

635 • Determine the interconnectivity of garnet grains as a function of strain, with
636 implication for mass transport, syn-reactive fluid flow and rock strength.

637 • Identify the 3-dimensional geometry of garnet coronas, find that they do not
638 encapsulate olivine grains and have no apparent preferred alignment. We interpret the
639 garnet coronas to outline fossilized fluid pathways.

640 • Identify the mechanisms by which garnet is reorganised during shearing:
641 microfracturing, nucleation and overgrowth. We interpret these observations as pointing
642 to a mechanical disintegration of garnet coronas during strain localisation and their

643 rearrangement into individual sheared isolated voxel clusters, with the ongoing
644 nucleation of new garnets and overgrowth while the rock was deforming. There is no
645 evidence for crystal plastic deformation, all garnets are internally strain free and in the
646 more deformed samples they show a very weak crystal preferred orientation.

647 Our study clearly shows what 3- or 4-dimensional datasets from reaction micro-fabrics
648 can add to the understanding of metamorphic processes. We reiterate that a 2-
649 dimensional analysis of deformation microfabrics can lead to incorrect petrological and
650 structural interpretations, and it does omit information that only become available when
651 rocks are investigated in three dimensions.

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868 **SUPPORTING INFORMATION**

869 **Appendix S1 Ground-truthing: Correlating synchrotron x-ray micro-tomography**
870 **data with chemical compositions**

871 **Appendix S2 Segmentation of micro-tomographic data**

872 **Appendix S3 4D evolution of grain shapes**

873 **Fig. S1** Grey value histograms calculated from three μ CT datasets. The calculated
874 absorption coefficients (μ) for the mineral phases correlate with grey scale values
875 measured on the microtomographic data. The histograms reflect the metamorphic
876 reactions during strain localization.

877 **Fig. S2** Schematic workflow used to analyse the microtomographic data.

878 **Fig. S3** EBSD results of low strain domain (sample 066B2). On EBSD-derived maps,
879 high-angle boundaries (grain boundaries, misorientation $> 10^\circ$) and low-angle boundaries
880 (subgrain boundaries, misorientation $> 3^\circ$ and $< 10^\circ$) were indicated with black and
881 fuchsia lines, respectively. A) Phase map: Olivine (yellow), Plagioclase (white),
882 Orthopyroxene (blue), Garnet (red), Hornblende (green). Red lines represent twinning
883 boundaries in plagioclase. B) Inverse Pole Figure of Garnet in relation to the stretching
884 lineation in the shear zone. Legend on bottom left corner. C) Local Misorientation Map,
885 and legend, representing local misorientations from 0 (blue) to 9 degrees misorientation
886 (red). The arrow indicates the average local internal misorientation. D) Misorientation
887 profile A-A', location shown in figure C.

888 **Fig. S4** EBSD results of low strain domain (sample 066B2). E) Pole figures of garnet. F)
889 Pole figure of hornblende. G) Misorientation axis in crystal coordinates for low angle

890 boundaries (3-10°).

891 **Fig. S5** EBSD results of intermediate strain domain (sample 0617). A) Inverse Pole
892 Figure of garnet. Legend as in Fig. S3B. B) Local Misorientation Map, and legend
893 representing local misorientations from 0 (blue) to 9 degrees misorientation (red). The
894 arrow indicates the average local internal misorientation. C) Misorientation profile A-A',
895 location is shown in figure A. D) Misorientation profile B-B', location shown in figure
896 A. E) Pole figures of garnet. The trace of the shear foliation is oriented NW-SE, pole
897 figures are oriented with the trace of the mylonitic foliation parallel to the diameter (E-
898 W). F) Misorientation axis of low angle boundaries (3-10°) in crystal coordinates.

899 **Fig. S6** EBSD results of high strain domain (sample 0618). A) Phase map: Grt (red), Am
900 (green), Opx (blue), Bt (yellow). B) Local Misorientation Map, and legend representing
901 local misorientations from 0 (blue) to 9 degrees misorientation (red). The arrow indicates
902 the average local internal misorientation. C) Inverse Pole Figure of garnet. Legend as in
903 Fig. S3B. D) Misorientation profile A-A', location is shown in figure C. E)
904 Misorientation profile B-B', location shown in figure C. F) Misorientation profile C-C',
905 location shown in figure C.

906 **Fig. S7** EBSD results of high strain domain (sample 0618). A) Pole figures of garnet.
907 The trace of the shear foliation is oriented NNE-SSW, pole figures are oriented with the
908 trace of the mylonitic foliation parallel to the diameter (E-W). B) Pole figures of
909 hornblende. C) Misorientation axis of low angle boundaries (3-10°) in crystal
910 coordinates.

911 **Fig. S8** The image shows the results of Statistical Region Merging technique for

912 increasing Q. Scale as in image A. A) Original data. B) SRM Q=2. C) SRM Q=10. D)
913 SRM Q=25: note that the image is more detailed. E, F, G) Histograms relative to the
914 three different SRM parameters.

915 **Fig. S9** Outputs of segmentation for olivine (green) and garnet (blue) grains, in the low
916 strain domain (different viewing angles). The red arrows indicate olivine grains that are
917 not completely enclosed by garnet coronas.

918 **Fig. S10** Label analysis of intermediate strain domain after erosion. The large
919 interconnected voxel cluster is now divided in disconnected subvoxel clusters. Long
920 side 2630 μm .

921 **Fig. S11** Quant3D explained. The tomographic data are first segmented to extrapolate
922 the material of interest. Star points are placed within the segmented material: the
923 distance of each star points to the next material boundary are calculated in many
924 orientations and normalised. Simplified from Ketcham (2005).

925 **Fig. S12** Results of Quant3D analysis on eroded data, from low strain (A) to high strain
926 (C). With increasing deformation, garnet grains evolve from isodiametric shapes to
927 more progressively discoid shapes as a results of the deformation.

928 **Table S1** Electron microprobe chemical compositions of oxides in garnets, used to
929 calculate the x-ray absorption coefficients.

930 **Table S2** Representative garnet structural formulae for the low (#066B2) and high
931 (#0618) strain domain obtained from the microprobe analyses at the University of
932 Münster.

933 **Table S3** Frequency distribution data for non-eroded data. The first column of each
934 dataset refers to absolute frequency, the second one to the cumulative frequency relative
935 to the total amount of garnet in each sample.

936 **Table S4** Frequency distribution data for eroded data. Bins refer to cubic micrometres.
937 The first column of each dataset refers to absolute frequency, the second one to the
938 cumulative frequency relative to the total amount of garnet in each sample.

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942 **FIGURE CAPTIONS**

943 **Fig. 1** The illustration shows the approximate original position (circles) of thin sections
944 in the hand specimen, and the positions of tomographic data in the thin sections which
945 are indicated by the red squares. 3D volume renderings, derived from tomographic data
946 from the three samples, are shown in the bottom part. Slice is cut parallel to the fabric
947 attractor. Axis for the kinematic frame (X, Y, Z) are indicated in the microtomographic
948 data.

949 **Fig. 2** Microtomographic datasets: A) low strain, B) intermediate strain, and C) high
950 strain. Figure A exhibits minor artefacts (horizontal stripes) that do not affect the
951 analyses. Mineral phases and features are recognizable from the corresponding SEM
952 images (Fig. 3). The images represent the XZ plane and are parallel to the thin sections.

953 **Fig. 3** BSE images of Krakeneset samples and corresponding microtomographic
954 datasets, from low to high strain domain respectively: A) Sample 066B2 (Low strain)-
955 Olivine grains are surrounded by complex coronas of orthopyroxene, garnet and
956 amphibole. B) 3-dimensional dataset of low strain domain: high-pressure amphibole-
957 garnet coronas surround olivine grains (dimensions 1503 x 1196 x 1831 cubic voxels).
958 Note the variable thickness of amphibole. C) Sample 0617 (Intermediate Strain)- In the
959 intermediate strain domain, olivine cores are replaced by orthopyroxene, while garnet
960 and amphibole are no more part of the corona structures. D) Corresponding
961 microtomographic dataset (dimensions 1322 x 1219 x 2023 cubic voxels). E) Sample
962 0618 (High Strain)- The high strain domain is characterized by a compositional layering
963 of elongated garnet and plagioclase versus orthopyroxene and amphibole rich layers. F)

964 Microtomographic dataset of the high strain domain (dimensions 1313 x 1234 x 1980
965 cubic voxels): note garnet grains behaving as rigid objects in a more ductile matrix of
966 orthopyroxene and amphibole.

967 **Fig. 4** A) Optical microscope image illustrating the mineral phases and microstructures
968 present in the more deformed samples. B) BSE image showing old olivine cores now
969 replaced by orthopyroxene-amphibole symplectites. Relict cores of magmatic
970 clinopyroxene are present (Mag_Cpx “relict”), and are surrounded by a thin rim of
971 omphacite (Omp), which is present also between garnet and orthopyroxene-amphibole
972 symplectites (“Opx-Amp Symp”). C) Symplectites of albite-clinozoisite are replacing the
973 plagioclase; omphacite surrounds relict magmatic clinopyroxene (Mag_Cpx “relict”)
974 and orthopyroxene-amphibole symplectites.

975 **Fig. 5** Grs-Alm-Py plot showing garnet compositions from EMPA analyses, as single
976 measurements across different grains. Filled symbols represent compositions closer to
977 the plagioclase source. Empty symbols represent compositions closer to Fe-Mg-rich
978 phases. End-members values are presented in the graph by the large symbols. With
979 increasing deformation, garnet compositions become more Alm-rich, a trend expected
980 for a gabbro that is equilibrating under P-T-t conditions of eclogite facies. In Tab. S2,
981 representative structural formulae are reported for the three samples.

982 **Fig. 6** Compositional maps for CaO and MgO for the low (A-C) and high (B-D) strain
983 domains, obtained using XMapTools v. 2.3.1 (Lanari *et al.*, 2014). CaO and MgO do
984 have the same compositional zoning (4-10%) in the most deformed sample. C) Many
985 garnets in the high strain domain have low CaO, reflecting an equilibration towards Alm-
986 rich compositions. Nevertheless, some grain do have a higher content in CaO (~10%)

987 (a') and MgO (~11%) (b'): we interpret this to results from coalescence (a, b) and
988 subsequent disintegration of individual zoned coronas. Further left in Figure C, garnets
989 are fragmented and forming a fine-grained matrix, indicating collapse of an old pre-
990 existing corona.

