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High transient stress in the lower crust: Evidence from dry pseudotachylytes in granulites, Lofoten Archipelago, northern Norway

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ABSTRACT

Seismic activity below the standard seismogenic zone is difficult to investigate because the geological records of such earthquakes, pseudotachylytes, are typically reacted and/or deformed. Here, we describe unusually pristine pseudotachylytes in lower-crustal granulites from the Lofoten Archipelago, northern Norway. The pseudotachylytes have essentially the same mineralogical composition as their host (mainly plagioclase, alkali feldspar, orthopyroxene) and contain microstructures indicative of rapid cooling, i.e., feldspar microlites and spherulites and "cauliflower" garnets. Mylonites are absent, both in the wall rocks and among the pseudotachylyte clasts. The absence of features recording precursory ductile deformation rules out several commonly invoked mechanisms for triggering earthquakes in the lower crust, including thermal runaway, plastic instabilities, and downward propagation of seismic slip from the brittle to the ductile part of a fault. The anhydrous mineralogy of host and pseudotachylytes excludes dehydration-induced embrittlement. In the absence of such weakening mechanisms, stress levels in the lower crust must have been transiently high.

INTRODUCTION

Below the brittle-ductile transition (at ~15 km depth for the continental crust), deformation is commonly assumed to be accommodated by crystal-plastic mechanisms, and earthquakes should not be possible. However, seismic data show that earthquakes do occur at these depths (e.g., Maggi et al., 2000). Exhumed lower-crustal rocks from a number of localities worldwide likewise record fossil earthquakes (e.g., Austrheim and Boundy, 1994; Steltenpohl et al., 2006; Pittarello et al., 2012; Menegon et al., 2017; Hawemann et al., 2018; Orlandini et al., 2019). The differential stresses necessary to allow frictional failure in intact, dry rocks at the confining pressures of the lower crust (≥1 GPa) are considerably higher than what can be sustained over orogenic time scales (Jamtveit et al., 2018). Hence, local weakening mechanisms have been invoked, such as thermal shear instabilities (Braeck and Podladchikov, 2007), and dehydration- or reaction-induced embrittlement (e.g., Austrheim and Boundy, 1994). Alternatively, upper-crustal earthquakes could migrate downward (Moecher and Steltenpohl, 2011) or cause transient stress transfers to the lower crust (Ellis and Stöckhert, 2004; Jamtveit et al., 2018).

Establishing the origin of lower-crustal earthquakes for specific cases is challenging because the structures produced by seismic events are often obliterated by subsequent deformation and metamorphism. Here, we describe an exceptional occurrence of pristine pseudotachylytes that developed in dry rocks from the Lofoten Vesterålen Archipelago in the northern Norwegian Caledonides. Their preserved microstructures provide the first glimpse into the incipient stages of Caledonian crustal transformation processes in an area with a high density of lower-crustal earthquakes (e.g., Steltenpohl et al., 2006; Moecher and Steltenpohl, 2011; Menegon et al., 2017; Jamtveit et al., 2019) and advance our understanding of earthquakes under high confining pressure.

GEOLOGICAL SETTING

The Lofoten-Vesterålen islands are part of the Norwegian Caledonides and consist of an Archean to Paleoproterozoic metamorphic complex of paragneisses and orthogneisses intruded at 1870–1770 Ma by an anorthosite-mangerite-charnockite-granite (AMCG) suite that makes up ~50% of the archipelago (Griffin et al., 1978; Corfu, 2004). The intrusive rocks were emplaced under granulite-facies conditions (Griffin et al., 1978). During the Caledonian orogeny (ca. 490–390 Ma), western Baltica was partially subducted under Laurentia; however, the relation of the Lofoten block to Baltica and the Caledonides is unclear.

Pseudotachylytes are abundant and have been reported from numerous localities in the Lofoten-Vesterålen area (Fig. 1A). They are often coeval with eclogite- or amphibolite-facies shear zones (Steltenpohl et al., 2006; Moecher and Steltenpohl, 2011; Menegon et al., 2017), indicating formation under lower-crustal conditions.

