We want to thank Matthias Konrad-Schmolke for his critical review and suggestions. Below is a list of all comments from the reviewer (RC), answers from the authors (AC) and manuscript changes (MC).

Reviewer 1, general comment

RC: One crucial argument for crystal plasticity in garnet is the observation of dislocation walls that mark the boundary of one subgrain in the garnet crystals. The authors state that these dislocation walls are the result of dislocation climb in the crystal (lines 252-253) and therefore indicate the activity of viscous deformation mechanisms in garnet. I am not entirely convinced that these dislocation walls are only produced by the migration of dislocations through the crystal, although I am not aware of studies that demonstrate neither pro nor contra arguments. The fact that the authors do not cite any references is also not helpful with this regard. However, there is evidence that such dislocation walls can be generated in undeformed rocks, e.g. during fluid infiltration, such as demonstrated in Konrad-Schmolke et al., 2018. Of course, fluid infiltration does not play a role in the rocks presented here, but other mechanisms for the formation of the dislocation walls must be discussed in this manuscript, as these structures are a fundamental argument for crystal plasticity. Furthermore, the interpretation of the presence of rotated subgrains in terms of subgrain rotation recrystallization is, in my opinion, also questionable. Konrad-Schmolke et al., 2007 demonstrate the presence of subgrains in garnets (and their slight misorientations) in undeformed rocks. In general, I think that the manuscript would very much benefit from a more indepth discussion of these features. The papers cited in this review should only serve as examples and I think that there are many other contributions to the topic that I am not aware of at the moment. However, I think the manuscript is very well suitable for publication after moderate revisions and a more thorough discussion.

AC: As noted by the reviewer, fluid infiltration does not play a role in the rocks presented here, so the mechanism proposed in Konrad-Schmolke et al., 2018 cannot be relevant in this case. The rocks we are considering here are also clearly deformed, with stresses being high enough (at least transiently) to cause fracturing of garnet. Progressive subgrain rotation by migration of dislocations into walls bounding such subgrains is a mechanism that has been very widely proposed both in the material and earth sciences. There is a large body of published work supporting and describing this mechanism – indeed as noted by the reviewer "I think that there are many other contributions to the topic". It is not the aim of the current manuscript to provide an exhaustive review be we have now added the following additional references as a representative selection:

Hobbs, B.E.: Recrystallisation of single crystals of quartz. Tectonophysics, 6, 353-401, 1968.

Passchier, C.W., Trouw, R.A.J.: Microtectonics (2nd Edition), Springer, Heidelberg, 366 pp., 2005.

Reviewer 1, specific comments

RC: Line 138: if the fractures a dilatant there must be some material in the cracks. Can that be evaluated?

AC: No, these fractures remain empty, as implied by the word "unfilled" in the original text. These fractures are Mode 1 extensional fractures, which we think open during propagation of the seismic wave and immediately close, preventing any mineral filling.

MC: The word “dilatant” is perhaps better replaced with “extensional”, so the text now reads “*An apparent late generation of unfilled extensional fractures […]*”. All other similar references to “dilatant fractures” have also now been changed to “extensional fractures”.

RC: What about the other, fast diffusing elements, such as Mn and Mg? Differences in diffusion lengths would indicate different diffusion velocities and thus support the idea of a diffusional modification.

AC: In Figure 4 d) we present the profiles for Fe, Mg, Mn. Fe and Mg show the same diffusion length as Ca. Mn does not show any measurable modification throughout the crystal.

MC: This observation was missing in the text, therefore we added the following sentence for clarification: “*The length-scale for variation in Fe (X_{Alm}) and Mg (X_{Pyp}) is identical to that for Ca (X_{Grs}), whereas the Mn content (X_{Sps}) does not show any variation (Fig 4d).”*

RC: Lines 196-197: This diffusional modification is likely due to subgrain boundaries that might or might not be associated with subgrain rotations. This has been demonstrated in Konrad-Schmolke et al., 2007 (EJM). This should be discussed or at least mentioned.

AC: Since a subgrain is defined by a relative crystallographic rotation (commonly taken arbitrarily as between ca. 4° and 15°, when it is considered to be a “high-angle boundary” to a “new grain”, e.g. Urai et al., 1986), the generally accepted argument is that subgrain boundaries are always associated with subgrain rotations, as new dislocations are continuously added to the subgrain boundaries (e.g. Passchier and Trouw, 2005, p.43). We have added the reference to Konrad-Schmolke et al. (2007), as well as recent publications of Petley-Ragan et al. (2019), Jamtveit et al. (2018a,b, in press), Engi et al. (2018), Giuntoli et al. (2018) and Angiboust et al. (2017) when comparing and contrasting our “dry” results to fracture and diffusion in garnets in deep-seated rocks where fluid infiltration plays an important role.

We want to thank the anonymous reviewer for his critical review and suggestions. Below is a list of all comments from the reviewer (RC), answers from the authors (AC) and manuscript changes (MC).

Reviewer 2, general comment

RC: The main message of this manuscript is the occurrence of crystal plasticity in garnet at temperatures well below the laboratory derived data for the onset of crystal plastic deformation in garnet. The authors, therefore, state that laboratory data fail to explain the natural observations. Of course laboratory experiments are most often very simplified rendering extrapolation to natural systems rather challenging. Though, I miss a bit the explanation why the laboratory data does not match natural observations. Is it because the samples in the laboratory were even drier than the natural rock delaying the onset of crystal plastic deformation in the laboratory? Obviously there were some fluids present due to the occurrence of biotite. Though in some parts of the manuscript, the authors state that a Ca-rich garnet forms instead of epidote, because of the low water activity (line 290). Perhaps there was enough water around to facilitate crystal plastic deformation but not enough to stabilize epidote? I think it would improve the manuscript to discuss the role of fluids on crystal plastic deformation in more detail. This might also explain the discrepancy between laboratory data and the natural observations.

AC: We have added text in several places to expand the discussion of the apparent discrepancy with laboratory data, in particular considering the potential effects of strain rate and role of fluids. We agree that this should have been treated in more detail, which is why we now have a rather more nuanced approach, considering factors that may have an influence rather than just stating that there is a difference.

RC: Line 71: In this context I think crystal plastic deformation instead of ductile deformation is more appropriate.

AC: agree

MC: changed sentence: *"between brittle and crystal plastic deformation of garnet"*

RC: Lines 276-278: Did you investigate/find garnet crystals that were cut by a pseudotachylyte? Both studies that you cite, Austrheim et al. (2017) and Papa et al. (2018), demonstrate garnet crystals that are situated right next to a pseudotachylyte-bearing fault. I mention this, because as strain rate and stresses decrease very rapidly with increasing distance, the required stresses and/or strain rates at a few mm to the fault might not be sufficient anymore to extensively fragment garnet.

