



HAL
open science

Nano-scale earthquake records preserved in plagioclase microfractures from the lower continental crust

Arianne J Petley-Ragan, Oliver Plümper, Benoit Ildefonse, Bjørn Jamtveit

► To cite this version:

Arianne J Petley-Ragan, Oliver Plümper, Benoit Ildefonse, Bjørn Jamtveit. Nano-scale earthquake records preserved in plagioclase microfractures from the lower continental crust. *Solid Earth*, 2020, 10.5194/se-2020-146 . hal-03206942v1

HAL Id: hal-03206942

<https://hal.science/hal-03206942v1>

Submitted on 28 Sep 2020 (v1), last revised 23 Apr 2021 (v2)

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



1 Nano-scale earthquake records preserved in plagioclase 2 microfractures from the lower continental crust

3 Arianne J. Petley-Ragan^{1*}, Oliver Plümper², Benoit Ildefonse³, and Bjørn Jamtveit¹

4 ¹Physics of Geological Processes, The Njord Centre, University of Oslo, Oslo, Norway

5 ²Department of Earth Sciences, Utrecht University, Utrecht, The Netherlands

6 ³Géosciences Montpellier, CNRS, University of Montpellier, Université des Antilles, Montpellier, France

7 *Corresponding to: Arianne J. Petley-Ragan (a.j.petley-ragan@geo.uio.no)

8 **Abstract.** Seismic faulting causes wall rock damage driven by both mechanical stress and thermal energy. In the
9 lower crust, coseismic damage has important implications for wall rock permeability, the progress of subsequent
10 fluid-driven metamorphic reactions, and rock rheology. Wall rock microstructures reveal high-stress conditions
11 near the slip surface during lower crustal earthquakes, however, there is limited documentation on the thermal
12 effect. Here, we present a transmission electron microscopy study of coseismic microfractures in plagioclase
13 feldspar from lower crustal granulites from the Bergen Arcs, Western Norway. Focused ion beam foils are
14 collected 1.25 mm and 1.8 cm from a 2 mm thick eclogite facies pseudotachylyte vein. Dislocation-free plagioclase
15 aggregates fill the microfractures and record a history of recovery from a short-lived high stress-temperature (σ -
16 T) state caused by seismic slip and frictional melting along the nearby fault surface. The plagioclase aggregates
17 retain the crystallographic orientation of the host rock and shape preferred orientation relative to the fault slip
18 surface. We propose that plagioclase partially amorphized along the microfractures at peak stress conditions
19 followed by repolymerization to form dislocation-free grain aggregates within the timeframe of pseudotachylyte
20 formation. The heat from the slip surface dissipated into the wall rock causing a short-lived temperature peak.
21 Subsequent cooling led to exsolution of intermediate plagioclase compositions by spinodal decomposition within
22 a few millimeters distance to the fault surface. Our findings provide microstructural evidence for the high σ -T
23 conditions that are expected in the proximity of seismic faults, highlighting the importance of micro- and
24 nanostructures for the understanding of earthquake ruptures.

25 1 Introduction

26 During continent-continent collisions, plagioclase-rich granulite- and amphibolite-facies rocks are strong, dry and
27 prone to seismic faulting and subsequent metamorphism (Jamtveit et al., 2016). Plagioclase responds to lower
28 crustal earthquakes by microfracturing and fragmentation followed by fluid- and stress-induced recrystallization
29 (Mukai et al., 2014; Petley-Ragan et al., 2018; Soda and Okudaira, 2018). Grain size reduction by fracturing and
30 subsequent recrystallization localizes strain in the lower crust, defining a transition from brittle to crystal-plastic
31 deformation mechanisms with the potential to develop into shear zones (Svahnberg and Piazzolo, 2010; Menegon
32 et al., 2013; Okudaira et al., 2016; Marti et al., 2017). Thus, recrystallization and subsequent shear may overprint
33 any microstructural record of the high-intensity stress conditions created by an earthquake. Analysis of plagioclase
34 microstructures that have not undergone extensive annealing may provide valuable insight into the stress and
35 temperature state experienced by the wall rock during a seismic event.

36 In a purely elastic model, Reches and Dewers (2005) showed that for a dynamic earthquake rupture propagating
37 at 91% of the Rayleigh wave speed wall rock stresses may approach 10 GPa within 3 mm of a propagating rupture.



38 Furthermore, for ambient lower crustal temperatures in the range 600-700°C, the transient temperature following
39 an earthquake may exceed 1000°C within 1 cm of the slip surface (Bestmann et al., 2012; Clerc et al., 2018). Such
40 conditions, although short-lived, are expected to drive irreversible processes within the rock record. Extensive wall
41 rock fragmentation without shear strain around amphibolite and eclogite facies faults provide some evidence for
42 the high stresses caused by the propagation of seismic ruptures (Austrheim et al., 2017; Petley-Ragan et al., 2019).
43 Recent experimental studies have reported generation of amorphous material associated with fracturing and
44 seismic slip under eclogite facies conditions (Incel et al., 2019). On the other hand, thermal radiation around
45 frictional melt veins can drive recrystallization processes and form fine-grained dislocation-free aggregates
46 (Bestmann et al., 2012; 2016). Signatures such as these are beneficial in extracting rupture and melting properties
47 of seismic faults.

48 Here we present a microstructural study of coseismic microfractures in plagioclase from granulites in the Bergen
49 Arcs of Western Norway at varying distances to a lower crustal pseudotachylyte (Fig. 1a). Microfractures
50 previously described by Petley-Ragan et al. (2018) were analyzed with a transmission electron microscope (TEM)
51 equipped with an energy dispersive X-ray (EDX) detector to observe the fine-grained aggregates at the nanoscale.
52 Our combined microstructural and chemical study aims at unravelling the thermo-mechanical evolution of
53 plagioclase during and after earthquake rupture.

54 **2 Geological Setting**

55 The Lindås Nappe of the Bergen Arcs of Western Norway is host to a population of seismic faults identified by
56 the presence of mm to cm thick pseudotachylytes that cut through granulite facies anorthosite (Austrheim and
57 Boundy, 1994). The pseudotachylytes contain either an eclogite-facies or amphibolite-facies mineralogy, and the
58 wall rock damage adjacent to them are spatially related to fine-grained products of the same metamorphic grade.
59 The earthquakes took place within the lower crust during the Caledonian collision at 423-429 Ma (Jamtveit et al.,
60 2019) and provoked fluid-driven amphibolitization at 600°C and 0.8-1.0 GPa (Jamtveit et al., 2018), and
61 eclogitization at 650-750°C and 1.5-2.2 GPa (Jamtveit et al., 1990; Boundy et al., 1992; Glodny et al., 2008;
62 Bhowany et al., 2017). The wall rock damage is best observed on the micro-scale due to the high density of
63 microfractures (<50 µm thick) that criss-cross the wall rock mineral phases (Fig. 1b and c).