PSEUDOTACHYLYTES ON MOSKENESØYA

We investigated four outcrops along the east coast of Moskenesøya (three road cuts and one small quarry) (for locations see Fig. 1A; see also the Supplemental Material[1]). The rocks are massive, without macroscopically visible foliation or lineation. Their compositions range

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[1] Supplemental Material. List of the localities, description of the methods, supplemental figures detailing the composition of the host rocks (Fig. S1), the distribution and orientation of pseudotachylytes (Fig. S2), the relationship between amphibole and pseudotachylytes (Fig. S3) and the residual pressures of quartz inclusions in garnet (Fig. S4), and supplemental tables on host rock geochemistry (Table S1) and Raman data (Table S2). Please visit https://doi.org/10.1130/GEOL.S.12915719 to access the supplemental material, and contact editing@geosociety.org with any questions.

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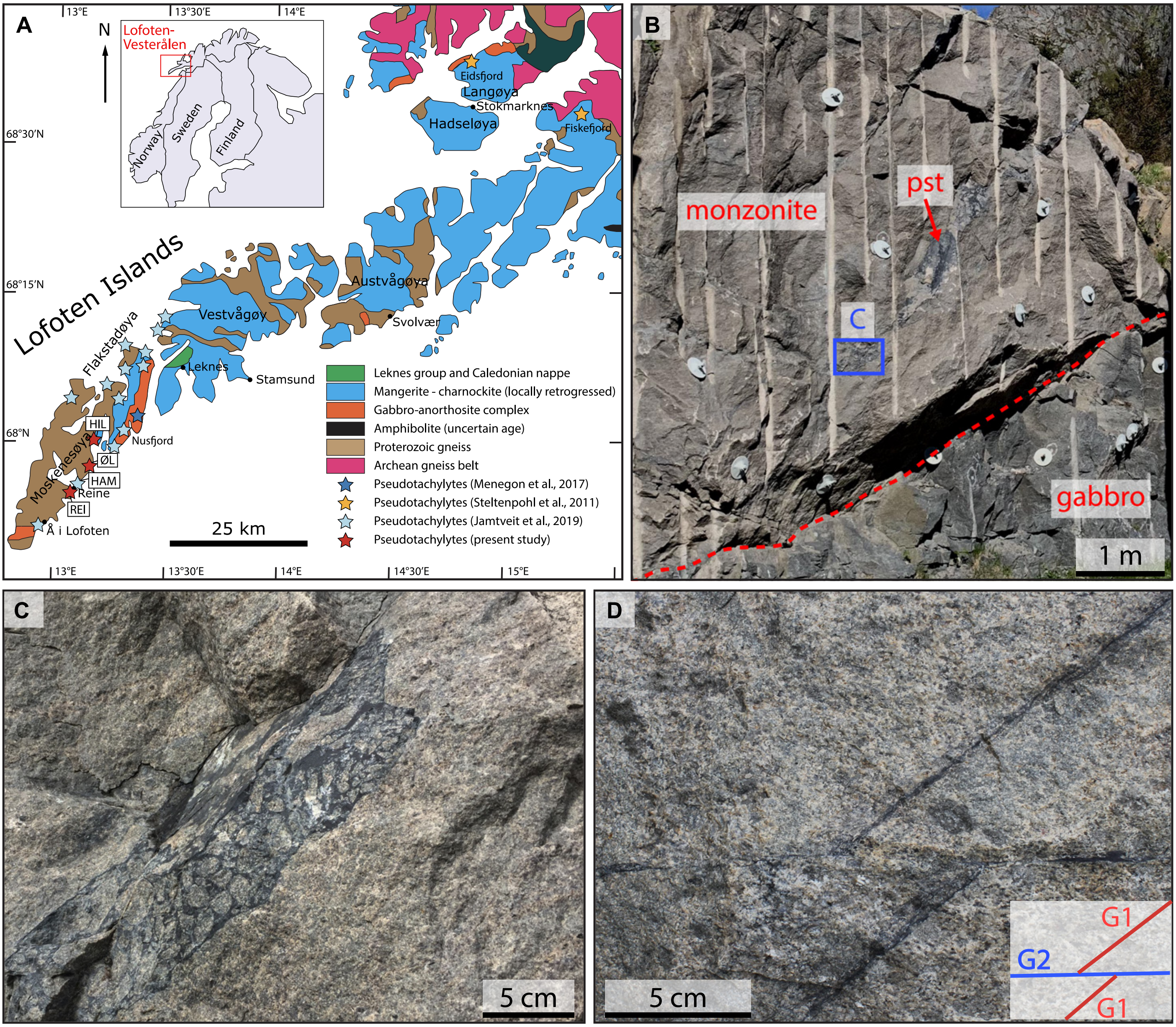

Figure 1. (A) Geological map of the Lofoten area, northern Norway (modified from Corfu, 2004), with sampling localities (HIL, ØL, HAM, REI) along the east coast of Moskenesøya. (B) Field photo illustrating different lithologies found within one outcrop, with a long, straight pseudotachylyte (pst) extending from bottom left to top right. (C) Pseudotachylyte breccia. (D) Two generations (G1 and G2) of crosscutting pseudotachylyte fault veins. B–D: Outcrop HAM.

from gabbroic to monzonitic. They follow a linear trend in a total alkalis versus silica (TAS) diagram (see Fig. S1), but the contact between monzonitic and gabbroic varieties is generally sharp (Fig. 1B). The monzonites show a grain size ranging from millimetric to centimetric size.