991 **Fig. 7** The figures illustrate the results of segmentation of garnet from the
992 microtomographic data. Top: cropped volumes of original datasets (~0.5 mm³); bottom:
993 garnets rendered in purple. Fog is added within the datasets to better visualize the 3D
994 architecture. A) Low strain, B) Intermediate strain, C) High strain. Note 3D orientation
995 and texture of garnet grains. Note the presence of more faceted grains in the intermediate
996 and high strain domain.

997 **Fig. 8** Garnet voxel cluster size distribution for non-eroded (solid lines) and eroded
998 (dashed lines) data. From low to high strain, there is an increase in frequency for all size
999 classes with increasing strain. Note the presence of the very large interconnected garnet
1000 voxel cluster in the low strain domain (blue solid curve), while the presence of much
1001 smaller sizes in the most deformed sample. The sketch on the top left corner illustrates
1002 the erosion process and the effects of particle size and shape: some particle might
1003 completely disappear. A, B) Absolute frequency and cumulative volume, respectively,
1004 for the low strain sample. C, D) Absolute frequency and cumulative volume,
1005 respectively, for the intermediate strain sample. E, F) Absolute frequency and cumulative
1006 volume, respectively, for the high strain sample.

1007 **Fig. 9** Label analysis of the end-members of the studied samples. A) 3D volume
1008 rendering of labels relative to low strain domain (dimensions 1503 x 1196 x 1831 cubic

1009 voxels). B) Intermediate Strain (dimensions 1322 x 1219 x 2023 cubic voxels). C) High
1010 strain (dimensions 1313 x 1234 x 1980 cubic voxels). Individual disconnected
1011 aggregates of garnet are identified with different colours.

1012 **Fig. 10** EBSD analysis results. Low strain: A) IPF map superposed on a pattern quality
1013 (Band Contrast) map. B) Profile X-Y, location in figure A). C) Misorientation axis by
1014 crystal coordinates for low angle boundaries (3-10°). Intermediate strain domain: D)
1015 IPF map. E) Profile X-Y, location in figure D; F) Misorientation axis by crystal
1016 coordinates for low angle boundaries (3-10°). High strain: G) IPF map. H) Profile X-Y,
1017 location in figure G; I) Misorientation axis by crystal coordinates for low angle
1018 boundaries (3-10°).

1019 **Fig. 11** Schematic sketch illustrating the evolution of reaction microfabrics, and in
1020 particular of garnet grains. 1) Low strain domain. 2) Intermediate strain. 3) High strain.
1021 See text for discussion.

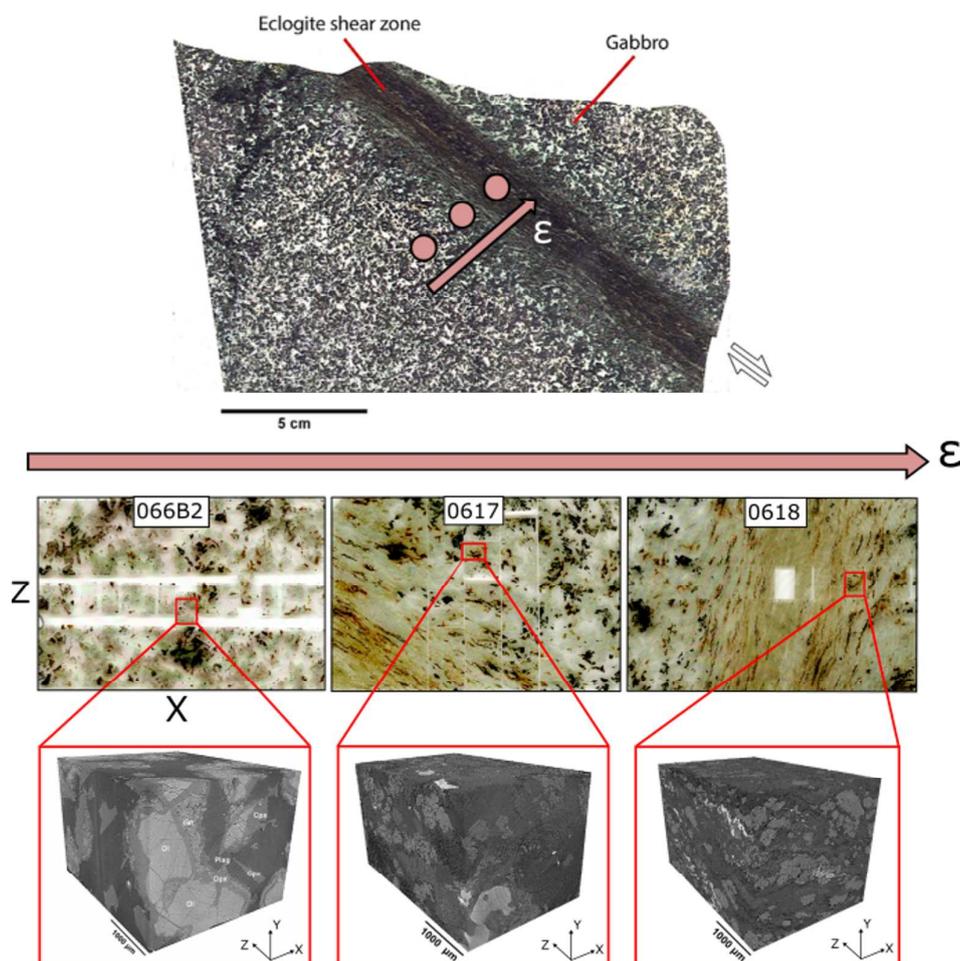


Fig. 1 The illustration shows the approximate original position (circles) of thin sections in the hand specimen, and the positions of tomographic data in the thin sections which are indicated by the red squares. 3D volume renderings, derived from tomographic data from the three samples, are shown in the bottom part. Slice is cut parallel to the fabric attractor. Axis for the kinematic frame (X, Y, Z) are indicated in the microtomographic data.

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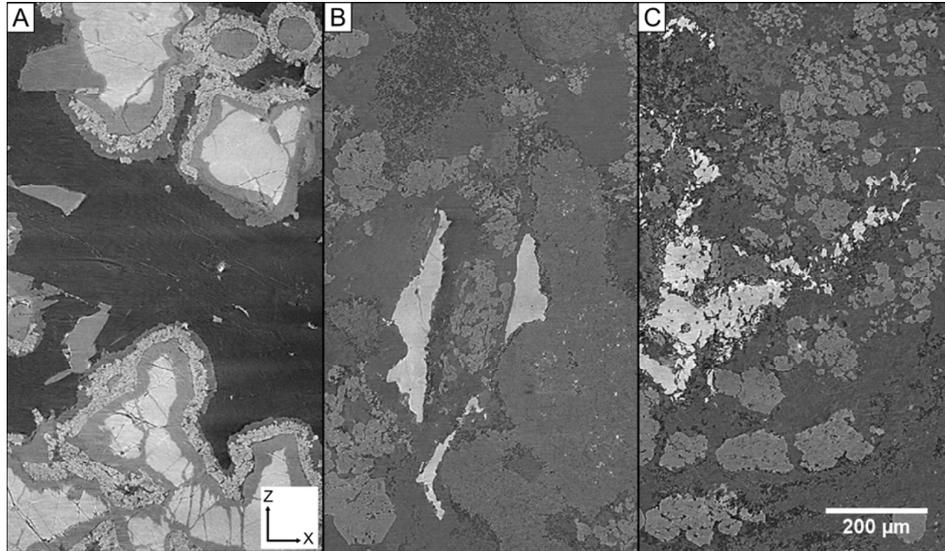


Fig. 2 Microtomographic datasets: A) low strain, B) intermediate strain, and C) high strain. Figure A exhibits minor artefacts (horizontal stripes) that do not affect the analyses. Mineral phases and features are recognizable from the corresponding SEM images (Fig. 3). The images represent the XZ plane and are parallel to the thin sections.

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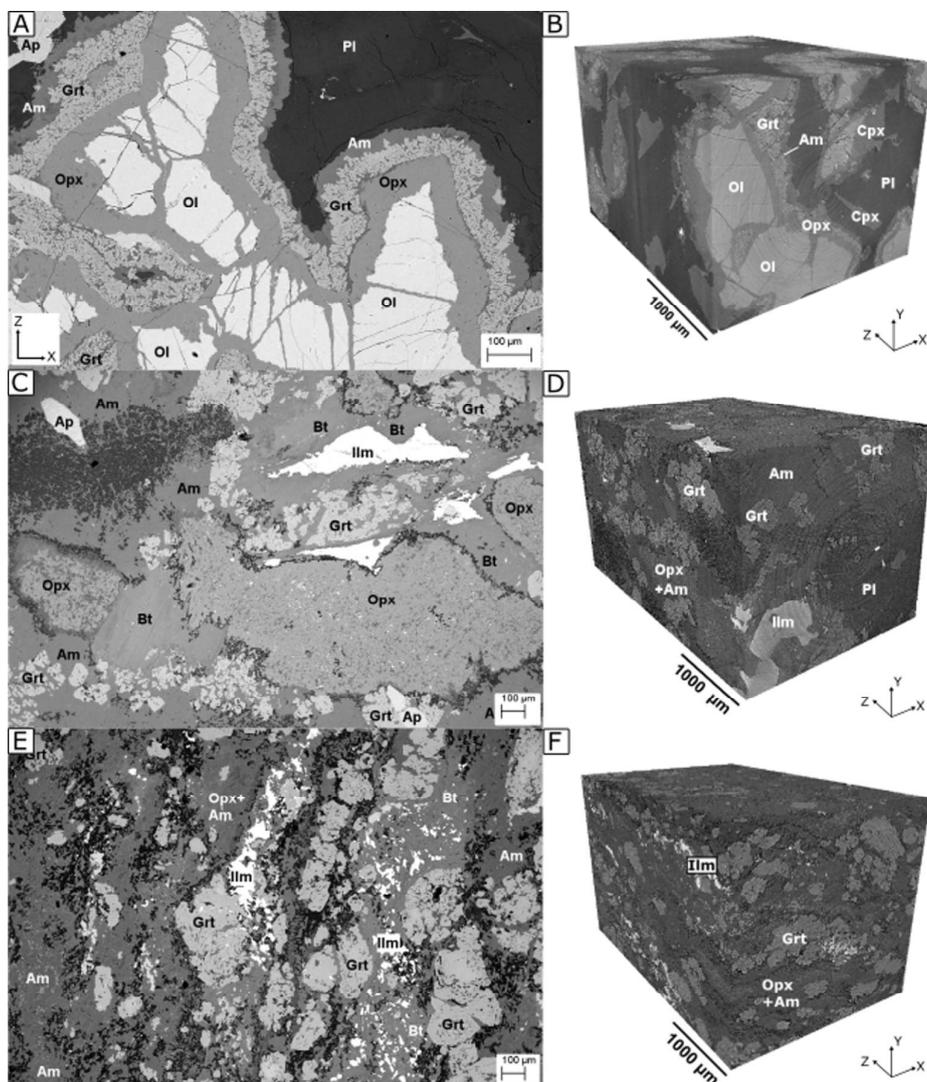


