https://doi.org/10.5194/se-2019-110
Preprint. Discussion started: 14 June 2019

Fracturing and crystal plastic behavior 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

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mostly evade 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 shear zones and with abundant pseudotachylyte, coeval with the neocrystallization of fine-grained, high-calcium garnet. The granulitic fractured garnet porphyroclasts in mylonites show high calcium content along rims and fractures. However, in certain cases, these rims are narrower than equivalent rims along original grain boundaries, indicating contemporaneous diffusion and fracturing of garnet. The fractured garnets exhibit internal crystal-plastic deformation, that coincide with areas of enhanced diffusion, usually along zones of crystal lattice distortions and dislocation walls and by 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

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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. Dalziel and Bailey (1968) interpreted elongate garnets in a high grade mylonites as the result of crystal plastic behavior. 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 only occurs at temperatures above 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, Austrheim et al. (2017) also associated brittle and crystal-plastic behavior of garnets with lower crustal seismic events. Papa et al. (2018) interpreted similar deep-seated dilatant fracturing of garnet

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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.

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 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 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; 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,

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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).

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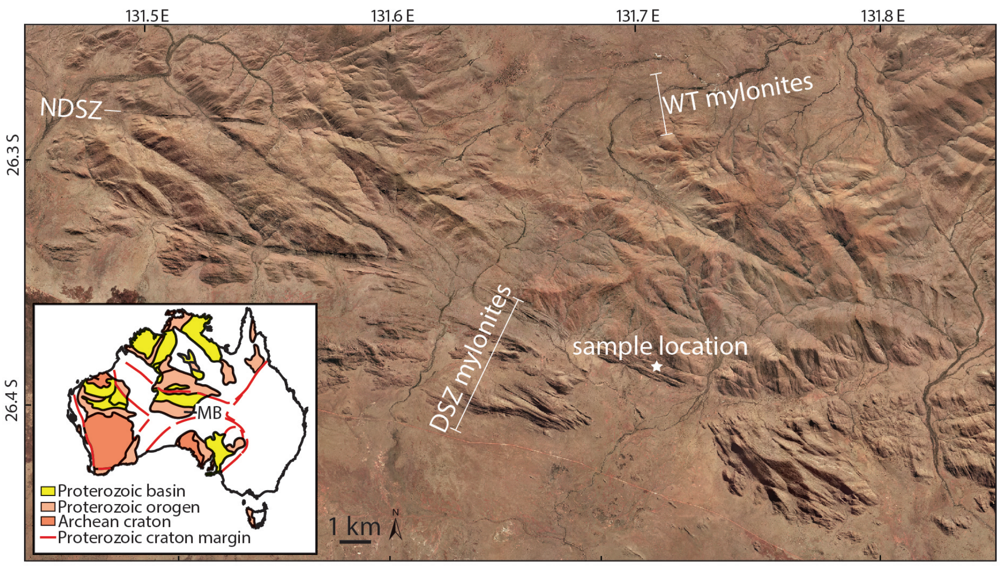

Figure 1: Airborne imagery of the study area with sample location (26.3849 S, 131.7067 E) in the Davenport Shear Zone (DSZ). NDSZ = North Davenport Shear Zone, WT = Woodroffe Thrust. Image from the Department of Primary Industries and Regions, South Australia (PIRSA), 2012. Inset: Location of the Musgrave Block (MB) in between the 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-sized, granulite facies garnets, that 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 and cuts perpendicular to the stretching lineation (Fig. 2b).

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The syn-mylonitic assemblage associated to the Petermann overprint of 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). The fine-grained garnet growing within the pseudotachylyte gives the rock its caramel-color in macroscopic images (Fig. 2 Fractured garnets 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).

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

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

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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 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). An apparent late generation of unfilled dilatant fractures 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).