64 **3 Plagioclase wall rock damage**

65 Microfractures in wall rock plagioclase are found across the island of Holsnøy, adjacent to both types of
66 pseudotachylytes, and their orientations are independent of the crystallographic orientation of the host grains. The
67 microfractures contain fine-grained aggregates (grain size <5 µm) of dominantly plagioclase and K-feldspar (Fig.
68 1d and e). The grains within the microfractures have a crystallographic preferred orientation (CPO) that is
69 controlled by the host plagioclase on either side of the microfracture (Fig. 2), and the K-feldspar grains have a
70 CPO that mimics that of the plagioclase grains (Petley-Ragan et al., 2018). The grains also show a strong shape
71 preferred orientation (SPO) with the long axis parallel to the pseudotachylyte wall (Fig. 2). Plagioclase
72 compositions in the ranges An₂₅₋₃₁ and An₆₅₋₈₃ were measured in the microfractures. These originate from a host
73 composition of An₄₀ (Petley-Ragan et al., 2018). A similar bimodal range of plagioclase compositions were also
74 observed at garnet-plagioclase phase boundaries and in an amphibolite facies micro-shear zone at Isdal ca. 40 km
75 NE of Holsnøy (Mukai et al., 2014).



76 The mineralogy of the microfractures and their associated reaction products varies locally. Some contain quartz
77 and kyanite, while others are associated with intergrowths of clinozoisite, quartz and K-feldspar. Few
78 microfractures contain minor amounts of carbonates or phengite. Microfracture mineralogy is found to depend on
79 the X_{CO_2} of the infiltrating fluid (Okudaira et al., 2016) and the orientation of the microfracture relative to the
80 principle stress (Moore et al., 2019). The detailed evolution of the microfractures is thus dependent on a multitude
81 of factors.

82 Two microfractures of dominantly plagioclase and K-feldspar previously described by Petley-Ragan et al. (2018)
83 were subject to further study with transmission electron microscopy (TEM). The grain size distributions within
84 these microfractures were characterized by electron backscatter diffraction (EBSD) (Aupart et al., 2018). The
85 microfracture from Figure 1d will hereafter be referred to as Microfracture 1 (MF1) and is located 1.25 mm away
86 from pseudotachylyte with a mean grain size of $1.73 \mu\text{m}^2$ (Aupart et al., 2018). The microfracture from Figure 1d
87 will be referred to as Microfracture 2 (MF2) and is located 1.8 cm away from the same pseudotachylyte (Fig. 1a)
88 with a mean grain size of $2.14 \mu\text{m}^2$ (Aupart et al., 2018). MF2 also contains a set of secondary fractures (Fig. 1c).
89 Both microfractures are associated with clinozoisite, quartz and kyanite growth, and only MF2 contains dolomite.
90 The lower J-index, greater misorientations and the presence of secondary fractures indicate that MF2 experienced
91 more shear deformation than MF1 (Petley-Ragan et al., 2018).

92 **4 Methods**

93 Mass balance calculations were performed on three microfractures by comparing the bulk microfracture
94 composition to the bulk host composition. Electron microprobe maps of the microfractures were obtained with a
95 Cameca SX100 at the University of Oslo's Department of Geosciences. The mass balance was calculated in
96 MATLAB. Focused ion beam (FIB) foils were prepared and TEM analyses were carried out at Utrecht University.
97 The FEI Helios Nanolab G3 was used to cut FIB foils perpendicular to the length of the microfractures and ~15-
98 20 μm in length in order to include both the host and microfracture constituents (Fig. 1d and e). The FEI Talos
99 200FX equipped with a high-sensitive 2D energy dispersive X-ray (EDX) system was used to obtain bright-field
100 (BF), dark-field (DF) and high angular annular dark-field (HAADF) images in scanning TEM (STEM) mode. Large
101 area EDX maps were acquired of the entire FIB foil for MF1 and parts of the FIB foil for MF2.

102 **5 Results**

103 Mass balance calculations based on three microfractures show that there is 5-11 times more K in the microfractures
104 compared to the host composition (Fig. 3). A bright field TEM image shows that MF1 contains dislocation-poor
105 and dislocation-free grains of dominantly plagioclase and K-feldspar defined by straight grain boundaries with
106 120° triple junctions (Fig. 4a). Few grains contain single dislocation walls within their centre. In contrast, the host
107 plagioclase is littered with free dislocations that have formed a subgrain wall made up of closely spaced
108 dislocations. Ankerite ($\text{Ca}(\text{Fe},\text{Mg})(\text{CO}_3)_2$), grossular-rich garnet and sphene are additional phases in MF1, with
109 apatite and rutile inclusions inside the grains, pinned along grain boundaries and concentrated along the subgrain
110 wall in the host (Fig. 4b).

111 The EDX map of MF1 displays homogeneous K-feldspar grains and plagioclase grains that are heterogeneous
112 with respect to their CaAl and NaSi content (Fig. 4b). The K-feldspar grains are clustered together creating a fabric



113 dominated by grain boundaries instead of phase boundaries. The irregular composition distribution of Na and Ca
114 in the plagioclase grains contradicts the backscatter electron image that suggests Ca zoning around the grains (Fig.
115 1d and 4b). Instead, the Ca-rich domains overlie areas with submicron lamellae (Fig. 5a-f). The lamellae are
116 discontinuous throughout the plagioclase grains and, locally, they are superimposed by tapered mechanical twins
117 (Fig. 5a). Other grains contain both lamellae and twins that are spatially distinct but are parallel to each other (Fig.
118 5d). In some grains, the lamellae appear slightly curved (Fig. 5c) while in others, the lamellae appear to form a
119 ‘tweed’ structure (Fig. 5f). The spacing between lamellae is approximately 10-30 nm. Due to the high anorthite
120 composition obtained for plagioclase within this microfracture (An_{65-83} ; Petley-Ragan et al., 2018) this structure
121 lies within the Bøggild-Huttenlocher miscibility gap (Smith and Brown, 1988; McConnell, 2008). The intergrowth
122 is not observed within the host plagioclase.