Fig. 3 BSE images of Krakeneset samples and corresponding microtomographic datasets, from low to high strain domain respectively: A) Sample 066B2 (Low strain)- Olivine grains are surrounded by complex coronas of orthopyroxene, garnet and amphibole. B) 3-dimensional dataset of low strain domain: high-pressure amphibole-garnet coronas surround olivine grains (dimensions 1503 x 1196 x 1831 cubic voxels). Note the variable thickness of amphibole. C) Sample 0617 (Intermediate Strain)- In the intermediate strain domain, olivine cores are replaced by orthopyroxene, while garnet and amphibole are no more part of the corona structures. D) Corresponding microtomographic dataset (dimensions 1322 x 1219 x 2023 cubic voxels). E) Sample 0618 (High Strain)- The high strain domain is characterized by a compositional layering of elongated garnet and plagioclase versus orthopyroxene and amphibole rich layers. F) Microtomographic dataset of the high strain domain (dimensions 1313 x 1234 x 1980 cubic voxels): note garnet grains behaving as rigid objects in a more ductile matrix of orthopyroxene and amphibole.

150x171mm (300 x 300 DPI)

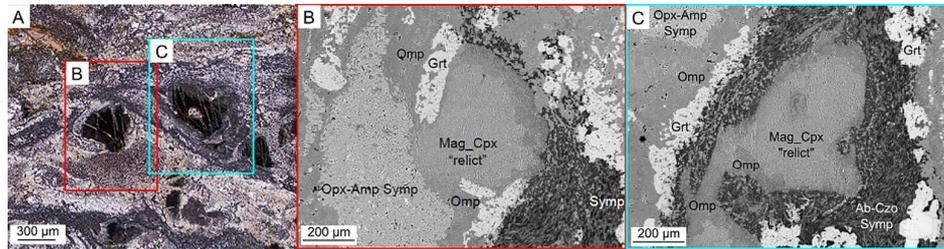


Fig. 4 A) Optical microscope image illustrating the mineral phases and microstructures present in the more deformed samples. B) BSE image showing old olivine cores now replaced by orthopyroxene-amphibole symplectites. Relict cores of magmatic clinopyroxene are present (Mag_Cpx "relict"), and are surrounded by a thin rim of omphacite (Omp), which is present also between garnet and orthopyroxene-amphibole symplectites ("Opx-Amp Symp"). C) Symplectites of albite-clinzoisite are replacing the plagioclase; omphacite surrounds relict magmatic clinopyroxene (Mag_Cpx "relict") and orthopyroxene-amphibole symplectites.

150x39mm (300 x 300 DPI)

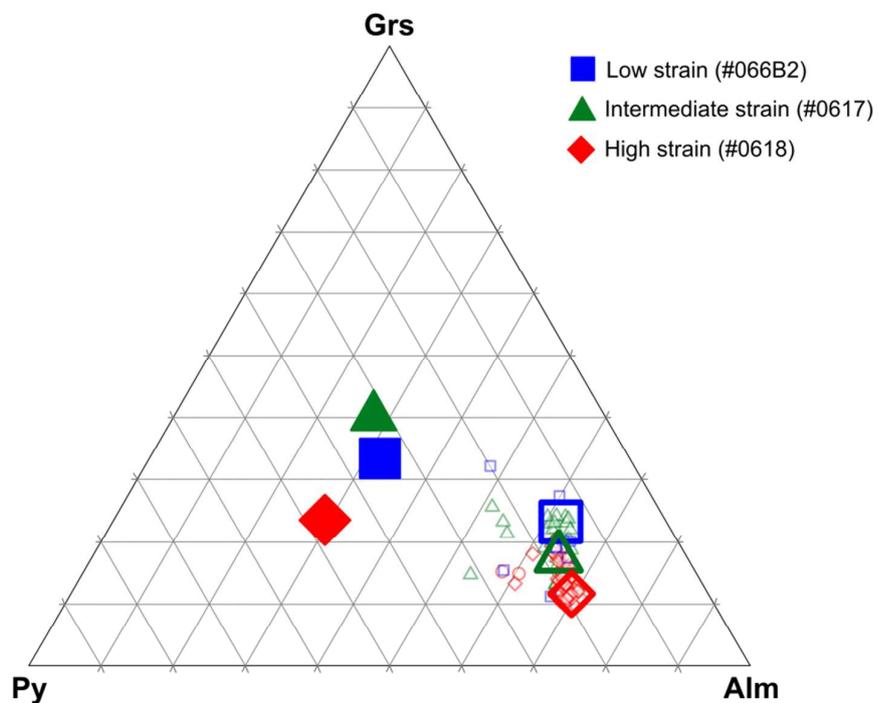


Fig. 5 Grs-Alm-Py plot showing garnet compositions from EMPA analyses, as single measurements across different grains. Filled symbols represent compositions closer to the plagioclase source. Empty symbols represent compositions closer to Fe-Mg-rich phases. End-members values are presented in the graph by the large symbols. With increasing deformation, garnet compositions become more Alm-rich, a trend expected for a gabbro that is equilibrating under P-T-t conditions of eclogite facies. In Tab. S2, representative structural formulae are reported for the three samples.

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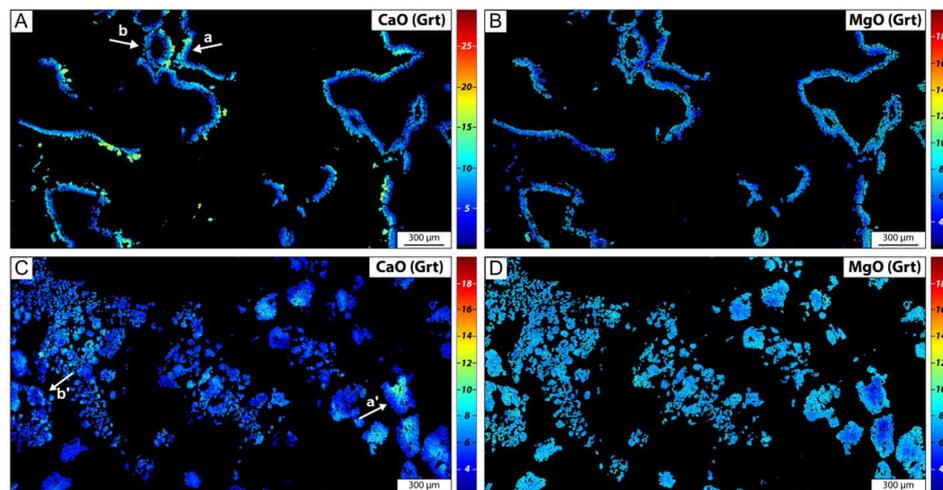


Fig. 6 Compositional maps for CaO and MgO for the low (A-C) and high (B-D) strain domains, obtained using XMapTools v. 2.3.1 (Lanari et al., 2014). CaO and MgO do have the same compositional zoning (4-10%) in the most deformed sample. C) Many garnets in the high strain domain have low CaO, reflecting an equilibration towards Alm-rich compositions. Nevertheless, some grain do have a higher content in CaO (~10%) (a') and MgO (~11%) (b'): we interpret this to results from coalescence (a, b) and subsequent disintegration of individual zoned coronas. Further left in Figure C, garnets are fragmented and forming a fine-grained matrix, indicating collapse of an old pre-existing corona.

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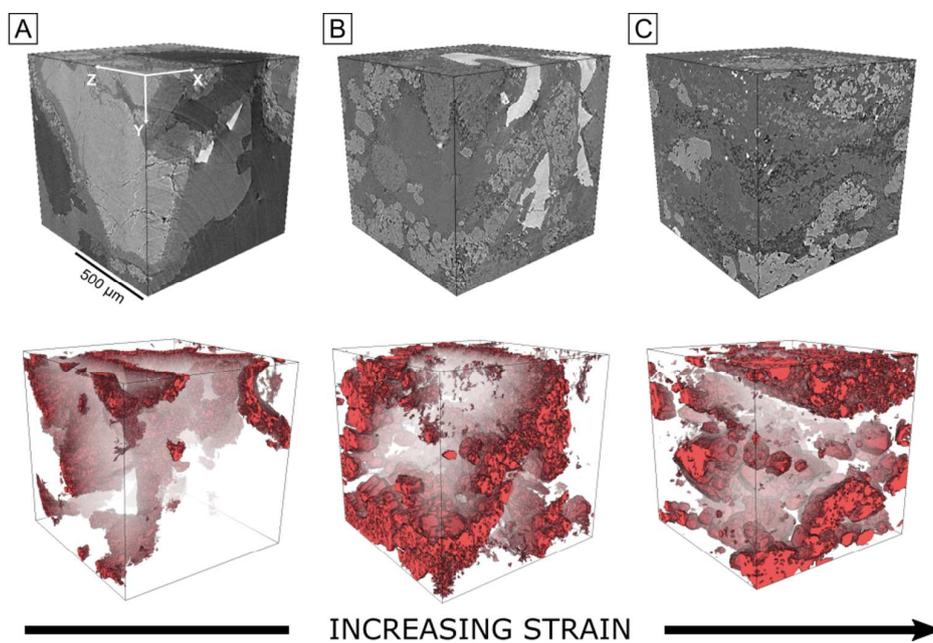


Fig. 7 The figures illustrate the results of segmentation of garnet from the microtomographic data. Top: cropped volumes of original datasets ($\sim 0.5 \text{ mm}^3$); bottom: garnets rendered in purple. Fog is added within the datasets to better visualize the 3D architecture. A) Low strain, B) Intermediate strain, C) High strain. Note 3D orientation and texture of garnet grains. Note the presence of more faceted grains in the intermediate and high strain domain.

