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Glassy pseudotachylyte veins from the Fuyun fault zone, northwest China

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Abstract—Glassy pseudotachylytes occur in granitic mylonites from the Fuyun fault zone, northwest China. Powder X-ray diffraction data indicate that the fine-grained matrices of the Fuyun pseudotachylytes vary from almost crystalline to complete glass (a few to 90 wt% glass). Powder X-ray diffraction patterns also indicate that clasts in the glass type pseudotachylyte veins mostly consist of quartz grains. Microlites displaying quenched or rapid-cooling textures, vesicles and amygdules, flow structures, and rounded fragments are also common in the Fuyun pseudotachylytes.

The average bulk chemical compositions of these pseudotachylytes are similar to those of the host rocks. But the glass matrix has a low SiO_2 component which is 5–15 wt% lower than that of the host rocks. The pseudotachylytes contain 2–3 wt% water (H_2O). Using experimental data which relate the solubility of water to pressure, approximately 400 bars lithostatic pressure corresponding to approximately 1.5 km depth, of pseudotachylyte formation is estimated. A minimum temperature estimate of 1450°C can be estimated due to the presence of the pure SiO_2 glass.

The X-ray diffraction and chemical data indicate that the Fuyun pseudotachylytes formed during seismic faulting at shallow depths by selective melting under water-saturated conditions rather than by total melting or by crushing of the host rocks along fault surfaces.

INTRODUCTION

PSEUDOTACHYLYTES have been recognized for over a century, however their origin is still in dispute. Two main mechanisms of formation have been proposed, one by frictional melting (e.g. Park 1961, Sibson 1975), the other is by cataclasis (e.g. Wenk 1978). Research within the last decade indicates that most workers believe that pseudotachylyte formed by frictional melting. The origin of pseudotachylyte has been fully reviewed recently by Magloughlin & Spray (1992), so here only the problem of the presence of glass in pseudotachylyte will be reviewed and discussed.

The presence of glass or glassy material in fault-generated pseudotachylytes has been reported in much of the literature, but most studies have been confined to observations by the optical microscope (Scott & Drever 1953, Park 1961, Philpotts & Miller 1963, Philpotts 1964, Gupta 1967, Ermanovics *et al.* 1972, Sibson 1975, Wallace 1976, Wenk 1978, Allen 1979, Sibson *et al.* 1981, Masch *et al.* 1985, Toyoshima 1990, Magloughlin 1992).

Scott & Drever (1953) described for the first time a rock truly formed by frictional fusion. They described glass, commonly brownish or pale yellowish-brown in color and less commonly colorless, that has penetrated into the interior of the porphyroclasts, is bubbly in appearance and has a reflective index 1.492–1.508. This glass is located on the Langtang Himalaya thrust fault (although later it was determined that this is a landslide surface—Masch 1977). This was the first conclusive proof that melt can be generated by frictional heat on a shear plane. Masch *et al.* (1985) re-examined and affirmed this vesicular glass of the Langtang Himalaya fault by TEM analysis. Their documentation of a glass formed by frictional melting on a landslide surface does not imply that a similar mechanism would produce a pseudotachylyte, as there are differences in geological conditions between landslide-generated pseudotachylytes and fault-generated pseudotachylytes.

Wenk (1978) examined the pseudotachylytes from the Outer Hebrides, Scotland, the Musgrave ranges, South Australia, and the Insubric line, Italy, by TEM analysis, and showed that only minor glass or devitrified textures were observed. He concluded that the pseudotachylytes are products of cataclasis rather than melting. Weiss & Wenk (1983) argued that the fine-grained component of the pseudotachylytes would most probably be identified as glass by conventional methods of analysis such as optical microscopy and X-ray diffraction. Thus, the presence of point, or pocket-like glass or glassy material is not conclusive evidence for the origin of fault-generated pseudotachylytes.

In order to confirm the presence of glass pseudotachylyte veins and clarify the origin of fault-generated pseudotachylytes, powder X-ray diffraction and petrological studies have been made for the pseudotachylytes from the Fuyun fault zone, northwest China.

GEOLOGICAL SETTING

The Fuyun region is located on the southwestern side of the Aertai mountains, northwest China (Fig. 1). The basement consists of Palaeozoic schists, gneisses, metavolcanic rocks, and Mesozoic granites and sediments. The tectonic evolution of the Fuyun region has been described in terms of two main tectonic events (Fig. 2): (i) a Hercynian movement which folded the basement and formed the NW–SE Aertai arch establishing the regional character of the terrain; and (ii) a Mesozoic

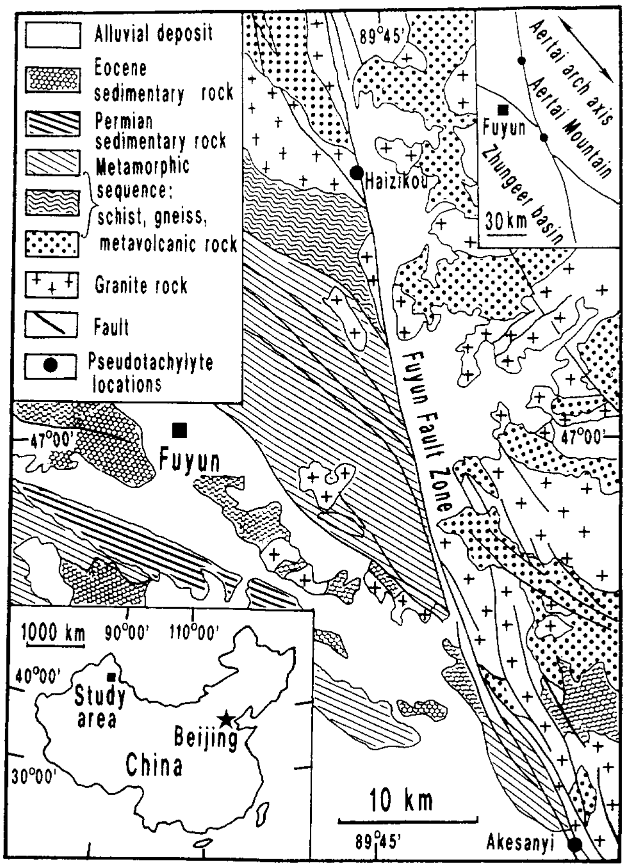

Fig. 1. Geological map of the Fuyun region, northwest China, simplified from the Regional Surveying Team of the Xingjiang Geological Bureau (1978).

Yanshan movement which produced the granites that intruded into the Palaeozoic metamorphic rocks (Bei *et al.* 1985). K–Ar dating studies show that the intrusion of granitic rocks occurred between 80 and 110 Ma (Bei *et al.* 1985).

The Fuyun fault zone, with a NNW–SSE trend, is about 170 km in length and cuts the NW–SE-trending Aertai arch obliquely, forming a boundary between the Aertai mountains and the Zhungeer basin (Fig. 1). The Fuyun fault dextrally displaces the Palaeozoic metamorphic rocks and Mesozoic granitic rocks about 26–30 km during the Paleogene (Ge *et al.* 1985). This fault also cuts and displaces the peneplains and terraces formed from the Miocene to the Holocene by vertical displacements ranging from 1 km to a few meters (Bei *et al.* 1985). This means that the Fuyun fault zone formed after the granite

Epoch	Tectonic events	Minor structures
Late Palaeozoic	Hercynian movement formed the NW-SE Aertai arch	Fold of the Palaeozoic basement
Early Mesozoic	Yanshan movement elevated the Aertai arch	Granitic rocks intrusion in the Palaeozoic basement
Middle Mesozoic	Formation of the Fuyun fault zone	Formation of mylonites along the fault zone
Late Mesozoic	Brittle deformation, earthquake faulting	Cataclasite, fault breccia, gouge and pseudotachylyte

Fig. 2. Deformation history of the Fuyun region.

intrusion (80–110 Ma) and its movement continued into the Quaternary. In 1931, surface faulting was caused by a magnitude 8.0 earthquake along the geological fault zone extending about 180 km in length. The maximum horizontal displacement which occurred due to this earthquake may be as large as 14 m. A dextral movement sense, marked by valley, scarp and woodland offsets coincides precisely with the fault. The results of trench investigation show that there were six large earthquake events in the Holocene.