123 MF2 is similarly dominated by dislocation-poor grains of plagioclase and K-feldspar with a number of grains
124 displaying twinning (Fig. 6a). The twins of separate grains are approximately parallel to each other and to (010)
125 of the host plagioclase (see Fig. 6 of Petley-Ragan et al., 2018), reinforcing the preservation of crystallographic
126 orientations of the host through the fracturing and recovery process. Kyanite and a K-rich micaceous phase are
127 additional phases in MF2. Apatite inclusions are present within the grains and pinned along grain boundaries. The
128 fabric is defined by 120° triple junctions with rare dislocation-rich grains that display irregular boundaries (Fig.
129 6b).

130 The EDX map of MF2 shows clustered homogeneous K-feldspar grains and zoned plagioclase grains (Fig. 6c)
131 creating again a grain boundary-dominated fabric. Unlike MF1, the plagioclase grains in MF2 display Ca-
132 enrichment at their grain boundaries and the submicron lamellae are absent. The Ca-rich rims are approximately
133 100-200 nm thick.

134 **6 Discussion**

135 The microfractures offer insight into the evolution of plagioclase feldspar that resulted from the high stress and
136 high-temperature environment created near an earthquake slip plane. The dislocation-free nature of almost all
137 grains in MF1 and MF2 suggest nearly complete annealing of the material within the microfractures (Fig. 4a and
138 6a). The grain fabric is dominated by straight phase and grain boundaries, 120° triple junctions and pinned apatite
139 inclusions suggesting the migration of grain boundaries. The inheritance of the crystallographic orientation of the
140 host plagioclase and its twins within the grains, furthermore, points towards an initial annealing process that is
141 able to transfer and preserve crystallographic information (Fig. 3). An equilibrium fabric with crystallographic
142 inheritance is generally created by dislocation creep and grain boundary migration (Passchier and Trouw, 2005).
143 However, the parallel shape preferred orientation of the grains to the pseudotachylyte wall suggests that annealing
144 was initiated while a stress or thermal field generated by the seismic slip was still present (Petley-Ragan et al.,
145 2018). This constrains the time scale of microfracture annealing to the duration of pseudotachylyte crystallization
146 and cooling (seconds to minutes). Dislocation- and grain boundary migration are too slow to have taken place
147 within this time scale, and it is additionally puzzling as to why these mechanisms were not active within the
148 dislocation-rich host. Thus, we postulate that a much more rapid recrystallization process took place prior to grain
149 boundary migration and final annealing within the microfractures, and this process must have been focused and
150 enhanced by local factors such as fluid infiltration and heat from the nearby pseudotachylyte. The resulting grain



151 size distributions as discussed by Aupart et al. (2018) furthermore show striking deviations from a steady-state
152 distribution.

153 **6.1 Stressed wall rock plagioclase**

154 Deformation experiments performed at eclogite facies conditions may offer some insight into the microstructures
155 that were present in the microfractures before complete recovery. Incel et al. (2017; 2019) observed brittle fractures
156 filled with amorphous material during deformation experiments on blueschist under eclogite facies conditions.
157 They interpret the amorphous material to result from shock loading during the propagation of a dynamic rupture.
158 Although their experiments involved a short recovery time (<1 hour) some of the amorphous material
159 recrystallized, creating idiomorphic garnet crystals with a size of ~20 nm.

160 The amorphization of plagioclase feldspar is dependent on pressure (P), temperature (T), composition (X),
161 compression rate (P/t) and pressure duration (t). Amorphization that is strongly dependent on temperature is
162 commonly referred to as heterogeneous amorphization or melting, and is a relatively slow process due to its
163 dependence on the diffusion of atoms (Wolf et al., 1990). On the other hand, amorphization that is strongly
164 dependent on pressure is referred to as pressure-induced amorphization, which may be static or dynamic,
165 depending on the compression rate (Sharma and Sikka, 1996). For the following, the pressure-induced
166 amorphization of plagioclase will be discussed. For anorthite-rich compositions (An_{51-100}) complete pressure-
167 induced amorphization occurs $P \geq 13$ GPa and $T = 660^\circ\text{C}$, while albite-rich (An_2) compositions are not completely
168 amorphous until $P \geq 26$ GPa and $T = 950^\circ\text{C}$ (Daniel et al., 1997; Kubo et al., 2009; Tomioka et al., 2010).
169 Furthermore, short pressure durations result in lower degrees of amorphization (Tomioka et al., 2010) while high
170 compression rates of 10^1 - 10^2 GPa/s can reduce the pressure required for amorphization (Sims et al., 2019). The
171 short-lived (microseconds) high intensity (10^6 GPa/s) conditions in the proximity of earthquake rupture tips
172 (Reches and Dewers, 2005) may partially amorphize plagioclase feldspar (An_{40}) in the wall rock, even if the local
173 pressure for *complete* amorphization is not reached. The presence of asymmetric tensile cracks on some of the
174 microfractures indicates that the propagation velocity of the microfractures approached the shear wave velocity
175 (Petley-Ragan et al., 2018) inducing similar short-lived high-intensity stresses within their vicinity. Therefore, a
176 mixture of amorphous material with remnant fragments may have been present within the microfractures
177 immediately after earthquake and microfracture rupture.

178 Repolymerization of amorphous material on the microfracture walls and remnant fragments would directly transfer
179 the crystallographic orientation of the host. Crystallographic information may also be preserved by the presence
180 of short-range atomic order within amorphous material, allowing for immediate repolymerization without the aid
181 of a fragment nucleus (Casey et al., 1993; Konrad-Schmolke et al., 2018). Repolymerization has also been
182 suggested to occur directly along crystal lattice defects where amorphous material originates (Konrad-Schmolke
183 et al., 2018). In this context, dislocations within the grains may have healed much more quickly than would be
184 expected from dislocation migration recrystallization and the fragments would have experienced healing from
185 multiple available interfaces. Other preferred areas of repolymerization were likely parallel to the minimum
186 principal stress direction, growing grains with a stress-dependent SPO. Therefore, recrystallization from an
187 amorphous material may be a likely candidate to create the observed dislocation-free fabric with a strong SPO
188 within the timeframe of pseudotachylite formation.