140x93mm (300 x 300 DPI)

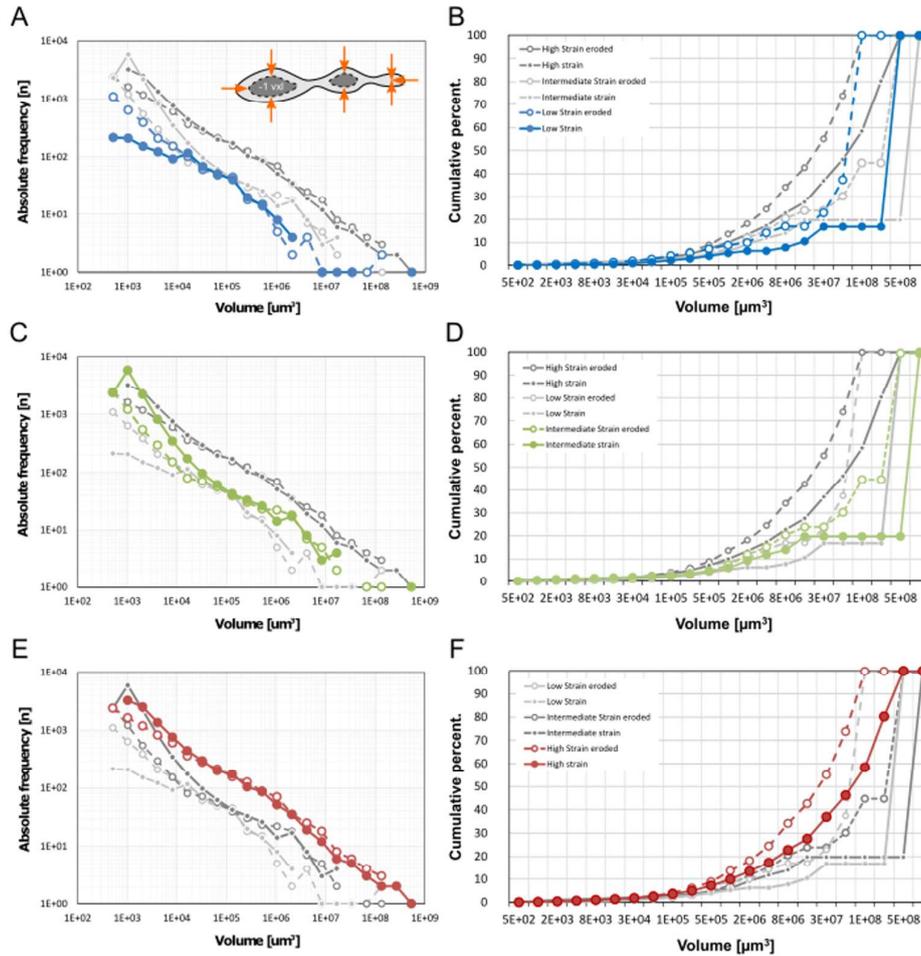


Fig. 8 Garnet voxel cluster size distribution for non-eroded (solid lines) and eroded (dashed lines) data. From low to high strain, there is an increase in frequency for all size classes with increasing strain. Note the presence of the very large interconnected garnet voxel cluster in the low strain domain (blue solid curve), while the presence of much smaller sizes in the most deformed sample. The sketch on the top left corner illustrates the erosion process and the effects of particle size and shape: some particle might completely disappear. A, B) Absolute frequency and cumulative volume, respectively, for the low strain sample. C, D) Absolute frequency and cumulative volume, respectively, for the intermediate strain sample. E, F) Absolute frequency and cumulative volume, respectively, for the high strain sample.

140x141mm (300 x 300 DPI)

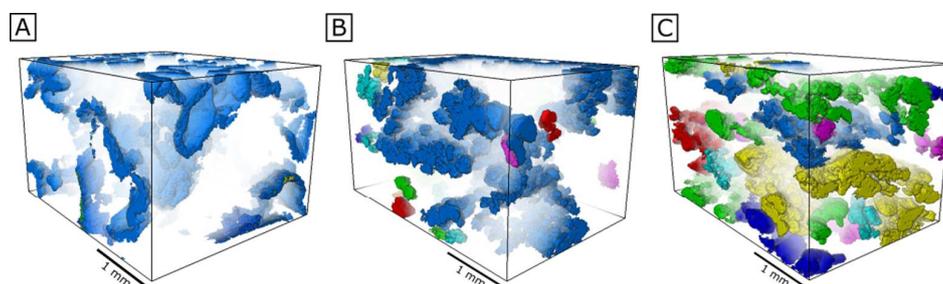


Fig. 9 Label analysis of the end-members of the studied samples. A) 3D volume rendering of labels relative to low strain domain (dimensions 1503 x 1196 x 1831 cubic voxels). B) Intermediate Strain (dimensions 1322 x 1219 x 2023 cubic voxels). C) High strain (dimensions 1313 x 1234 x 1980 cubic voxels). Individual disconnected aggregates of garnet are identified with different colours.

150x44mm (300 x 300 DPI)

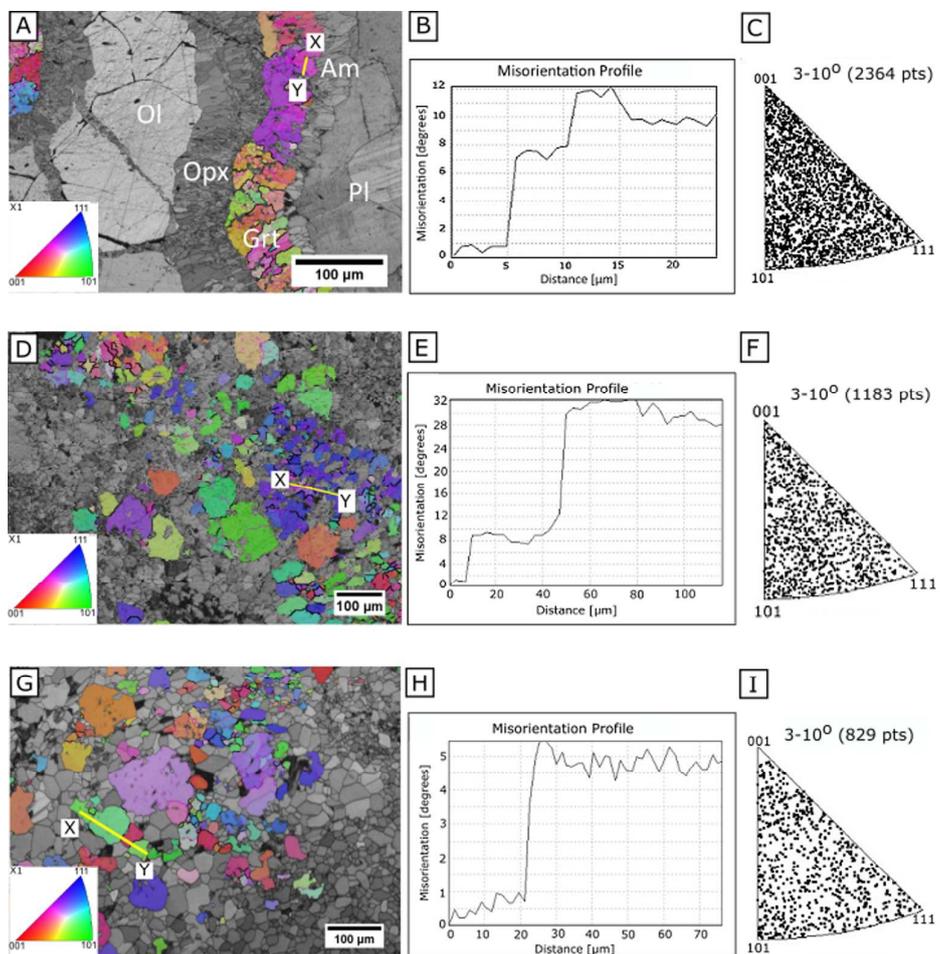


Fig. 10 EBSD analysis results. Low strain: A) IPF map superposed on a pattern quality (Band Contrast) map. B) Profile X-Y, location in figure A). C) Misorientation axis by crystal coordinates for low angle boundaries (3-10 $^\circ$). Intermediate strain domain: D) IPF map. E) Profile X-Y, location in figure D; F) Misorientation axis by crystal coordinates for low angle boundaries (3-10 $^\circ$). High strain: G) IPF map. H) Profile X-Y, location in figure G; I) Misorientation axis by crystal coordinates for low angle boundaries (3-10 $^\circ$).

150x151mm (300 x 300 DPI)

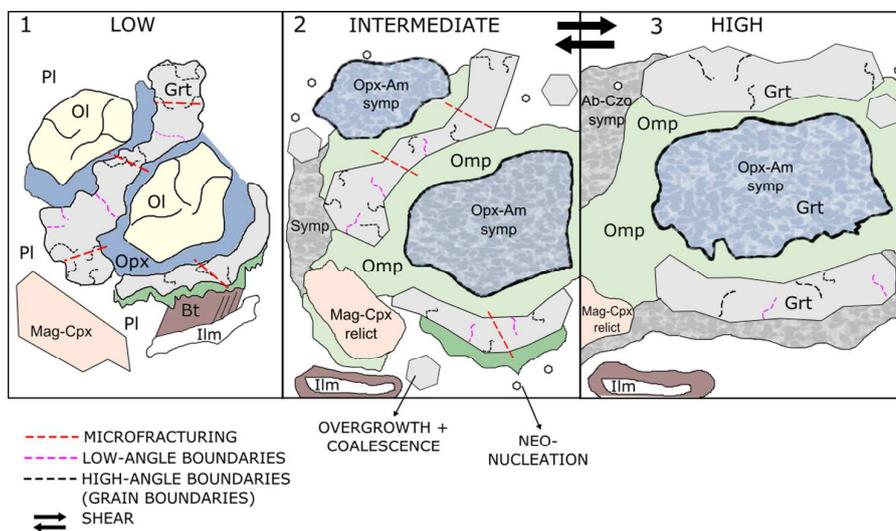


Fig. 11 Schematic sketch illustrating the evolution of reaction microfabrics, and in particular of garnet grains. 1) Low strain domain. 2) Intermediate strain. 3) High strain. See text for discussion.

150x82mm (300 x 300 DPI)

SUPPORTING INFORMATION

The strain-dependent evolution of garnet in a high-pressure ductile shear zone from the Western Gneiss Region (Norway): a Synchrotron x-ray microtomography study

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Appendix S1 Ground-truthing: Correlating synchrotron x-ray micro-tomography data with chemical compositions

Appendix S2 Segmentation of micro-tomographic data

Appendix S3 4D evolution of grain shapes

Fig. S1 Grey value histograms calculated from three $S_{\mu}CT$ datasets. The calculated absorption coefficients (μ) for the mineral phases correlate with grey scale values measured on the microtomographic data. The histograms reflect the metamorphic reactions during strain localization.