Along the fault zone, the granitic rocks have been mylonitized from tens of meters to 1 km in width. The mylonitic foliations are uniformly parallel to those of the schist and gneiss on a regional scale (Lin & Fan 1984). Studies of the mineralogy and microstructures show that mylonization took place under sub-epidote–amphibolite facies conditions at 10–15 km depth (Lin & Fan 1984).

After formation of the mylonites, progressive brittle deformation developed in the mylonite which was followed by the injection of veins of quartz, calcite and epidote, and the formation of cataclastic rocks including fault breccia and gouge. Structures in the intensely fractured basement indicate a complex history during which brittle deformation followed ductile deformation.

FIELD OCCURRENCES OF PSEUDOTACHYLYTES

Pseudotachylytes were found at two locations, Haizikou and Akesanyi, along the northern segment of the Fuyun fault zone (Fig. 1). A prominent outcrop of pseudotachylytes and associated fault rocks is exposed in the Haizikou location and sketched in Fig. 3. The pseudotachylyte-bearing fractured zones are composed of granitic mylonites and cataclastic rocks including fault breccias and gouges (using the terminology of Sibson (1977) in this study).

The pseudotachylytes occur as single veins or as injected complex networks in some fractured zones (Figs. 3 and 4a–c). The fractured zones containing pseudotachylyte occur over an interval of a few meters to about 20 m in the section perpendicular to the Fuyun fault zone, and are about a few tens of centimeters to a few meters in width. The single veins typically occur as a thin layer film of a few millimeters in width, or locally as a lump on concave surfaces up to 20–30 cm in diameter on the marked shear surfaces (Figs. 3 and 4a) where the country rocks have been intensely fractured. The width of pseudotachylyte veins is variable from a few millimeters to 10 cm, but generally from 5–6 mm to 2 cm.

In several locations, branching pseudotachylyte veins inject into the quartz veins along small fractures, where there is no obvious displacement (Fig. 4b). The boundary between the quartz veins and the pseudotachylyte veins is sharp, along which the pseudotachylyte veins can be easily cleaved. Small cracks perpendicular to the margin of the vein can be observed in some pseudotachylyte veins with the naked eye. The network veins injected in fractures never show any regularity or

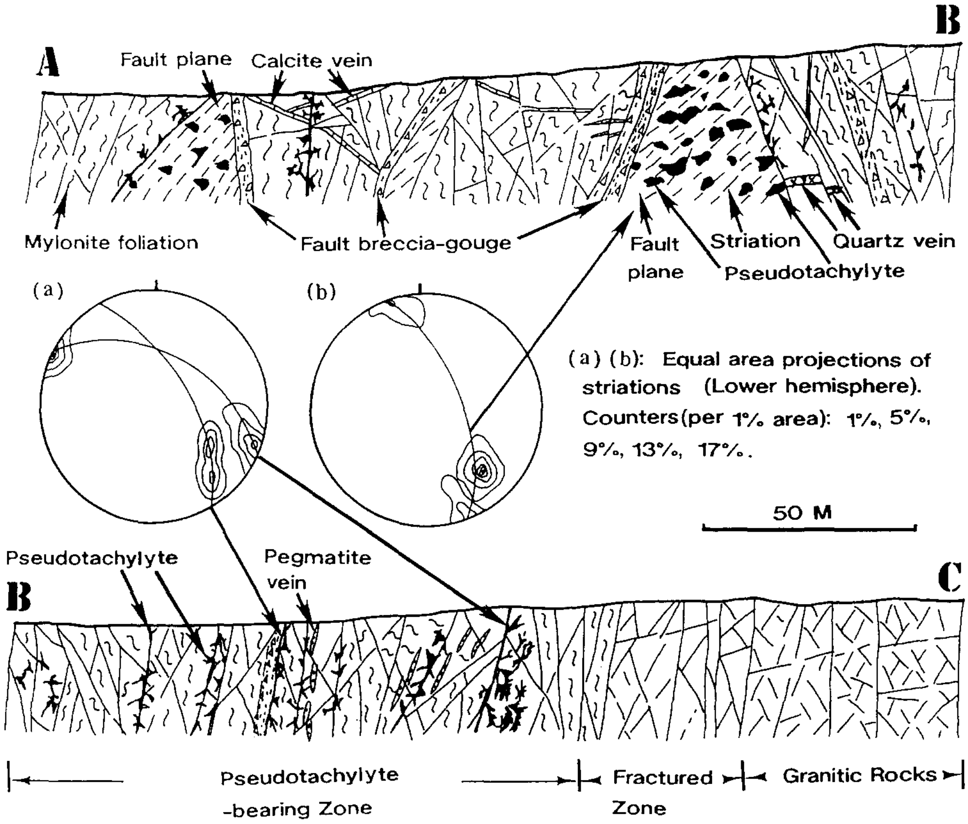

Fig. 3. Outcrop sketch of the Haizikou location showing the distribution of pseudotachylytes. (a) 142 data points. (b) 138 data points.

oriented direction. Some injected veins can be traced back to the parent pseudotachylyte-generated fault plane by a continuity of veins.

These pseudotachylytes are generally brown, brown–black and black in color. In some thick veins, the variation in color between the margin and center of a vein can be observed with the naked eye. The margin commonly exhibits a more dull color than the center. The contact between the pseudotachylyte veins and the country rock, as seen with the naked eye, is sharp even on weathered surfaces, where pseudotachylytes generally are rusty or brown in color.

Pseudotachylytes typically have an aphanitic, flint-like appearance. Some freshly exposed surfaces of pseudotachylytes have an obvious vitreous luster and perlitic cracks, similar to those of glassy volcanic rocks such as obsidian.

PSEUDOTACHYLYTE MICROSCOPY

The Fuyun pseudotachylytes have some distinctive characteristics. Using conventional 30 μm thin-sections, the pseudotachylytes are typically opaque and brown to black in color. Therefore, ultra-thin sections were prepared to observe the microstructures. Microstructurally, pseudotachylyte veins occur both as simple veins and as complex networks. The contact between pseudotachylytes and the country rock is typically sharp, but, in some cases, highly irregular. In some samples, where new pseudotachylyte veins were injected into old pseudotachylyte veins, the contact between these two veins is also sharp and locally irregular (Fig. 4d). This mode indicates that pseudotachylyte-generating events occurred repeatedly in the same location.

Matrices

Microstructurally, the pseudotachylyte matrices can be divided into five types based on the textures observed under the microscope, the SEM–EDS and from powder X-ray diffraction patterns (described later). These textural types are: glassy (type I); cryptocrystalline (type II); microcrystalline (type III); microlitic (type IV); and mixed character (type V).

Type I (Fig. 4e). This type of matrix is nearly isotropic under the microscope and variable in color from colorless, grey, brown to yellowish-brown. It is locally transparent or translucent, and exhibits the optical character of glass in volcanic rocks. The transparent and translucent glass matrices typically occur around the quartz fragments which probably came from the host rocks. Some glass occurs as pockets or slight streaks parallel to the flow streaks in the pseudotachylyte veins. This glass consists of pure silica or a feldspar component (described more fully later). Powder X-ray diffraction data show that the type I matrix consists almost entirely of glass or glassy material. Some samples exhibit a very obvious vitreous luster, like that of obsidian.