189 **6.2 Cooling within the vicinity of pseudotachylyte**

190 The nano-scale intergrowth within the plagioclase grains from MF1 is here interpreted as exsolution lamellae that
191 formed as a result of rapid cooling from high temperatures within the vicinity of the pseudotachylyte. Similar
192 intergrowths were found in what is called the ‘complex feldspar’, a microstructure of fragmented plagioclase first
193 described in an amphibolite facies shear zone at Isdal, approximately 40 km east of Holsnøy (Mukai et al., 2014).
194 They interpreted the structure as fluid- and stress-induced coarsening of exsolution lamellae. Although plausible,
195 this would require that plagioclase exsolution occurred prior to the stress and thermal anomaly created by the
196 earthquake. No intergrowths are observed within the host plagioclase in the present study, and it is unlikely that
197 diffusion rates were high enough to form lamellae within the dry granulite. Our documentation of the exsolution
198 lamellae within plagioclase grains from the microfracture nearest the pseudotachylyte (Fig. 1a) suggests that the
199 thermal anomaly produced by the frictional melt vein affected the intracrystalline structure of the plagioclase grains.

200 Intergrowths form when plagioclases of intermediate composition cool from high temperature and enter a
201 miscibility gap below 800°C, exsolving into separate calcic and sodic regions (Carpenter, 1994; McConnell, 2008).
202 Although the ambient eclogite facies conditions (650-750°C) place the plagioclase within the miscibility gap, the
203 absence of fluids hinders chemical diffusion and thus exsolution. It is only until after an earthquake causes wall
204 rock damage that fluids enter the wall rock through coseismic microfractures, and these fluids are likely overheated
205 by the frictional slip (Bestmann et al., 2016). Simultaneously, the wall rock within <1 cm of the pseudotachylyte
206 experiences a thermal anomaly before rapidly cooling back to ambient conditions at rates on the order of a few °C/s
207 (Bestmann et al., 2012). NaSi-CaAl diffusivity in plagioclase at 900-1000°C is $\sim 10^{-15}$ cm²/s (Korolyuk and Lepezin,
208 2009). Assuming that elevated temperatures lasted for up to a minute within 1 mm of the pseudotachylyte (MF1),
209 diffusion would be efficient over a distance of 25 nm, similar to the spacing of lamellae observed (Fig. 5). At
210 distances greater than 1 cm from the pseudotachylyte (MF2), the wall rock experiences minor heating to a few
211 10°C above ambient. Therefore, rapid cooling from elevated temperatures back to ambient conditions and into the
212 miscibility gap only took place within close proximity to the pseudotachylyte.

213 **7 Conclusion**

214 Our nanostructural observations are relevant for understanding plagioclase deformation during and after an
215 earthquake in the lower crust, prior to any subsequent shear zone development. We propose that plagioclase within
216 the microfractures experienced partial amorphization at peak pressures coeval with earthquake propagation and
217 microfracturing in the wall rock. Repolymerization on microfracture walls, remnant fragments, dislocations and
218 from short-range atomic ordering in the direction parallel to the minimum principal stress formed a strong CPO
219 and SPO in the grains. Repolymerization and recrystallization within the timeframe of pseudotachylyte formation
220 explain the presence of dislocation-free grains, as has been interpreted for similar structures observed in quartz
221 (Bestmann et al., 2012). In close proximity to the pseudotachylyte, wall rock temperatures reached 900-1000°C
222 before rapidly cooling back to ambient eclogite facies conditions and into the plagioclase miscibility gap. This
223 caused exsolution of intermediate plagioclase compositions and formation of nano-scale lamellae. We hypothesize
224 that the lamellae described here are a unique signature of rapid cooling within plagioclase-rich wall rock in the
225 vicinity of pseudotachylyte. A study of a larger number of plagioclase microfractures at varying distances to
226 pristine pseudotachylyte would provide more information and constraints on the occurrence of these intergrowths.



227 The dependence of plagioclase microstructures on temperature and cooling rate and their sensitivity to fluid
228 interaction offers a new tool for unraveling the history of wall rocks and their associated earthquakes.

229 **Data and Sample Availability**

230 Raw electron backscatter diffraction and geochemical data are available on Open Science Framework at
231 osf.io/g36m7/. Rock samples are available through A. P.-R. and FIB foils are available through O. P.

232 **Author Contribution**

233 B. J. designed the project. A. P.-R. collected the samples, obtained and analyzed the EBSD and geochemical data.
234 B. I. helped collect and interpret the EBSD data. O. P. cut the FIB foils, and obtained and interpreted the TEM
235 images. A.P.-R., O. P. and B. J. were part of discussions. A. P.-R. and B. J. wrote the manuscript.

236 **Competing Interests**

237 The authors declare that they have no conflict of interest.

238 **Acknowledgements**

239 This project was supported by the European Research Council (ERC) Advanced Grant Agreement 669972,
240 “Disequilibrium Metamorphism” (“DIME”) to B. J., and the Natural Science and Engineering Research Council
241 (NSERC) of Canada Postgraduate Scholarship Doctoral (PGS-D) 489392 to A. P.-R. O. P. has been supported by
242 an ERC Starting Grant “nanoEARTH” (852069). We thank H. Austrheim for field guidance on Holsnøy and
243 hospitality in Western Norway. We thank X. Zhong for help with the mass balance calculations, F. Barou for
244 assistance with EBSD measurements and M. Erambert for help on the electron microprobe.