AC: In the text, we clearly state that *"Granulite facies garnet porphyroclasts in Musgravian peraluminous gneisses mylonitized during the Petermann Orogeny are almost invariably fractured, irrespective of their proximity to pseudotachylyte (Fig. 3)."* This is different than what was observed in the examples of Austrheim et al. (2017) and Papa et al. (2018) mentioned above, which is why we made such a clear statement originally. On the basis of this observation, we argue in the text that the whole rock was affected by high stresses during transient seismic events and that garnet fracturing is not restricted to the localized damage zone of a propagating fracture (Petley-Ragan et al, 2019; Austrheim et al., 2017) or thermal shock immediately adjacent to the high temperature pseudotachylyte (Papa et al., 2018).

RC: Line 286: Delete 'of some'.

AC: agree

MC: Typing error corrected.

RC: Lines 291-292: So everything is dry, but suddenly there is biotite? You should discuss the presence/absence of hydrous minerals a bit more.

AC: Biotite is a typical mineral of granulite facies assemblages up to the point of melting (with biotite then providing the water for "anhydrous" melting) and even then biotite is a common mineral in the restite assemblage. "Kinzigite", which is a typical "dry" lower-crustal granulite facies rock, is actually defined as having garnet + biotite. As noted by Pennacchioni and Cesare (1997), under upper amphibolite facies conditions, newly grown biotite can actually act as a sink for any free water available and the same will be true for the “dry” high pressure upper amphibolite (“sub-eclogitic”) facies conditions relevant to the current study.

Pennacchioni, G. & Cesare, B., 1997. Ductile-brittle transition in pre-Alpine amphibolite facies mylonites during evolution from water-present to water-deficient conditions (Mont Mary nappe, Italian Western Alps). Jour. Metm. Geol. 15, 777-791.

RC: Lines 304-305: Shimada et al. (1983) experimentally investigated that the angle changes from around 30 to approx. 45◦ with increasing pressure.

MC: The reference was added to the text: *“This plot is only qualitative, since the angle of internal friction could decrease towards higher pressure (Shimada et al., 1983).”*

RC: Lines 311-313: See comment above. As water seems important you should perhaps quantify the amount of water? There is some water present in the other field studies mentioned, but not very much. How should the presence of a fluid help to fragment the rock?

AC: As noted already in Wex et al. (2018), for the relevant pressure and temperature conditions, the presence of kyanite as the result of plagioclase breakdown, to the exclusion of clinozoisite / epidote, implies a water activity of less than ca. 0.004, according to Wayte et al. (1989) (as is also noted again in the current manuscript). The examples from Holsnoy all have extensive development of clinozoisite during eclogite formation.

RC: Figure 5: The difference between fracture types I and II is not very clear to me. The magnification at which the image was taken is quite low and therefore it is difficult to see subgrains.

AC: The step-size for this map was 2 micrometres, which is obviously a compromise due to the large area of the garnet, and individual points are still visible in the figure. Unfortunately, we do not have a higher resolution scan for the specific area. We hope that the subgrains are still visible as slight changes in colour and grey-values, as seen and highlighted in the red area. We admit that there is no genetic difference between the proposed fracture sets I and II and have therefore dropped any differentiation between the two.

MC: Figure 5 was changed in regard to the labelling of the fractures and the text was changed accordingly.

MANUSCRIPT INCLUDING CHANGES

Fracturing and crystal plastic behaviour of garnet under seismic stress in the dry lower continental crust (Musgrave Ranges, Central Australia)

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Highlights

- garnet deformed by fracturing and crystal-plasticity under dry lower crustal conditions
- Ca-diffusion profiles indicate multiple generations of fracturing
- diffusion is promoted along zones of higher dislocation density
- fracturing indicates transient high-stress (seismic) events in the lower continental crust

Abstract

Garnet is a high strength mineral compared to other common minerals such as quartz and feldspar in the felsic crust. In felsic mylonites, garnet typically occurs as porphyroclasts that mostly evade ~~intracrystalline~~crystal-plastic deformation, except under relatively high temperature conditions. The microstructure of granulite facies garnet in felsic lower-crustal rocks of the Musgrave Ranges (Central Australia) records both fracturing and crystal-plastic deformation. Granulite facies metamorphism at ~ 1200 Ma generally dehydrated the rocks and produced mm-sized garnets in peraluminous gneisses. A later ~ 550 Ma overprint under sub-eclogitic conditions (600-700 °C, 1.1-1.3 GPa) developed mylonitic shear zones and ~~with~~ abundant pseudotachylyte, coeval with the neocrystallization of fine-grained, high-calcium garnet. In the mylonites, ~~The~~ granulite-~~g~~facies~~ic~~ ~~fractured~~ garnet porphyroclasts ~~in mylonites show~~ ~~have high~~are enriched in calcium ~~content~~ along rims and fractures. However, ~~in certain cases,~~ these rims are locally narrower than ~~equivalent~~ otherwise comparable rims along original grain boundaries, indicating contemporaneous diffusion and fracturing of garnet. The fractured garnets exhibit internal crystal-plastic deformation, ~~that~~ which coincides with areas of enhanced diffusion, usually along zones of crystal lattice distortion~~s~~ and dislocation walls ~~and by~~associated with subgrain rotation recrystallization. Fracturing of garnet under dry lower crustal conditions, in an otherwise viscously flowing matrix, requires transient high differential stress, most likely related to seismic rupture, consistent with the coeval development of abundant pseudotachylyte.

Keywords

Garnet, Fracture, Crystal-Plasticity, Dry Lower Continental Crust, Pseudotachylyte, Seismicity

1 Introduction

A fundamental problem in geology is the limited preservation of processes in the rock record. This is especially the case for transient events, like earthquakes, traces of which are hardly preserved due to later reworking. The best indicators for seismicity in the rock record are pseudotachylytes (Sibson, 1975; Toy et al., 2011), although not every seismic event produces frictional melts and, once formed, ductile creep or later brittle fracturing may erase most traces (Sibson and Toy, 2006; Kirkpatrick and Rowe, 2013).

Garnet is stable in many metamorphic rocks over a large part of the pressure-temperature space, is commonly preserved, and is suitable for a range of geothermobarometers and geochronometers and their combination for geospeedometry (Lasaga, 1983; Caddick et al., 2010; Baxter and Scherer, 2013). Being a high strength mineral (Karato et al., 1995; Wang and Ji, 1999), both brittle and crystal plastic deformation are rarely observed in garnet when compared to the common matrix minerals of the crust, such as quartz and feldspar. However, Dalziel and Bailey (1968) already interpreted elongate garnets in ~~a~~ high grade mylonites ~~as~~ to be the result of crystal plastic ~~behavior~~behaviour~~.~~ and ~~Advancements~~ advancements since then in electron microscopy, and especially EBSD (electron backscatter diffraction), have allowed detailed investigation of garnet textures (Kunze et al., 1993; Prior et al., 2000, 2002).

