Pseudotachylytes Generated During Seismic Faulting and Eclogitization of the Deep Crust

H. Austrheim* and T. M. Boundy

Pseudotachylytes are typically interpreted to have formed by frictional melting during coseismic faulting within the upper to middle crust. Pseudotachylytes in the Bergen arcs of western Norway contain microlites including omphacite, garnet, plagioclase, and quartz. This eclogite facies assemblage is stable at temperatures of about 800°C and pressures of 18 to 19 kilobars, corresponding to depths of 60 kilometers or more. The pseudotachylytes are exposed in Grenvillian granulites that locally underwent fluid-induced eclogitization and corresponding volume reduction of approximately 10 percent during the Caledonian continental collision. The pseudotachylytes may have formed as a result of the rapid relaxation of stresses caused by the eclogitization process.

Earthquakes take place when physical conditions at depth allow stresses resulting from active geological processes to be released rapidly. The occurrence of earthquakes is used to infer tectonic processes and to constrain petrophysical properties of the crust and mantle. Recordings of seismic activity during the last few decades have shown that earthquakes occur in the lower continental crust (*1*) down to 70 km in continent collision zones (*2*). The reason for deep earthquakes is still a matter of debate and involves mechanisms such as runaway phase transitions (*3*), changes in stress state caused by phase transitions (*4*), stress amplification due to rigidity contrasts (*5*), gravitationally induced stresses due to lateral discontinuities in density (*6*), and weakening of the crust by fluids (hydroseismicity) (*7, 8*). These models arise from mathematical and geophysical reasoning and laboratory experiments, but less so from geological field observations. Frictional heating during rapid faulting can result in melting and formation of pseudotachylyte. Pseudotachylytes are dark aphanitic veins showing an intrusive relation and sharp boundaries and containing clasts or crystals of the host rock. They are associated with fault and shear zones (*9–11*). In this report, we describe eclogite facies pseudotachylytes that may have formed from rapid faulting and seismic activity at a depth of about 60 km or more.

A slice of the former root zone to the Caledonian mountain range is exposed in a thrust sheet in the Bergen arcs of western Norway (*12*). The rocks brought up from this part of the lithosphere are Grenvillian granulite facies rocks (800° to 900°C, ≤10 kbar), some of which were locally transformed to dense eclogite facies rocks (670°C, >15 kbar) during the Caledonian orogeny, apparently as a result of deformation and interaction with fluids (*12–15*). The transition from granulite to eclogite facies rocks takes place over a few centimeters. A mixture of granulite and eclogite facies rocks is exposed over an area of 100 km^2. Eclogitization increased the ductility (*16*) and density (*12*). Eclogites are formed along fractures, along shear zones up to 120 m thick and continuous for several kilometers, and in breccias where angular blocks of granulites are surrounded by eclogite.

Veins with a flinty, green to black homogeneous matrix with variable (5 to 20%) amounts of wall rock fragments containing plagioclase and rarely garnet (Fig. 1) occur within granulites. The veins form at the border of eclogitized areas and have been observed at 10 outcrops distributed over several square kilometers. Locally, veins can be traced from the granulite to the adjacent eclogite, but they are also found completely enclosed in the granulites. Often the veins are adjacent to or jut out from eclogite facies shear zones into the surrounding granulites.

The veins are typically about 1 cm thick, but locally they are 5 cm thick. Contacts between the veins and the neighboring rocks are sharp (Figs. 1 and 2). The granulite host rocks are anorthositic to gabbroic in composition and consist of garnet, clinopyroxene, and plagioclase and locally of pleonaste, orthopyroxene, scapolite, and hornblende. The grain size in the host rock is 1 to 5 mm. Initial eclogitization can be detected in the granulite wall rock as thin rims of omphacite forming between garnet and plagioclase grains and as clinozoisite or zoisite [(clino)zoisite] (the two could not be distinguished because the grain size was too small) and kyanite forming within the plagioclase grains. Large garnets at the border of the veins are penetrated by numerous fractures (Fig. 2), and some are disaggregated.

