Pseudotachylyte veins associated with granitic cataclasite along the Median Tectonic Line, eastern Kii Peninsula, Southwest Japan

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Abstract

Fault-generated pseudotachylytes showing reddish, greenish and grayish color have recently been found from the mylonitized Ryoke Granites along the Median Tectonic Line (MTL). These pseudotachylytes are suggested to have a melt origin on the basis of petrographic observations of typical melt-quenched microstructures such as microlites and amygdales. Preferential melting of low melting point minerals is the most probable melting process. The absence of lithic fragments of hornblende and biotite, and systematic decrease of bulk SiO₂ contents in the pseudotachylytes compared with their host rocks support this interpretation. These pseudotachylytes were formed after mylonitization and were post-dated by weak cataclasis resulting from movement of the MTL. Similar orientation of the MTL, fault veins of pseudotachylytes, and mylonitic foliation indicate that the deformation sequence of mylonite, pseudotachylyte, and cataclasite formation probably progressed under a single tectonic stress field. These pseudotachylytes are examples of the remnants of ancient faulting with frictional melting indicating seismic activity of the MTL.

Key words: pseudotachylyte, frictional melting, Ryoke Belt, Median Tectonic Line, Mie Prefecture

Introduction

Fault-generated pseudotachylytes (PST) form in fault zones at typically shallow depths in the crust (generally at temperatures lower than 500°C; e.g., Swanson, 1992; White, 1996). A long-standing debate on whether PST forms by local frictional melting or comminution (cataclasism) (e.g., Philpotts, 1964; Wenk, 1978) has reached a considerably firm conclusion in favor of a dominantly melt origin (e.g., Park, 1961; Sibson, 1975; Maddock, 1983; Toyoshima, 1990; Magloughlin, 1992; Shimamoto and Nagahama, 1992; Lin, 1994 a), though comminution (cataclasism) is thought to be a prerequisite to frictional melting (e.g., Spray, 1995). Great variety in the degrees of melting are observed in naturally and experimentally-generated PST (e.g., Lin and Shimamoto, 1998; Curewitz and Karson, 1999). Recently, PST formed by crushing with little evidence of melting has also been reported (Lin, 1996; Shigetomi and Lin, 1999; Wenk et al., 2000). Whether PST is of melt origin or not, it is commonly thought to be an indicator of ancient seismic faulting (e.g., Sibson, 1975; Lin, 1996; Passchier and Trouw, 1996). One can, therefore, infer past seismic motion in fault zones from PST (Spray, 1996).

Newly found PST veins hosted in mylonitic rocks along the Median Tectonic Line (MTL), Southwest Japan, are described here. In spite of many geological investigations on the MTL, no PST has been reported until now. To clarify the geotectonic history of the MTL, we should evaluate genetic mode and formation timing of the PST in relation to the spatial distributions of fault-related rocks along the MTL.

Aims of this paper are as follows: (1) to designate the genetic mode of the PST for an evaluation in diversity of natural PST; and (2) to interpret the timing of formation of the PST and the host fault-related rock in relation to the activity of the MTL.

Geologic outline

The MTL is one of the major geotectonic boundaries traversing Southwest Japan and running nearly parallel to the trench axis off the southern coast of the Japanese Islands (Fig. 1a). Late Cretaceous plutonometamorphic complexes (Ryoke Belt)
are bounded by the north-dipping MTL. The southern marginal zone of the Ryoke Belt underwent polyphase mylonitization (~1 km thick) with sinistral/top-to-the-west shear movement (e.g., Hara et al., 1980; Takagi, 1986; Yamamoto, 1994; Sakakibara, 1995) during Late Cretaceous, especially in the Chubu and the Kinki districts (Fig. 1a).