Experimental deformation of garnet indicates that differential stresses on the order of a few GPa are required to produce shear fractures~~ (Wang and Ji, 1999)~~, and that the onset of ~~ductile~~ crystal plastic ~~behavior~~behaviour for strain rates typical of actively deforming regions (10^{-12} – 10^{-15} s^{-1}; e.g. Behr and Platt, 2011) should only occur~~s~~ at corresponding temperatures above ca. 750-640 ~~850~~ °C (Karato et al., 1995; Wang and Ji, 1999). The observation of fractured garnets in natural samples may therefore be linked to seismic stresses, as suggested by

Austrheim et al. (1996), who described fracturing of garnets during pseudotachylyte formation and fluid-assisted eclogitization of granulites. Trepmann and Stöckhert (2002) also interpreted the microstructure of fractured and offset garnets as evidence for syn-seismic loading and post-seismic creep. In addition, and, m. More recently, Austrheim et al. (2017) againalso associated both brittle (Austrheim et al., 2017; Engi et al., 2017; Angiboust etal., 2017; Giuntoli et al., 2018; Hawemann et al., 2018; Petley-Ragan et al., 2019) and associated crystal-plastic behaviorbehaviour (Austrheim etal., 2017; Petley-Ragan et al., 2019) of garnets has been related towith lower crustal seismic events in lower continental crust or deeply subducted continental fragments. Papa et al. (2018) interpreted similar deep-seated dilatant fracturing of garnet immediately adjacent to pseudotachylyte to be related to thermal shock due to frictional heating rather than to damage associated with propagation of the seismic rupture. Konrad-Schmolke et al. (2007) described enhanced diffusion of Mg along subgrain boundaries in garnet (but not of slow diffusing elements, such as Ca, Ti and Y) from meta-granitoid high pressure meta-granitoidrocks of the deeply subducted Sesia Zone (Western Alps).- However, in contrast to more recent studies in the Sesia Zone, which propose that precursor fracturing was crucial for dissolution–precipitation and diffusion processes in garnet (Engi et al., 2018; Giuntoli et al., 2018), they considered that there were no signs of crystal-plastic deformation in their garnet samples and concluded that a diffusion--induced dislocation migration and/or diffusion--induced recrystallisation process was responsible for development of the observed subgrain texture.

Here we present a study of garnet microstructures from lower crustal rocks of the Musgrave Block in Australia, which:

(1) illustrates the close association between brittle and ~~ductile~~ crystal-plastic deformation of garnet under well-established pressure-temperature conditions;
(2) infers deformation mechanisms from the observed microstructure;
(3) explores the close link between deformation and diffusion in garnet;
(4) complements other independent observations indicating transient high stresses in the lower crust.

2 Geological setting

2.1 Regional geology

The Musgrave Block is located in an intraplate position close to the ~~center~~centre of the Australian continent (inset Fig. 1). Amalgamation of the different cratonic blocks took place during the Musgravian Orogeny (1120-1200 Ma), which pervasively overprinted ca. 1550 Ma gneisses (Gray, 1978; Camacho and Fanning, 1995). The Petermann Orogeny (~550 Ma) produced a series of crustal-scale fault zones, most prominently the Woodroffe Thrust and the Mann Fault (Collerson et al., 1972; Major, 1973; Bell, 1978; Camacho and Fanning, 1995; Raimondo et al., 2010; Hawemann et al., 2018, 2019; Wex et al., 2017, 2018, 2019). The south-dipping Woodroffe Thrust has a top-to-the-north sense of shear, and juxtaposes the Fregon Subdomain in the south (hanging wall) against the Mulga Park Subdomain in the north (footwall). During the Musgravian Orogeny, the Mulga Park Subdomain attained amphibolite facies conditions while the Fregon Subdomain reached granulite facies (Camacho and Fanning, 1995; Scrimgeour et al., 1999; Scrimgeour and Close, 1999), and depleted the rocks of OH-bearing minerals (Wex et al., 2018; Hawemann et al., 2018).

The Woodroffe Thrust hosts one of the largest occurrences of pseudotachylyte worldwide (Camacho et al., 1995), but all larger scale shear zones in the hanging wall also show abundant pseudotachylyte that developed under lower crustal conditions (Camacho, 1997; Hawemann et al., 2018). Deformation in the Fregon Subdomain associated with the Petermann Orogeny is concentrated along the sub-eclogitic (~650 °C, 1.2 GPa) Davenport Shear Zone and the North Davenport Shear Zone (Fig. 1), with little discernible overprint of the earlier granulites in between (Camacho et al., 1997). The Davenport Shear Zone is a WNW-ESE-striking, strike-slip zone, with a near horizontal stretching lineation. Deformation inside the Davenport Shear Zone itself is heterogeneous and strongly localized (Hawemann et al., 2019).

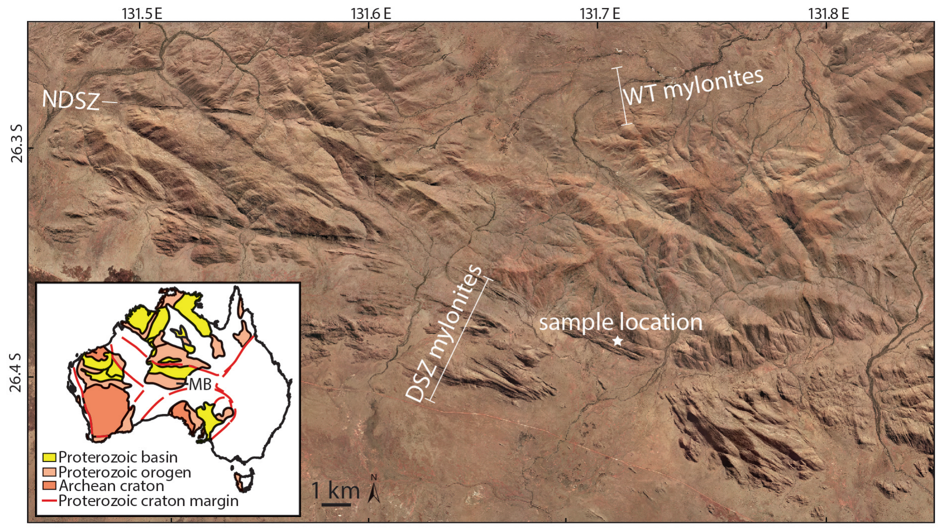

Figure 1: Airborne imagery of the study area with sample location (26.3849 S, 131.7067 E) in the Davenport Shear Zone (DSZ). NDSZ = North Davenport Shear Zone, WT = Woodroffe Thrust. Image from the Department of Primary Industries and Regions, South Australia (PIRSA), 2012. Inset: Location of the Musgrave Block (MB) in between the amalgamated Australian Cratons. Modified after Evins et al. (2010)

2.2 Sample description

Fractured garnet is ubiquitous in the Fregon Subdomain and is not exclusively found in association with pseudotachylyte veins. However, this study focuses on a representative outcrop for which field relationships, metamorphic, and deformation conditions have been well established (F68, Hawemann et al., 2018; 26.3849 S, 131.7067 E). This outcrop consists of a quartzo-feldspathic mylonite~~,~~ with ~~millimeter~~millimetre-sized, granulite facies garnets, ~~that~~ and includes multiple pseudotachylyte veins and breccias. Pseudotachylytes in the studied outcrop are sheared, as indicated by elongated clasts (Fig. 2a, c), and show the same stretching lineation as the host mylonite. The original discordant relationship to the host foliation is still preserved, with the crosscutting relationship most obvious in sections ~~and cuts~~ perpendicular to the stretching lineation (Fig. 2b).