Fig. S2 Schematic workflow used to analyse the microtomographic data.

Fig. S3 EBSD results of low strain domain (sample 066B2). On EBSD-derived maps, high-angle boundaries (grain boundaries, misorientation $> 10^{\circ}$) and low-angle boundaries (subgrain boundaries, misorientation $> 3^{\circ}$ and $< 10^{\circ}$) were indicated with black and fuchsia lines, respectively. A) Phase map: Olivine (yellow), Plagioclase (white), Orthopyroxene (blue), Garnet (red), Hornblende (green). Red lines represent twinning boundaries in plagioclase. B) Inverse Pole Figure of Garnet in relation to the stretching lineation in the shear zone. Legend on bottom left corner. C) Local Misorientation Map, and legend, representing local misorientations from 0 (blue) to 9 degrees misorientation (red). The arrow indicates the average local internal misorientation. D) Misorientation profile A-A', location shown in figure C.

Fig. S4 EBSD results of low strain domain (sample 066B2). E) Pole figures of garnet. F) Pole figure of hornblende. G) Misorientation axis in crystal coordinates for low angle boundaries ($3-10^{\circ}$).

Fig. S5 EBSD results of intermediate strain domain (sample 0617). A) Inverse Pole Figure of garnet. Legend as in Fig. S3B. B) Local Misorientation Map, and legend representing local misorientations from 0 (blue) to 9 degrees misorientation (red). The arrow indicates the average local internal misorientation. C) Misorientation profile A-A', location is shown in figure A. D) Misorientation profile B-B', location shown in figure A. E) Pole figures of garnet. The trace of the shear foliation is oriented NW-SE, pole figures are oriented with the trace of the mylonitic foliation parallel to the diameter (E-W). F) Misorientation axis of low angle boundaries ($3-10^{\circ}$) in crystal coordinates.

Fig. S6 EBSD results of high strain domain (sample 0618). A) Phase map: Grt (red), Am (green), Opx (blue), Bt (yellow). B) Local Misorientation Map, and legend representing local misorientations from 0 (blue) to 9 degrees misorientation (red). The arrow indicates the average local internal misorientation. C) Inverse Pole Figure of garnet. Legend as in Fig. S3B. D) Misorientation profile A-A', location is shown in figure C. E) Misorientation profile B-B', location shown in figure C. F) Misorientation profile C-C', location shown in figure C.

Fig. S7 EBSD results of high strain domain (sample 0618). A) Pole figures of garnet. The trace of the shear foliation is oriented NNE-SSW, pole figures are oriented with the trace of the mylonitic foliation parallel to the diameter (E-W). B) Pole figures of hornblende. C) Misorientation axis of low angle boundaries ($3-10^{\circ}$) in crystal coordinates.

Fig. S8 The image shows the results of Statistical Region Merging technique for increasing Q. Scale as in image A. A) Original data. B) SRM Q=2. C) SRM Q=10. D) SRM Q=25: note that the image is more detailed. E, F, G) Histograms relative to the three different SRM parameters.

Fig. S9 Outputs of segmentation for olivine (green) and garnet (blue) grains, in the low

strain domain (different viewing angles). The red arrows indicate olivine grains that are not completely enclosed by garnet coronas.

Fig. S10 Label analysis of intermediate strain domain after erosion. The large interconnected voxel cluster is now divided in disconnected subvoxel clusters. Long side 2630 μm .

Fig. S11 Quant3D explained. The tomographic data are first segmented to extrapolate the material of interest. Star points are placed within the segmented material: the distance of each star points to the next material boundary are calculated in many orientations and normalised. Simplified from Ketcham (2005).

Fig. S12 Results of Quant3D analysis on eroded data, from low strain (A) to high strain (C). With increasing deformation, garnet grains evolve from isodiametric shapes to more progressively discoid shapes as a results of the deformation.

Table S1 Electron microprobe chemical compositions of oxides in garnets, used to calculate the x-ray absorption coefficients.

Table S2 Representative garnet structural formulae for the low (#066B2) and high (#0618) strain domain obtained from the microprobe analyses at the University of Münster.

Table S3 Frequency distribution data for non-eroded data. The first column of each dataset refers to absolute frequency, the second one to the cumulative frequency relative to the total amount of garnet in each sample.

Table S4 Frequency distribution data for eroded data. Bins refer to cubic micrometres. The first column of each dataset refers to absolute frequency, the second one to the cumulative frequency relative to the total amount of garnet in each sample.

Appendix S1 Ground-truthing: Correlating synchrotron x-ray micro-tomography data with chemical compositions

Where x-ray microtomographic data allow for a complete visualisation of microfabrics in rocks in 3D (Denison and Carlson, 1997; Gualda and Rivers, 2006; Whitney et al., 2008; Wang et al., 2011; Goergen and Whitney, 2012; Sayab et al., 2014), the combination with established microanalytical techniques critically expands our insight into tectonic and metamorphic processes. High-resolution microtomographic data and electron microscopic analyses have similar resolutions on the μm -scale, and analytical results from the same samples can therefore be extrapolated between the techniques. The obvious gain from this is that metamorphic microfabrics can then be fully quantified in 3D. However, the marriage of 2D with 3D analyses hinges on a) a registration of the 2D data within the 3D dataset, b) a correlation of actual compositional data from the mineral phases with intensities recorded in the 3D scalar fields that make a microtomographic dataset (Gualda and Rivers, 2006) and c) the involved procedure of segmenting individual mineral volumes from the 3- dimensional datasets to allow for a further quantitative analysis. While routines for image registration are readily available, also in *AvizoFire*[®], and segmentation is discussed in section 7.2, the following summarises our

strategy to correlate x-ray absorption with compositional information.

In most microtomographic data material-specific x-ray absorption is recorded as a function of position in the sample and, as an output of the reconstruction process, stored in an array of intensity values. The relationship between absorption and intensity (usually visualised as grey scale values) in the tomographic data is given by the Lambert-Beer law:

$$I = I_0 \exp \left[- \int_{-\infty}^{\infty} \mu(x) dx \right]$$

where I represents the intensity of the x-ray source before it hits the sample, I_0 is the attenuated intensity after x-rays passed through a sample of thickness x , and μ is a linear attenuation coefficient (e.g., Baker *et al.*, 2012; Fuisseis *et al.*, 2014). The intensity distribution in a polymineralic sample can be plotted in a histogram that relates voxel frequency to recorded intensity (e.g., Fig. S1). Given that intensity is material-specific, these data can, in the best of cases, be used to quantify the volume of a particular mineral phase. However, it is important at this stage to establish a tight link between x-ray absorption microtomographic and actual compositional data from the same sample, and confirm that the grey values correspond to the minerals of interest. To achieve this we calculated the x-ray absorption coefficients for each mineral phase based on the chemical compositions acquired through EMPA analysis, and compared them with the grey scale distribution in the tomographic data (Fig. S1). X-ray mass attenuation coefficients are listed in a NIST (National Institute of Standards and Technology) database for elements $Z=1$ to 92, and for a number of substances of radiological interest. Where the energy of the incoming photons is known (in our case 27 KeV) and compositional data are available, the absorption coefficients can be calculated for any mineral. We used averaged electron microprobe analyses (EMPA) to calculate the theoretical x-ray mass attenuation coefficients of the minerals in our samples. Fig. S1 compares the calculated absorptions with three grey value histograms from the three studied datasets. Our analytical strategy, where the actual microtomography sample was polished and used for electron microscopy and EMPA analyses, allowed to combine compositional measurements with intensity signals and thereby anchor the two x-axes against each other. Fig. S1 does indeed capture some of the metamorphic processes that affect the samples. For example the peak for plagioclase, which is clearly present in the low strain dataset, is replaced by a minimum in the high strain domain, reflecting the lack (or a very small presence) of plagioclase in the eclogitic shear zone centre.

Appendix S2 Segmentation of micro-tomographic data

To be able to segment garnets from the tomographic images, we denoised the images in Fiji. The parameters for Anisotropic Diffusion Filter in 2D included 20 iterations, a_1 and a_2 were set up at 0.7 and 0.5 respectively. Before applying the filter, we improved the contrast on the images and saved them in Bitmap format in order to preserve the new contrast.

On the filtered data, Statistical Region Merging (SRM) technique was applied (Nock and Nielsen, 2004). This algorithm is a region growing technique, which groups

homogeneous pixels together and grow them iteratively together by merging other pixels or smaller regions. The limit of regions to be merged together is determined by a statistical test and the scale is controlled by the size of the parameter Q : the higher is Q , the higher is the number of subregions and the more detailed is the resulting image but it is also noisier (Nock and Nielsen, 2004) (Fig. S8). The changes operated by SRM can be visualised in the image histograms. Each boundary phase is marked in the histogram by a vertical bar, which allows *Global Threshold* to segment the material of interest in a more controlled way (Fig. S8). Global thresholding allows to select from the grey scale values in the histogram, and therefore from their x-ray absorption coefficient, a particular phase that can be extrapolated from the context. In some cases, the choice of using one single output of SRM was insufficient. In Fiji, it was thus possible to combine different SRM outputs to obtain the best segmentation for garnet grains by using *Image Calculator* and the *Multiply* operator to get rid of unwanted segmented phases or islands.

A summary of the workflow used to analyse the data is shown in Figure S2.

Appendix S3 4D evolution of grain shapes

We performed Quant3D analysis to investigate the 3-dimensional shape of garnet grains and to understand if Synchrotron x-ray micro-tomography can be used to gain information on the dynamic evolution of grain shapes. Quant3D is a fabric analysis software developed by Ketcham and Ryan (2004) and Ketcham (2005), written in IDL programming language and it includes three main fabric analysis methods. Originally developed by previous works for two-dimensional analysis (Ketcham (2005b) and references therein), these methods can now be used also to analyse 3-dimensional structures. The software gives the eigenvectors ($\hat{u}_1, \hat{u}_2, \hat{u}_3$) and eigenvalues (τ^1, τ^2, τ^3) of the fabric tensors, which define orthogonal principal axes and are related to the moment of inertia, the degree of anisotropies (DA), the isotropy index I and the elongation index (E) (Ketcham, 2005). The results can be visualized as a 3-dimensional rose diagram. In the rose diagram, each vertex is projected from the unit sphere either inward or outward from the origin of the star points. The vertex positions from the origin are normalized by the maximum distance value. In the rose diagram, eigenvectors, scaled by their respective eigenvalues, are also plotted. The rose diagram can be visualized as rendered surface with a colour code mode, where the red colour represents a normalized value of 1.0, as a distance from the origin equal to the coordinate axis length: lower values, indicating closer distances to the origin, are represented with cooler rainbow colours (Ketcham and Ryan (2004)). The results can be exported as VRML format, containing all the spatial information and readable by lots of applications. In our analysis, star points were placed outside the material of interest by assigning black values (0) to the garnets. In this way, the distances to the next material boundary represent distances to the material of interest, and thus they give an indication of the grain shapes. Analysis parameters were as followed: uniform distribution of orientations (513), random rotation, dense vectors. The results were exported as rose diagrams and VRML format files.