The host rocks of the PST described here are mylonites derived from tonalite (Hatai Tonalite). The Hatai Tonalite consists of plagioclase (sericitized or saussuritized), quartz, hornblende (chloritized), biotite (mostly chloritized), and minor amounts of K-feldspar, with allanite, apatite, zircon, rutile and titanite as accessory minerals. Quartz grains often include rutile needles (Takagi, 1985). The Hatai Tonalite underwent mylonitization under amphibolite to greenschist facies conditions (Sakakibara, 1995; Shimada et al., 1998). The mylonitization has been post-dated by cataclasis at shallower depths forming a cataclastic fault zone (200–300 m thick) immediately on the north of the MTL (e.g., Takagi, 1985). The deformation sequence is considered to have progressed under a transpressional setting at an oblique convergent margin during the Late Cretaceous to early Paleogene (Shimada et al., 1998).

The outcrop of the PST described in this paper is located about 100 m north of the MTL, close to the Seiwa-Taki Interchange of the Ise Motorway (Fig. 1b). The PST are found sporadically over 30 m on a southwest-facing exposure (Fig. 1c). The MTL strikes east and dips steeply to the north (Figs. 1c and 2). Cataclasism overprinted the mylonite during and after the formation of the PST, accompanied by mineral veining and alteration. However, mesoscopic continuity of the mylonitic foliation (Sm) and lineation (Lm) have survived. The Sm is defined by elongation of quartz ribbons and shape preferred orientation (SPO) of long axes of hornblende and plagioclase grains, and the Lm is defined by SPO of long axis of hornblende and plagioclase. It is difficult to recognize the PST veins at the outcrop because of extensive weathering and blue-green color of the PST veins similar to that of the surrounding fault rocks (mylonite and cataclasite). The thin PST veins are clearly identified on the polished sections of oriented samples. Some of these veins can be classified into ‘fault vein’ and ‘injection vein’ (Sibson, 1975). Other veins show geometry disturbed by cataclasism.

The attitude of fault veins, Sm and Lm of host rocks, and the MTL are shown in Fig. 2. Sm strikes E-W and dips steeply to the north. Lm plunges to the east at a moderate angle. Attitudes of fault veins are similar to those of the Sm and the MTL. Poles to Sm, fault veins and the MTL are distributed within a small circle with a half opening angle of 23° (Fig. 2).

A quartz c-axis fabric of the mylonite (Fig. 3) has a Type-I crossed girdle pattern (Lister, 1977) with weak internal asymmetry suggesting low-temperature mylonitization occurred (e.g., Passchier and Trouw, 1996) bearing a sinistral sense of shear with a thrusting component. This movement picture, temperature of mylonitization and attitudes of Sm are similar to those in the itakata area (Shimada et al., 1998).

Along the MTL, intensively altered cataclastic rocks occur up to 40 m in width (Fig. 1c). These rocks are recognized as cataclasites derived mainly
from the mylonitized Hatai Tonalite since fragments of mylonitized polycrystalline aggregates of quartz are included.

Mesoscopic characteristics

The structures of fault veins and injection veins can be clearly observed on polished sections of hand samples (Figs. 4a, b, c and f). Fault veins have thicknesses less than 10 mm (generally less than 3 mm), and cut the mylonitic foliation obliquely with sharp boundaries. The color of the PST found in the MTL is grayish blue green, reddish brown or grayish blue (see the pictorial in this volume). Some of the injection veins branch from the fault vein at high angle with somewhat regular profile (Figs. 4a and e). In most cases, however, injection veins show irregular profiles partly delineated by minor linear fractures or lithic fragments itself (Figs. 4b and f). These irregularities also apply to a network of veins (Figs. 4c and g). The largest PST vein observed is up to 7 cm in thickness and more than 50 cm in length (Figs. 4d and h). This injection vein has flow layering indicating one way injection, although the corresponding fault vein is not visible. Some injection veins have relatively fine-grained flinty chilled margins (mostly less than 1 mm in thickness).

Petrography

Typical pseudotachylyte textures such as microlites and amygdales in the PST (Fig. 5) are revealed by optical microscopy with transmitted/reflected light and by backscattered electron (BSE) imaging under the scanning electron microscope. In addition, PST have been cut by chlorite or calcite veins after the formation of the PST. In the following section we describe the petrographic characteristics of (1) textures of PST and (2) mineral veins cutting PST. Minerals are identified qualitatively by using the EDS mode of a JEOL-JXA733 electron microprobe at Waseda University.