The syn-mylonitic assemblage associated ~~to~~ with the Petermann overprint of the felsic granulites is Qz+Kfs+Pl+Gt+Bt+Ky+Ilm+Rt (mineral abbreviations following Whitney and Evans, 2010), and is similar to that of the associated sheared pseudotachylyte (Qz+Kfs+Pl+Gt+Bt+Ky+Rt) (Hawemann et al., 2018). The fine-grained garnet growing within the pseudotachylyte gives the rock its macroscopic caramel-~~color~~colour ~~in macroscopic images~~ (Fig. 2). ~~Fractured~~ Larger fractured garnets within the granulites are clearly recognizable in polished hand specimens (Fig. 2c) and are very apparent in thin section (Fig. 3). The metamorphic conditions during shearing of this pseudotachylye are estimated at ~600 °C and ~1.1 GPa (Fig. 7 of Hawemann et al., 2018).

Figure 2: Sheared pseudotachylyte in a view orthogonal to the foliation of host felsic mylonite, and looking perpendicular (a) and parallel (b) to the stretching lineation. c) Polished hand specimen of a sheared pseudotachylyte breccia with the caramel-coloured foliated pseudotachylyte matrix including elongated clasts and an elongate fragment of mafic granulite. The host rock shows ~~millimeter~~millimetre-sized garnets with fractures. Plane of the polished surface is perpendicular to the foliation and parallel to the stretching lineation.

3 Garnet microstructure and compositional variation

3.1 Optical microstructure

Granulite facies garnet porphyroclasts in Musgravian peraluminous gneisses mylonitized during the Petermann Orogeny are almost invariably fractured, irrespective of their proximity to pseudotachylyte (Fig. 3). Large garnet porphyroclasts (>1 mm) are typically slightly elongated with their long axis parallel to the foliation, which is attributed at least partially to resorption. Fractures in garnets often show offsets ~~in~~ on the order of a few 100 µm. It is not possible to determine whether these offsets are primarily due to the initial shear fracture or result from subsequent sliding during ongoing ductile shear. Moreover, no consistent sense of shear can be derived from the offsets (Fig. 3a, b). These discrete fractures are sub-planar, commonly have a consistent orientation at a moderate angle to the foliation, and locally occur in conjugate sets (Fig. 3b). Wide fractures are filled with biotite, kyanite and quartz (Fig. 4b). A~~n apparent~~ later generation of unfilled ~~dilatant~~ fractures, without any discernible offset, is oriented perpendicular to both the foliation and stretching lineation (Fig. 3b). Garnet porphyroclasts commonly contain rutile exsolution lamellae and inclusions of monazite and kyanite (Fig. A1). The latter are present as aggregates with an overall prismatic shape, possibly representing pseudomorphs after sillimanite (Camacho and Fitzgerald, 2010).

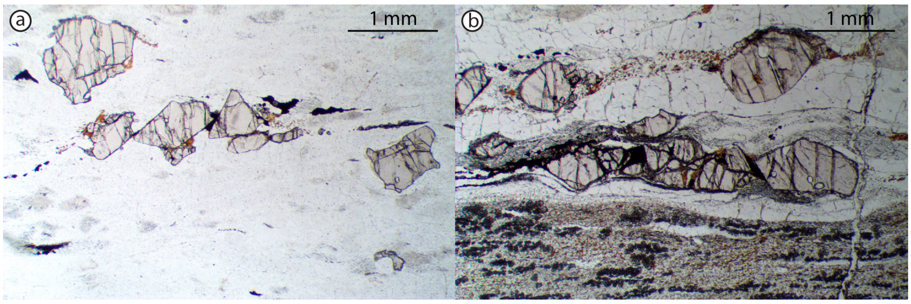

Figure 3: Thin section photomicrographs in plane polarized light of fractured garnets away from pseudotachylyte (a), and close to sheared and recrystallized pseudotachylyte in the lower part of the figure (b). The dark trails of grains elongated in the foliation of the sheared pseudotachylyte are small new garnets. Section is perpendicular to the foliation and parallel to the stretching lineation.

3.2 Analytical techniques

Quantitative mineral compositions were measured with a JEOL JXA-8200 electron probe micro-analyzer (EPMA), equipped with a tungsten filament, at the Institute of Geochemistry and Petrology at ETH Zurich (Switzerland). Natural standards were used for quantification, and, when available, natural garnet standards were preferred. To reach a spatial resolution of about 1 µm, an acceleration voltage of 10 kV was set (Fig. 8 in Hofer and Brey, 2007). Elemental maps were acquired using energy wavelength-dispersive spectrometers in parallel for calcium, to increase the signal-to-noise ratio. Backscatter electron images (BSE), energy-dispersive spectrometry (EDS) and electron backscatter diffraction (EBSD) mapping was carried out on a Quanta 200F field emission gun (FEG) scanning electron microscope at the ScopeM (Scientific Center for Optical and Electron Microscopy, ETH Zurich). EBSD maps were collected with an acceleration voltage of 20 kV, a sample tilt of 70° and a working distance of 15 mm. Data were post-processed using chemical indexing with the software OIM 7 by EDAX. When necessary, three different clean-up techniques were used: ~~neighbor~~neighbour confidence index correlation, ~~neighbor~~neighbour orientation correlation and grain dilation. Point and map analyses, as well as BSE images, were combined for correlation with optical microscope images in a QGIS-project (Open Source Geospatial foundation). Two lamellae were cut with a focused ion beam (FIB) for transmission electron microscopy (TEM). The microscope used for TEM is a Tecnai F30 with a FEG source operated at 300 kV and equipped with a Gatan 794 MultiScan CCD (ScopeM, ETH Zurich).

3.3 ~~Compostional~~Compositional gradients

Granulite facies garnet has a homogeneous composition of X_{Alm} 0.54, X_{Pyp} 0.40, X_{Grs} 0.03, X_{Sps} 0.03, whereas garnet neocrystallized during the Petermann Orogeny is more Ca-rich (X_{Alm} 0.48, X_{Pyp} 0.28, X_{Grs} 0.22, X_{Sps} 0.02). Grain boundaries of granulite facies garnet and fractures are decorated with a Ca-enriched rim, 20 to 40 µm wide (Fig. 4c). ~~The enrichment is mostly concentric, also affects resorbed areas of the garnet and is therefore most likely the result of diffusion (Camacho et al., 2009).~~ The length-scale for variation in Fe (X_{Alm}) and Mg (X_{Pyp}) is identical to that for Ca (X_{Grs}), whereas the Mn content (X_{Sps}) does not show any variation (Fig 4d).~~The diffusion length for iron and magnesium is identical to Ca, while the manganese content does not show any variations (Fig 4c).~~ Neocrystallized garnet is present where the grain boundary is in contact with, or close to, plagioclase. The outermost rim of remnant garnet has the same composition as the neocrystallized garnet (Fig. 4d, profile 1). The ~~granulitic~~ granulite-facies plagioclase is partially transformed to a more Na-rich plagioclase with needle shaped inclusions of kyanite (bottom of Fig. 4e). This reaction provides Ca for the observed diffusion into garnet (Camacho et al., 2009).

