Microstructural evidence for the deep pulverization in a lower crustal meta-anorthosite

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Abstract
We report on the evidence of the pulverization in a deep-seated meta-anorthosite in the Eidsfjord shear zone, Vesterålen, northern Norway. Some plagioclase porphyroclasts comprise a few large relict clasts and many fine grains that preserve the outlines of the original grains. The fine-grained plagioclase does not show any plastic-deformation microstructures and has strong crystallographic preferred orientations, which are inherited from the twinned porphyroclast. Misorientation-axis distributions indicate that the grains have rotated randomly, so that the misorientation axes are not aligned with either the crystallographic or kinematic axes. The observed grain-size distribution has a fractal dimension, suggesting their fracturing/fragmentation origin. The microstructures are characterized by the fracturing/fragmentation with a very low shear strain, indicating that it may be associated with pulverization at ~20–25 km depth.

1 | INTRODUCTION

Understanding the deep ruptures below the seismogenic zone, that are caused due to dynamic fracturing by major earthquakes is important to evaluate the recurrence of major earthquakes in the continental crust (Jiang & Lapusta, 2016). Fracturing in the lower crust may also increase, at least temporarily, the permeability of the damaged rock, thus leading to episodic fluid flow that modifies mechanical and rheological properties of the damaged rock and its upward extension, i.e., faults in the seismogenic zone (Austrheim et al., 2017; Jamtveit, Ben-Zion, Renard, & Austrheim, 2018; Sibson, 1992). It is considered that pseudotachylytes are an evidence of seismic faulting in the lower crust (Austrheim & Boundy, 1994). Pulverized rocks that are characterized by a very low shear strain and a very high fracture density at or below the hand-specimen scale are also a candidate for the evidence of dynamic fracturing (Dor, Ben-Zion, Rockwell, & Brune, 2006; Rempe et al., 2013). Pulverized rocks have been found along various crustal-scale faults, such as the San Andreas fault (Dor et al., 2006) and the Arima–Takatsuki Tectonic Line (Mitchell, Ben-Zion, & Shimamoto, 2011). The current view on pulverized rocks is that they are formed by stress waves with high stress- or strain-rate loadings released by the rupturing fault (Aben et al., 2016; Doan & Gary, 2009). The pulverization is thought to have occurred in the top few kilometres of the crust (Dor et al., 2006). Based on the results of numerical analyses (Andrews, 2005; Ben-Zion & Shi, 2005), the spontaneous generation of damage produced by rupture propagation along the fault is suppressed by an increase in the confining stress. However, the effects of normal stress on the local behaviour of a fault tip where the intact rock is being dynamically fractured remain unclear (Ando & Yamashita, 2007).

In meta-anorthosites from an exhumed lower crustal shear zone of Vesterålen in northern Norway, some mesoscopic plagioclase porphyroclasts have been found to comprise a few large relict clasts and many fine grains that preserve the outlines of the original grains. The microstructures indicate that fracturing and fragmentation occurred without substantial shear strain, thus suggesting the grains originated through pulverization. These rocks provide us with new insights into the formation of fault damaged zones and the
development of ductile shear zones, occurring in the uppermost region of the lower crust (i.e., middle crust).

2 | SAMPLE AND METHODS

The Eidsfjord shear zone is a 200-m-thick mylonite zone that underwent down-to-the-west normal-slip movement along the crustal-scale detachment fault (Moecher & Steltenpohl, 2011). In this region, Caledonian metamorphism and deformation are strictly limited to shear zones (Steltenpohl et al., 2011). In the Eidsfjord shear zone, pseudotachylites are frequently observed. Some pseudotachylites deform plastically along with mylonites, while some pseudotachylites cut across the mylonitic foliation and encloses angular clasts of meta-anorthosite mylonite. The anorthosite mylonites are often recognized in the coastal area (Figure 1). The lateral extent of each mylonite in the field is unclear, but the width of the mylonite shear zone is less than a few metres.