1. Textures of pseudotachylyte

(1) Matrices and their textures

Cryptocrystalline, microcrystalline and microlitic matrices (Type II to IV matrices of Lin, 1994a) are observed in the PST. Glass has not been identified so far. Some PST veins composed of cryptocrystalline or microcrystalline matrices show foliations defined by compositional banding or grain size differences. Chilled margin and flow layering are typical examples. On the other hand, the microlitic matrix shows a random fabric. Combinations among three types of matrix and textures (see below) are schematically shown in Fig. 6.

Chilled margin: Cryptocrystalline matrix including few amygdales and lithic fragments is sometimes observed along the rim of injection veins constituting chilled margins. The grain size is too small to identify under the microscope. Boundaries between chilled margins and the inner portions of the veins are usually shown by clear grain size differences depicting a foliation.

Flow layering: Injection veins commonly have flow layering (e.g., Figs. 4a, d, e, h and 5a). They are generally characterized by reddish brown and grayish blue green layers (Figs. 4a, e and 5a). Reddish brown layers are composed of abundant hematite, pyrite, limonite and rutile as well as transparent minerals of chlorite and calcite. Under reflected light, internal reflection of hematite (deep red) and rutile (bright grayish white) is conspicuous. Grayish blue green layers are composed mainly of transparent and translucent minerals with scarce opaque minerals.

(2) Microlites

Terminology: Recently, Lin (1994 b) studied microlites in PST veins generated at a depth of about 1.5 km from the Fuyun Fault Zone in detail, and divided various microlites into four morphological groups (simple shape group, skeletal group, dendritic group, and spherulitic group). In Lin (1994 b), the term 'spherulite' is used as a contracted form of his 'spherulitic microlite'. Thus, the 'spherulite' is one group of microlites in his terminology. In contrast, the 'spherulite' and the 'microlite' are regarded as two
separate textural categories in some reports (e.g., Park, 1961; Philpotts, 1964; Passchier, 1982; Magloughlin and Spray, 1992). In addition, other terms such as 'radiating textures' (Macaudière et al., 1985) or 'radial arrangements of intergrown plagioclase' (Koch and Masch, 1992) are used to describe microstructures identical to the 'spherulitic microlite' of Lin (1994b). Here, the classification of microlites by Lin (1994b) is adopted, and the term 'spherulitic microlite' is used for precision.

Two different modes of occurrence of microlites in relation to three types of matrix are observed: (1) rimmed radial spherulitic microlite and ellipsoidal microlite with sharp boundaries in cryptocrystalline or microcrystalline matrices, and (2) radial spherulitic microlite and sheaf spherulitic microlite (Lin, 1994b) constituting the microlitic matrix (Fig. 6).

**Microlites observed in cryptocrystalline and microcrystalline matrices**: Rimmed radial spherulitic microlite and ellipsoidal microlite included in cryptocrystalline and microcrystalline matrices are observed in one PST vein.

The rimmed radial spherulitic microlite is composed of three parts: core, mantle and rim (Figs. 5b and c). The core is microcrystalline, and composed of fine-grained aggregates of K-feldspathic composition rarely including quartz fragments. The mantle is composed of thin radial lamellae of quartz, K-feldspar and chlorite with minor amount of rutile. The rim (under 50 µm in thickness) is clearly depicted by fine-grained translucent minerals (mainly composed of chlorite) contrasting with the matrix (Fig. 5b and c). These rimmed radial spherulitic microlites range in diameter from 150 µm to over 1 mm, larger than most of spherulitic microlites (under 200 µm) reported by Lin (1994b).

The ellipsoidal microlite consists of fine-grained (less than a few µm in diameter) polycrystalline quartz, and fine lamellae or particles of hematite (Fig. 5g) with possibly minor amounts of goethite or limonite. Traceable Ti is sometimes detected by EPMA analysis of quartz. Ellipsoidal microlites range from 7 µm to 50 µm in diameter showing a log normal size distribution (Fig. 7). Ellipsoidal microlites are included in the mantle of some rimmed radial spherulitic microlites. These ellipsoidal microlites show relatively circular sections in comparison to those in matrix (Fig. 5c).