Both monzonites and gabbros are cut by dark, fine-grained pseudotachylyte veins (Figs. 1B–1D). They are ~1–15 mm thick and generally straight, and they can commonly be followed for several meters (Fig. 1B). Many have injection veins or form breccias (Fig. 1C), and some cut each other at high angles (Fig. 1D). On one outcrop (HAM-1) with a width of ~80 m and a height of up to 15 m, 47 pseudotachylyte veins longer than 1 m were mapped (Fig. S2A). The pseudotachylytes in the four investigated localities exhibit two main orientations: One set strikes approximately NNW-SSE, and the other one strikes ENE-WSW. The east-west–striking and northwest-southeast–striking veins are less prominent (Fig. S2B). Major ductile shear zones are absent in the investigated outcrops and have not been found in any of the road cuts along the 24-km-long road along the east coast of Moskenesøya (from the bridge over Kåkersundet to the village Å i Lofoten).

Compositionally, the host rocks and pseudotachylytes are very similar. Whole-rock geochemical analyses of two host-pseudotachylyte pairs showed only very small changes in major- and trace-element compositions (Table S1). In the monzonites, there are no hydrous minerals except for minor amounts of amphibole as reaction rims around orthopyroxene. The more gabbroic rocks contain more amphibole. However, the distribution of amphibole is not correlated to that of the pseudotachylytes. This is especially clear at one outcrop (ØL), where gabbro contains dark, amphibole-rich patches several centimeters in diameter that are homogeneously distributed in the outcrop (Fig. S3). Because the pseudotachylyte microstructures are the same in the (amphibole-bearing) gabbroic and the monzonitic rocks, we treat them together here.