In order to avoid errors introduced by image segmentation, the analysis were performed on eroded data, as previously mentioned (subsection 4.3). The results are shown in Fig.

S12. With increasing strain, garnet shapes evolve from an isodiametric grain to increasingly discoidal and oblate shapes.

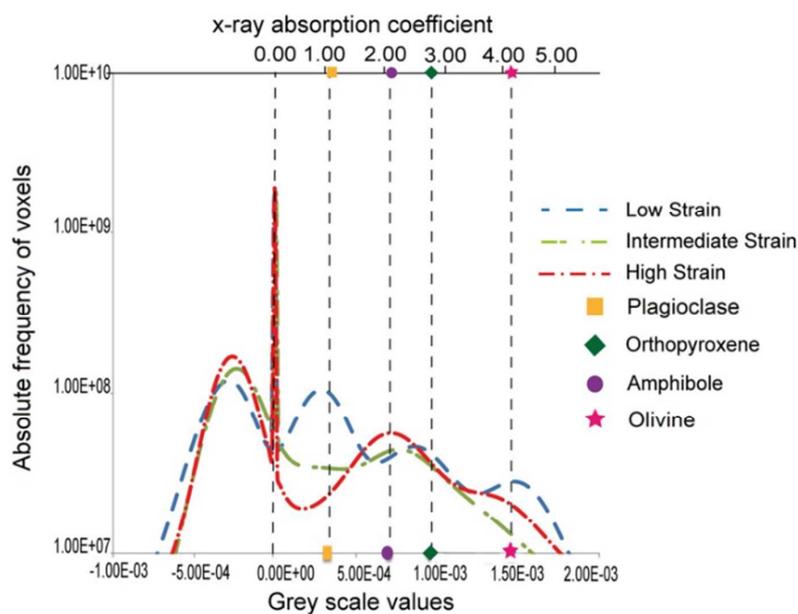


Fig. S1

Fig. S1 The graph shows grey value histograms calculated from three S μ CT datasets. The calculated absorption coefficients (μ) for the mineral phases correlate with grey scale values measured on the microtomographic data. The histograms reflect the metamorphic reactions during strain localization.

Fig. S2

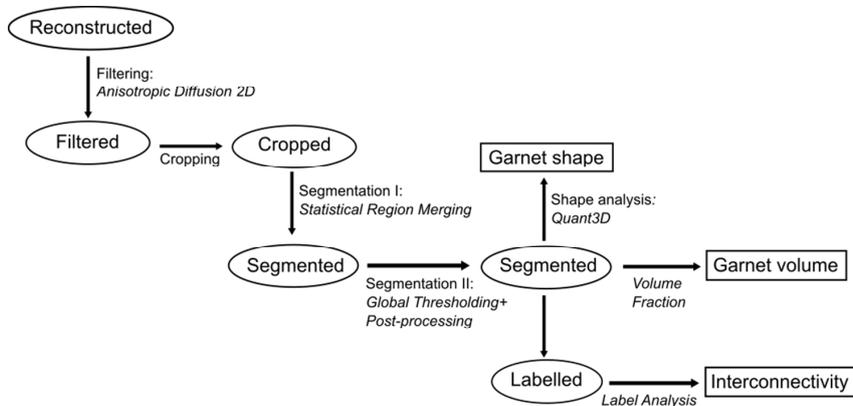


Fig. S2 Schematic workflow used to analyse the microtomographic data.

Fig. S3

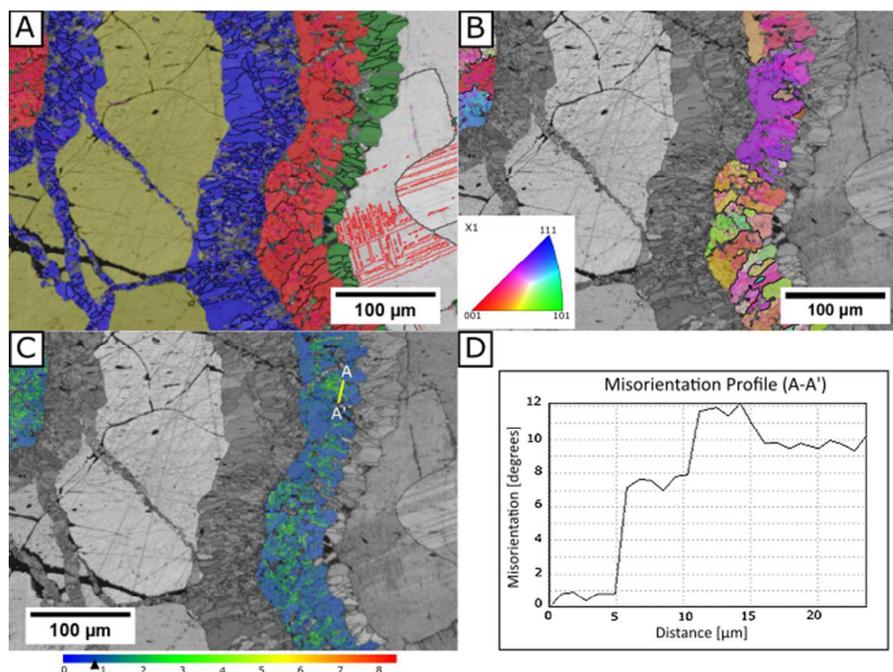


Fig. S3 EBSD results of low strain domain (sample 066B2). On EBSD-derived maps, high-angle boundaries (grain boundaries, misorientation $> 10^\circ$) and low-angle boundaries (subgrain boundaries, misorientation $> 3^\circ$ and $< 10^\circ$) were indicated with black and fuchsia lines, respectively. A) Phase map: Olivine (yellow), Plagioclase (white), Orthopyroxene (blue), Garnet (red), Hornblende (green). Red lines represent twinning boundaries in plagioclase. B) Inverse Pole Figure of Garnet in relation to the stretching lineation in the shear zone. Legend on bottom left corner. C) Local Misorientation Map, and legend, representing local misorientations from 0 (blue) to 9 degrees misorientation (red). The arrow indicates the average local internal misorientation. D) Misorientation profile A-A', location shown in figure C.

Fig. S4

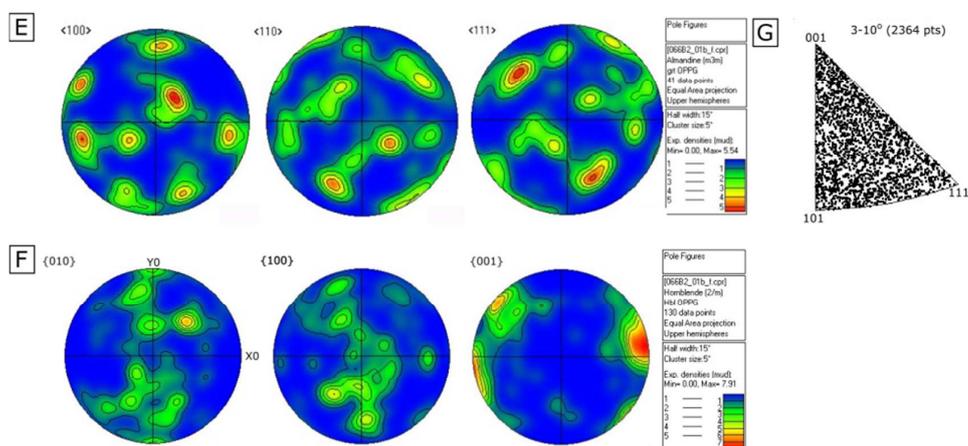


Fig. S4 EBSD results of low strain domain (sample 066B2). E) Pole figures of Garnet. F) Pole Figure of Hornblende. G) Misorientation axis in crystal coordinates for low angle boundaries (3-10°).