Commented [n1]: This text is eliminated here because it is interpretation and best considered the discussion section below.

Along fractures across the porphyroclasts, the Ca enrichment is narrower than along the grain boundaries and the grossular component only reaches up to about X_{Grs} 0.1 (Fig. 4d, profile 2). Compositional gradients are also present around inclusions in garnet connected to the outer garnet boundary, providing evidence of Ca diffusion along grain boundaries (right part of Fig. 4c, profile 3 in Fig 4d). Profile 4 (Fig. 4d) was measured next to a kyanite inclusion: the diffusion length is still comparable to those of profiles 1-3, but Ca concentrations are much lower. Ca probably diffused along fractures (invisible in the plane of the thin section) towards the inclusion. In summary, the diffusion length at the original grain boundaries is maximized where in contact with plagioclase, and otherwise constant at about 20 µm width. However, variations in diffusion lengths do occur around garnet fragments, without any correlation with the proximity to plagioclase, although the exact relationship in the third dimension is unknown. Surfaces with limited diffusion can often be identified as fracture surfaces, which were exposed to diffusion for a shorter time than original grain boundaries (Fig. 4e). Fractures oriented perpendicular to the foliation and stretching lineation lack any signs of diffusion and are therefore interpreted as later stage ~~dilatant~~ extensional fractures.

Some garnets display more complicated compositional patterns, with zones >100 µm of Ca enrich~~e~~ment extending into the porphyroclast's interior, which are not associated with fractures (e.g. the garnet fragment on the far right in Figure 4e). EBSD ~~-~~analysis highlights that the three fragments in the right part of Figure 4e most likely originated from the same grain, as they share a common rotation axis (Fig. 4f). The ~~colors~~colours in the inverse pole figure map are not solid, reflecting slight variations of orientation within the crystal. Furthermore, the image quality map shows areas of suppressed Kikuchi patterns (grey value) suggestive of higher dislocation density and therefore possible subgrain boundaries (Fig. 4f). The misorientation angle map (Fig. 4g) reveals a complex pattern of varying crystal orientation (all within the order of 5°) in the fragments, with very distributed zones connected to the edges of the crystal, triangular-shaped zones of misorientation (upper left of Fig. 4g), and discrete zones (lower right of Fig. 4g). The discrete zones of misorientation, about 5 µm wide, correlate well with the Ca-enriched zones (compare Fig. 4e, f, garnet fragment on the right).

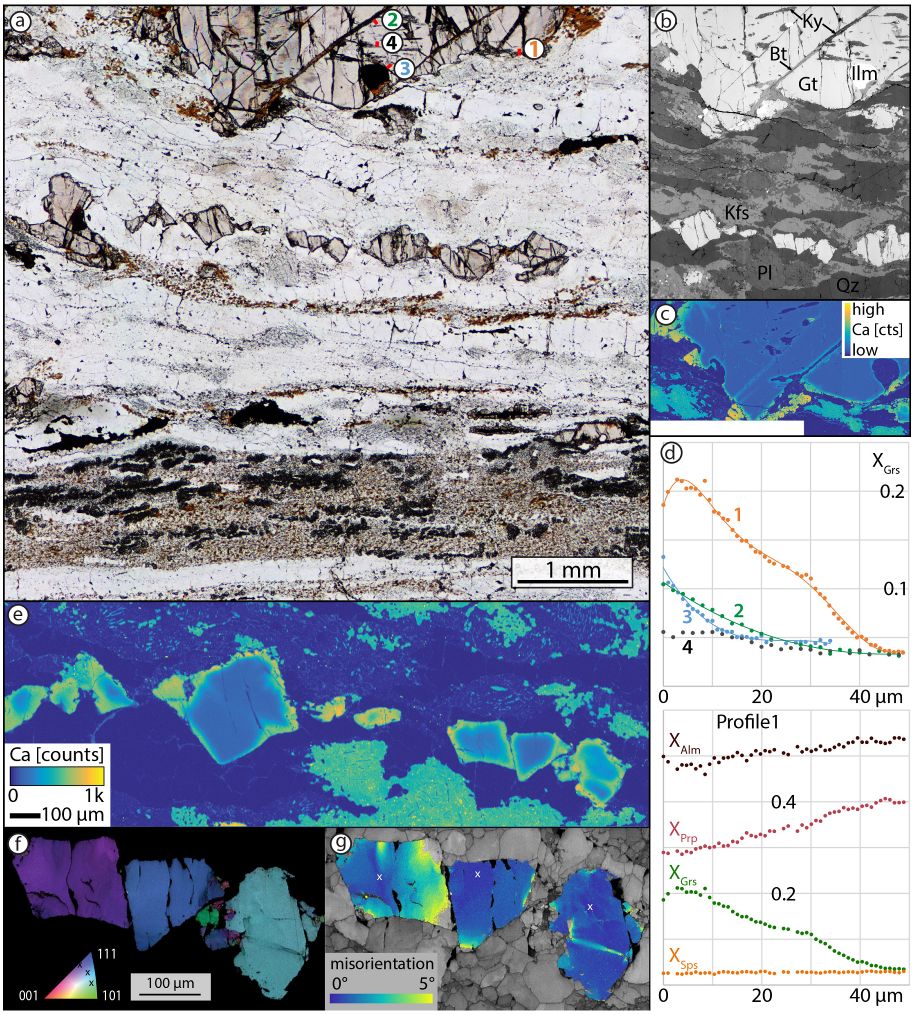

Figure 4: a) Plane polarized light image of thin section with fractured garnets and a pseudotachylyte vein in the lower part of the image. b) BSE image of the upper area of (a), with same scale as (a). c) EPMA X-ray map for Ca reveals an enrichment ~~the~~ in thin ~~diffusion~~ gradational rims along grain boundaries~~,~~ and fractures, and within neocrystallized garnet (euhedral, orange). d) Grossular component profiles indicated on (a) (~~Profile~~ profile lines are not to scale for the sake of visibility)~~;~~ and compositional profiles for four garnet end-members in profile 1. e) EPMA X-ray map for Ca for the garnet fragments in the center of (a). Note the uneven colours in the plagioclase and the blue kyanite needles. f) Inverse pole figure map with superimposed image quality map for garnet fragments shows a common rotation pole. g) Misorientation map relative to reference point for each fragment reveals internal lattice distortions.

3.4 Texture of deformed garnets

Two to three orientations of fractures are generally present in a single garnet crystal and coincide with the trace of the (101)-plane derived from EBSD data (Fig. 5a, b). Fracture set (I) in the example of Figure 5a is often associated with a relative rotation of both sides, as visible from the difference in ~~color~~colour. In the lower part of the grain, where the fracture density is very high, more subgrains are present. The subgrain spatial density increases towards the original grain boundary and some subgrains are "eroded" by ductile shearing and strung out along the foliation. This demonstrates that ductile shearing outlasted subgrain formation and fracturing. ~~Subgrains of less than 10 µm in size formed in the fracture plane (III in Fig. 5a).~~ The fractures described above are all crosscut by ~~dilatant~~ extensional fractures (set I~~I~~II in Fig. 5a), oriented perpendicular to the stretching lineation and foliation, which do not show any associated distortion of the crystal lattice.