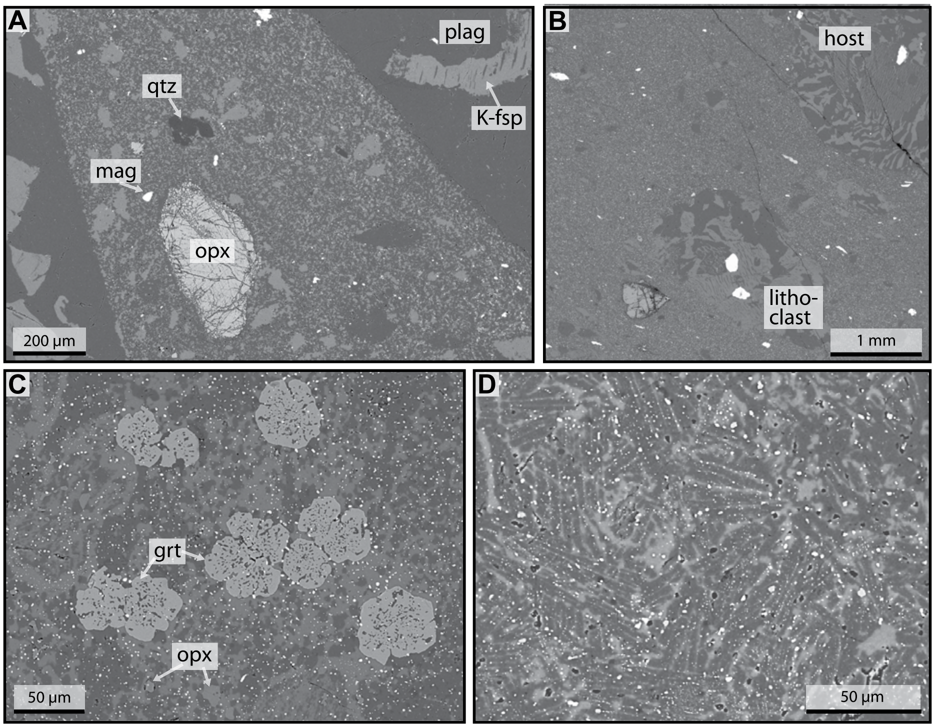

Figure 2. **(A) Pseudotachylyte with sharp borders to undeformed host rock. qtz—quartz; plag—plagioclase; K-fsp—K-feldspar; mag—magnetite; opx—orthopyroxene. (B) Pseudotachylyte with a large lithoclast that shows similar perthitic microstructures as the host. (C) Cauliflower garnets (grt) and small grains of orthopyroxene. Matrix consists of two feldspars and magnetite. (D) Plagioclase microlites (dark gray) surrounded by K-feldspar (light gray). Magnetite is white; porosity black. A, B, D: sample HAM-3, C: sample HAM-2.**

MICROSTRUCTURES OF HOST AND PSEUDOTACHYLYTE

The host rock does not display evidence for mylonitization, and the borders between host rock and pseudotachylyte are sharp (Fig. 2A). Plagioclase, alkali feldspar, magnetite, pyroxenes, and (in the monzonitic varieties) quartz occur as clasts in the pseudotachylyte and show no signs of ductile deformation. The feldspars exhibit the same perthitic exsolution features as those in the host rock (Fig. 2B). Smaller grains of pyroxene and (in the gabbroic varieties) amphibole with more constant diameters on the order of 10 µm occur as well. The pseudotachylyte contains rounded to angular pores (Figs. 2C and 2D).

Microstructures indicative of rapid cooling are crucial to determine the melt origin of a pseudotachylyte (Kirkpatrick and Rowe, 2013) and are shown by several minerals in the pseudotachylytes analyzed here. Garnet has a dendritic to cauliflower habit (Fig. 2C) and contains inclusions of the other mineral phases in the pseudotachylyte. Feldspar occurs as equant grains or elongated microlites (Fig. 3D), which are sometimes arranged as spherulites. Plagioclase microlites are often surrounded by alkali feldspar (Fig. 3D). The feldspar microstructures and their distribution were analyzed in detail by Dunkel et al. (in press).

While most of the pseudotachylytes do not show any evidence for postseismic deformation or annealing (the microlitic microstructures are