The matrix of the vein consists of a fine-grained mosaic of crystals of omphacite, garnet, kyanite, (clino)zoisite, hornblende, plagioclase, potassium feldspar, quartz, and pyrite. The grain size increases from typically <10 μm at the margins of veins toward their centers where microlites of garnet and (clino)zoisite reach 100 μm. The fine grain size toward the rim may be a chilled margin. Kyanite and (clino)zoisite are acicular, whereas the plagioclase has an equidimensional form, often surrounding kyanite. Typically, the center of the vein contains randomly oriented, coarse (clino)-zoisite crystals. Garnets are euhedral (Fig. 3) and have a dusty appearance (Fig. 2) due to abundant minute (typically 1 to 5 μm across) inclusions of all the other minerals in the vein except for amphibole.

Mineral compositions of omphacites (*17*) from the veins are Jd_{30} to Jd_{50} (where Jd is jadeite), which is similar to the range found in the eclogites (*15*), although the range in the pseudotachylyte is greater. In contrast, the pyroxene in the granulites is an aluminous

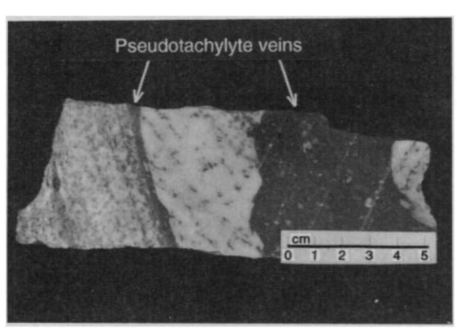

Fig. 1. Hand specimen (sample HA25/92A) from Holsnøy, western Norway, showing two veins of pseudotachylyte in anorthosite gabbro granulite. The veins contain wall rock fragments of plagioclase. The smaller vein shows evidence of dextral movement, suggesting ductile deformation before pseudotachylyte formation.

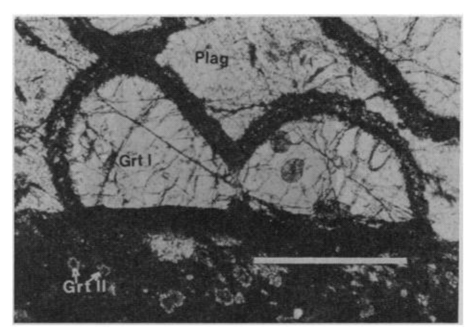

Fig. 2. Photomicrograph showing the sharp contact between pseudotachylyte and wall rock (sample HA25/92A). The granulite facies garnet (Grt I) of the wall rock is sharply truncated and contains numerous fractures. The dark rim separating granulite garnet (Grt II) and plagioclase (Plag) consists of omphacite and represents initial eclogitization. Scale bar, 1000 μm.

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diopside. Garnet in the pseudotachylyte has a composition of $Gr_{28-54}Al_{36-54}Py_{11-26}$ (where Gr is grossular, Al is almandine, and Py is pyrope). These garnet compositions differ dramatically from that of the granulite garnets (Gr_{17} Al_{30} Py_{52}) of the host. Plagioclase in the host granulite has a composition of An_{27} (where An is anorthite), whereas that in the vein is An_{19}. The textures of omphacite, garnet, and plagioclase along with the significantly different compositions compared to those of the wall-rock minerals demonstrate that the minerals in the vein are not inherited fragments from the granulite.

Calculated temperatures from omphacite-garnet pairs in the eclogites are 670° ± 50°C at 15 kbar (*15*) for the experiments in (*18*). Omphacite-garnet pairs from the pseudotachylyte yields temperatures of 790° to 820°C (with one at 690°C). Despite the limitations implicit in the thermometer, such as the significant correction for Ca required for the garnets and the ordering state of the omphacitic clinopyroxenes (*19*), the temperature estimates are reasonable. A pressure estimate may be obtained with the use of the reaction of albite to jadeite + quartz and application of the activity models of Fuhrman and Lindsley (*20*) and Lindsley and Nekvasil (*21*) for the albite component in plagioclase and of Holland (*22*) for the jadeite component in omphacite. This estimation yields 18 to 19 kbar at 820°C, which is similar to the value recorded in the eclogites (*15*).