The microlites differs from quartz fragments in the following ways: (1) the shape of the microlites is smoother than the quartz fragments (Fig. 5g); (2) the microlites always contain hematite though the quartz fragments do not; (3) the microlites consists of polycrystalline quartz (less than a few µm in diameter) whereas the quartz fragments of similar size consists mainly of monocrystalline quartz; (4) the maximum size of the microlites (50 µm) is much smaller than the maximum size of quartz fragments (1 mm or lager in diameter). Around the microlites, concentric compositional zoning is occasionally observed (Fig. 5g) implying that these microlites are not amygdales, which do not show any compositional zoning (e.g., Maddock et al., 1987; see below).

The ellipsoidal microlite coexists with the rimmed radial spherulitic microlite (Figs. 5b and c) within a matrix composed of transparent microcrystalline and cryptocrystalline layers (Fig. 6). The microcrystalline matrix consists of quartz and feldspars, and a cryptocrystalline portion with light brown tint includes fine-grained rutile or Fe-oxide minerals. An alternation of these two types of matrices defines a foliation nearly parallel to the vein walls. The alternation zone including these microlites consists of a layer (3 mm in thickness) between microlitic matrices at a medial zone of one planar PST vein (15 mm in thickness).

**Microlites constituting microlitic matrix**: Radial spherulitic microlites and sheaf spherulitic microlites are the main constituents of the microlitic matrix.

The radial spherulitic microlites consist of two parts: a core of usually rounded lithic fragments of both quartz and feldspar, and fine crystal fibres radiat-
Fig. 4. (a)-(d) Photographs of polished slabs of the PST veins hosted in mylonitic rocks. Black/white divisions on the scale bars are 1 cm. (e)-(h) Sketches of PST veins observed in the polished slabs shown in left column (a-d). Flow layerings are emphasized in (e) and (h), whereas outlines of fault and injection veins (black colored) are emphasized in (f) and (g). Gray colored portions represent mineral veins in (e)-(h). Orientations of elongated crosses show mylonitic foliations of the host rocks. f: fault vein, i: injection vein in (e) and (f).
Fig. 5. (a) A flow layering observed in a tip of the injection vein shown in Figs. 4a and e. Plane-polarized light (PPL). (b) A typical rimmed radial spherulitic microlite (R-R) observed in a micro- and cryptocrystalline matrices (PPL). (c) A BSE image showing the same rimmed radial spherulitic microlite shown in (b) where a K-feldspathic core, a mantle composed of quartz, K-feldspar, chlorite and rutile and chlorite rim occur. Small white arrows show the elliptoidal microlites. (d, e) Radial spherulitic microlites (R) around a core of lithic fragments (PPL), and sheaf spherulitic microlites (S) constituting microlitic matrix. Black/white arrowheads in (e) show amygdales composed of quartz and calcite. (f) An enlarged BSE image of a radial spherulitic microlite shown as a square in (e). A quartz amygdale (lower right) is included in the fine crystal fibres composed of quartz, K-feldspars and chlorite around a K-feldspathic core (upper right). (g) A BSE image of a typical elliptoidal microlite composed of hematite and quartz (E). Elliptical sections of the microlite differ from lithic fragments of quartz (QF). A compositional halo around the microlite is observed. (h) Amygdales in the microcrystalline matrix are slightly elliptical. Cross-polarized light. (i) An enlarged BSE image of an amygdale composed of quartz, calcite, chlorite, hematite and rutile is shown as a square in (h). Cal : calcite, Chl : chlorite, Hem : hematite, Kfs : K-feldspar, Qtz : quartz, Rt : rutile.
Type of matrix