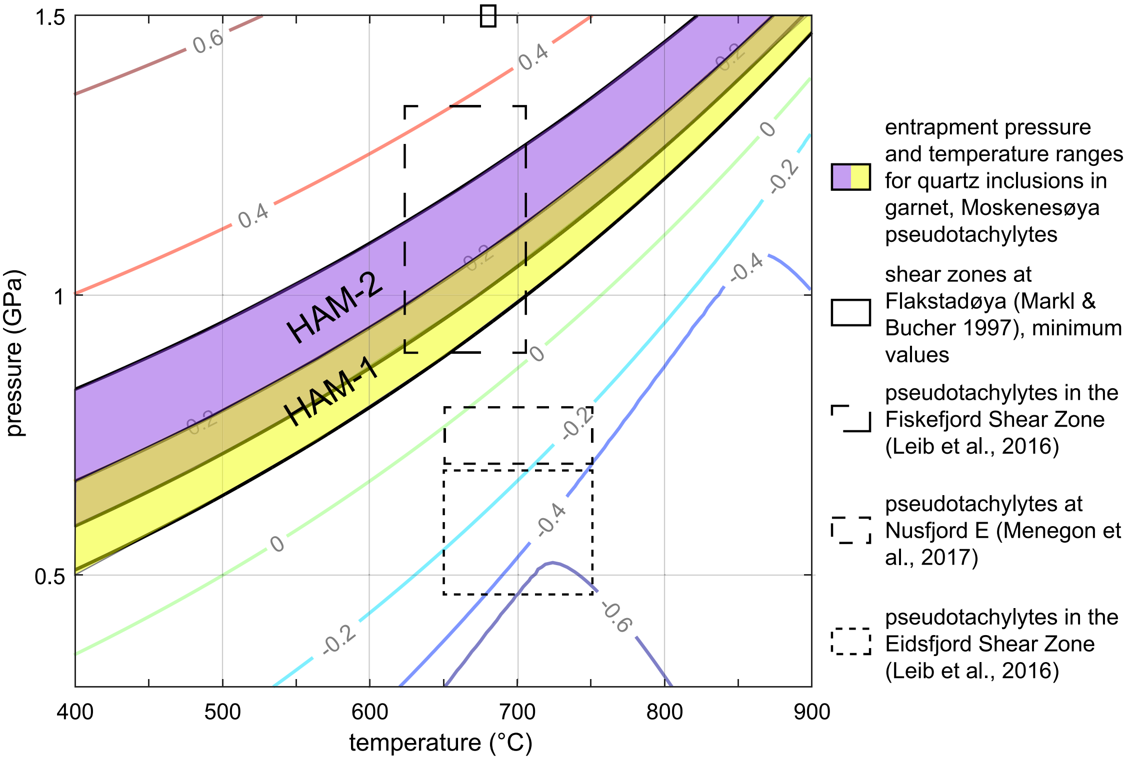

Figure 3. Entrapment pressure versus temperature for quartz in garnet, compared to the formation conditions of other pseudotachylytes in Lofoten/Vesterålen (northern Norway). Shear zones on Flakstadøya are coeval with pseudotachylytes (Steltenpohl et al., 2006). The entrapment pressure that can be calculated from residual inclusion pressure depends on the entrapment temperature. These pressure-temperature relationships are shown as isopleths. The ranges of possible entrapment conditions for samples HAM-1 and HAM-2 are marked by yellow and purple bands, respectively. Assuming temperatures similar to those of other pseudotachylytes in Lofoten (650–750 °C), entrapment pressures were ~0.8–1.2 GPa. See Figure S4 and Table S2 (see footnote 1) for details.

preserved), stretching of clasts and a development of a crystallographic preferred orientation in the matrix feldspar were observed along the straight margins of some pseudotachylytes. This was interpreted as minor reactivation of some seismic faults by plastic deformation.

AMBIENT CONDITIONS DURING PSEUDOTACHYLYTE FORMATION

Previous work has shown that the pseudotachylytes from the Lofoten-Vesterålen area formed under amphibolite- to eclogite-facies conditions (Steltenpohl et al., 2006; Moecher and Steltenpohl, 2011; Leib et al., 2016), but, so far, no direct estimate of the pressure during pseudotachylyte formation has been performed. All pressure estimates have been based on mineral equilibria from hydrated, recrystallized, and often mylonitized rocks. In this case, traditional thermobarometry based on the mineral assemblages in pristine pseudotachylytes is hampered by the limited number of new phases and the potential chemical disequilibrium during rapid quenching. Clasts are inherited from the wall rocks and show very little or no reaction with the feldspar-dominated matrix. For this reason, quartz-in-garnet elastic barometry is a powerful alternative to recover the paleopressure of the rocks, because it is based not on a chemical equilibrium, but on the mechanical equilibrium between inclusion and host. This method requires the determination of residual pressures of quartz inclusions sealed in garnet hosts with Raman spectroscopy. A higher wave-number shift of quartz inclusions is related to a higher residual pressure (e.g., Schmidt and Ziemann, 2000). The residual pressure develops due to a relative expansion/contraction during exhumation caused by the different thermal expansivity and compressibility of the two phases (Zhang, 1998). Wave-number shifts for quartz inclusions within garnets in the pseudotachylytes from Moskenesøya are ~0.9–1.9 cm^{-1} (sample HAM-1) and ~1.3–2.9 cm^{-1} (HAM-2) for the 464 cm^{-1} band (Table S2; Fig. S4). A gem-quality quartz crystal was used as the standard for stress-free quartz. Based on the calibration from Schmidt and Ziemann (2000), the residual inclusion pressures are in the range of 0.10–0.21 GPa for HAM-1 and 0.14–0.32 GPa for HAM-2. Using a one-dimensional, radially symmetric elastic model and assuming isotropic elasticity and an infinite host medium (Guiraud and Powell, 2006; see the Supplemental Material for details), the pressure at which the quartz inclusion was entrapped in the garnet host can be calculated (e.g., Zhong et al., 2019). For the analyzed samples, the resulting pressure is ~0.8–1.2 GPa (Fig. 3) at the temperature conditions estimated for pseudotachylytes in "wet" systems from other localities in Lofoten (650–750 °C; Markl and Bucher, 1997; Leib et al., 2016; Menegon et al., 2017).

The absence of fluids during faulting is in itself evidence that faulting did not occur in the shallow parts of the crust. Usually, fluid infiltration accompanies or directly follows a seismic event in the upper crust, but in the lower crust, anhydrous pseudotachylytes are more common (Musgrave Ranges, Australia—Camacho et al., 1995; Hawemann et al., 2018, 2019; Cora Lake shear zone, Canada—Orlandini et al., 2019; Minas fault zone, Canada—White, 2012; Ivrea zone, Italy—Pittarello et al., 2012; Mont Mary Nappe, Italy—Mancktelow and Pennacchioni, 2004; Pennacchioni and Cesare, 1997). There are also some examples of dry pseudotachylytes reported from subduction zone settings (Austrheim and Andersen, 2004; John and Schenk, 2006; Scambelluri et al., 2017).