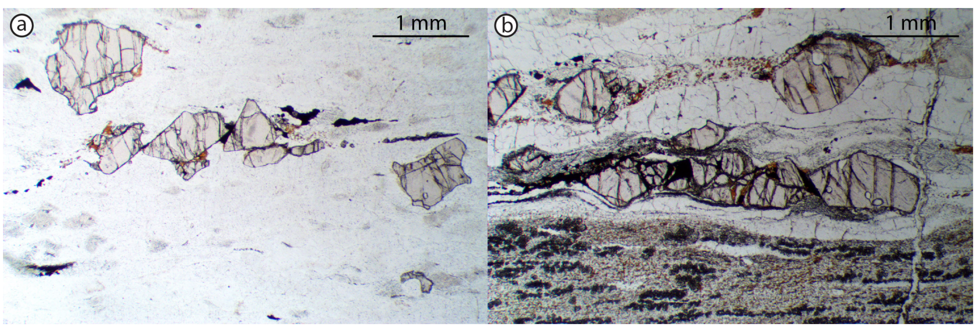

Figure 3: Thin section photomicrographs in plane polarized light of fractured garnets away from pseudotachylyte (a), and close to sheared and recrystallized pseudotachylyte in the lower part of the figure (b). The dark trails of grains elongated in the foliation of the sheared pseudotachylyte are small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

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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 confidence index correlation, neighbor 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 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}

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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). 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 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).

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 fractures.

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Some garnets display more complicated compositional patterns, with zones >100 µm of Ca enrichement 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 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).

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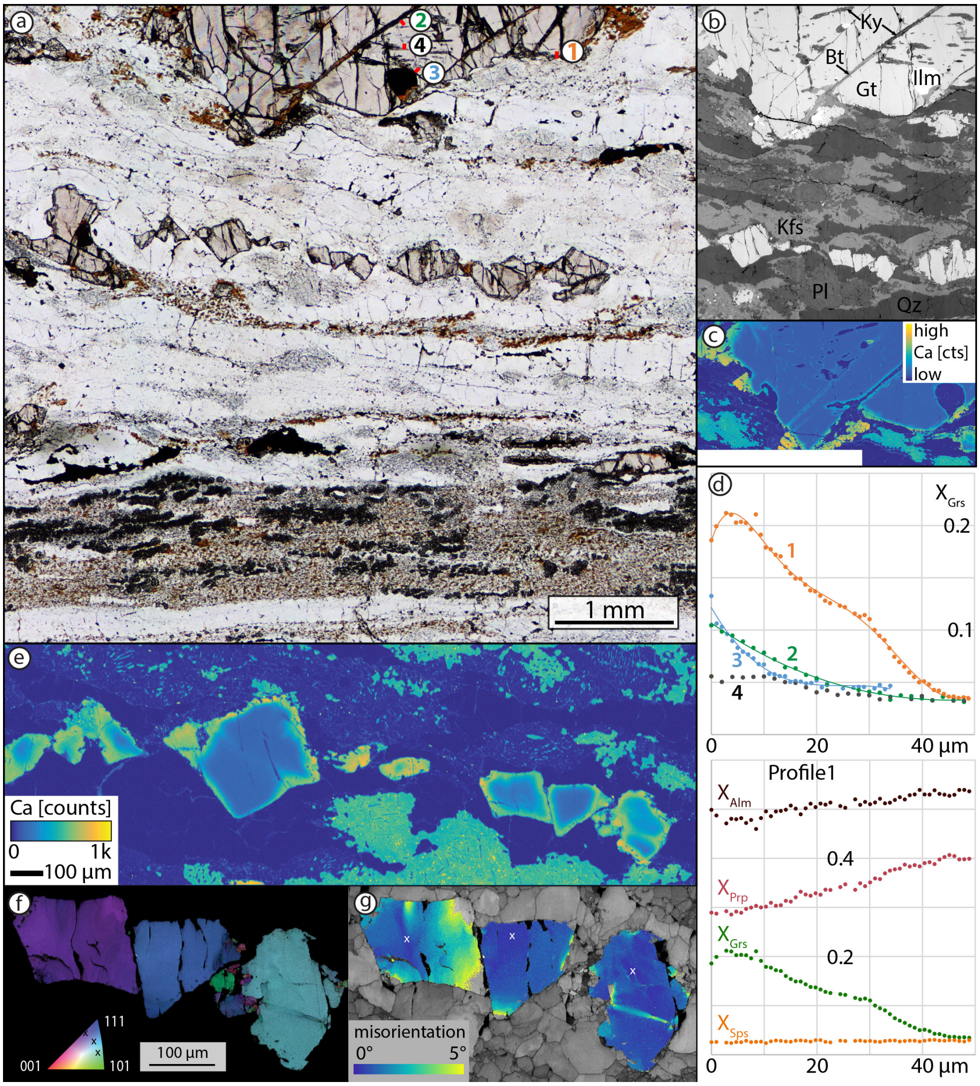

