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PSEUDOTACHYLITE FROM McINTYRE ISLAND, ENDERBY LAND, EAST ANTARCTICA: EVIDENCE FOR A RAPID CRYSTALLIZATION

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Abstract: Pseudotachylite from McIntyre Island in Enderby Land, East Antarctica, occurs in a breccia zone composed of black material with glassy luster and fragments of host pyroxene gneiss which has undergone ultra-high temperature metamorphism as a constituent of the Archean Napier Complex. Under the optical and electron microscopes, the rock in the zone demonstrates a distinct sheared texture with extremely fine-grained materials, a part of which may be a glass. Abundant euhedral garnets occur in the fine-grained part, and their chemical compositions are quite heterogeneous from domain to domain. In view of the evidence that no garnet was observed in the host pyroxene gneiss, these garnets are likely to have crystallized very rapidly in the melt or solidified melt.

Because of the chemical heterogeneity of garnet in the pseudotachylite even in a small domain, it is highly difficult to estimate the *P-T* conditions by means of geothermobarometric techniques using the mineral chemistries of microlites.

key words: pseudotachylite, McIntyre Island, Enderby Land, Antarctica, WDS-compositional mapping

1. Introduction

A pseudotachylite is a dense rock composed of extremely fine-grained matrix and cataclastic fragments, and it occurs within fault zones and/or nearby in the form of vein and network. There have been numerous studies on pseudotachylite in the world since Shand (1916), and in most cases they are associated with fault or shear zones (see Takagi (1991) and references therein). From East Antarctica, pseudotachylites have been reported from Fyfe Hills–Khmara Bay regions, Enderby Land (Sandiford and Wilson, 1984) and from several localities in the vicinity of Mawson Station in MacRobertson Land (Clarke, 1988, 1990; Clarke and Norman, 1993; White and Clarke, 1994). In these regions, the pseudotachylites are associated with mylonite–ultramylonite zones emplaced probably during the Cambrian (~500 Ma).

It has been accepted that pseudotachylite can be derived from frictional melting during seismic faulting (Sibson, 1975, 1977, 1980; Allen, 1979; Maddock, 1983; Hobbs *et al.*, 1986). In other words, it is referred to as an 'earthquake fossil' in ancient times (Takagi, 1991). Other origins include meteorite impact in Vredefort Ring, South Africa (Dietz, 1961; Wilshire, 1971; Schwarzman *et al.*, 1983; Reimold *et al.*, 1985; Fricke *et al.*, 1990), and landslides in Langtang, Himalaya (Masch and Preuss, 1977) and in Köfels, Austria (Erismann, 1979).

There has been a debate on the origin of pseudotachylite, as to whether it was derived from melt, or it was produced through cataclasis (see Takagi (1991) and references therein). Recent studies by Masch *et al.* (1985), Toyoshima (1990), Lin (1994), Shimamoto and Nagahama (1992) and Nagahama *et al.* (1994) presented several lines of evidence for melt origin. However, pseudotachylite by cataclasis origin possibly exists as reported by Lin *et al.* (1994).

This paper reports the mode of occurrence, textures under the optical and electron microscopes, and WDS-compositional mapping and chemical analyses of garnet of pseudotachylite from McIntyre Island in Enderby Land, Antarctica. The main object is to demonstrate a possible former presence of melt in the rock, and a rapid growth of garnet in the melt or solidified melt. The pseudotachylite studied in this paper was collected by the author during the JARE-34 operation in Enderby Land in 1993.