Fig. S5

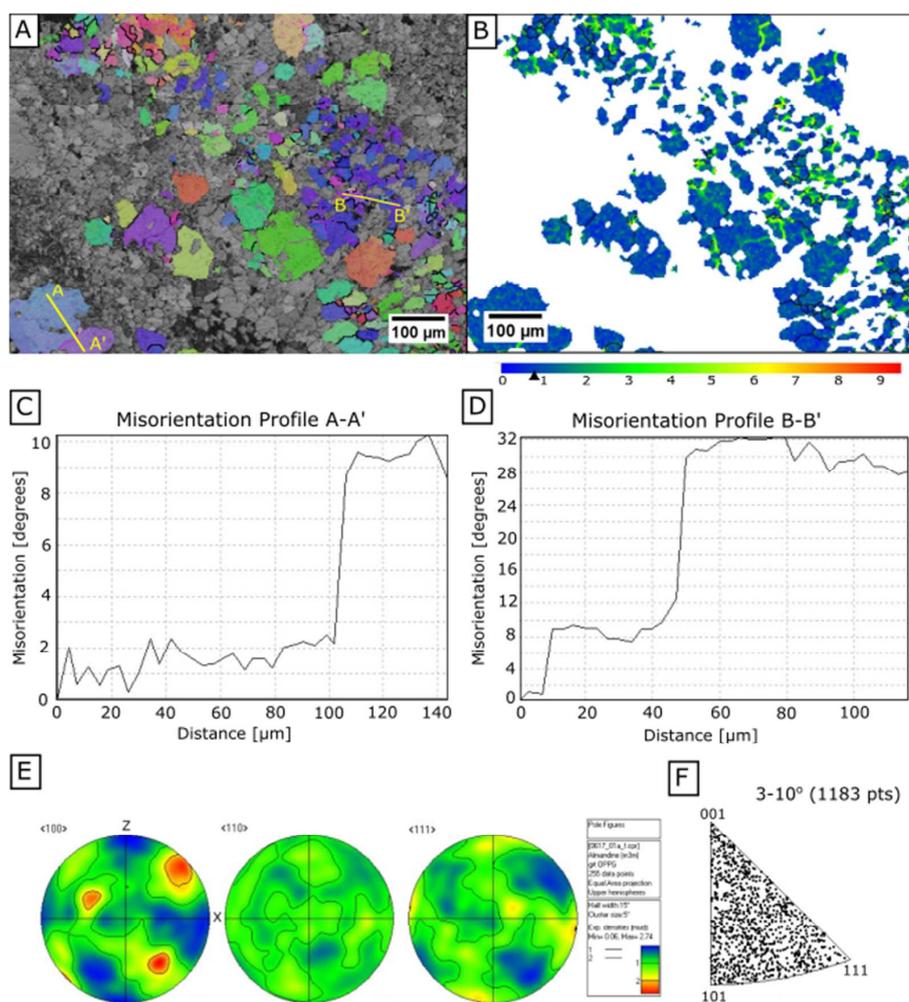


Fig. S5 EBSD results of intermediate strain domain (sample 0617). A) Inverse Pole Figure of Garnet. Legend as in Fig. S3B. B) Local Misorientation Map, and legend representing local misorientations from 0 (blue) to 9 degrees misorientation (red). The arrow indicates the average local internal misorientation. C) Misorientation profile A-A', location is shown in figure A. D) Misorientation profile B-B', location shown in figure A. E) Pole figures of Garnet. The trace of the shear foliation is oriented NW-SE, pole figures are oriented with the trace of the mylonitic foliation parallel to the diameter (E-W). F) Misorientation axis of low angle boundaries ($3-10^\circ$) in crystal coordinates.

Fig. S6

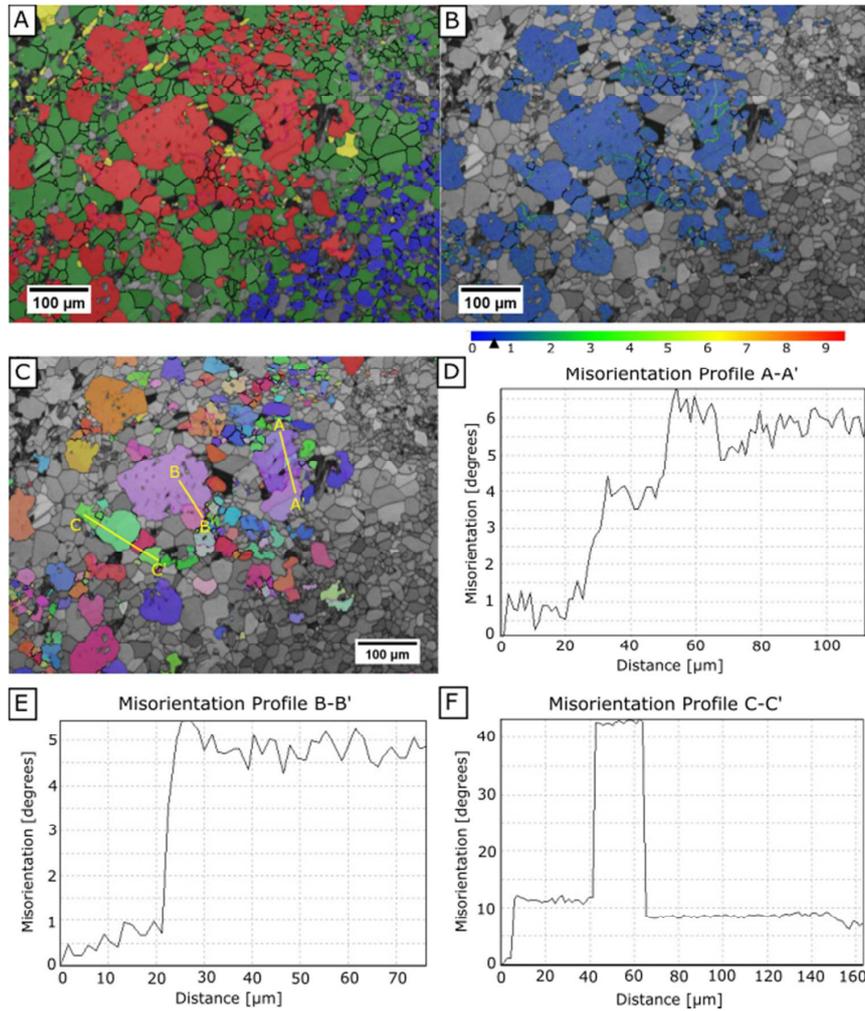


Fig. S6 EBSD results of high strain domain (sample 0618). A) Phase map: Grt (red), Am (green), Opx (blue), Bt (yellow). B) Local Misorientation Map, and legend representing local misorientations from 0 (blue) to 9 degrees misorientation (red). The arrow indicates the average local internal misorientation. C) Inverse Pole Figure of Garnet. Legend as in Fig. S3B. D) Misorientation profile A-A', location is shown in figure C. E) Misorientation profile B-B', location shown in figure C. F) Misorientation profile C-C', location shown in figure C.

Fig. S7

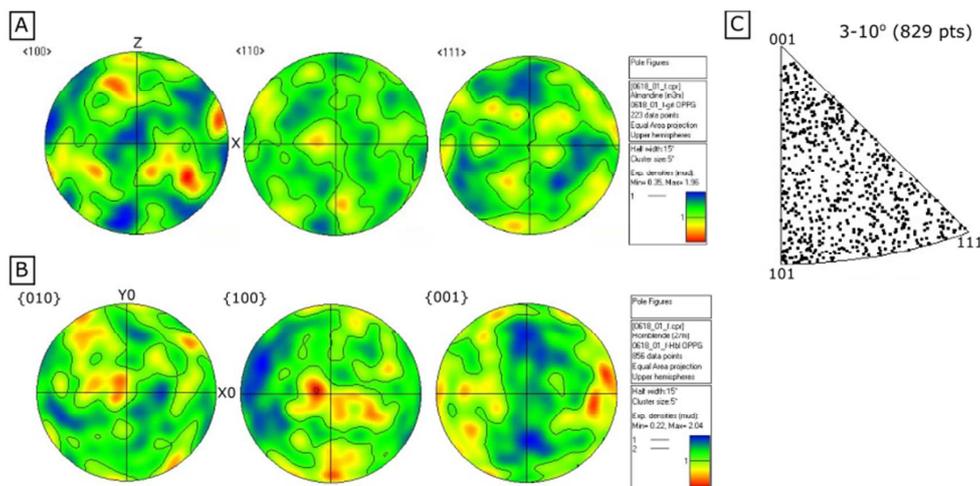


Fig. S7 EBSD results of high strain domain (sample 0618). A) Pole figures of Garnet. The trace of the shear foliation is oriented NNE-SSW, pole figures are oriented with the trace of the mylonitic foliation parallel to the diameter (E-W). B) Pole figures of Hornblende. C) Misorientation axis of low angle boundaries ($3-10^\circ$) in crystal coordinates.

Fig. S8

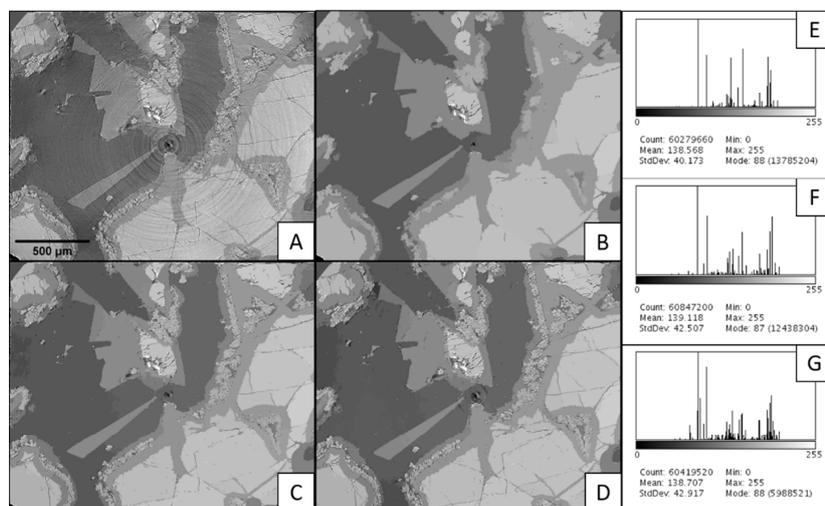


Fig. S8 The image shows the results of Statistical Region Merging technique for increasing Q . Scale as in image A. A) Original data. B) SRM $Q=2$. C) SRM $Q=10$. D) SRM $Q=25$: note that the image is more detailed. E, F, G) Histograms relative to the three different SRM parameters: note the increasing vertical lines for increasing Q .

Fig. S9

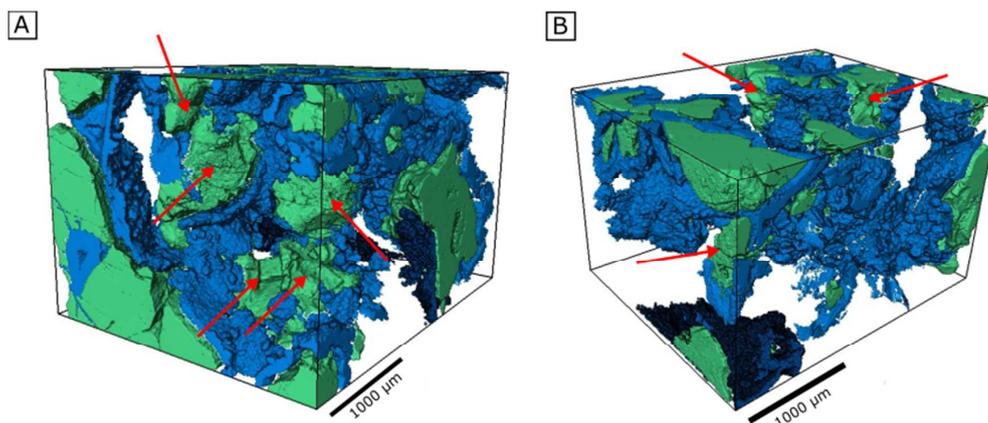


Fig. S9 Outputs of segmentation for olivine (green) and garnet (blue) grains, in the low strain domain (different viewing angles). The red arrows indicate olivine grains that are not completely enclosed by garnet coronas.