The deformed meta-anorthosite that is examined in this study constitutes the narrow shear zone (<2 m wide) occurring at the western part of the Eidsfjord shear zone (Figure 1). The outcrop is at a distance from the high-strain zone that is developed near the crustal-scale detachment fault. This meta-anorthosite sample is not overprinted by later stage deformation concentrated along the detachment fault (Steltenpohl et al., 2011). A mylonitic foliation that is defined by an alignment of mafic-mineral patches is observed (Figure 2a). The degree of development of the foliation varies within the sample and may reflect the degree of shear deformation. In a domain with high shear strains (lower part of the sample in Figure 2a), a weak stretching lineation that is defined by an alignment of the long axes of mafic-mineral patches occurs on the foliation planes. The sample comprises plagioclase, amphibole, biotite, and quartz, and minor amount of garnet, epidote, apatite, K-feldspar, and scapolite exist as secondary phases. Plagioclase occurs as fine-grained matrix grains and porphyroclasts. The matrix-forming mineral assemblage is similar to that in the meta-anorthosite mylonites that have been previously reported from the Eidsfjord shear zone the symmetamorphic deformation occurred at ~600–700 MPa and ~600–750°C (Leib, Moecher, Steltenpohl, & Andresen, 2016; Okudaira, Shigematsu, Harigane, & Yoshida, 2017; Steltenpohl et al., 2011), which corresponds to crustal depths of ~20–25 km, assuming the rock density of 2,800 kg/m³. Some plagioclase porphyroclasts are partially altered to epidote and muscovite. The long axes of muscovite and epidote are randomly oriented, which indicates their postkinematic crystalization. In the matrix-forming plagioclases, An-poor cores and An-rich rims are developed; however, the crystallographic orientation between these plagioclases is continuous.

Some rectangular-shaped plagioclase porphyroclasts can be recognized at the scale of hand specimens with grain sizes of up to 4 cm and comprise a few large clasts and numerous fine microscopic grains (hereafter referred to as “pseudomorphic porphyroclasts”). We measured the crystallographic orientations of plagioclase grains within the pseudomorphic porphyroclast in a domain with low shear strains (the upper part of the sample is depicted in Figure 2a) using a scanning electron microscope (SEM; Hitachi SU3500) equipped with an electron-backscatter diffraction system (EBSD; Oxford Instruments, with AZtec software) at the Geological Survey of Japan, AIST. We performed EBSD data analysis using the MATLAB toolbox MTEX (ver. 4.5; Mainprice, Bachmann, Hielscher, & Schaeben, 2014). The thin sections are oriented normal to the foliation and parallel to the stretching lineation.

3 | RESULTS

The pseudomorphic plagioclase porphyroclast for the EBSD measurements exhibits a rectangular-shaped grain outlined by the matrix-forming mafic minerals (Figure 2a,b). The Albite-Carlsbad/Carlsbad twins that are developed in the pseudomorphic plagioclase porphyroclast are recognized by the differences in their optic
extinction angles. The plagioclase grains in each twin domain form an aggregate exhibiting uniform extinction under cross-polarized light, which is reflecting small misorientation angles within the neighbouring grains. Some areas (e.g., Area 1 in Figure 2b) in the pseudomorphic porphyroclast contain equigranular, fine-grained plagioclase with a relatively uniform grain size of ~0.1 mm (Figure 2c). The fine-grained plagioclase in Area 1 exhibits equilibrium (foam-like) structure, i.e., straight grain boundaries and triple junctions with dihedral angles of ~120°. Some of the fine-grained plagioclase exhibit compositional zoning, similar to that in the matrix-forming grains, indicating that metamorphic recrystallization has modified the previous microstructures to some degree. The other areas in the pseudomorphic porphyroclast comprise a few coarse grains along with fine grains having a variable grain size (e.g., Area 2 in Figure 2b). Most of the plagioclase grains have angular grain shapes and variable grain sizes <5 mm (Figure 2d). They are chemically homogeneous and their compositions are similar to those of large relict clasts. The preservation of the “previous” microstructures in this area may be due to an insufficient supply of aqueous fluid. Most Albite and Pericline twins developed in plagioclases show bent and tapering forms, thus suggesting their deformation origin. Other plastic-deformation microstructures, such as subgrain boundaries, wavy extinctions, or bulges are absent in the plagioclase grains. The grain-size distribution of the plagioclase in Area 2 is characterized by large numbers of fine grains and few coarse grains (Figure 3a). Figure 3b shows the relationship between the cumulative number N (d) and the grain size d; it can be fitted by the power-law equation $N(d) \propto d^{-D}$, and the resulting fractal dimension is $D = 1.02 \pm 0.02$. The value of the fractal dimension is smaller than those ($D = 1.68–2.35$) reported from the natural fault rocks (Muto, Nakatani, Nishikawa, & Nagahama, 2015) and similar to those ($D = 0.9–1.1$) for small grains with the particle size of <~2 μm from the deformation experiments (Keulen, Heilbronner, Stünitz, Boullier, & Ito, 2007). The low value of the fractal dimension may be caused by metamorphic recrystallization or grain growth via absorption of small grains and growth of large grains.