<table>
<thead>
<tr>
<th>Type of matrix</th>
<th>Cryptocrystalline</th>
<th>Micropore</th>
<th>Microlitic</th>
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<tr>
<td>Rimmed radial spherulitic microlite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ellipsoidal microlite</td>
<td>*</td>
<td></td>
<td></td>
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<tr>
<td>Radial spherulitic microlite</td>
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<td></td>
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<td>Sheaf spherulitic microlite</td>
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<tr>
<td>Amygdales</td>
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</tr>
<tr>
<td>Foliations</td>
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<td>Chilled margin</td>
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<tr>
<td>Flow layering</td>
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<td>SPO of amygdales</td>
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<tr>
<td>Alternation of two types of matrix</td>
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</table>

Fig. 6. A schematic diagram showing the relationship between the type of matrix and observed textures. Solid lines represent the range of matrix types that a texture usually occurs in. Broken lines represent the range of matrix types that a texture sometimes occurs in. *: Observed in one vein.

Fig. 7. A histogram showing a size distribution of the ellipsoidal microlite. Insets depict a formula giving the size (d) and schematic diagram showing the measurement (a, b).

ving from the core (Figs. 5 d-f). These crystal fibres are a few μm in width and up to 200 μm in length, and their size decreases towards the margin. These fibres are composed of chlorite, K-feldspar, plagioclase, quartz and fine-grained translucent minerals (Figs. 5 d-f). Fine interlayering of dark portions (quartz) and light portions (chlorite and feldspars) is observed in BSE images (Fig. 5f). The radial sphaleritic microlites are identical to the overgrowth sphaleritic microlites described by Lin (1994 b). The term 'radial' is adopted to exclude a genetic meaning from the morphological descriptions of microlites.

The sheaf spherulitic microlites consist of sheaf or fan shaped arrangements of fine crystal fibres devoid of a core of lithic fragments. These crystal fibres are a few μm in width and up to 300 μm in length, slightly larger than those of radial sphaleritic microlite. These fibres consist of chlorite, plagioclase, K-feldspar, quartz and fine-grained translucent minerals (Figs. 5d and e). The sheaf spherulitic microlites increase in number from the center to the margin of the veins in tandem with their size reduction.

(3) Amygdales

Amygdales are composed of chlorite, calcite, quartz, hematite, pyrite and limonite. They show circular to slightly elongated sections depending on the composition of amygdales or on the type of matrix. They can be divided into two groups: monomineralic and polymineralic amygdales. The monomineralic amygdales are composed of quartz, calcite, or chlorite ranging from 20 μm to 60 μm in diameter. The polymineralic amygdales composed of quartz with calcite cores vary from 30 μm to 70 μm in diameter (Fig. 5e), and amygdales composed of calcite, chlorite, quartz and some opaque minerals vary from 50 μm to 550 μm in diameter (Figs. 5 h and i).

Amygdales are included in all types of matrix: microlitic, microcrystalline and cryptocrystalline matrices (Fig. 6). Some elongated amygdales included in the microcrystalline matrix show an SPO (Figs. 5 h and i) usually oblique to the vein walls. In such cases, monomineralic and polymineralic amygdales containing chlorite or calcite usually show more elliptical shapes than quartz monomineralic amygdales. These foliations are conspicuous in the center of the vein bearing richer (under 10 modal %) amygdales as compared with the margin. The cryptocrystalline matrix contains fewer and smaller monomineralic amygdales showing no SPO. Amygdales included in the microlitic matrix consist of quartz or quartz with calcite cores (Fig. 5e) which also make no SPO because of their circular sections.

(4) Lithic fragments

Lithic fragments are included in three types of matrix and are generally composed of quartz, K-feldspar, plagioclase, zircon and opaque minerals. Lithic fragments composed of hornblende and biotite are not observed. Quartz fragments occur as polycrystalline aggregates that are identical to mylonitic texture observed in the host mylonite. Feldspar fragments usually occur as fine-grained microcrystalline aggregates (under 3 mm in diameter), occa-
Table 1. (a) Major element compositions (wt. %) of four pairs of PST veins (vein) and their host rocks (host) analyzed by XRF. (b) Values for the total alkalisilica plot recalculated to 100 % on L.O.I. free basis. (c) Values for the SiO2-Al2O3-all other components diagram recalculated as same as (b).