The garnet porphyroclast of Figure 5c shows a central fracture as well as a set of two other parallel fractures. The central fracture is the only one with significant offset and is filled with kyanite and quartz. This fracture displays misorientations of more than 5° towards the right-hand side of the scan, but none towards the left-hand side. In the lower left corner of the fragment, subgrains are observed with misorientations, relative to the average orientation, typically in the range of 10°. Misorientation axes are often parallel to (111) and (101). The lowermost fragment shows a wide zone of progressive rotation. The chemical profile in Figure 5e shows the highest Ca counts towards the boundaries of the porphyroclasts and, internally, towards two fractures. The larger fracture with apparent offset of the two garnet fragments exhibits a less well-developed zone of ~~calcium~~Ca enrichment~~efficient calcium diffusion~~ when compared to the tight fracture with introduced lattice distortion.

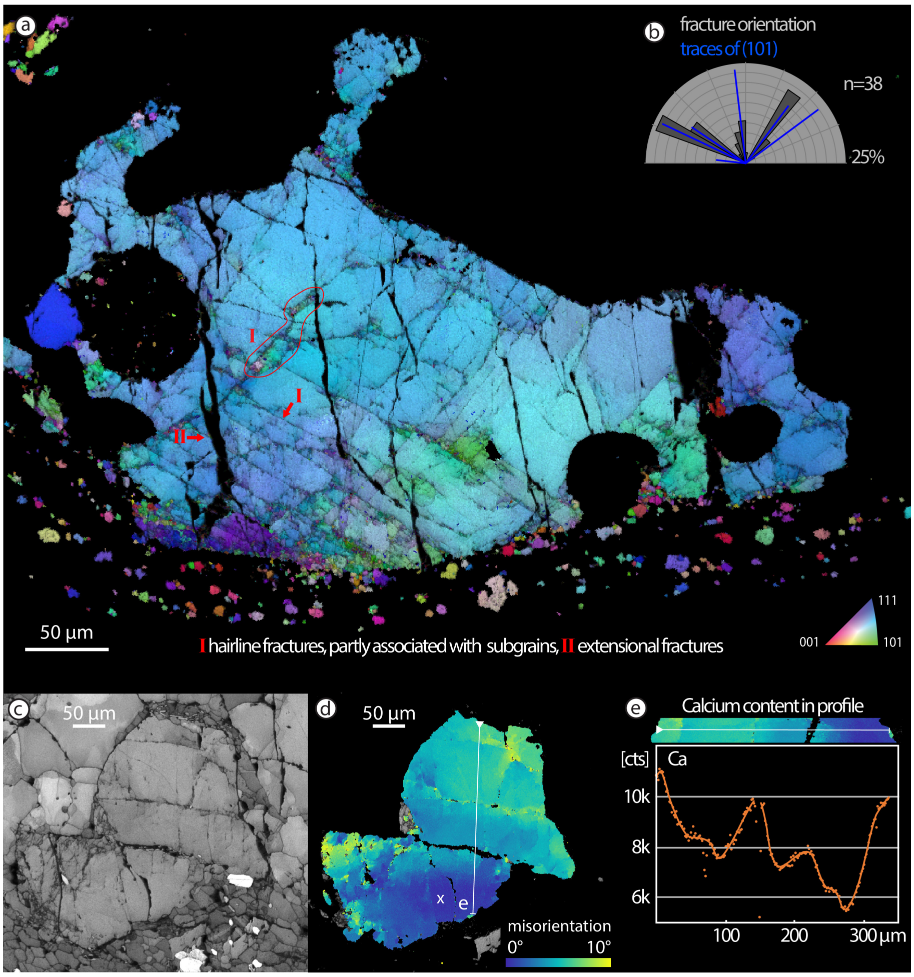

Figure 5: a) Inverse pole figure map of fractured garnet with three dominant orientations of fractures. b) Rose diagram correlating traced fracture orientations and (101)-planes for garnet in (a). c) Image quality map of a fragmented garnet with subgrains. d) Misorientation plot (with respect to the point marked with the white x) shows long wavelength bending in the lower fragment and distortion in the crystal lattice induced by a fracture in the upper fragment. e) EDS-calcium counts for the profile marked as a thin white line in (d).

3.5 TEM investigations

The garnet fragment of Figure 4g was further investigated using TEM, as it includes a narrow zone of misorientation without fractures and is therefore suitable for preparation of FIB-lamellae. As visible in Figure 6a (around profile 1), the image quality map shows a well-defined narrow, darker graeey band, possibly indicating high dislocation density. The zone is even more evident in the misorientation plot (Fig. 6b) and changes from about 5 µm wide, with discrete boundaries to the right, to a wider (> 10 µm) band towards the left of the image. In the upper left part of the image, a subgrain boundary with > 5° misorientation transitions into a zone of gradual misorientation. The misorientation axis is consistently parallel to (101) with minor rotation around (111) (Fig. 6c, Fig. A2). Misorientation profiles reveal a slight asymmetry within the narrow band, where the lower boundary appears to be sharper. Misorientation changes more gradually within the wider portion of the misorientation band. Locally, subgrains developed with discrete boundaries, documenting a misorientation of usually around 5-10° (profile 3 in Fig. 6d). The FIB-lamella was cut across the narrow band of misorientations (Fig. 6e). The lower boundary corresponds to a narrow discrete zone, without visible dislocations (Fig. 6f). The upper boundary is marked by a series of dislocation walls and only a few free dislocations are visible, which are often organized in arrays (Fig. 6g, h). The existence of dislocation walls and subgrain boundaries indicates recovery by dislocation climb (e.g., Hobbs, 1968; Passchier and Trouw, 2005).