Type II (Fig. 4d). This type of matrix is composed of fine-grained material which is too small to be recognized or distinguished separately, even under the optical microscope. However, powder X-ray diffraction patterns show that the matrix consists mostly of fine-grained crystals. Using 30 μm thin-sections, the matrix appears opaque, from which nothing can be observed. The matrix typically appears brown to brown–black in color.

Type III (Fig. 4f). This type of matrix is mainly composed of very fine-grained crystals with some small microlites which can be recognized under the microscope. The crystals however are so small that the mineral type cannot be identified under the microscope. The matrix varies in color from transparent to brown to brown–black, and some appear transparent or translucent and opaque. Powder X-ray diffraction data show that the matrix mostly consists of crystals.

Type IV (Fig. 4g). The microlitic matrix consists mostly of microlites which range from a few microns to a few tens of microns in size. The microlites vary in size and morphology from the margins to the center of the microlitic pseudotachylyte veins. In the marginal zones, where the matrix is generally glass or glassy, and opaque under the microscope, the microlites are commonly small, single crystals with simple shapes. They are usually arranged parallel to the flow lamellae of the matrix. Towards the center of the pseudotachylyte vein, microlitic single crystals become progressively larger in size and the morphologies become complex ranging from simple shapes to skeletal, dendritic and spherulitic (Fig. 4g).

The microlites are predominantly sanidine, anorthoclase, pyrope, plagioclase (An_{30}–An_{70}), biotite and hornblende with a high-Ti component. None of these is present in the host rocks. The details of these microlites are described in another paper (Lin in preparation).

Type V (Fig. 4h). This matrix is similar in character to type I and type III, and is optically non-isotropic. Powder X-ray data also show a mixed character between glass and microcrystalline type veins. The glass and crystalline matrices form separate single veins, and often occupy the marginal zones of microcrystalline and microlitic type veins.

Fragments

The fragments set in the matrices consist mostly of quartz and very rare feldspar. Fragments of mafic minerals are extremely rare—a feature characteristic of all pseudotachylytes.

Fragments of quartz commonly have rims showing some transparency or translucency in the glass type vein (Figs. 5a & b) and zoned structures in the microlitic veins (Figs. 5c & d). The transparent rims, consisting mainly of pure silica and some feldspar components, around fragments of quartz are isotropic and possess optical characteristics similar to the thin section glass. It can be very difficult to distinguish these transparent rims and the thin section glass. The rims are variable in width, ranging from a narrow submicron zone, which represents only a small fraction of the total bulk of the grain, to a wide zone representing most of the grain.

The fragments exhibit a variety of shapes, such as rounded, embayed and other irregular outlines (Figs. 4e & h and 5a–d). Rounded shapes are the most common in all type pseudotachylytes.

The volume percentages of fragments larger than 2 μm in size in pseudotachylytes were measured and calculated under the microscope and from SEM–BSE photographs. Three types of vein (types I, III and V) were measured. The results obtained show that the volume percent of fragments in types I, III and V are 10, 14 and 16%, respectively.

Flow structures

Flow structures typically exhibit an alteration of thin colored layers and streaks which curve around the fragments (Fig. 4e, f & h). The changes of color mainly reflect the non-uniform chemical composition of the matrix, which will be fully discussed later. Flow streaks are typically parallel to the margins of the pseudotachylyte veins. Fragments are generally arranged parallel to the flow streaks as shown in Fig. 4(e).

Some flow structures are very similar in shape to similar-folds. These flow streaks bend in the center of a pseudotachylyte vein and become straight flow streaks parallel to, and near to, the margins of pseudotachylyte veins (Fig. 5e). The intervals between the flow streaks become progressively larger close to the center of the vein.

Vesicles and amygdules

Vesicles and amygdules are common in the Fuyun pseudotachylytes (Fig. 5f). The volume proportion of vesicles and amygdules, which varies from the marginal zone to the center of a well-studied 1–2 cm thick vein, ranges from 1 to 5%, with an average value of 3%. The vesicles and amygdules are almost perfectly circular, although some are elliptical in shape, and vary from a few microns to a few tens of microns in diameter. Along some microfractures, which are filled by carbonate and cut the pseudotachylyte vein, the amygdules are also filled only by carbonate and are related to the microstructures. This indicates that both filled structures were formed by coeval filling of carbonate from the same material source, after the pseudotachylyte formation.

POWDER X-RAY ANALYSIS

Experimental procedures and X-ray diffraction patterns

An MXP SCIENCE X-ray diffractometer was used to obtain the diffraction patterns for the Fuyun pseudotachylytes. The experimental conditions were: filtered