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<th>0805 host</th>
<th>0802-4 host</th>
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<th>23 vein</th>
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<td>99.95</td>
<td>99.46</td>
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</table>

(b)

| Na2O + K2O | 5.38      | 5.47      | 5.40        | 4.53   | 5.60    | 5.04    | 5.99    | 6.10    |
| SiO2        | 61.85     | 59.27     | 60.10       | 58.24  | 60.29   | 56.90   | 62.90   | 61.01   |

(c)

| SiO2        | 61.85     | 59.27     | 60.10       | 58.24  | 60.29   | 56.90   | 62.90   | 61.01   |
| Al2O3       | 16.80     | 17.10     | 17.37       | 18.28  | 16.84   | 17.23   | 17.93   | 17.68   |
| All other components | 21.35 | 23.63 | 22.53 | 23.48 | 22.87 | 25.87 | 19.17 | 21.32 |

Fe2O3*: Total Fe as Fe2O3. L.O.I.: Loss of ignition.

Table 1. (a) Major element compositions (wt. %) of four pairs of PST veins (vein) and their host rocks (host) analyzed by XRF. (b) Values for the total alkalisilica plot recalculated to 100 % on L.O.I. free basis. (c) Values for the SiO2-Al2O3-all other components diagram recalculated as same as (b).

2. Mineral veins cutting pseudotachylyte

Mineral veins composed of chlorite, calcite, chlorite + calcite, and calcite + hematite cut the PST veins (Figs. 4 and 8). Chlorite veins show deep blue anomalous interference colors suggesting higher Fe content (Fig. 8a). Some calcite veins show recrystallization accompanied by formation of small scale dextral shear zones (Fig. 8b). Most calcite shows the Type-II and the Type-III deformation twins (Burkhard, 1993; Fig. 8b). Chlorite usually precipitates along the vein walls in chlorite + calcite veins. Hematite particles under 50μm in diameter are distributed randomly in some calcite veins.

Bulk chemical composition

Bulk chemical composition (major elements) of four pairs of PST veins (powdered heavier than 50g) and their host rocks (powdered heavier than 200g) was analyzed by X-ray fluorescence (XRF) (Table 1). Each PST vein has a similar composition to the host rock, though a small systematic difference is observed as follows; up to 1.2 wt.% higher in concentrations of MgO, 0~0.5 wt.% higher in TiO2 and MnO, and 1.4~3.6 wt.% lower in SiO2 compared to their host rocks (including loss of ignition (L.O.I.); Table 1a). Other components show higher or lower concentrations with a fluctuation of a few percent. The L.O.I. in all samples are relatively high (about 6~9 wt.%).
pared with those (or crystalline water) in PST veins previously reported (e.g., up to 4.4 wt.\% ; Philpotts, 1964, up to 6.56 wt.\% ; Curewitz and Karson, 1999, up to 10 wt.\% ; Toyoshima, 1990).

Almost all samples fall in the region of intermediate rocks (andesite and basaltic andesite) on the basis of the values for total alkali-silica plot (recalculated to 100\% on an L.O.I free basis ; Table 1 b). However, the Na₂O and K₂O may have mobilized during cataclasis accompanied by alterations after the formation of the PST.

In each pair of host rock and PST vein, Al₂O₃ contents show smaller variations than that of SiO₂ or all other components (recalculated to 100\% on an L.O.I free basis ; Table 1 c, Fig. 9), in spite of the main minerals containing Al₂O₃ being different between the host rocks (feldspars, hornblende, biotite and chlorite) and the PST veins (feldspars and chlorite). Contents of SiO₂ in PST veins, on the other hand, are systematically a few wt.\% less than host rocks. The Al₂O₃ is considered to be much more immobile than other elements, and thus the constant-alumina isoson diagrams (e.g., Magloughlin, 1992) are adopted for each sample (Fig. 10). Relative concentrations of oxide (PST veins/host rocks) on the basis of the constant-alumina isoson are 0.92~0.98 for SiO₂, 1.05~1.19 for TiO₂, 0.88~1.30 for Fe₂O₃, 1.23~5.60 for MnO, 1.07~1.37 for MgO, 0.53~1.94 for CaO, 0.49~1.12 for Na₂O, 0.91~1.34 for K₂O, and 0.81~1.11 for P₂O₅, with respect to each host rock.