GENERATION OF EARTHQUAKES IN DRY LOWER CRUST

The pseudotachylytes at Moskenesøya are the results of multiple lower-crustal earthquakes (Fig. 2D). Several models have been proposed to explain seismic slip and the presence of pseudotachylytes below the brittle-ductile transition depth (~15 km) in the continental crust. Dehydration embrittlement (Raleigh and Paterson, 1965) is a commonly invoked mechanism for lower-crustal earthquakes (Austrheim and Boundy, 1994). In the present case, however, both the wall rock and the pseudotachylytes are essentially devoid of hydrous minerals (except for some of the more gabbroic samples). Hence, dehydration embrittlement can be excluded here.

Plastic instability (Hobbs et al., 1986) or thermal runaway (Braeck and Podladchikov, 2007) models, which invoke a feedback between shear heating and thermal softening within a ductile shear zone, are not applicable either, because there is no evidence for preexisting ductile shear deformation, neither in the wall rock nor in the clasts within the pseudotachylytes.

Moecher and Steltenpohl (2011) described lower-crustal pseudotachylytes associated with the Eidsfjord and Fiskefjord shear zones in the northern part of the Lofoten-Vesterålen Archipelago, featuring a mutual overprinting of brittle and ductile deformation features. They explained the occurrence of lower-crustal earthquakes by the propagation of a dynamic rupture that nucleated in the upper part of a fault and moved downward into its ductile extension. This would imply a preexisting ductile shear zone, which is not observed in the present case.

In the absence of weakening mechanisms, brittle failure of the dry granulites from Moskenesøya would require very high stresses. The earthquakes may have been triggered by a stress pulse from the shallower seismogenic regime. Ellis and Stöckhert (2004) analyzed the effect of coseismic displacement in the upper crust on the middle and lower crust and found that stresses reaching several hundred megapascals may arise below the brittle-ductile transition, even for a weak (wet-quartz) rheology. For a strong lower crust initially subject to high but sustainable stresses during plate convergence, transient stress perturbations caused by upper-crustal earthquakes may trigger lower-crustal aftershocks at all crustal depths, as observed, for example, during the 2001 M_W 7.6 Bhuj earthquake in India (Copley et al., 2011). Based on observed earthquake frequencies and scaling relations from the seismogenic regime, Jamtveit et al. (2018) demonstrated that this mechanism is expected to create significant damage in the lower crust.

Another possibility to generate transiently high stresses has been presented by Hawemann et al. (2019), who suggested that high stresses in the lower crust arise from the jostling of strong blocks within a shear zone network (Musgrave Ranges, Australia). This hypothesis was supported by observations from Nusfjord East in Lofoten (Campbell et al., 2020), where pseudotachylytes occur in blocks between granulite-facies shear zones. In this part of Lofoten, ~15 km from the Nusfjord ridge, no shear zones have been observed so far. However, at least one set of pseudotachylytes on Moskenesøya is comparable to one of the most prominent shear zone orientations at Nusfjord East (Fig. S1C). Hence, we propose that the Moskenesøya case represents a precursor to what is now observed at Nusfjord and represents the first stage of seismically induced reworking of the lower crust. Aftershocks from upper-crustal earthquakes may have triggered the first generation of pseudotachylytes along preexisting structures, which are common in large areas of Lofoten, such as cooling joints in the plutonic rocks. Some of these pseudotachylytes were then mylonitized and developed into shear zones as described by Menegon et al. (2017) for Nusfjord. Stress amplifications within blocks bounded by shear zones may subsequently have triggered the formation of a second generation of pseudotachylytes (Campbell et al., 2020).

CONCLUDING REMARKS

Pseudotachylytes from the dry lower crust of Moskenesøya in southern Lofoten, Norway, are neither fluid-bearing nor associated with mylonites. This excludes the most commonly suggested weakening mechanisms that may cause earthquakes below the brittle-ductile transition: reaction-induced embrittlement, plastic instability, thermal runaway, and downward propagation of a seismic rupture from shallow faults into their deeper ductile extensions. Transient stress pulses in a strong lower crust, possibly caused by shallower earthquakes, seem to be the only plausible explanation for these rocks.

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