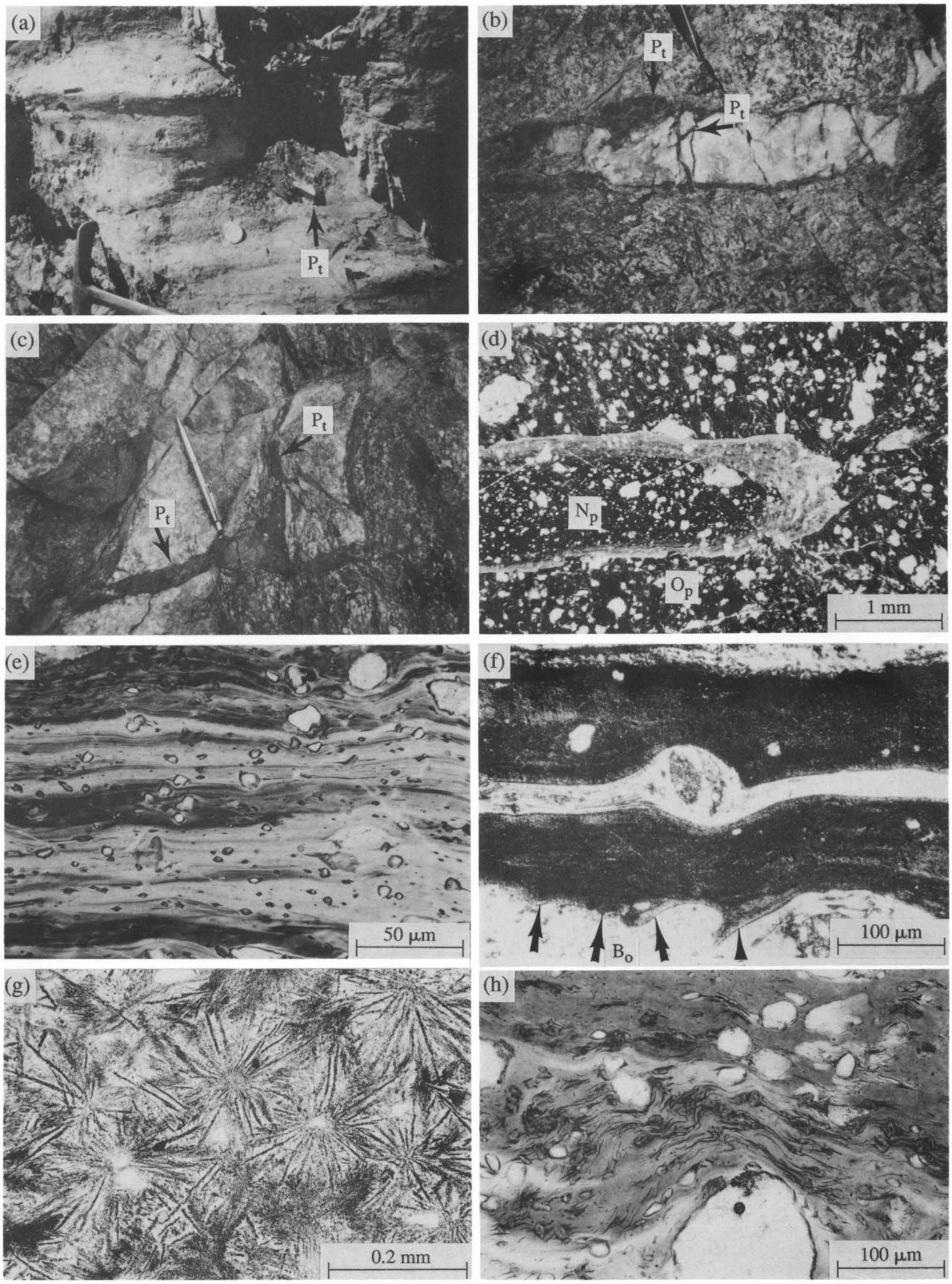

Fig. 4. Photographs showing the occurrences of pseudotachylyte veins (a–c) and photomicrographs showing the textures of fine-grained matrices of type I–V pseudotachylyte veins (d–h). (a) Pseudotachylyte remaining as a lump on concave surface on the fault plane. (b) Pseudotachylyte veins which cut and inject into a quartz vein (white portion) which has been cataclastically deformed and not displaced. (c) Network of pseudotachylyte veins injected into granitic country rock. (d) Cryptocrystalline pseudotachylyte where the new pseudotachylyte vein (Np) is injected into the old pseudotachylyte vein (type II, Op) (PPL). (e) Glass matrix in glass-type pseudotachylyte (type I) showing flow streaks (PPL). (f) Microcrystalline type pseudotachylyte (type III) exhibiting a flow structure similar to a sheared porphyroclast in mylonite (PPL). (g) Microlitic pseudotachylyte (type IV) showing spherulitic texture (PPL). (h) Mixed pseudotachylyte (type V) with the trichitic microlites (Mi) aligned parallel to the flow streaks (PPL). Pt, pseudotachylyte; Bo, boundary between pseudotachylyte and country rock; Np, new pseudotachylyte; Op, old pseudotachylyte; Mi, microlites; PPL, plane polarized light.

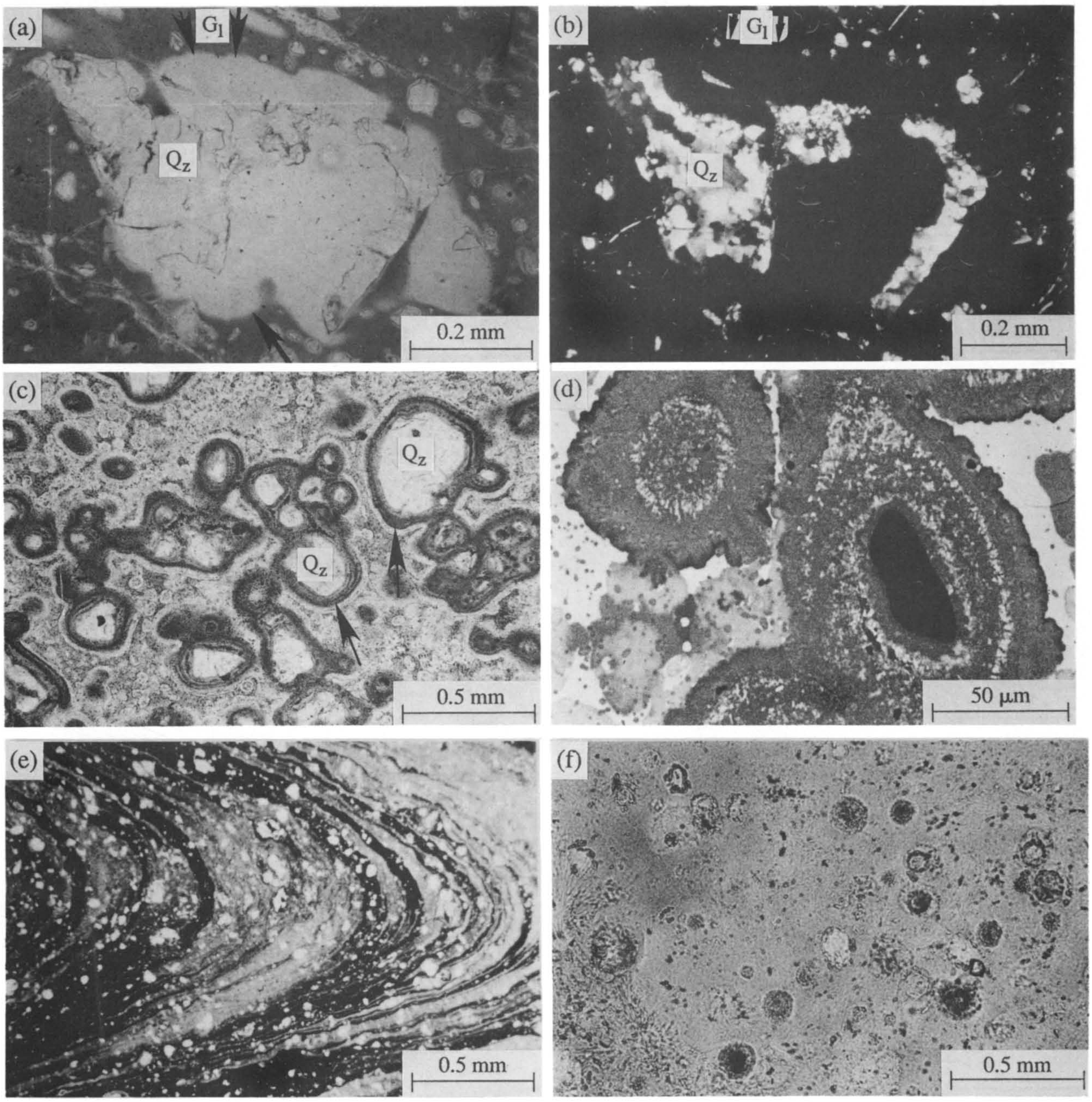

Fig. 5. Photomicrographs exhibiting microstructures of the pseudotachylytes. (a) & (b) Transparent glass (Gl) with a silica halo around quartz fragment (Qz); the arrows point the glass portion. (a) PPL; (b) CPL (crossed polarized light). (c) Rounded fragments around which the opaque minerals form spherical textures; arrows point to the spherical textures (PPL). (d) Spherical textures displaying zoning structure around the rounded fragment. (e) Flow structure resembling a similar-fold in shape (PPL). (f) Vesicles and amygdules (PPL).

CuKα (1.54050 Å) radiation, X-ray generator 3 kW, 40 kV, 20 mA, sampling width 0.02° scanning speed 3.0° min^{-1}, divergence slit 1.0°, scattering slit 1.0°, receiving slit 0.15 mm, θ position 5.0°.

Diffraction patterns of pseudotachylytes. Samples of the five different types of pseudotachylyte veins (types I–V) were selected after careful observation under the optical microscope. It was impossible to obtain a pure pseudotachylyte matrix free from fragments. Therefore, the selected samples contain both matrix and fragments.

The X-ray diffraction spectra of the five pseudotachylyte veins are shown in Figs. 6(b)–(g) and one spectrum of volcanic glass of obsidian is also shown for comparison (Fig. 6a). All these X-ray diffraction patterns show a very broad band ranging from 2θ 12° to 42° similar to that of the volcanic glass shown in Fig. 6(a). It was also determined that the integrated intensity of the glass, or non-crystalline material (the area of broad band), in the glass pseudotachylyte (type I), as shown in Fig. 6(b), is the largest, and that the mixed type pseudotachylyte (type V), as shown in Fig. 6(c), is between type I and type II, III, IV pseudotachylytes. This means that the amount of glass or non-crystalline material is the largest in the type I pseudotachylyte, and second largest in the type V pseudotachylyte. This result is consistent with that observed under the microscope as stated above.