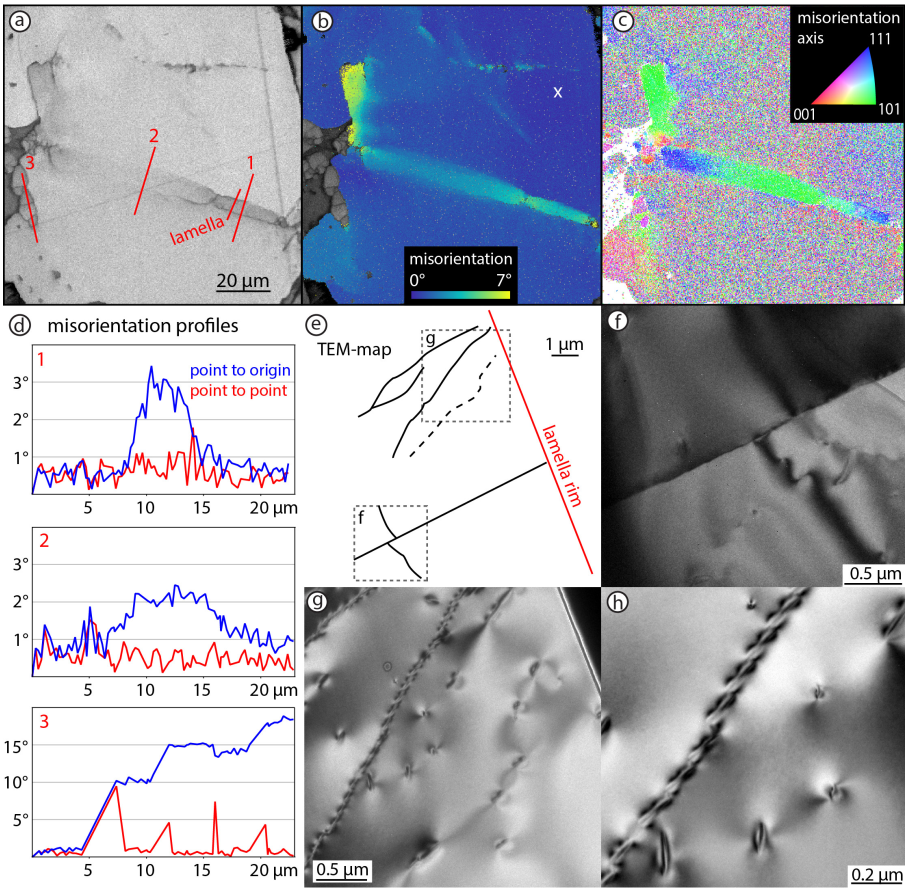

Figure 6: a) Image quality map of the garnet fragment (compare Fig. 4f) with darker zones that can be interpreted as areas of high dislocation density and location of the FIB-lamella. b) Misorientation plot with respect to the reference point (marked with the white x) shows a discrete zone of misorientation, which has discrete boundaries in the right part of the image, but is more distributed towards the left. c) Misorientation axis plot with respect to the average orientation of the grain shows a consistent rotation around the (101) and (111) axes. For pole figure plots, see Fig. A2. d) Misorientation profiles indicated in a), for (1) the narrow zone, (2) the more distributed zone and (3) for subgrains. e) Overview sketch of the FIB-lamella used for TEM-analysis for correlation with the EBSD data. f) Sharp contrast boundary in the lower part of the lamella. g) Two dislocation walls with a few free dislocations, which are partly linking up parallel to the dislocation walls. h) Detail of the ~~center~~ centre of (g)

4 Discussion

Garnets in this study show evidence for both brittle and ductile deformation under relatively low temperatures of about 600 °C, as inferred from synchronous diffusion and ductile shearing of pseudotachylyte (Hawemann et al, 2018). This is ~~well~~ below the experimentally determined values for the onset of crystal-plastic deformation of garnet (Wang and Ji, 1999) at the higher strain rates considered typical of mylonitic shear zones (> 10^{-14} s^{-1})~~(>850 °C; Wang and Ji, 1999)~~. In contrast to experiments, many natural examples (Vollbrecht et al., 2006; Bestmann et al., 2008; Austrheim et al., 2017) indicate crystal plasticity of garnet at lower temperatures between 650 °C and 700 °C~~, challenging the reliability of extrapolation of experimental data to natural conditions~~.

The presence of microstructures and ~~-~~textures consistent with dislocation climb and recovery, as well as subgrain rotation, in garnet at around 600 °C is in agreement with previous studies (Bestmann et al., 2008; Massey et al.,2011). No evidence for grain boundary sliding is observed, since subgrains show rotation around a specific crystallographic axis. Rotation around (111) and (101) is in accordance with the slip systems described by Voegelé et al. (1998).

Multiple generations of overprinting fractures with different orientation demonstrate repeated fracturing events. ~~Tensile~~ Extensional fractures do not show any induced lattice distortion or diffusion and therefore occurred after the temperature ~~was~~ had decreased to values too low for diffusion (Camacho et al., 2009), possibly during exhumation (compare Prior, 1993 and Ji et al., 1997).

In contrast to the observations of Austrheim et al. (2017), ~~and~~ Papa et al. (2018) and Petley-Ragan et al. (2019) from other examples in the deep continental crust, no "explosive fracturing” ~~or~~, “shattering” or “fragmentation” of garnet is observed in relict porphyroclasts immediately adjacent to pseudotachylyte. The fractures described here are generally planar and often consistently oriented, in some cases showing single and conjugate shear offsets. Fractured garnet is not restricted to the boundary with pseudotachylyte and is still present even in samples without pseudotachylyte, where the nearest pseudotachylyte is possibly many ~~meters~~ metres or more away. Fracturing in this case cannot be related to thermal shock (Papa et al., 2018) or localized high stress due to (seismic) fracture propagation (Austrheim et al., 2017; Petley-Ragan et al., 2019), but must reflect a larger scale distribution of differential stresses in the lower crust that were, at least transiently, high enough to cause brittle garnet failure (Hawemann et al., 2019). This could be due to stress pulses from earthquakes in the shallower brittle regime (Trepmann and Stöckhert, 2002; Ellis and Stöckhert, 2004; Jamtveit et al., 2018a, b; Jamtveit et al., in press) or a more local, lower crustal source due to jostling of less-deformed strong blocks within an irregular shear zone network (Hawemann et al., 2019).

The narrower Ca diffusion profiles on some fractures relative to garnet rims and crosscutting relationships suggest that fracturing was recurrent under sub-eclogite facies metamorphic conditions, as also indicated by the occasional presence of kyanite in ~~some of~~ some fractures. The presence of kyanite needles and the absence of zoisite/clinozoisite or epidote, as a breakdown product of plagioclase during sub-eclogitic metamorphism (Fig. 3b), indicate relatively dry lower crustal conditions (Hawemann et al., 2018). According to Wayte et al. (1989), this indicates a water activity of < 0.004, calculated for rocks of comparable composition and P-T conditions. However, new biotite did form in ~~dilatant~~ fractures across relict garnet, so conditions were probably not strictly anhydrous. The sheared and recrystallized pseudotachylyte developed a similar synkinematic assemblage as the host mylonite, demonstrating that there is also no marked partitioning of water into the frictional melt, which implies little free or bound water available in the original source rock (e.g. Wex et al., 2018). The effect of pore-fluid pressure on the effective confining pressure must therefore have been negligible.