245 **References**

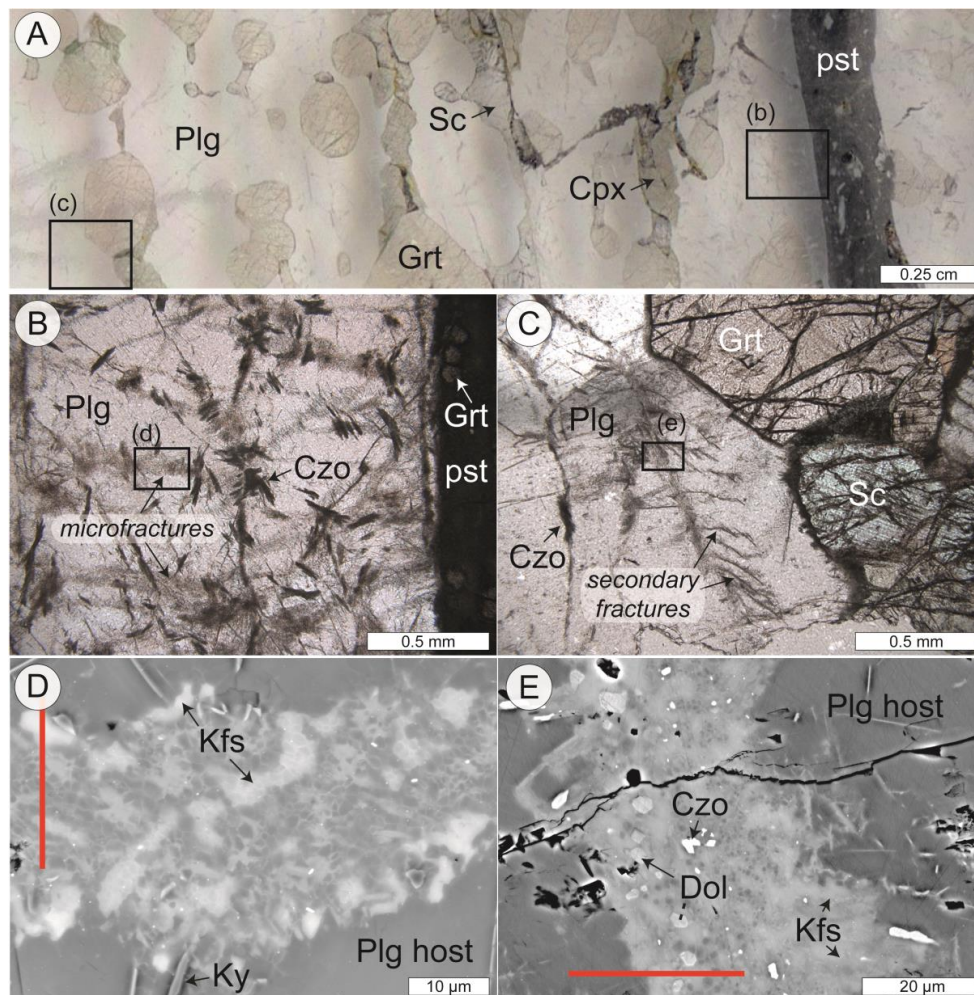
- 246 Austrheim, H. and Boundy, T. M.: Pseudotachylytes generated during seismic faulting and eclogitization of the
247 deep crust, *Science*, 265, 82-83, <http://www.jstor.org/stable/2884364>, 1994.
- 248 Austrheim, H., Dunkel, K. G., Plümper, O., Ildefonse, B., Liu, Y., and Jamtveit, B.: Fragmentation of wall rock
249 garnets during deep crustal earthquakes, *Sci. Adv.*, 3, 1-8, <https://doi.org/10.1126/sciadv.1602067>, 2017.
- 250 Bestmann, M., Pennacchioni, G., Nielsen, S., Göken, M., and de Wall, H.: Deformation and ultrafine dynamic
251 recrystallization of quartz in pseudotachylyte-bearing brittle faults: A matter of a few seconds. *J. Struct.
252 Geol.*, 38, 21-38, <https://doi.org/10.1016/j.jsg.2011.10.001>, 2012.
- 253 Bestmann, M., Pannecchioni, G., Mostefaoui, S., Göken, M. and de Wall, H.: Instantaneous healing of micro-
254 fractures during coseismic slip: Evidence from microstructure and Ti in quartz geochemistry within an
255 exhumed pseudotachylyte-bearing fault in tonalite, *Lithos*, 254-255, 84-93,
256 <https://doi.org/10.1016/j.lithos.2016.03.011>, 2016.
- 257 Bhowany, K., Hand, M., Clark, C., Kelsey, D. E., Reddy, S. M., Pearce, M. A., Tucker, N. M., and Morrissey, L.
258 J.: Phase equilibria modelling constraints on P-T conditions during fluid catalysed conversion of granulite
259 to eclogite in the Bergen Arcs, Norway, *J. Metamorph. Geol.*, <https://doi.org/10.1111/jmg.12294>, 2017.