We interpret these veins as pseudotachylyte because of their aphanitic texture, their association with shear zones, and their distribution over a local area that exclude a migmatitic origin. From the eclogite facies mineralogy found in the pseudotachylyte veins together with the temperature and pressure estimates, we conclude that the pseudotachylytes formed before or contemporaneously with the eclogite facies event. Furthermore, the apparent chilled margins of the veins and the coarsening microlites toward the core suggest that the pseudotachylyte minerals crystallized directly from the melt and that the faulting occurred under eclogite facies conditions. Thus, it is inferred that the pseudotachylytes formed at depth during the Caledonian orogeny in an area that was undergoing fluid-induced eclogitization. The higher temperature recorded by the pseudotachylyte as compared to the surrounding eclogites may indicate that the thermometer closed at a temperature between that of the melt and that of the regional eclogite facies at the time of faulting.

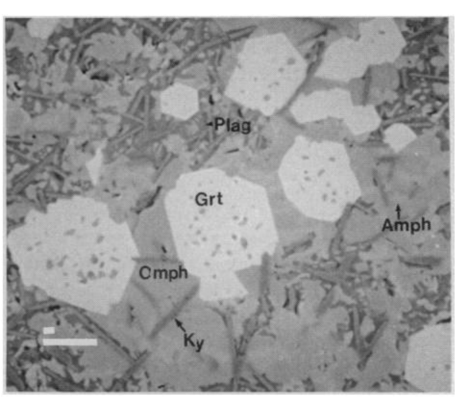

Fig. 3. Back-scattered electron image showing euhedral garnet (Grt) microlites from a pseudotachylyte vein (sample HA25/92B). Note inclusions in the garnet. Garnets are enclosed in omphacite (Omph) and minor amphibole (Amph) with needles of kyanite (Ky) and plagioclase (Plag). Scale bar, 10 μm.

In some of the completely eclogitized areas, trails of minute garnets are found with numerous small inclusions and compositions similar to those in the pseudotachylyte. This texture might be interpreted as the relict of a former pseudotachylyte vein and could mean that pseudotachylyte veins formed early in the eclogitization process were later recrystallized. Although faulting and pseudotachylyte formation may have been more important in the eclogitization process than is apparent today, there are also eclogites formed in unfaulted rocks.

Volume changes related to the olivine-spinel phase transition have been proposed to cause deep (>300 km) earthquakes (*3*, *23*). Likewise, the transition from basalt to eclogite has been used to explain earthquakes at depths of about 100 km in subduction zones (*24*, *25*). The eclogitization process involved several mechanisms that have been proposed to cause earthquakes. In addition to runaway phase transitions (*3*, *23*), eclogitization results in stresses in the surrounding granulites due to changes in volume that, because of the difference in rheology, concentrate at the borders of the eclogite bodies. Hydroseismicity has also been suggested to cause earthquakes (*7*, *8*). Fluids were obviously the key to the eclogite formation in the Bergen arcs and had multiple roles in this process. In addition to causing hydrofracturing (*15*, *26*) and having a lubricating effect, the fluids initiated and controlled the metamorphic reactions.

Applying these conclusions to active collision zones, we speculate that the Himalayan deep crustal to subcrustal earthquakes (*2*) may be related to fluid-induced eclogitization. In the case of the Alps, where a seismic lower crust under the foreland is followed by an aseismic lower and middle crust under the main mountain range (*27*), this relation could be interpreted as initial hydration and eclogitization under the foreland and complete ductile behavior due to extensive hydration under the main Alps.

The presence of pseudotachylytes indicates that stresses in the lower parts of a thickened crust, down to 60 km or more, can be released through brittle failure that is sufficiently rapid to cause melting and results in earthquakes. Eclogitizing deep crust may be brittle as a result of high fluid pressure. Fluids also play an active role in deep crustal processes by bringing about metamorphic reactions (eclogitization) that dramatically change petrophysical properties of the deep crust, such as rheology and density. It is these changes that may be the indirect reason for the observed pseudotachylytes.

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