Discussion

1. Genetic mode of the pseudotachylite

The genetic mode of the PST can be assessed on the basis of the following criteria suggested by many authors. Magloughlin and Spray (1992) suggested criteria providing evidence of a melt origin of the PST on the basis of a review of literature as follows : (1) quenched vein margins (e.g., Philpotts, 1964) ; (2) a variation in microlite textures and size with respect to position in a vein (e.g., Macaudière et al., 1985) ; (3) vesicles and amygdales (e.g., Maddock et al., 1987) ; (4) newly crystallized minerals stable only at high temperatures (e.g., Toyoshima, 1990) ; (5) dendritic microlite habits (e.g., Maddock, 1983) ; (6) sulfide droplets (Magloughlin, 1992) ; (7) spherulites ; (8) melting effects in clasts within pseudotachylite (e.g., Maddock, 1986) ; (9) certain recrystallization features (e.g., Macaudière et al., 1985) ; and (10) certain systematic chemical relations between pseudotachylite and host rocks (e.g., Maddock, 1992). Lin (1994 b) demonstrated that the spherulitic (spherulites), dendritic, and skeletal microlites grew from melt during solidifying stages. The clast (lithic fragment) -size distribution (Shimamoto and Nagahama, 1992), presence of 90\% glassy matrices in glassy PST veins (Lin, 1994 a), absence of X-ray spectra of minerals contained in the host rocks depicted by XRD (Lin, 1994 a), and roundness of (lithic) fragments (Lin, 1999) are also indicators of the melt origin of the PST.

The PST described here show variations in size of spherulitic microlites from the vein center to the margin, occurrence of the rimmed radial spherulitic microlite with the ellipsoidal microlite only at the center of a vein, and the existence of amygdales. These structural and textural features are consistent with several of the criteria (e.g., Macaudière et al., 1985 ; Maddock et al., 1987 ; Lin, 1994 b) listed above. We therefore infer the PST to be of a melt origin. The similarity of bulk chemical compositions between the PST veins and their host rocks (Table 1, Fig. 10) is easily explained by in-situ formation of the PST derived from each host rock (e.g., Sibson, 1975 ; Toyoshima, 1990 ; Techmer et al., 1992 ; Lin, 1994 a ; Killick, 1994 ; Wenk et al., 2000).

Melting processes during the formation of PST have been also discussed in relation to the origin of the PST (e.g., Philpotts, 1964 ; Magloughlin, 1989). Recently, Lin and Shimamoto (1998) discussed the melting mechanism and melting chemical processes on the basis of results of high-speed friction experiments. They concluded that the frictional melting mainly occurred by preferential melting of low melting point minerals with a chemically non-equilibrium process on the basis of SiO₂ depression revealed by XRF and SEM-EDS analysis, and quantitative XRD analysis of fused glassy matrix and mineral clasts. Chemical compositions of their fused glassy matrix are lower in SiO₂ by a few wt.\% to 30 wt.\% than their host rocks (coarse-, medium-, and fine-grained granite and fine-grained gabbro). The PST veins described here show smaller SiO₂ contents, by a few wt.\%, than their host rocks, though analyzed PST veins include lithic fragments. The absence of lithic fragments of lower melting point minerals such as hornblende (about 750°C ; e.g., Spray, 1992) and biotite (650°C ; e.g., Spray, 1992), as well as the systematic depression of SiO₂.
contents suggest that the present PST are formed by preferential melting of low melting point minerals (Lin and Shimamoto, 1998) because host mylonitic and cataclastic rocks contain hornblende and biotite. The systematic chemical change may be used as one of the criteria for a melting origin (Magloughlin and Spray, 1992).