Figure 4: a) Plane polarized light image of thin section with fractured garnets and a pseudotachylyte vein in the lower part of the image. b) BSE image of the upper area of (a), with same scale as (a). c) EPMA X-ray map for Ca reveals the thin diffusion rim along grain boundaries, fractures, and neocrystallized garnet (euhedral, orange). d) Grossular component profiles indicated on (a) (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 colors in the plagioclase and the blue kyanite needles. f) Inverse pole figure map with superimposed image quality map for garnet fragments shows common rotation pole. g) Misorientation map relative to reference point for each fragment reveals internal lattice distortions.

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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. In the lower part of the grain, where the fracture density is very high, 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 (II in Fig. 5a). The fractures described above are all crosscut by dilatant fractures (set III 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 efficient calcium diffusion when compared to the tight fracture with introduced lattice distortion.

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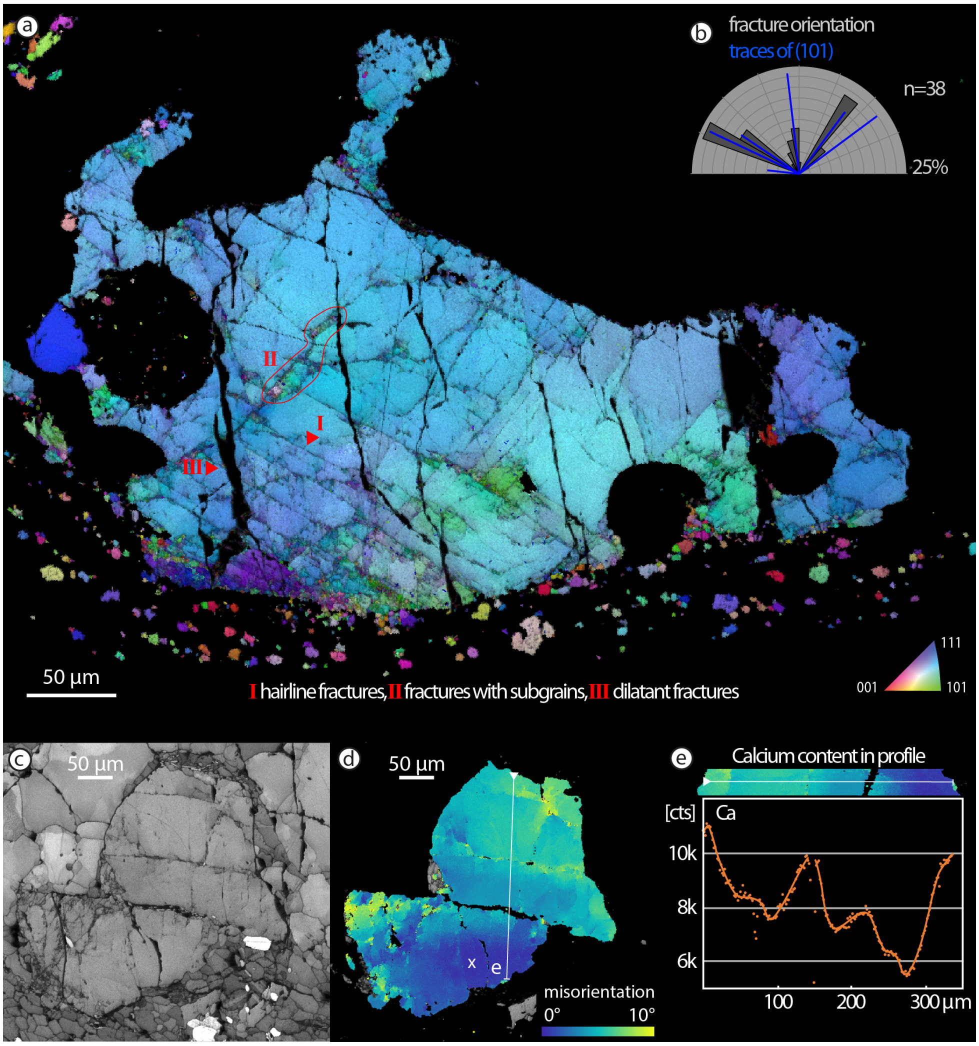