2. Mode of Field Occurrence

The pseudotachylite in McIntyre Island occurs in the central part of the island (Fig. 1). The basement rocks in the island, as a whole, consist of charnockitic gneiss, garnet-orthopyroxene gneiss, felsic gneiss, well-layered garnet-bearing pelitic gneiss, and subordinate discordant pegmatite veins which show sharp contact against the basement rocks. The rocks belong to the Archean Napier Complex, and they (excluding pegmatite) have experienced ultra-high temperature metamorphism (>1000°C) in Archean probably at around 2800–3100 Ma (Sheraton *et al.*, 1987; Black and Harley, 1995), followed by another significant event at around 2500 Ma

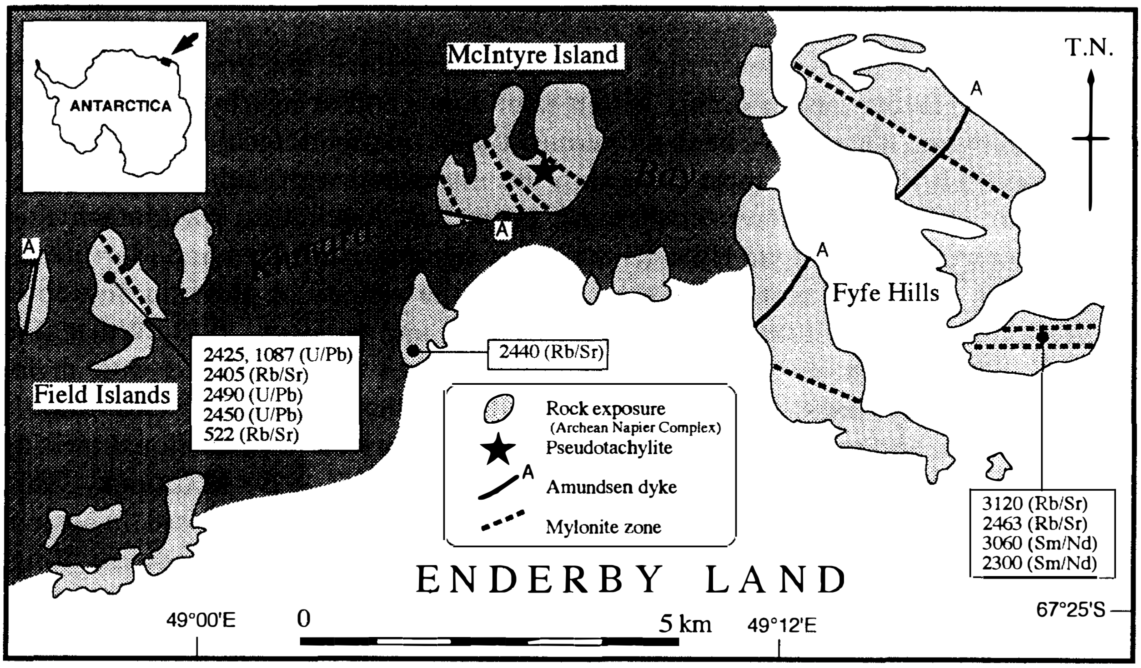

Fig. 1. Locality of studied pseudotachylite in McIntyre Island, Enderby Land, East Antarctica. Distribution of the Amundsen dyke and mylonite is after Sandiford *and* Wilson *(1984). Radiometric ages are after* Sheraton *et al. (1987).*

Fig. 2. Mode of field occurrence of pseudotachylite. Black material with irregular shape is pseudotachylite. Leucocratic parts are fragments of sheared host rocks. Pseudotachylite is also recognized in the surrounding gneisses as lens, sigmoid or bleb.

(SHERATON *et al.*, 1987; TAINOSHO *et al.*, 1994; OWADA *et al.*, 1994). Younger ages on pegmatite have been reported to be 1000 Ma and 500 Ma. The radiometric ages summarized by SHERATON *et al.* (1987) are presented in Fig. 1.

As shown in Fig. 2, the pseudotachylite occurs in a nearly vertical zone of approximately 60 cm wide. The pseudotachylite, a black material with glassy luster, and fragments of partly sheared host rock (pyroxene gneiss) are embedded in the zone. Some host fragments are obviously rotated. The occurrence of this zone totally looks like a breccia zone. Pseudotachylite is also seen outside the zone as lens, sigmoid and bleb in the host gneiss.