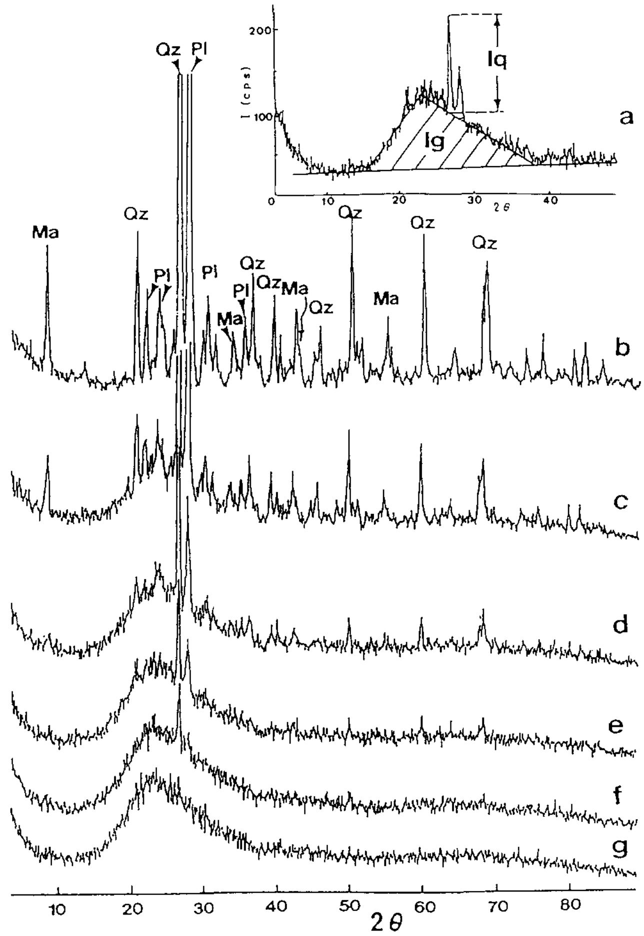

Fig. 7. X-ray spectra of calibration substances. (b)–(g) are the standard samples containing 0, 50, 80, 90, 95 and 100 wt% glass material fused from the granitic country rock. The vertical axis scale is the same in (b)–(g) curves and also in all spectra in this paper. Ma, micas; Qz, quartz. Pl, plagioclases; Iq, intensity of quartz; Ig, integrated intensity of glass material.

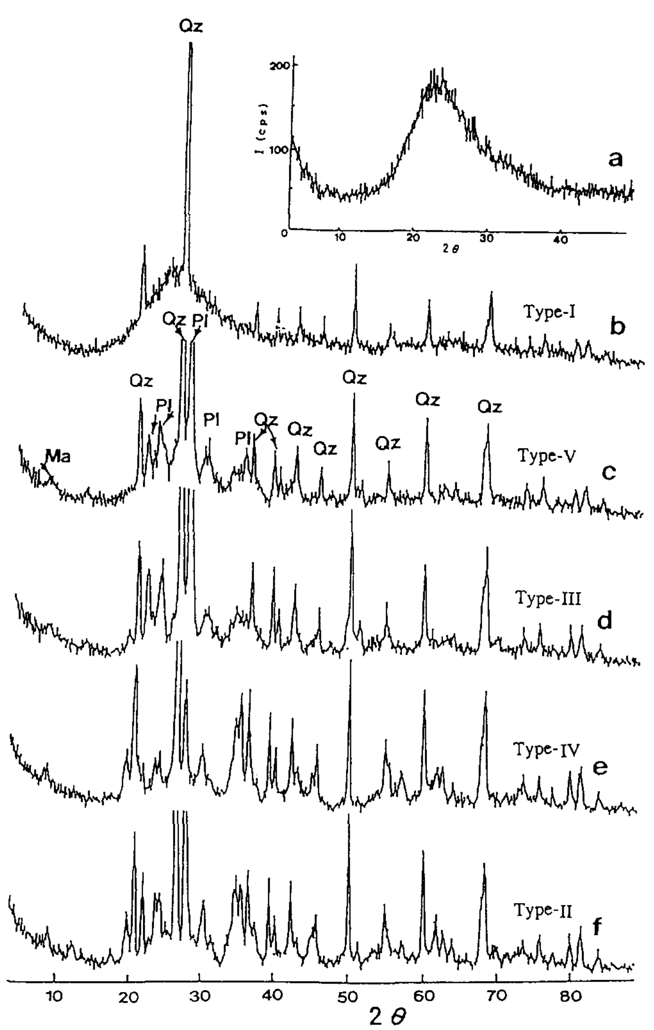

Fig. 6. X-ray spectra of pseudotachylytes and volcanic glass. (a) Volcanic glass (obsidian) from the Wadatoge volcanic area, central Japan. (b)–(f) Type I, V and II–IV pseudotachylyte veins from the Fuyun fault zone, northwest China.

The crystalline peaks in the type IV pseudotachylytes mainly indicate the presence of quartz, feldspar and a small amount of mica (Fig. 6c). The X-ray spectra of type II–IV pseudotachylytes show that the intensity scattered by mica is weaker than that of the granitic country rock as shown in Fig. 7(b). The spectrum (b) (Fig. 6, glass pseudotachylyte) shows that there are only quartz peaks, and no feldspar, mica or other mineral peaks, consistent with the microscope observations. The absence of feldspar and mica in the glass pseudotachylyte indicates that they were preferentially fused during melting.

Diffraction patterns of calibration substances. In order to obtain a pure glass sample as a calibration substance for the quantitative analysis of the pseudotachylytes, one of the granitic country rocks, in which the glass type pseudotachylyte occurred, was completely fused at 1500°C for 1 day and quenched by water. This artificially-generated glass fused from the granitic country rock, as well as a sample of the granitic country rock, were used as standard samples for calibration purpose. It was observed by SEM–EDS and powder X-ray method that some vesicles exist but no fragments remained in the fused glass.

Six standard samples which are made up of 0, 5, 10, 20, 50 and 100 wt% granitic country rock were prepared by weighing and mixing the powders of the artificially-fused glass and the granitic country rock. The X-ray diffraction spectra of the six standard samples are shown in Fig. 7. The X-ray diffraction patterns show a very broad band ranging from 2θ 12° to 42° in the spectra (Figs. 7c–g). It was found that the integrated intensity (Ig) of glass fraction diffraction (broad band), the area of oblique lines as sketched in Fig. 7(a) increases with an increase in the amount of glass. This will be discussed in more detail later.

The crystalline peaks were determined to consist mainly of quartz, feldspar and some micas. The scattered intensity of peaks in the same 2θ position decreases with the increase in the amount of glass. The peaks of quartz and feldspar can be recognized even if the amount of crystalline material of the granitic rock is as little as 5 wt%, and the mica peak can only be recognized when the amount of crystalline material is more than 10 wt%. This means that if 10 wt% of the fragments remained in glass, all the quartz, feldspar, and mica can be recognized from X-ray diffraction patterns.

Quantitative analysis of glass

As shown in Fig. 6, the pseudotachylytes produce diffraction patterns containing a broad band with some sharp peaks. These observations are explained by the presence of both crystalline and glass matrices in these pseudotachylytes.

The integrated intensities of glass fractions in the standard samples were measured using the triangle approximate method as shown in Fig. 7(a). The measured data were plotted in the diagram showing the relationship between the integrated intensity of the glass and the amount of glass (Fig. 8a). The integrated intensity of the glass clearly increases with the amount of glass as a linear function. This curve was thus used as a calibration curve.

The integrated intensity of the glass fractions in the pseudotachylytes was also measured using the triangle approximation method as shown in Fig. 7(a) and plotted on the calibration curve shown in Fig. 8(a). The amounts of glass read directly from the calibration curve vary from a few weight percent to as much as 89 wt%. Fragments producing the sharp crystalline peaks represent only 11 wt% in the glass pseudotachylyte. It is possible that the crystalline material, contained in type II–V pseudotachylyte veins, consists of the relict fragments from the granitic country rock and microlites formed from melt, as well as some clay minerals formed by subsequent metamorphism.