Figure 5: a) Inverse pole figure map of fractured garnet with three dominant orientations of fractures. b) Rose diagram correlating traced fracture orientations and (101)-planes for garnet in (a). c) Image quality map of a fragmented garnet with subgrains. d) Misorientation plot (with respect to the 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).

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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 grey 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 indicates recovery by dislocation climb.

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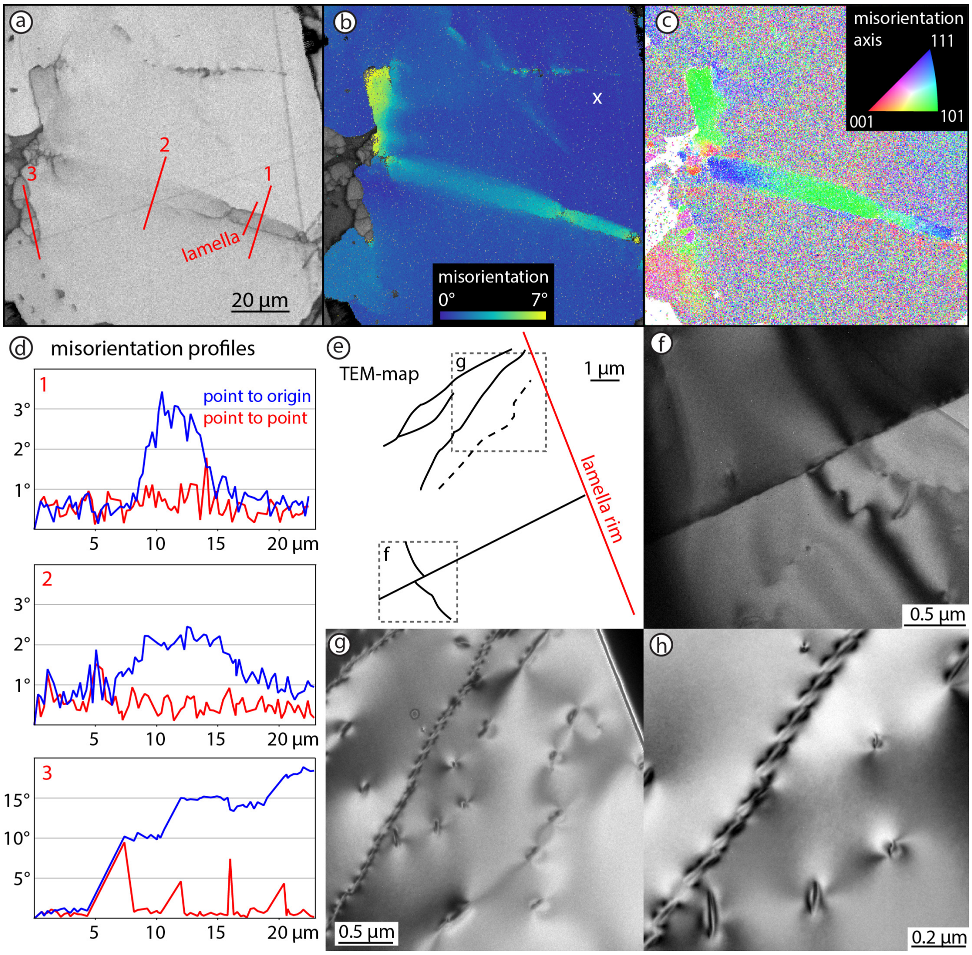