3. Microscopic Observations

3.1. *Optical microscope*

Prior to the description of the pseudotachylite, petrographical observations on the host pyroxene gneiss are briefly given. The host pyroxene gneiss is composed of clinopyroxene, orthopyroxene, plagioclase, quartz, ilmenite and subordinate biotite (probably secondary). Pyroxenes show wavy extinction, and are partly transformed to fine-grained aggregates. Clinopyroxene exsolves lamellae and tiny rutile. Plagioclase has been sheared to show deformed albite twins and aggregates of rounded crystals of various sizes. It is noteworthy that no garnet is observed in the assemblage of the host gneiss.

The pseudotachylite displays a variety of textures as shown in Fig. 3. Probably due to a high strain rate, a part of the rock demonstrates mylonitic or cataclastic structure, or occasionally flow structure (Fig. 3A). Orthopyroxene and plagioclase in Fig. 3A are relict minerals from the host gneiss. Plagioclase has been sheared to form aggregates of fine-grained crystals, whereas orthopyroxene seems to be almost undeformed. Some of the pyroxene is clearly penetrated by fine-grained veins, but occasionally it seems that pyroxene partly melted into the vein.

In the extremely fine-grained part of the pseudotachylite, two kinds of dark material can be observed, *i.e.*, black irregular-shaped material and brownish material (Fig. 3B). Anhedral quartz grains are seen in them. It is stressed that no flow structure is recognized in these dark materials. Garnet crystals occur only in the fine-grained materials (Figs. 3A and 3D), and they are mostly euhedral. Some of larger garnets carry aggregates of tiny inclusions in them, probably due to growth of garnet being rapid enough to allow for entrapment of abundant inclusions (Fig. 3B). The mode of occurrence of the garnet-bearing domain is best seen in Fig. 3D as it displays an injection into the host rocks.

3.2. *Backscattered electron image*

The backscattered electron images (BEI) of the pseudotachylite from McIntyre Island have been obtained with the JEOL JCXA-8800M electron microprobe analyzer at the National Institute of Polar Research in order to unravel the fine-grained textures in more detail. An overall view is shown in Fig. 4A. A number of bright spots in the figure are garnet crystals and they demonstrate very heterogeneous distribution, *i.e.*, in the lower half zone, garnets concentrate along the margin of the vein which has a sharp contact against the upper half where garnets align in a different direction. Such occurrence implies that the movement of vein was neither a single cycle nor single direction. Figure 4B is an enlarged view of a part of Fig. 4A. Euhedral garnets and tabular crystals of biotites are seen. Other phases in the matrix are unknown. This texture is similar to that of volcanic rocks with phenocrysts in the groundmass.