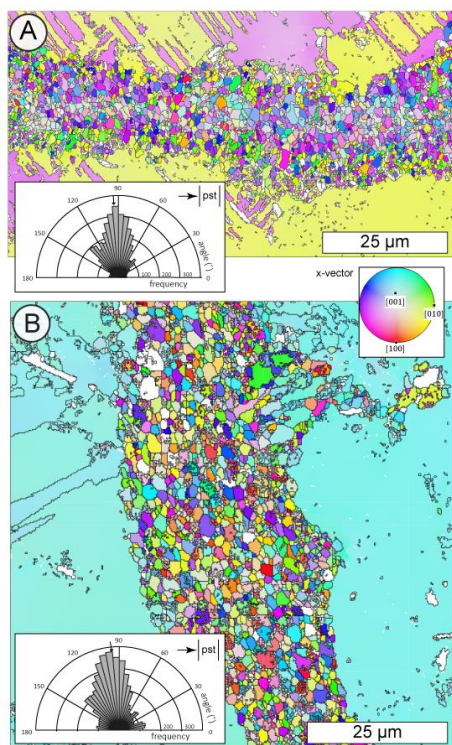
- 260 Boundy, T.M., Fountain, D.M., and Austrheim, H.: Structural development and petrofabrics of eclogite facies
261 shear zones, Bergen Arcs, western Norway: implications for deep crustal deformational processes, *J.*
262 *Metamorph. Geol.*, 10, 2, 127-146, <https://doi.org/10.1111/j.1525-1314.1992.tb00075.x>, 1992.
- 263 Carpenter, M. A.: Mechanisms and kinetics of Al-Si ordering in anorthite: I. Incommensurate structure and domain
264 coarsening, *Am. Mineral.*, 76, 1110-1119, 1991.
- 265 Casey, W. H., Westrich, H. R., Banfield, J. F., Ferruzzi, G. and Arnold, G. W.: Leaching and reconstruction at the
266 surfaces of dissolving chain-silicate minerals, *Nature*, 366, 253-256, <https://doi.org/10.1038/366253a0>,
267 1993.
- 268 Daniel, I., Gillet, P., McMillan, P. F., Wolf, G. and Verhelst, M. A.: High-pressure behavior of anorthite:
269 Compression and amorphization. *J. Geophys. Res.*, 102, 10313-10325.
270 <https://doi.org/10.1029/97JB00398>, 1997.
- 271 Glodny, J., Kühn, A., and Austrheim, H.: Geochronology of fluid-induced eclogite and amphibolite facies
272 metamorphic reactions in subduction-collision system, Bergen Arcs, Norway, *Contrib. Mineral. Petr.*,
273 156, 1, 27-48, <https://doi.org/10.1007/s00410-007-0272-y>, 2008.
- 274 Incel, S., Hilaret, N., Labrousse, L., John, T., Deldicque, D., Farrand, T., Wang, Y., Renner, J., Morales, L. and
275 Schubnel, A.: Laboratory earthquakes triggered during eclogitization of lawsonite-bearing blueschist.
276 *Earth Planet. Sci. Lett.*, 459, 320-331, <https://doi.org/10.1130/G45527.1>, 2017.
- 277 Incel, S., Labrousse, L., Hilaret, N., John, T., Gasc, J., Shi, F., Wang, Y., Andersen, Renard, F., Jamtveit, B. And
278 Schubnel, A.: Reaction induced embrittlement of the lower continental crust, *Geology*, 47, 3, 235-238,
279 <https://doi.org/10.1130/G45527.1>, 2019.
- 280 Jamtveit, B., Austrheim, H., and Putnis, A.: Disequilibrium metamorphism of stressed lithosphere, *Earth Sci. Rev.*,
281 154, 1-13. <https://doi.org/10.1016/j.earscirev.2015.12.002>, 2016.
- 282 Jamtveit, B., Bucher-Nurminen, K. and Austrheim, H.: Fluid controlled eclogitization of granulites in deep crustal
283 shear zones, Bergen Arcs, Western Norway, *Contrib. Mineral. Petr.*, 104, 184-193,
284 <https://doi.org/10.1007/BF00306442>, 1990.
- 285 Jamtveit, B., Moulas, E. Andersen, T. B., Austrheim, H., Corfu, F., Petley-Ragan, A. and Schmalholz, S. M.: High
286 pressure metamorphism caused by fluid induced weakening of deep continental crust. *Sci. Rep.*, 8, 17011,
287 <https://doi.org/10.1038/s41598-018-35200-1>, 2018.
- 288 Jamtveit, B., Petley-Ragan, A., Incel, S., Dunkel K. G., Aupart, C., Austrheim, H., Corfu, F., Menegon, L. and
289 Renard, F.: The effects of earthquakes and fluids on the metamorphism of the lower continental crust, *J.*
290 *Geophys. Res.*, 124, 8, 7725-7755, <https://doi.org/10.1029/2018JB016461>, 2019.
- 291 Konrad-Schmolke, M., Halama, R., Wirth, R., Thomen, A., Klitscher, N., Morales, L., Schreiber, A. and Wilke,
292 F. D. H.: Mineral dissolution and reprecipitation mediated by an amorphous phase, *Nature contrib.*, 9,
293 <https://doi.org/10.1038/s41467-018-03944-z>, 2018.
- 294 Kubo, T., Kimura, M., Kato, T., Nishi, M., Tominaga, A., Kikegawa, T. and Funakoshi, K.: Plagioclase breakdown
295 as an indicator for shock conditions of meteorites, *Nat. Geosci.*, 3, 41-45, <https://doi.org/10.1038/ngeo704>,
296 2009.
- 297 Marti, S., Stünitz, H., Heilbronner, R., Plümper, O. and Drury, M.: Experimental investigation of the brittle-viscous
298 transition in mafic rocks – Interplay between fracturing, reaction, and viscous deformation, *J. Struct. Geol.*,
299 105, 62-79, <https://doi.org/10.1016/j.jsg.2017.10.011>, 2017.



- 300 McConnell, J.: The origin and characteristics of incommensurate structures in the plagioclase feldspars, *Can.*
301 *Mineral.*, 46, 1389-1400, <https://doi.org/10.3749/canmin.46.6.1389>, 2008.
- 302 Menegon, L., Stünitz, H., Nasipuri, P., Heilbronner, R. and Svahnberg, H.: Transition from fracturing to viscous
303 flow in granulite facies perthitic feldspar (Lofoten, Norway), *J. Struct. Geol.*, 48, 95-112,
304 <https://doi.org/10.1016/j.jsg.2012.12.004>, 2013.
- 305 Moore, J., Beinlich, A., Austrheim, H. and Putnis, A.: Stress orientation-dependent reactions during
306 metamorphism, *Geology*, 47, 1-4, <https://doi.org/10.1130/G45632.1>, 2019.
- 307 Mukai, H., Austrheim, H., Putnis, C. V., and Putnis, A.: Textural evolution of plagioclase feldspar across a shear
308 zone: Implications for deformation mechanism and rock strength, *J. Petrol.*, 55, 1457-1477,
309 <https://doi.org/10.1093/petrology/egu030>, 2014.
- 310 Okudaira, T., Shigematsu, N., Harigane, Y., and Yoshida, K.: Grain size reduction due to fracturing and subsequent
311 grain-size-sensitive creep in lower crustal shear zone in the presence of a CO₂-bearing fluid, *J. Struct.*
312 *Geol.*, 95, 171-187, <https://doi.org/10.1016/j.jsg.2016.11.001>, 2016.
- 313 Petley-Ragan, A., Dunkel, K. G., Austrheim, H., Ildefonse, B. and Jamtveit, B.: Microstructural records of
314 earthquakes in the lower crust and associated fluid-driven metamorphism in plagioclase-rich granulites.
315 *J. Geophys. Res.-Sol Ea.*, 123, 1-18, <https://doi.org/10.1029/2017JB015348>, 2018.
- 316 Petley-Ragan, A., Ben-Zion, Y., Austrheim, H., Ildefonse, B., Renard, F. and Jamtveit B.: Dynamic earthquake
317 rupture in the lower crust, *Sci. Adv.*, 5, <https://doi.org/10.1126/sciadv.aaw0913>, 2019.
- 318 Passchier, C., and Trouw, R.: *Microtectonics*. Springer, Berlin., 2005.
- 319 Reches, Z. and Dewers, T. A.: Gouge formation by dynamic pulverization during earthquake rupture, *Earth Planet.*
320 *Sc. Lett.*, 235, 361-374, <https://doi.org/10.1016/j.epsl.2005.04.009>, 2005.
- 321 Sharma, S. and Sikka, S.: Pressure Induced Amorphization of Materials, *Progress in Materials Science*, 40, 1-77,
322 1996.
- 323 Sims, M., Jaret, S. J., Carl, E.-R., Rhymer, B., Schrodt, N., Mohrholz, V., Smith, J., Konopkova, Z., Liermann,
324 H.-P., Glotch, T. D. and Ehm, L.: Pressure-induced amorphization in plagioclase feldspars: A time-
325 resolved powder diffraction study during rapid compression, *Earth Planet Sc. Lett.*, 507, 166-174,
326 <https://doi.org/10.1016/j.epsl.2018.11.038>, 2019.
- 327 Smith, J. V. and Brown, W. L.: *Feldspar Minerals*, vol. 1, Springer, Berlin, 1988.
- 328 Soda, Y. and Okudaira, T.: Microstructural evidence for the deep pulverization in a lower crustal meta-anorthosite,
329 *Terra Nova*, 1-7, <https://doi.org/10.1111/ter.12355>, 2018.
- 330 Svahnberg, H. and Piazzolo, S.: The initiation of strain localisation in plagioclase-rich rocks: Insights from detailed
331 microstructural analyses, *J. Struct. Geol.*, 32, 1404-1416, <https://doi.org/10.1016/j.jsg.2010.06.011>, 2010.
- 332 Tomioka, N., Kondo, H., Kunikata, A. and Nagai, T.: Pressure-induced amorphization of albitic plagioclase in an
333 externally heated diamond anvil cell, *Geophys. Res. Lett.*, 37, 1-5,
334 <https://doi.org/10.1029/2010GL044221>, 2010.
- 335 Wolf, D., Okamoto, P., Yip, S., Lutsko, J. F. and Kluge, M.: Thermodynamic parallels between solid-state
336 amorphization and melting, *J. Material Res.*, 5, 286-301, <https://doi.org/10.1557/JMR.1990.0286>, 1990.