Figure 6: a) Image quality map of the garnet fragment (compare Fig. 4f) with darker zones that can be interpreted as areas of high dislocation density and location of the FIB-lamella. b) Misorientation plot with respect to the reference point (marked with the white x) shows a discrete zone of misorientation, 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 of (g)

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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 (>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 fractures do not show any induced lattice distortion or diffusion and therefore occurred after the temperature was 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) from other examples in the deep continental crust, no “explosive fracturing” or “shattering” 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

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single and conjugate shear offsets. Fractured garnet is still present in samples without pseudotachylyte, where the nearest pseudotachylyte is possibly many meters or more away. Fracturing in this case cannot be related to thermal shock (Papa et al., 2018), but must reflect differential stresses high enough to cause brittle garnet failure.

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

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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. 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. 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.

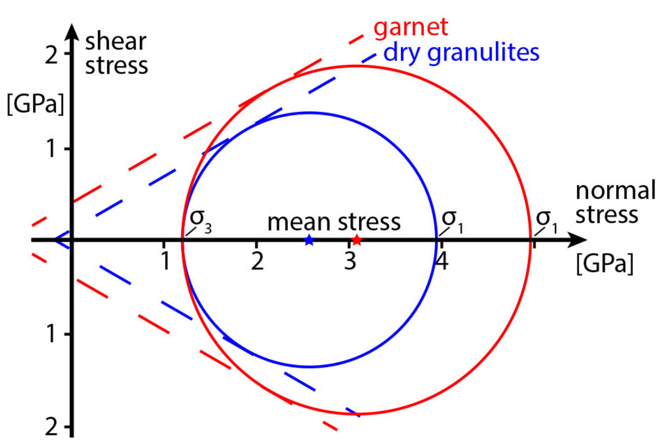

Figure 7: Mohr circles for fracturing of dry granulites and garnet at 1.2 GPa lithostatic load

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 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, 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 (Hawemann et al. 2009b). The studied example represents one end-member of lower continental crustal behavior 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.

Acknowledgements

We gratefully acknowledge permission granted to work on the Anangu Pitjantjatjara Yankunytjatjara Lands (APY) to carry out our field work in the area. The Northern Territory Geological Survey (NTGS) and Basil Tikoff (Department of Geoscience, University of

Wisconsin) are thanked for their logistical support and the Nicolle family of Mulga Park station for their hospitality. The Scientific Center for Optical and Electron Microscopy (ScopeM) provided the facilities for the scanning electron microscopy work, and help by Karsten Kunze, Luiz Morales and Fabian Gramm is especially acknowledged. Luca Menegon is thanked for his review of the first author's doctoral thesis. This project was financed by the Swiss National Science Foundation (SNF) grant 200021_146745 and by the University of Padova (BIRD175145/17: The geological record of deep earthquakes: the association pseudotachylyte-mylonite).