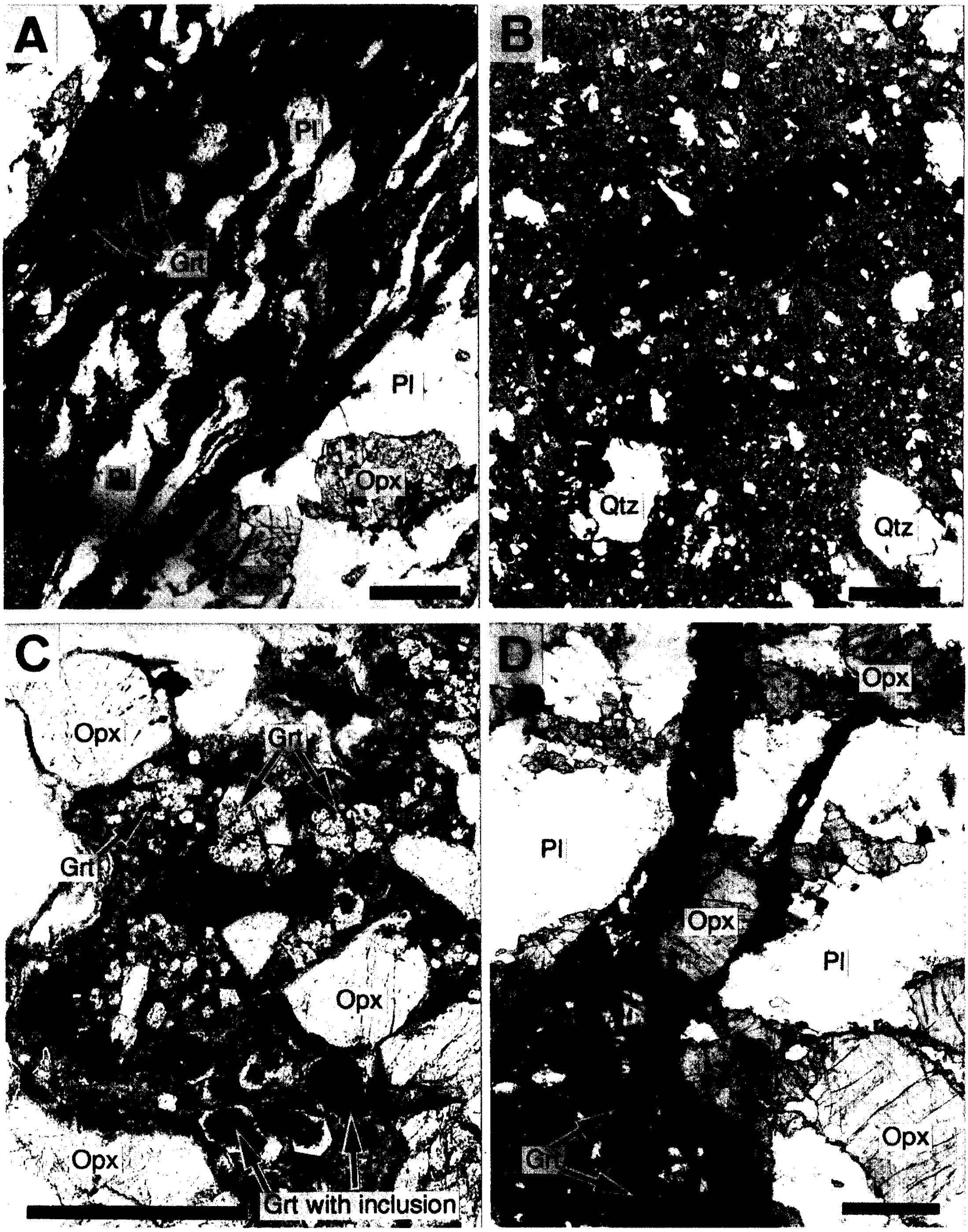

Fig. 3. Photomicrographs of pseudotachylite. Mineral abbreviations: Grt - garnet; Opx - orthopyroxene; Pl - plagioclase; Qtz - quartz. Plane polarized light. Scale bars are all 1 mm. A: Flow structure of fine-grained materials in which tiny garnet with inclusions is observed. Orthopyroxene next to the flow structure does not seem to be deformed, whereas plagioclase has been sheared to form aggregates of fine-grained crystals. B: Two kinds of glass-like dark materials, black and brown, in fine-grained part. C: Two varieties of garnet in fine-grained part. One is relatively large and containing black inclusions in it, and the other is smaller and free from inclusions. D: Possible pseudotachylite vein in the rock. It clearly cuts the texture of the host rock. Note that nearby orthopyroxene is not sheared.