Quantitative analysis of quartz

As shown in Fig. 7, the scattered intensities of quartz, feldspar and mica peaks in the same 2θ position increase with increasing amounts of crystalline material. The intensities of the quartz peaks in the same 2θ position in the standard samples were measured, as shown in Fig. 7(a), and the results were plotted in the diagram showing the relationship between intensity and weight percent of the standard samples (Fig. 8b). It was also found that the intensity of quartz peaks in the same 2θ position increases with an increase in amount of crystalline material as a linear function.

The intensities of the quartz peaks, in the same 2θ 26–27° position in the type I–V pseudotachylytes, were measured and the results were plotted on the calibration curve shown in Fig. 8(b). From this it can be directly determined that the amount of quartz is 34 wt% in the glass type pseudotachylyte, and 28–80 wt% in the type II–IV pseudotachylytes (using total quartz contained in the granitic country rock as 100 wt%). This means that 66 wt% quartz grains were melted in the glass pseudotachylyte during the pseudotachylyte formation. There are no feldspar or mica peaks in the glass type pseudotachylyte. This means that virtually all the feldspar and

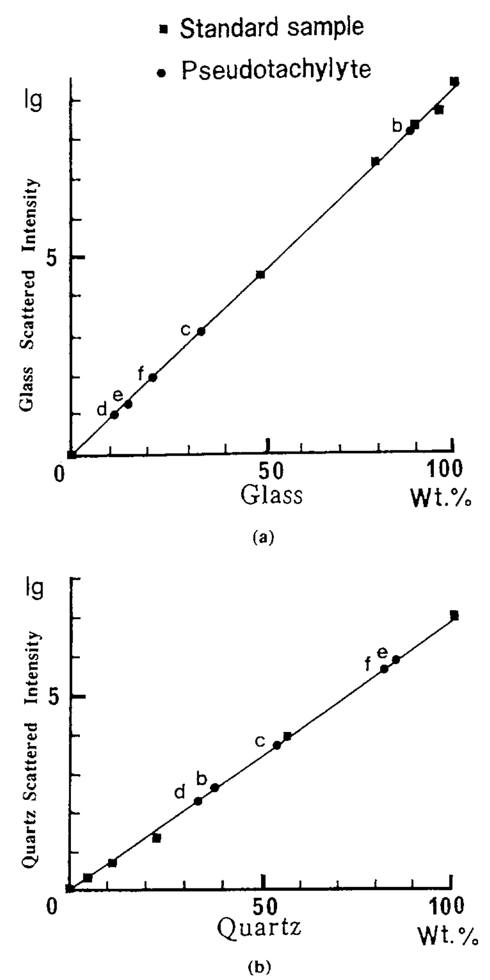

Fig. 8. Diagrams showing the relation between the intensity and weight percentage of (a) glass matrix and (b) crystalline quartz in calibration substances and pseudotachylytes. Points b–f correspond to those of the spectra (b)–(f) shown in Fig. 6.

mica contained in the host rocks were melted during pseudotachylyte formation.

As stated above, the volume percentage of fragments remaining in the pseudotachylytes is about 10 vol. %, corresponding to 10 wt% (using an average density of 2.70 g cm^{-3} for quartz and granitic country rock) in the glass pseudotachylyte. This is consistent with the results of the quantitative analysis from the X-ray diffraction data. The amounts of glass fraction in the type II–V pseudotachylytes vary from a few wt% to 34 wt%. This can be explained by the fact that the crystallization was advanced in the original melt and only some melt was quenched to form glass during the pseudotachylyte formation.

CHEMICAL COMPOSITIONS

Bulk chemistry of pseudotachylytes

The average bulk chemical compositions of the pseudotachylytes and their associated country rocks analyzed by XRF on ignited dry material are displayed in Tables 1 and 2. The water contents were determined independently by ignition loss which were corrected for oxidation of iron using the FeO contents as shown in Tables 1 and 2.

Shand (1916) was the first to note that pseudotachylytes have a composition similar to the rocks in which they occur. The average bulk compositions of the pseudotachylyte veins, including the fine-grained matrix and the fragments of country rocks are also very similar to those of the country rocks in the Fuyun fault zone. Thus, the pseudotachylytes are interpreted to have formed from the rock in which they occur, based on this similarity between the chemical composition of the pseudotachylytes and the country rocks as well as the field occurrences.

Chemistry of glass matrices

The chemistry of the glass matrix of the Fuyun pseudotachylytes was analyzed in detail. This analysis was carried out by SEM–EDS. The results of this analysis are given in Tables 3 and 4.

In general, the Fuyun pseudotachylytes are chemically very heterogeneous, varying not only from vein to vein, but also within different parts of a single vein. Although there is a similarity in chemical composition between the pseudotachylyte veins and the country rock, there is, in general, a significant change in composition between the fine-grained matrix–glass matrix and the country rock. As shown in Fig. 9, the glass matrices

Table 1. Chemical compositions of the Fuyun pseudotachylytes analyzed by XRF. The water contents (H_2O^- and H_2O^+) were determined independently by ignition loss, which was corrected for oxidation iron using Fe as FeO in this study. FeO*, total Fe calculated as FeO

wt%	A-1	A-2	A-3	A-4	A-5	A-6	A-7
SiO_2	68.52	67.82	67.57	62.86	59.77	63.53	63.90
TiO_2	0.46	0.47	0.48	0.70	0.54	0.71	0.59
Al_2O_3	14.55	15.53	15.31	16.84	17.74	16.50	16.66
FeO*	3.60	4.42	4.10	5.33	5.04	6.72	6.20
MnO	0.08	0.09	0.08	0.07	0.06	0.10	0.13
MgO	0.64	1.28	1.20	2.47	4.52	3.39	2.78
CaO	2.28	3.24	3.19	3.01	2.31	1.03	0.75
Na_2O	3.51	3.11	3.77	4.40	4.64	1.40	2.85
K_2O	3.96	2.93	2.26	2.69	2.51	4.07	3.48
P_2O_5	0.14	0.13	0.14	0.22	0.12	0.17	0.13
H_2O^+	2.34	2.65	2.05	2.10	2.11	3.24	3.15
H_2O^-	0.26	0.55	0.81	0.81	0.83		
Total H_2O	2.60	3.21	2.87	2.91	2.94	3.24	3.15

Table 2. Bulk compositions of the country rocks where the pseudotachylytes injected as analyzed by XRF. FeO*, total Fe calculated as FeO

wt%	B-1	B-2	B-3	B-4	B-5	B-6	B-7
SiO_2	68.12	72.77	71.32	69.75	74.13	68.00	67.15
TiO_2	0.42	0.25	0.32	0.48	0.21	0.50	0.50
Al_2O_3	15.15	13.98	14.10	14.28	13.83	15.83	15.83
FeO*	3.65	2.10	2.95	3.73	1.81	4.87	3.95
MnO	0.09	0.05	0.07	0.06	0.03	0.10	0.08
MgO	1.24	0.49	0.63	0.67	0.47	2.43	1.94
CaO	3.60	2.00	2.28	2.31	0.95	0.99	2.42
Na_2O	3.67	3.57	3.77	3.61	3.73	3.10	4.48
K_2O	2.10	3.88	3.63	4.01	3.80	3.14	2.66
P_2O_5	0.13	0.07	0.10	0.14	0.12	0.14	0.11
H_2O^+	0.54	0.51	0.83	0.52	0.94	0.93	0.89
H_2O^-	0.38	0.34		0.43			
Total H_2O	0.92	0.84	0.83	0.95	0.94	0.93	0.89

Table 3. Chemical compositions of the glass matrices in the type I pseudotachylyte analyzed by EDS. FeO*, total Fe calculated as FeO