Data Availabilty

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

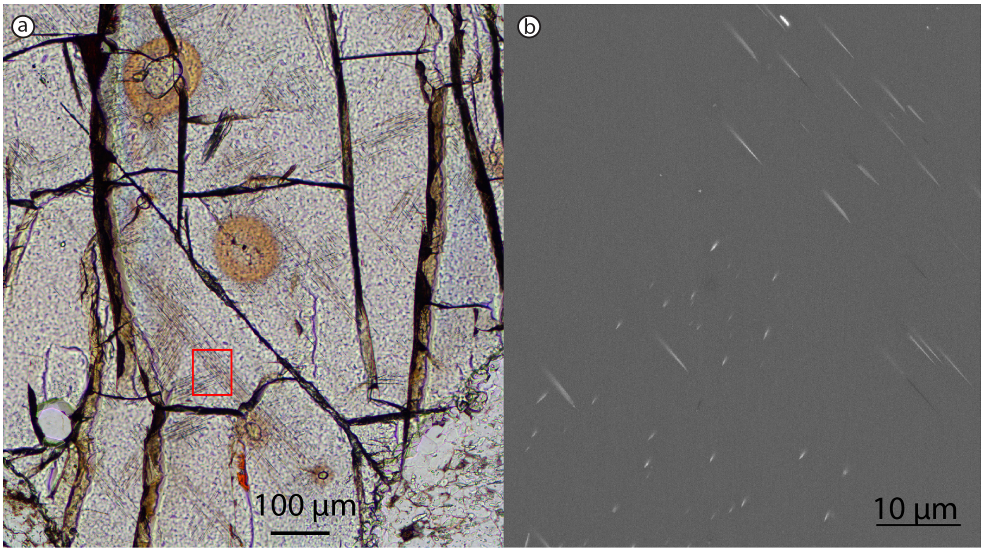
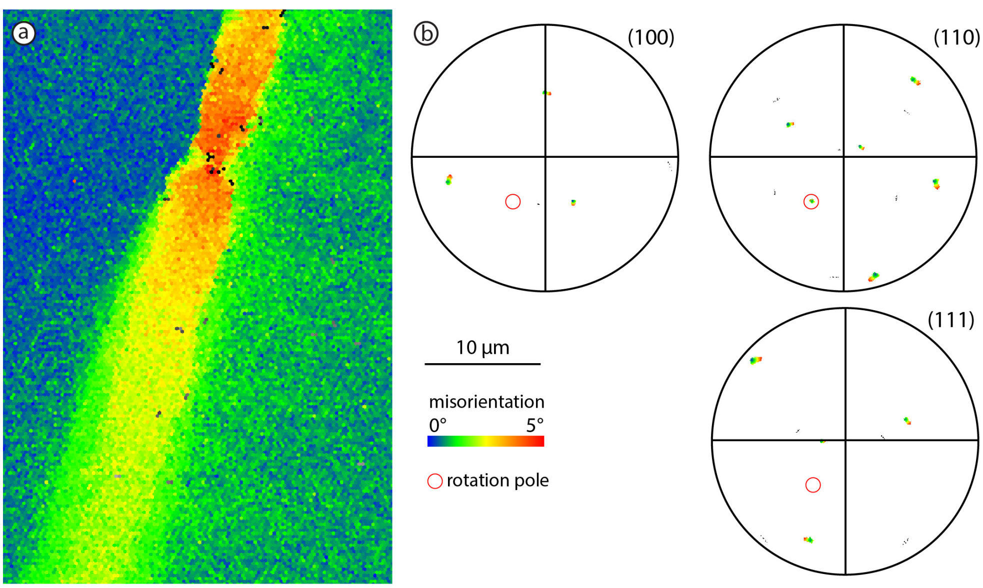


Figure A1: Thin section image in plane polarized light of a garnet crystal with monazite inclusions (with halos) and rutile-exsolution needles. b) BSE-image of the area indicated with the red box.



https://doi.org/10.5194/se-2019-110
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Figure A2: a) Misorientation map-detail for Fig. 6b), with b) pole figure plots for garnet axis with the same color scheme. The plots reveal a rotation around a (101)-axis, as indicated by the red circle.