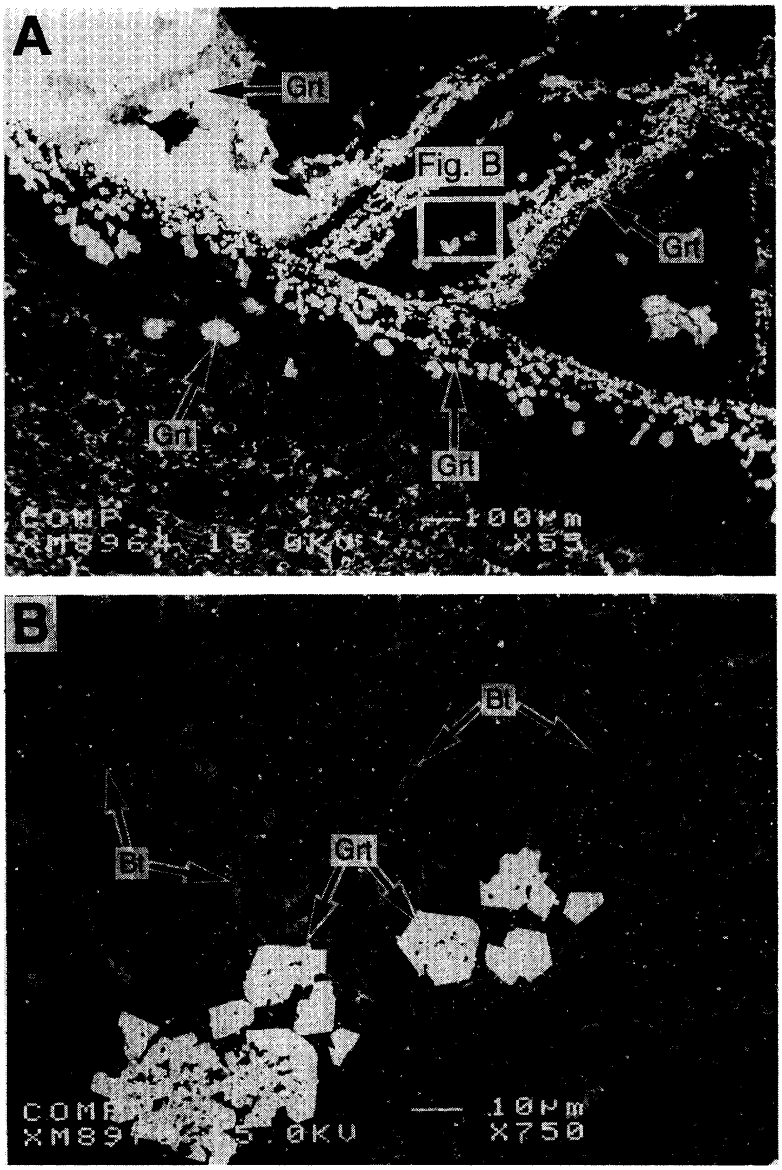

Fig. 4. Back scattered electron images of pseudotachylite. A: Distribution of garnet (bright spots) in a small domain. These are at least two lines of garnet alignment demonstrated by groups of small garnets. Subhorizontal alignment clearly cuts the rest of the domain. B: Enlargement of a domain bounded by square in Fig. A. Note euhedral garnet and biotite crystals sitting like phenocrysts in volcanic rocks or those of melting experimental run products.

3.3. *WDS-compositional mapping*

In order to examine chemical heterogeneity of phases in the fine-grained matrix, WDS (Wavelength Dispersive Spectroscopic)-compositional mapping for Fe, Mn, Mg and Ca on garnet and surrounding phases was performed. The measuring conditions were 4.6×10^{-7} A and accelerating voltage at 15 kV. Probe diameter was focused to 5 μm and step intervals are 10 μm for both X and Y axes.