	Glass matrix in glass pseudotachylyte								
wt%	Glas1	Glas2	Glas3	Glas4	Glas5	Glas6	Glas7	Glas8	Glas9
SiO_2	67.32	63.90	63.50	64.94	64.41	65.73	97.41	92.68	88.52
TiO_2	0.56	0.59	0.64	0.60	0.58	0.59	0.00	0.07	0.30
Al_2O_3	15.52	17.44	17.26	18.03	16.92	16.41	0.00	2.24	6.13
Cr_2O_3	0.05	0.07	0.00	0.02	0.00	0.01	0.00	0.03	0.00
FeO*	3.07	3.35	3.43	3.40	3.49	3.31	0.00	0.81	0.63
MnO	0.08	0.14	0.10	0.13	0.09	0.08	0.00	0.00	0.08
MgO	0.66	0.85	0.92	0.86	0.68	0.75	0.00	0.03	0.08
CaO	2.00	2.81	3.01	2.93	2.68	2.48	0.00	0.70	0.31
Na_2O	3.05	3.04	3.02	3.16	2.97	2.84	0.09	0.36	2.00
K_2O	4.56	4.13	3.83	3.99	4.07	4.30	0.00	0.00	1.52
P_2O_5	0.49	0.59	0.38	0.55	0.44	0.62	0.73	0.16	0.11
NiO	0.00	0.11	0.01	0.00	0.02	0.06	0.04	0.00	0.00
Total	97.36	97.02	96.08	98.95	96.36	97.18	98.14	97.08	99.73

Table 4. Chemical compositions of the glass matrices in the type V pseudotachylyte analyzed by EDS. FeO*, total Fe calculated as FeO

	Glass matrix in mixed type pseudotachylyte								
wt%	Gla10	Gla11	Gla12	Gla13	Gla14	Gal15	Gla16	Gla17	Gla18
SiO_2	62.01	61.77	61.59	61.16	60.09	60.84	64.75	57.06	59.05
TiO_2	0.59	0.62	0.55	0.68	0.57	0.42	0.36	0.50	0.28
Al_2O_3	19.06	18.92	18.91	18.76	18.00	19.25	13.26	15.63	9.65
Cr_2O_3	0.04	0.07	0.04	0.00	0.02	0.00	0.01	0.00	0.00
FeO*	4.28	4.32	4.28	3.67	4.62	5.24	7.47	8.55	16.88
MnO	0.21	0.11	0.05	0.00	0.06	0.12	0.08	0.17	0.17
MgO	1.68	1.55	1.56	1.56	2.14	1.71	1.08	2.73	2.29
CaO	4.39	4.32	4.28	3.67	4.62	5.24	2.17	2.43	2.21
Na_2O	2.37	2.22	2.29	2.03	1.81	1.80	2.85	3.43	1.02
K_2O	3.08	3.33	3.32	3.62	3.16	2.84	3.34	4.39	2.13
P_2O_5	0.36	0.35	0.31	0.66	0.37	0.36	0.18	0.20	0.37
NiO	0.21	0.02	0.17	0.03	0.02	0.00	0.04	0.00	0.09
Total	98.23	97.64	97.42	96.90	97.57	98.79	95.57	95.08	94.84

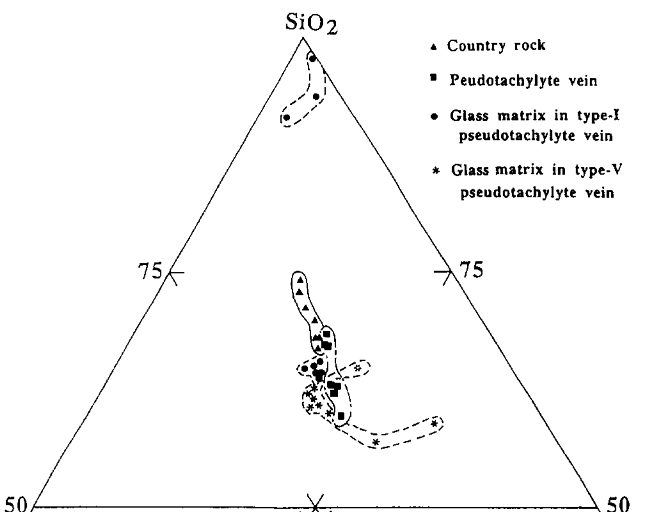

Fig. 9. SiO_2–Al_2O_3—all other components diagram showing the relation between the glass matrices in the glass pseudotachylytes and the country rocks.

in type I and V veins are generally poorer in the SiO_2 component than those of the country rocks (columns Glas1–Glas6 in Table 3 and Table 4), except for local occurrences of pure SiO_2 glass halos around the clasts (columns Glas7–Glas9 in Table 3). The average weight percentages of SiO_2 are 60–64 wt% in the glass matrices which are about 5–10 wt% poorer than that of the country rock. The chemical compositions of the glass matrices may represent the initial compositions of the melt formed during pseudotachylyte generation. The depleted SiO_2 contents of the glass matrices indicate that some quartz crystals remained as fragments in pseudotachylyte veins, so that the glass matrices have a lower SiO_2 component than those of the country rock.

The glass matrices are generally 3–5 wt% higher in Al_2O_3 than those of the country rock, and have a component of feldspar with the range contained in the country rock. There is generally a slight increasing trend in CaO and K_2O contents from the country rock to the pseudotachylyte veins to the glass matrices. The FeO and MgO components are also higher in the glass matrices than in the country rock.

As stated previously, the fragments remaining in the glass pseudotachylyte veins are mostly quartz, although feldspar and biotite are also main rock-forming minerals in the granitic country rock. The low SiO_2 and high Al_2O_3, CaO, K_2O, FeO and MgO nature of the chemical composition of the glass matrices indicate that the melt was formed by preferential melting of biotite and feldspars rather than total melting of the country rock.

The flow layers and streaks in the glass matrix, with a variation in color, mainly reflect the change of chemical composition of its mafic components such as FeO and MgO. The total FeO and MgO components range from 0.5 to 15 wt%.

Water contents

The water contents in the pseudotachylyte veins and the country rock are shown in Tables 1 and 2. The crystalline water (H_2O^+) and pore water (H_2O^-) were measured independently by ignition loss. The crystalline water (H_2O^+) contents in type I–V veins only range between 2.0 and 2.65 wt%. These are 1.5–2.0 wt% higher than that of the country rock which contains about 0.5 wt% crystalline water (H_2O^+). As stated previously, the glass matrices, in which the vesicles and amygdules are commonly present, were not metamorphosed. Therefore, it can be supposed that the crystalline water contents in type I and V veins represent the initial water contents entering the melt as hydroxyl ions formed by the quenching of the melt. These high crystalline water contents and the presence of vesicles and amygdules indicate that the melting was formed under water-saturated conditions rather than dry conditions. The water-saturated conditions demonstrate that some water was previously present in fractures in the country rock.

DISCUSSIONS AND CONCLUSIONS

Origin of pseudotachylyte

One of the most important questions concerning the origin of pseudotachylyte is if fault-generated pseudotachylytes, intruded into fractures or remaining on a fault plane, were generated as melts that were formed by frictional heating on shear plane. In the light of the work by Wenk (1978), Allen (1979), Wenk & Weiss (1982), Maddock (1983), Weiss & Wenk (1983), Macaudiere *et al.* (1985) and Maddock *et al.* (1987), most studies have focused on the origin of the cryptocrystalline matrix textures. Wenk & Weiss (1982) suggested two possible explanations for these textures: (1) that they were from originally glassy or partly glassy veins that formed by frictional fusion of rocks during faulting which have devitrified with time; or (2) that the textures originated in veins that were never initially glassy but consisted of fine-grained powders produced by some kind of high-pressure brittle failure in strong rocks. Wenk & Weiss (1982) argued that there is insufficient evidence available to permit a clear choice between these alternatives.

The evidence from the Fuyun fault zone suggests that the pseudotachylytes were once fused, and include glass or glassy material, microlites displaying a variety of quenched or rapid-cooling crystal forms, vesicles and amygdules, flow bandings and corroded or partly melted inclusions.