As reported in Hawemann et al. (2019), the dynamically recrystallized quartz grain size and microstructure in the host rock mylonites indicates that long-term flow stresses were not particularly high, on the order of less than 10 MPa. The ambient pressure of ca. 1.1-1.2 GPa determined for the host rocks should therefore be close to the lithostatic value (Mancktelow, 2008). Figure 7 shows a simple linear plot of the Mohr-Coulomb failure criterion for an angle of internal friction of 30° (coefficient μ = 0.6), a lithostatic load of 1.2 GPa, and no pore fluid pressure. This plot is only qualitative, since the angle of internal friction could decrease towards higher pressure (Shimada et al., 1983). However, the summary of experimental results in Byerlee (1978) indicates that there may be little change at least up to pressures similar to those considered here. It follows that the differential stress for fracture initiation must have been of the same order as the confining pressure (Fig. 7). As discussed in detail in Hawemann et al. (2019), such high differential stresses, leading to garnet fracture and the development of abundant pseudotachylyte, can only have been transient and presumably related to repeated short-term seismic events in the lower continental crust (Hawemann et al., 2018; Jamtveit et al, 2018a, b; Menegon et al., 2017). The lack of shattered garnet adjacent to pseudotachylyte in these samples may reflect drier conditions relative to those in the Bergen Arc (Austrheim et al., 2017) and Mont Mary (Papa et al., 2018). The samples studied could therefore represent one end-member of the lower continental crust, where deformation occurs without the initial presence or influx of free water during fracturing and subsequent crystal-plastic deformation.

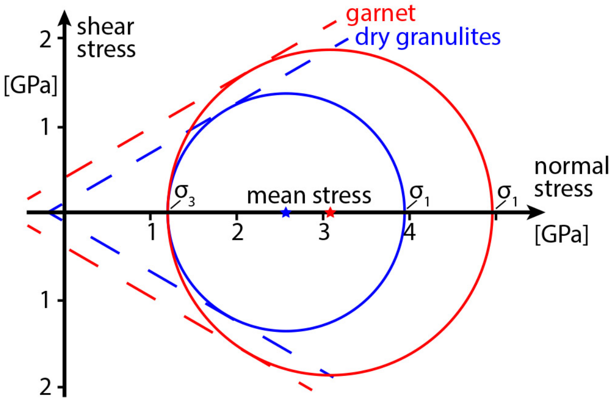

Figure 7: Mohr circles for fracturing of dry granulites and garnet at 1.2 GPa lithostatic load

5 Conclusions

In dry lower continental crust deformed under conditions of ca. 600 °C and 1.1 GPa, garnet shows both single and conjugate sets of shear fractures, fractures with associated subgrains and induced lattice damage around fractures, subgrain formation without fracturing, and late-stage ~~dilatant~~ extensional fractures. Most of these fractures show a strong crystallographic control, with fracturing preferentially occurring along the (101) planes of garnet. Dynamic recrystallization is evident from inferred subgrain rotation recrystallization and recovery is manifested by the presence of dislocation walls. The observed microstructures of garnets are interpreted to record transient high stresses during deep seismic events in the lower crustal Fregon Subdomain~~,~~. This~~which~~ is also indicated by the abundant occurrence of pseudotachylyte developed under similar lower crustal conditions and, possibly, by the variability of recrystallized quartz grain sizes including values down to a few ~~micrometers~~micrometres (Hawemann et al. 2009b). The studied example represents one end-member of lower continental crustal ~~behavior~~behaviour where, because of earlier metamorphic dehydration and the intracratonic position well removed from the plate margin, rocks were initially dry and water was not introduced during fracturing and crystal-plastic deformation.

Author contributions

All authors listed took part in at least two of the three field seasons. NM assisted FH in the data collection and interpretation. AC's and GP's knowledge in the field of garnet deformation and diffusion processes were crucial in preparing the manuscript. SW contributed to the microprobe and SEM work. FH prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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Data ~~Availabilty~~Availability

All data used in this paper can be accessed through the depository of the Open Science Framework here: https://osf.io/yrzgh/

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Appendix

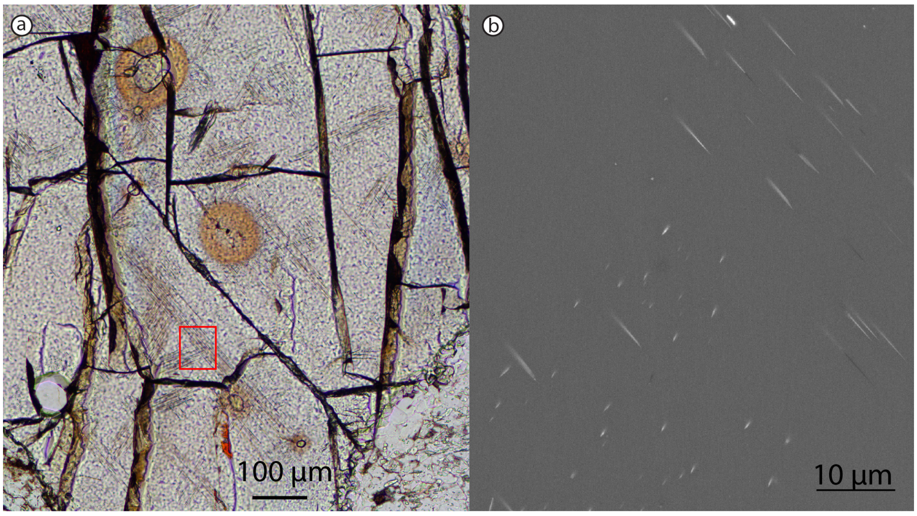

Figure A1: Thin section image in plane polarized light of a garnet crystal with monazite inclusions (with halos) and rutile-exsolution needles. b) BSE-image of the area indicated with the red box.

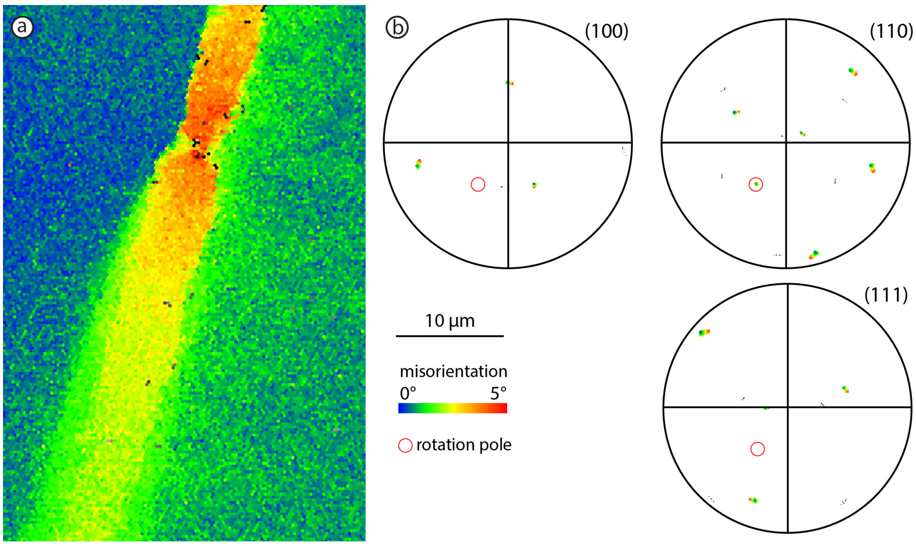

Figure A2: a) Misorientation map-detail for Fig. 6b), with b) pole figure plots for garnet axis with the same ~~color~~colour scheme. The plots reveal a rotation around a (101)-axis, as indicated by the red circle.