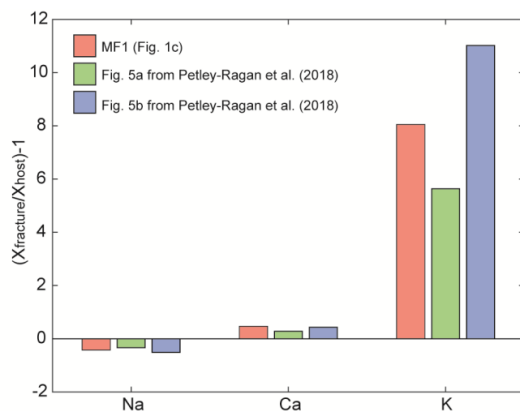


337
338 **Figure 1: Fractured wall rock plagioclase.** (a) Thin section scan of wall rock plagioclase (Plg), garnet (Grt),
339 clinopyroxene (Cpx) and scapolite (Sc) adjacent to an eclogite facies pseudotachylyte (pst) on Holsnøy. (b) Fine-
340 grained reaction products of clinozoisite (Czo) are associated with the microfractures. Box denotes the location of
341 MF1. (c) Some microfractures in plagioclase display secondary cracking. Box denotes the location of MF2. (d)
342 Backscatter electron image of MF1 with fine-grained plagioclase, alkali feldspar (Kfs) and minor kyanite (Ky). (e)
343 Backscatter electron image of MF2 with fine-grained plagioclase, K-feldspar, dolomite (Dol) and clinozoisite. Red
344 lines indicate the location of focused ion beam cuts for TEM analysis shown in Figs. 4-6.



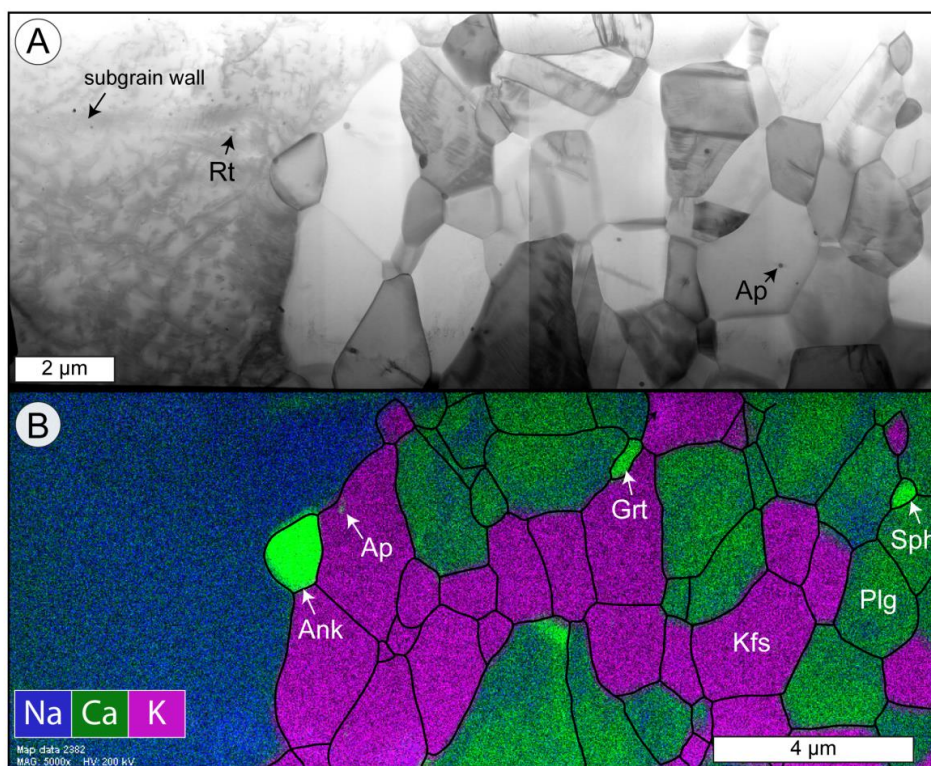
345

346 **Figure 2: Crystallographic orientations of the grains within the microfractures.** (a) Inverse pole figure
 347 coloring orientation map of MF1 with inset of grain SPO. (b) Orientation map of MF2 with inset of grain SPO.
 348 Modified after Petley-Ragan et al. (2018).