Glass and glassy matrices. In previous studies (Willemse 1938, Maucaudiere *et al.* 1985, Toyoshima 1990), X-ray power diffraction patterns have been used to determine whether or not the isotropic or anisotropic fine-grained matrix in pseudotachylytes is glass. However, no typical glass-diffraction pattern has been thus far found in the fine-grained matrix, even when the fine-grained matrix is submicron-sized (Macaudiere *et al.* 1985). Generally, it is impossible to obtain fine-grained matrix free from clasts. It is therefore impossible to obtain a typical glass-diffraction pattern even if some glass remained in the pseudotachylyte. In most of these cases, the pseudotachylyte was crystallized during the pseudotachylyte formation or devitrified after the pseudotachylyte formation. Therefore there is no glassy material or only a little glass remaining which can not give a typical X-ray diffraction pattern of glass material.

The X-ray diffraction patterns of the Fuyun pseudotachylytes clearly show glass or non-crystalline material diffraction patterns. Of course, these glass X-ray diffraction patterns cannot completely negate the possibility that the matrix consists mostly of ultra-fine-grained material ($<$submicron size). But, this possibility can be rejected for the following reasons.

First, if the fine-grained matrices were composed mostly of finely crushed clasts of the country rocks as suggested by Wenk (1978), there would be characteristic crystal peaks of mica and feldspar in the X-ray spectra such as those in the X-ray spectra of the country rock. But, with the exception of the quartz peaks, no other mineral crystal peaks can be clearly recognized in the glass type pseudotachylyte. So, it is not possible that a matrix with non-crystal diffraction pattern represents an assemblage of crushed clasts of the country rock.

Second, if the fine-grained matrices represent an assemblage of ultrafine crushed clasts, there would be a similarity in chemical composition between both of them. But, the matrices are 5–15 wt% lower in SiO_2 than that of the host rocks.

Additionally, quantitative analysis shows that the matrices in the Fuyun pseudotachylytes possess a gradation from almost completely crystalline to completely glassy varying from a few wt% to 89 wt%. In the glass-type pseudotachylyte, crushed clasts, which are larger than 2 μm in size only comprise 10 wt% of the whole, while 89 wt % of the glass matrix has a typical glass X-ray diffraction pattern. If the matrix is the assemblage of ultrafine crushed clasts, about 90% clasts in the pseudotachylyte must be smaller than submicron size. Typically, the fine clasts in fault-rocks are generated simultaneously with the coarse clasts. Thus, the matrix in the glass-type pseudotachylyte cannot be regarded as the assemblage of ultrafine clasts.

Furthermore, the flow structures, vesicles and amygdules, microlites (of high temperature indicators exhibiting a great variety of quenched or rapid-cooling crystal forms—Lin in preparation), and rounded fragments show a fore-melt state during the pseudotachylyte formation. These are characteristically impervious to light under crossed polarized light optically indicating a glass state.

Therefore, the X-ray glass-diffraction patterns were formed by glass matrices rather than fine-grained crushed clasts in the Fuyun pseudotachylytes. The presence of the glass pseudotachylyte veins undoubtedly demonstrates that the Fuyun pseudotachylytes were formed by frictional melting rather than by crushing of the host rocks.

Depth of the pseudotachylyte formation

The presence of vesicles, amygdules and a glass matrix implies a shallow depth of pseudotachylyte formation under water-saturated conditions. The quantitative use of measured water content, whole-rock composition, solubility function and amygdule (vesicle) contents to determine the depth of pseudotachylyte formation was first attempted by Maddock *et al.* (1987) and also by Toyoshima (1990). The problem concerning the use of this method is how to determine the water content during the pseudotachylyte formation. Although Toyoshima (1990) estimated the water content for the Hidaka pseudotachylytes from the total amount of oxides in the bulk composition determined by microprobe analysis, a heterogeneous fine matrix makes it difficult to determine the water content accurately by this method. Toyoshima (1990) also reported a variation from 86 to 100 wt% for the total amount of oxides in the pseudotachylyte compositions.

The analysis of water contents also clearly indicates the presence of water during the Fuyun pseudotachylyte formation in this study. The water contents of the pseudotachylytes are about 2 wt% greater than that of the country rock. In addition, the presence of vesicles and amygdules also indicates a water-saturated state in the melt during pseudotachylyte formation. It is impossible that the total water in the pseudotachylytes came from the hydrous minerals from the country rock because of the lower water contents of country rock. Thus, the Fuyun pseudotachylytes were generated under water-saturated conditions in a fault zone rather than under dry conditions. This same result was also suggested by Magloughlin (1992).

The preservation of glass which seems to be rare or absent in many pseudotachylytes is very significant, particularly when the water content of pseudotachylyte appears to be quite high (which would tend to favor devitrification) (Maddock 1983, Magloughlin & Spray 1992). The presence of glass with high water content suggests that the Fuyun pseudotachylyte formed recently and at a shallow depth. The Fuyun pseudotachylytes contain 2.3–2.65 wt% water (H_2O^+) which are the initial water contents in the melt during the pseudotachylyte formation. The largest value of water contents, 2.65 wt%, was used here to estimate a maximum depth of pseudotachylyte formation. Although the matrices have a heterogeneous chemical composition, most of them have a composition similar to andesite as shown in Tables 3 and 4. Using the graph of weight percent water against pressure in andesitic glass (Hamilton *et al.* 1964), a maximum lithostatic pressure of about 400 bars is obtained corresponding to a depth of about 1.5 km.

Temperature

The vesicles and amygdules in the matrix indicate the presence of an excess fluid phase. Using the experimental results in the system SiO_2–H_2O (Kennedy *et al.* 1962), an estimate of a minimum temperature of 1450°C was obtained for the melt generated by frictional heating during the pseudotachylyte formation by the presence of pure SiO_2 composition glass at a depth of 1.5 km. The melt formed by frictional melting has a very transient existence, with cooling half-lives for injection veins of 1 cm in width on the order of 40 s (Sibson 1975). Therefore, considerable overstepping of the temperature was necessary for melting the quartz grains in a melt. Thus, the estimated 1450°C represents a minimum temperature estimate of the melt.

Melting process

From the above discussion, the Fuyun pseudotachylytes have clearly been melted. The average chemical compositions of pseudotachylytes are often similar to those of the rocks in which they occur, therefore it is typically suggested that frictional fusion invokes total melting rather than selective melting of the country rock (e.g. Philpotts 1964, Ermanovics *et al.* 1972, Masch *et al.* 1985, Toyoshima 1990). Because it is impossible to free the fine-grained clasts from the pseudotachylytes, the average composition of matrix and fragments has a similar composition to the country rock.

However, it is often found that the chemical composition of the matrix or pseudotachylytes generally have a lower SiO_2 component than that of the country rock in which the pseudotachylytes occur (e.g. Shand 1916, Ermanovics *et al.* 1972, Sibson 1975, Toyoshima 1990). The average chemical compositions of the Fuyun pseudotachylyte are very similar to that of the granitic country rock, but the chemical compositions of matrices are 5–10 wt% lower in SiO_2 component than that of the granitic country rock. Powder X-ray diffraction data indicate that 11 wt% quartz fragments remained and micas and feldspars completely disappeared in the glass pseudotachylyte. This can explain why the matrices have a lower SiO_2 component than that of the granitic country rock, suggesting that lower melting point minerals, such as mica and feldspar, were completely melted and high melting point quartz crystals remained as fragments during the pseudotachylyte formation.

Powder X-ray diffraction data and chemical compositions of the Fuyun pseudotachylytes demonstrate that the Fuyun pseudotachylytes formed mainly by selective melting of low melting point minerals under water-saturated conditions rather than total melting or partial melting of the country rocks. This same conclusion was reached by Spray (1992).

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