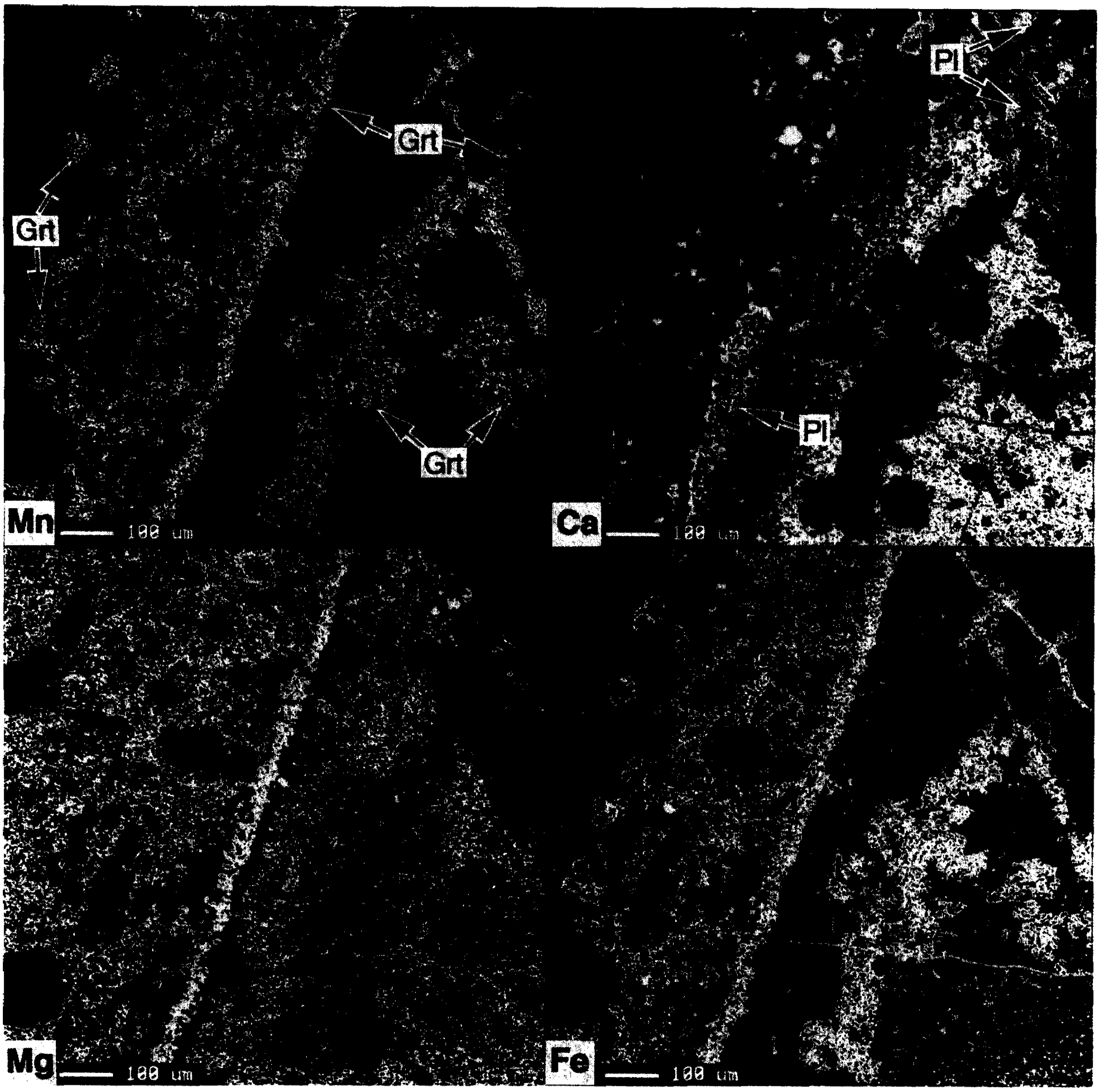

Fig. 5. WDS-compositional mapping for Mn, Ca, Mg and Fe on garnet in pseudotachylite. High concentration is indicated by warm color. Because Mn is mostly concentrated in garnet, the shape and distribution of garnet in fine-grained part is best seen in Mn map (upper left). Note garnet is chemically heterogeneous even in such a small domain.

The WDS mapping (Fig. 5) demonstrates that the chemical compositions of garnet are obviously heterogeneous. Moreover, it is stressed that very euhedral and clear garnet sits close to the aggregate of anhedral garnet. These features suggest that growth of garnet occurred by different processes, *i.e.*, different reaction, different growth rates, *etc.*, implying disequilibrium crystallization. Representative garnet analyses are listed in Table 1. It is noted that there is a relatively wide range in abundance of CaO (0.94–7.47 wt%) and MnO (0.37–1.72 wt%). X_{Mg} (=Mg/(Fe+Mg)) varies from 0.17 to 0.37.

Table 1. Representative garnet analyses of pseudotachylite (Sp. 93022005).