Most grains are free from internal orientation differences, displaying no distinguishable subgrain boundaries. In some grains, there is a gradual increase in the internal orientation difference from the geometrical grain centre to the margin (grains 1 and 2 in Figure 2d), and the internal orientation difference in each grain is very small (<~3°; Figure 4a,b). The crystallographic axes within these grains do not rotate with respect to specific crystallographic axes (Figure 4c). These suggest no obvious evidence of subgrain rotation via an intracrystalline slip system. The fine-grained plagioclase in both the Areas 1 and 2 in Figure 2b has a strong crystallographic preferred orientation (CPO) (Figure 5). In Area 1, each crystallographic axis, [100], [010], and [001], shows a point maximum. Each maximum point overlaps the crystallographic orientation of the adjacent large relict clast (the stars in Figure 5). Although Area 2 also shows a point maximum, the crystallographic orientations of the plagioclase grains overlap the CPO pattern of Area 1.
In sample coordinates, rotation axes with angles of 10° maxima do not correspond to low bits scattered and weak point maxima (Figure 6b). The weaken point coordinates suggest no crystallographic control of grain rotation. Distributions of rotation axes shown in the crystal and sample coordinates from Area 2 are distributed randomly (Figure 6c). Consequently, the crystalline axis or plane in the IPF (Figure 6b), the rotation of grains is (a) Frequency vs. logarithmic grain size with a rotation of 180° around [100], explained by the Albite-Carlsbad/Carlsbad twins.

Figure 6a shows the frequency of misorientation angles among neighbouring pairs (correlated misorientations) and among random pairs (uncorrelated misorientations) from Area 2, which is expected to have less microstructural modifications. Except for a strong peak at 180° representing the twins, the frequency histograms show one broad peak at 10°–90°. Inverse pole figure (IPF) for misorientation axes between neighbour pairs with a rotation angle of 10°–15° exhibits scattered and weak point maxima (Figure 6b). The weak point maxima do not correspond to low-index crystal axes and planes in the IPF. In sample coordinates, rotation axes with angles of 10°–70° from Area 2 are distributed randomly (Figure 6c). Consequently, the distributions of rotation axes shown in the crystal and sample coordinates suggest no crystallographic control of grain rotation.