The temperature reached during the PST formation can be constrained by the absence of hornblende, and existence of quartz and zircon as lithic fragments. It is considered to be higher than the break down temperature of hornblende (about 750°C ; e.g., Spray, 1992) and lower than that of quartz (1730°C ; e.g., Spray, 1992) and zircon (1695°C ; e.g., Spray, 1992). Lithic fragments of microcrystalline feldspars imply the melting of feldspathic lithic fragments showing that the formation temperature reached the breakdown temperature of feldspars (about 1100~1550°C ; e.g., Spray, 1992).

2. Tectonic implications of the pseudotachylyte for the activity of the MTL

The following interpretation of the deformation sequence is consistent with evidence from field observations and laboratory studies: first, low-temperature mylonitization occurred along the MTL; second, the PST veins were formed by frictional melting during high speed faulting accompanied by cataclasis; third, weak cataclasis with mineral veins overprinted the PST studied. The sequence had most probably progressed in a single tectonic stress field on the basis of the parallelism of the fault veins of the PST, with the mylonitic foliation (Sm), and the MTL.

Development of quartz c-axis fabrics (Fig. 3) indicate shear zone activity in the region of quartz-intracrystalline plastic deformation was dominant. The formation of the PST was accompanied by cataclasis (communition) of the host rocks on the bases of the existence of lithic fragments and irregular profiles of injection veins partly delineated by minor fractures. The formation of the PST and subsequent cataclastic deformation accompanied with chlorite and calcite veining show shear zone activities in the region dominated by cataclasis. Accordingly, before the formation of the PST, intracrystalline plasticity of quartz declined during the transition of deformation conditions along the MTL by cooling across the cataclastic - plastic transition of quartz.

The existence of the calcite showing the Type-III deformation twin observed in veins cutting PST (Fig. 8b) suggests that the deformation sequence occurred.
higher than 200°C (Burkhard, 1993). The cataclastic-plastic transition of quartz (about 300°C; e.g., Scholz, 1988) on the other hand should constrain the upper limit of the temperature of the host rocks before the PST formation. In this way, the temperature of the host rocks just before the PST formation can be estimated to be in between 200°C and 300°C, assuming a steady decrease in deformation temperature.

Many studies have focussed on fault rocks along the MTL, the largest fault zone in Japan, since the 1970’s. However, this paper gives the first reported occurrence and implicates the seismic faulting accompanied by frictional melting in the geotectonic history of the MTL. Careful field surveys will make it possible to determine the distribution of PST from the entire length of the MTL. Problems of the estimation of the seismic energy and the determination of the absolute age of the PST formation remain to be solved in the future.

Conclusions

The following conclusions can be drawn:

(1) Fault-generated pseudotachylites (PST), considered to be evidecence of faulting associated with earthquakes, are described for the first time from the Median Tectonic Line (MTL).

(2) The PST has a melt origin on the basis of occurrences of spherulitic micromelites and amygdalae.

(3) Frictional melting is considered to have occurred by preferential melting of the low melting point minerals.

(4) The formation of the PST was accompanied by cataclasis after the mylonitization along the MTL.

(5) The temperature of the host rocks just before the PST formation is considered to be from 200°C to 300°C.

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### （要旨）


中央構造線沿いのマイロナイト化した頑家岩脈類から，新たに断層生成型シュートタキライトが発見された。本シュートタキライトはマイクロライトや蛇紋状組織の存在に基づき，メルト起源である。メルト生成過程は，低い融解温度を持つ鉱物の選択融解によるものと考えられ，シュートタキライト中の岩脈として，角閃石，黒雲母が存在しないこと，SiO2含有量の岩脈に対する系統的な減少は，この解釈を支持する。本シュートタキライトは，マイロナイト化の後に形成され，その後にMTLの活動に由来するカクレサート化を受けている。MTLのシュートタキライトの断層面，マイロナイト化断層の類似した姿勢は，一連の断層岩脈の形成が，1つの造構応力場のもとで進行したことを示している。本シュートタキライトは，摩擦融解過程を伴った過去の断層構造運動の一例であり，中央構造線の地震性断層運動を示している。