Fig. S10

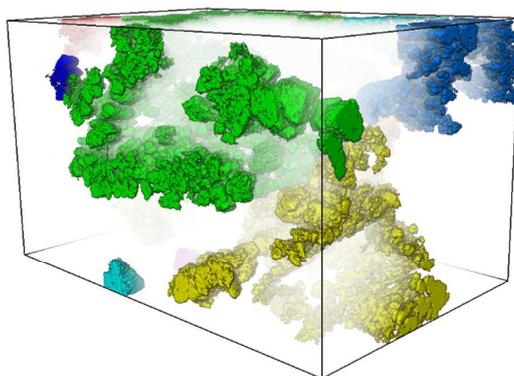


Fig. S10 Label analysis of intermediate strain domain after erosion. The large interconnected voxel cluster is now divided in disconnected subvoxel clusters. Long side 2630 μm .

Fig. S11

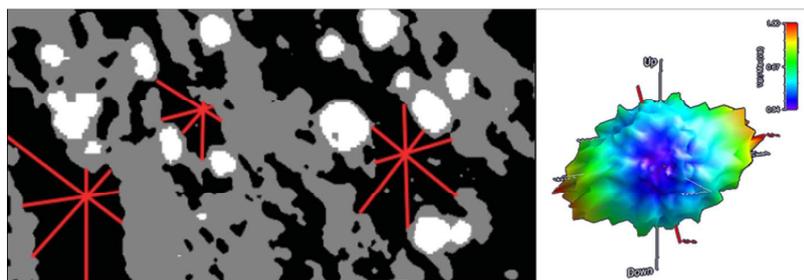


Fig. S11 The tomographic data are first segmented to extrapolate the material of interest. Star points are placed within the segmented material: the distance of each star points to the next material boundary are calculated in many orientations and normalised. Simplified from Ketcham (2005).

Fig. S12

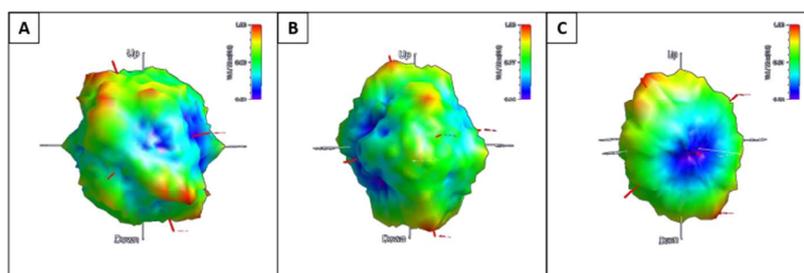


Fig. S12 Results of Quant3D analysis on eroded data, from low strain (A) to high strain (C). With increasing deformation, garnet grains evolve from isodiametric shapes to more progressively discoid shapes as a results of the deformation.

Sample	Na ₂ O	MgO	Al ₂ O ₃	FeO	CaO	SiO ₂	K ₂ O	TiO ₂	Cr ₂ O ₃	MnO	NiO	Total
#0618	0.009	6.853	21.605	28.263	5.709	38.981	0.004	0.039	0.004	0.705	0.000	102.171
#0618	0.036	6.405	21.874	28.018	5.360	39.270	0.003	0.097	-0.011	0.831	-0.011	101.873
#066B2	0.020	6.602	22.120	27.765	5.651	38.714	0.147	0.008	-0.003	1.157	0.015	102.196
#066B2	0.627	5.039	21.453	21.712	11.288	40.526	0.009	0.042	0.003	0.441	-0.008	101.131
#0617	-0.003	5.760	22.149	26.420	7.838	38.513	0.018	0.044	-0.009	0.865	-0.008	101.586
#0617	0.035	7.050	22.245	26.945	5.648	38.935	0.005	0.009	0.006	0.811	-0.010	101.679
#0617	0.044	5.801	22.150	25.930	8.612	38.965	0.006	0.051	-0.007	0.580	-0.009	102.122
#0617	0.021	5.868	22.291	25.077	9.592	38.815	0.000	0.065	-0.009	0.414	-0.013	102.120
#0617	0.030	6.173	22.366	24.130	9.262	38.685	0.001	0.043	0.004	0.971	0.005	101.668

Table S1 Electron microprobe chemical compositions of oxides in garnets, used to calculate the x-ray absorption coefficients.

	Low strain	Intermediate strain	High strain			
SiO ₂	38.86	39.17	38.33	38.06	38.9	38.56
TiO ₂	0	0.02	0	0	0	0
Al ₂ O ₃	21.77	21.1	21.09	21.54	21.22	21.05
Cr ₂ O ₃	0	0.01	0.01	0	0	0.03
Fe ₂ O ₃	0.53	0.23	0.42	1	0	0.07
FeO	24.9	24.33	25.2	23.21	26.04	26.73
MnO	1.15	1.17	0.58	0.6	0.56	0.59
MgO	5.79	6.64	6.03	6.66	7.74	7.08
CaO	7.87	7.42	7.26	7.67	4.58	4.81
Na ₂ O	0	0	0	0	0	0
K ₂ O	0	0	0	0	0	0
Totals	100.86	100.1	98.92	98.74	99.04	98.92
Oxygens	12	12	12	12	12	12
Si	2.996	3.03	3.011	2.977	3.031	3.024
Ti	0	0.001	0	0	0	0
Al	1.978	1.924	1.953	1.986	1.949	1.946
Cr	0	0.001	0.001	0	0	0.002
Fe ₃	0.03	0.013	0.025	0.059	0	0.004
Fe ₂	1.605	1.574	1.655	1.518	1.697	1.753
Mn	0.075	0.076	0.039	0.04	0.037	0.039
Mg	0.665	0.765	0.706	0.776	0.899	0.827
Ca	0.65	0.615	0.611	0.643	0.382	0.404
Na	0	0	0	0	0	0
K	0	0	0	0	0	0
Sum	8	8	8	8	7.995	8

Table S2 Representative garnet structural formulae for the low (#066B2) and high (#0618) strain domain obtained from the microprobe analyses at the University of Münster.

Bins [μm^3]	Low Strain	Cum. Freq.	Intermediate Strain	Cum. Freq.	High Strain	Cum. Freq.
2.00E+00	0		0		0	
4.00E+00	0		0		0	
8.00E+00	0		0		0	
1.60E+01	0		0		0	
3.20E+01	0		0		0	
6.40E+01	0		0		0	
1.28E+02	0		0		0	
2.56E+02	0		0		0	
5.12E+02	215	0.02%	2341	0.14%	0	0.00%
1.02E+03	209	0.05%	5868	0.64%	3244	0.18%
2.05E+03	152	0.09%	2208	1.01%	2502	0.43%
4.10E+03	122	0.17%	822	1.29%	1352	0.70%
8.19E+03	92	0.28%	348	1.54%	761	1.01%
1.64E+04	116	0.56%	174	1.78%	443	1.36%
3.28E+04	68	0.89%	97	2.04%	298	1.84%
6.55E+04	51	1.40%	62	2.40%	198	2.48%
1.31E+05	41	2.19%	42	2.85%	173	3.59%
2.62E+05	20	2.93%	33	3.59%	104	4.95%
5.24E+05	14	4.07%	26	4.74%	86	7.21%
1.05E+06	8	5.34%	14	6.03%	51	9.97%
2.10E+06	4	6.28%	17	9.24%	35	13.44%
4.19E+06	0	6.28%	8	11.80%	19	17.25%
8.39E+06	1	7.77%	3	13.94%	12	22.76%
1.68E+07	1	10.41%	4	19.72%	6	27.58%
3.36E+07	1	16.82%	0	19.72%	5	36.93%
6.71E+07	0	16.82%	0	19.72%	3	46.25%
1.34E+08	0	16.82%	0	19.72%	2	58.37%
2.68E+08	0	16.82%	0	19.72%	2	80.30%
5.37E+08	1	99.98%	0	19.72%	1	100.00%
1.07E+09	0	99.98%	1	100.00%	0	100.00%
Tot. Grt Vol.	4.81E+08		8.19E+08		1.43E+09	

Table S3 Frequency distribution data for non-eroded data. The first column of each dataset refers to absolute frequency, the second one to the cumulative frequency relative to the total amount of garnet in each sample.

Bins [μm^3]	Low Strain (eroded)	Cum. Freq.	Intermediate Strain (eroded)	Cum. Freq.	High Strain (eroded)	Cum. Freq.
2.00E+00	0		0		0	
4.00E+00	0		0		0	
8.00E+00	0		0		0	
1.60E+01	0		0		0	
3.20E+01	0		0		0	
6.40E+01	0		0		0	
1.28E+02	0		0		0	
2.56E+02	0		0		0	
5.12E+02	1101	0.14%	2428	0.15%	2379	0.08%
1.02E+03	638	0.30%	1215	0.15%	1628	0.18%
2.05E+03	390	0.49%	546	0.13%	1183	0.34%
4.10E+03	208	0.70%	297	0.15%	827	0.55%
8.19E+03	153	1.00%	153	0.15%	604	0.86%
1.64E+04	102	1.40%	80	0.16%	361	1.23%
3.28E+04	61	1.91%	71	0.29%	281	1.82%
6.55E+04	49	2.69%	56	0.44%	213	2.72%
1.31E+05	45	4.22%	39	0.63%	156	4.00%
2.62E+05	18	5.37%	30	0.96%	126	6.10%
5.24E+05	15	7.14%	23	1.39%	87	8.82%
1.05E+06	5	8.78%	22	2.81%	70	13.57%
2.10E+06	2	9.85%	18	4.46%	35	18.14%
4.19E+06	4	14.19%	7	3.28%	25	24.47%
8.39E+06	1	16.95%	5	5.27%	18	34.18%
1.68E+07	0	16.95%	2	3.43%	8	42.66%
3.36E+07	1	22.88%	0	0.00%	6	55.06%
6.71E+07	1	37.39%	1	6.32%	4	73.84%
1.34E+08	2	99.86%	1	14.54%	3	99.83%
2.68E+08	0	99.86%	0	0.00%	0	99.83%
5.37E+08	0	99.86%	1	54.73%	0	99.83%
1.07E+09	0	99.86%	0	0.00%	0	99.83%
Tot. Grt Vol.	2.89E+08		5.83E+08		1.13E+09	

Table S4 Frequency distribution data for eroded data. Bins refer to cubic micrometres. The first column of each dataset refers to absolute frequency, the second one to the cumulative frequency relative to the total amount of garnet in each sample.

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