4 | DISCUSSION

As described above, some pseudomorphic plagioclase porphyroclasts comprise a few large relict clasts and many fine microscopic grains, which preserve the outlines of the original grains. The microstructures for Area 2 in the pseudomorphic plagioclase porphyroclast are different from typical plastic-deformation microstructures. The CPO patterns are inherited from the twinned pseudomorphic porphyroclast rather than from the activation of a specific crystalline slip system. Because the small rotation angles (10°–15°) do not concentrate on any crystalline axis or plane in the IPF (Figure 6b), the rotation of grains is not controlled by the crystal structure. During subgrain rotation recrystallization, a new grain develops via the progressive misorientation of subgrains controlled by the crystal structure (Passchier & Trouw, 2005); therefore, the misorientation relations cannot be explained by subgrain rotation recrystallization. This is supported by the lack of obvious subgrain boundaries in plagioclase grains (Figure 2d). In some grains, there is a gradual increase in the orientation difference from the geometrical grain centre to the margin (Figure 4b), and the value of the internal orientation difference in each grain is very small (<3°). The increase in internal orientation difference at the grain margin may be the result of lattice distortion due to fracturing. There is a possibility that the absence of subgrain boundaries and the very low orientation difference in grains may have resulted from high-T annealing after deformation. The high-T annealing would obliterate the substructure.
in the plagioclase grains but not disturb the crystallographic relation between neighbouring grains (Heilbronner & Tullis, 2000); therefore, if subgrain rotation recrystallization was a dominant grain-size reduction process, the misorientation relation would be controlled by the crystal structure, but it is not observed. After the grain-size reduction, the rotations caused by the displacement along the grain boundaries due to shear deformation along the mylonitic foliation (i.e., the shear plane) would disturb the crystallographic relation between the neighbouring grains. If the rotations were caused by the displacement, the rotation axes would be concentrated along the direction normal to the slip direction in the shear plane (i.e., the Y-direction of the finite-strain ellipsoid; Menegon, Stünitz, Nasipuri, Heilbronner, & Svahnberg, 2013). However, they are distributed more or less randomly in sample coordinates (Figure 6c), suggesting the absence of displacement after the grain-size reduction. Well-preserved, original twinned relationships as well as the random distribution of rotation axes indicate fracturing without shear strain. Even though microstructural modification occurred after fracturing, the fractal size distribution of the plagioclase grains (Figure 3b) would imply that fragmentation/fracturing is the fundamental process to reduce the grain size rather than dynamic recrystallization. These microstructural observations indicate the pulverization of the original grain.

The microstructures indicative of metamorphic recrystallization or annealing suggest that the pulverization occurred coeval with or prior to the metamorphic recrystallization. The meta-pseudotachylite- and meta-anorthosite mylonites formed under conditions of ~600–700 MPa and ~600–750°C (Leib et al., 2016; Okudaira et al., 2017; Steltenpohl et al., 2011), corresponding to a crustal depth of ~20–25 km. Thus, our microstructural analyses of the deformed meta-anorthosite reveal pulverization in the uppermost region of the lower crust. The pulverization may result from stress waves with high stress-rate loadings released by the rupturing fault. Stresses of over a few hundreds of MPa build up with a sharp maximum in the uppermost ductile region (~20 km depth) near the tip of a seismically active fault in the lower crust, causing deep aftershocks, demonstrated by numerical simulations (Ellis & Stöckhert, 2004; Jiang & Lapusta, 2016; Shimamoto & Noda, 2014). In rocks deformed naturally under lower crustal conditions, it has been reported the fragmentation of jadeite and garnet from the Sesia Zone, Western Alps (Trepmann & Stöckhert, 2001, 2002), and garnet and plagioclase associated with pseudotachylite from the Bergen Arcs, SW Norway (Austrheim et al., 2017; Petley-Ragan, Dunkel, Austrheim, Ildefonse, & Jamtveit, 2018). This also implies that fragmentation or pulverization is associated with seismic faulting in the lower crust. In this study, pulverization of plagioclase that is the dominate phase of the meta-anorthosite implies the bulk pulverization of the rock. Such pulverization would result in the formation of a high-permeability zone, at least temporally, leading to
episodic fluid flow that modifies the mechanical and rheological properties of the zone and its upward extension.

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APPENDIX 1

ADDITIONAL INFORMATION FOR THE EBSD ANALYSIS

The EBSD data were recorded with a step size of 5 μm. For indexing, we used data in Aztec of andesine An38, muscovite, and epidote. The grain size (equivalent diameter) of the plagioclase was calculated using the areas of the grains having a segmentation angle of greater than 10°, and the Pericline and Albite twins are merged along the twin boundaries. We excluded the grains having sizes smaller than 10 pixels. Systematically misindexed points, which appear as a mosaic of pixels composed of two orientations in EBSD orientation maps, are removed by rotation about specific angle-and-axis pairs. These processes have been done using MTEX.

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