Anal. No.	1	2	3	4	5	6	7
SiO_2	38.06	38.46	38.13	39.38	38.94	37.22	36.52
TiO_2	0.00	0.05	0.00	0.00	0.12	0.02	0.02
Al_2O_3	22.09	22.02	22.02	21.31	21.17	20.83	20.29
Cr_2O_3	0.12	0.09	0.00	0.13	0.09	0.12	0.03
FeO	28.25	29.39	28.07	29.41	30.15	30.37	28.89
MnO	0.62	0.58	0.71	0.37	0.49	0.58	1.72
MgO	9.12	9.00	8.97	7.69	7.97	7.85	3.26
CaO	0.94	1.03	0.93	1.46	1.35	1.32	7.47
Na_2O	0.02	0.00	0.00	0.02	0.03	0.02	0.00
K_2O	0.02	0.01	0.01	0.01	0.00	0.04	0.00
Total	99.24	100.63	98.84	99.78	100.31	98.37	98.20
Almandine	0.610	0.621	0.611	0.648	0.647	0.651	0.628
Spessartine	0.014	0.012	0.016	0.008	0.011	0.013	0.038
Pyrope	0.351	0.339	0.348	0.302	0.305	0.300	0.126
Grossular	0.026	0.028	0.026	0.041	0.037	0.036	0.208
X_{Mg}	0.365	0.353	0.363	0.318	0.320	0.315	0.167

X_{Mg}=Mg/(Fe+Mg).

4. Summary and Implications

On the basis of the field occurrence and the textural evidence under the optical and electron microscope, the pseudotachylite from McIntyre Island has probably formed through frictional shearing. Moreover, the following lines of evidence strongly support that it was derived from melt, rather than a product of cataclasis.

(1) Fine-grained material constitutes a ‘vein’ in the host rock.

(2) Although existence of glass has not been confirmed yet, irregular-shaped dark material in the fine-grained part may be a trace of glass material itself.

(3) Small, but euhedral garnet crystals are seen only in the vein. Because no discrete garnets are observed in the host rock, the garnets probably nucleated in the melt, or they recrystallized in the solidified melt.

(4) BEI of a part of the fine-grained material looks quite similar to those of textures of volcanic rocks, namely phenocrysts in the groundmass, or run products of melting experiment after quenching. It is noteworthy that no shearing structure is seen in the fine-grained part. However, as mentioned by Takagi (1991), cataclastic part is probably associated with pseudotachylites in many cases.

In addition, the author proposes a rapid crystallization of garnet in the melt or solidified melt based on the following observations and investigations.

(5) Some of the garnets carry substantial amount of inclusions (opaque phase) in them, probably due to a rapid growth rate to allow inclusion entrapment.

(6) The mode of occurrence of garnet is different from place to place even in a small domain, *e.g.* lines of garnet aggregate, isolated euhedral garnet, and irregular-shaped

garnet sit close to each other.

(7) WDS-compositional mapping and microprobe analyses demonstrate significant chemical heterogeneity of the garnets, but this does not exclude a possibility that local equilibrium has been attained in a microdomain.

Because of the lack of relevant data, this paper does not concern the physical (pressure and temperature) conditions under which the pseudotachylite has formed. Previous workers have assessed that the melting temperatures have exceeded 1100°C, up to 1500°C (Sibson, 1975; Spray, 1987; Toyoshima, 1990; Shimamoto and Lin, 1994). With respect to the pressure condition, it has been generally considered that pseudotachylites form in the shallow crustal level because they preserve glass material, quenched textures, and cataclastic structures. The quantitative estimations have been performed by Sibson (1975), Allen (1979), Seward and Sibson (1985), Maddock *et al.* (1983) and Toyoshima (1990), and they have yielded 1–5 km depth in the crust. On the other hand, Sandiford and Wilson (1984) argued that pseudotachylite from Enderby Land formed at least 12 km depth because they observed that the pseudotachylite has been metamorphosed by pegmatite which crystallized in the muscovite-quartz-melt field, *i.e.*, >3.5 kbar based on the experimental work by Kerrick (1972). Passchier (1984) estimated 2–3.5 kbar for pseudotachylite from French Pyrenees based on CO_2 concentration in fluid inclusions. Chemical compositions of microlites in pseudotachylites probably reflect the physical conditions. However, in view of the chemical heterogeneity of garnet in the pseudotachylite even in a small domain, it is highly difficult, or even dangerous to estimate the *P-T* conditions by means of geothermobarometric techniques using the mineral chemistries of microlites.

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