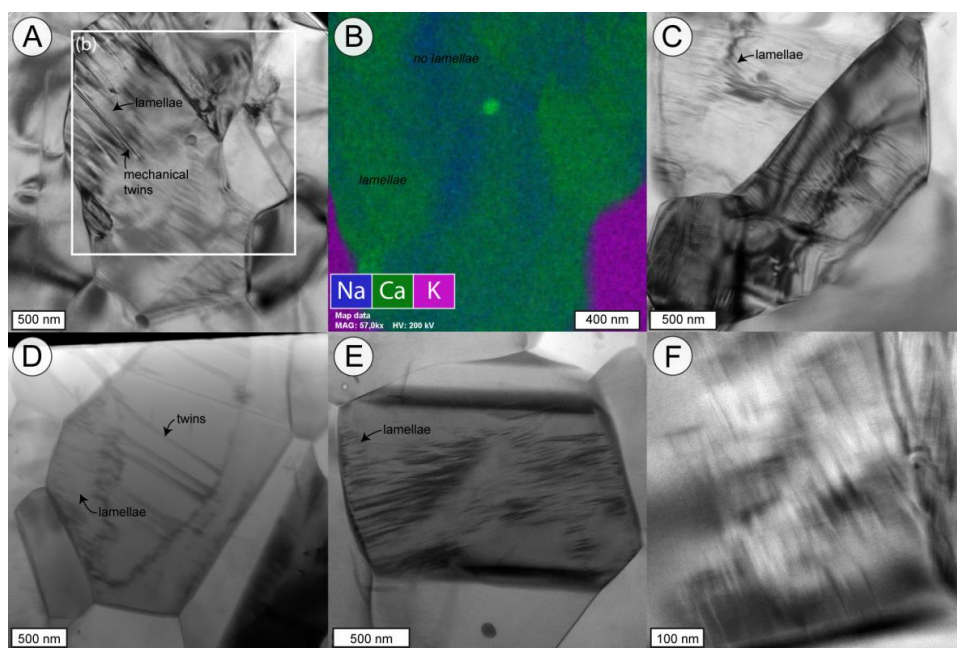
349

350 **Figure 3: Mass balance of plagioclase microfractures.** Three separate plagioclase microfractures were analyzed
 351 for Na, Ca and K. X_{fracture} is the bulk composition of the fracture and X_{host} is the bulk composition of the adjacent
 352 plagioclase host.



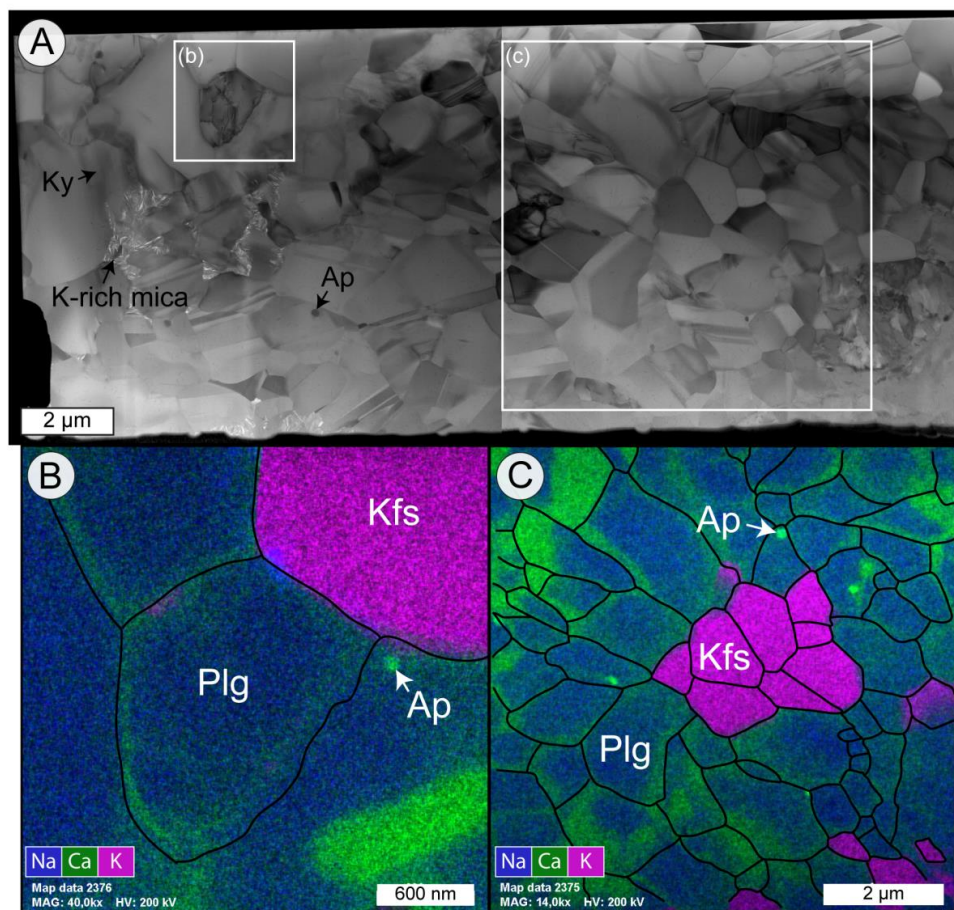
353

354 **Figure 4: Microstructures of MF1.** (a) BF-STEM image of the entire FIB cut from Fig. 1d. The plagioclase (Plg)
355 host to the left is rich in dislocations while the grains within the microfracture to the right are poor to absent of
356 dislocations. Apatite (Ap) and rutile (Rt) inclusions are present within the host and the grains, as well as pinned
357 along grain boundaries in the microfracture. (b) EDX map overlain with grain and phase boundaries (black).
358 Ankerite (Ank), garnet (Grt) and sphene (Sph) are additional phases within the microfracture.



359

360 **Figure 5: Plagioclase intergrowths in MF1.** (a) BF-TEM image of the submicron lamellae in a plagioclase grains
361 that are overlain by mechanical twins. (b) EDX map showing the distribution of Ca and Na in the plagioclase
362 grains associated with the intergrowth in (a). The Ca-rich domains overlay the lamellae. (c) BF-TEM image of
363 lamellae in two separate grains that show slight curvature. (d) BF-STEM image of discontinuous lamellae within
364 a grain that hosts twins in its core. (e) STEM bright field image of discontinuous lamellae within a plagioclase
365 grain. (f) Bright field TEM image of lamellae resembling 'tweed' exsolution within plagioclase.



366

367 **Figure 6: Microstructures of MF2.** (a) Bright field image of the entire FIB cut from Fig. 1e. The plagioclase
368 (Plg) microfracture contains dislocation-free grains with some twins. (b) EDX map of a dislocation-rich grain
369 overlain with grain and phase boundaries (black). (c) EDX map of the area in (a) overlain with grain and phase
370 boundaries (black). The Ca-rich domains are present along grain boundaries.