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The nature and significance of pseudotachylite from the Nason terrane, North Cascade Mountains, Washington

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Abstract—Pseudotachylite has been recently discovered at numerous localities in the Nason terrane of the North Cascade Mountains, Washington. The pseudotachylite is widespread, not associated with any single major fault or shear zone, and tends to occur in narrow foliation-parallel zones. Single pseudotachylite veins range in thickness from less than 0.1 to 10 cm. Veins and networks of veins occur in six distinct types, and these form the basis of a suggested classification scheme. Multiple generations of pseudotachylite are present in some samples. Host lithologies include quartz diorite, semipelitic schist, tonalite, amphibolite and especially graphitic pelitic schist. Glassy veins are rare; most pseudotachylite is apparently holocrystalline. Spherulites, vesicles and dendritic microphenocrysts are present and indicate a frictional melt origin.

The ubiquitous occurrence of cataclasite xenoliths within the pseudotachylite, along with other textural observations, indicates that in the Nason terrane, the development of cataclasite zones was the precursor to pseudotachylite generation. It is inferred that cataclastic deformation of the schist provided the strain softening which resulted in faulting and pseudotachylite generation. The water-rich and ultra-fine-grained matrix of the cataclasite was an ideal starting material for pseudotachylite generation.

Based upon bulk chemistry of host lithologies and microprobe analyses of the pseudotachylite, it appears that the pseudotachylite formed as a result of a virtually complete melting of the pelitic (i.e. non-quartz vein) component of the schist. Where pseudotachylite occurs within pelitic schist alone, the composition of the pseudotachylite is very similar to the pelitic component of the schist, while the composition of veins cutting tonalite gneiss in addition to pelitic schist appears to define a mixing line between these two lithologies. This suggests either participation of the tonalite during initial melting, or subsequent assimilation of gneiss into the melt.

INTRODUCTION

PSEUDOTACHYLITE was discovered at two localities in the Nason terrane of the North Cascade Mountains in the state of Washington, U.S.A., in 1984 and preliminary descriptions were reported (Magloughlin 1986a,b). The purpose of this paper is to describe the morphological and chemical characteristics of this pseudotachylite, and provide a basis for interpretation of its significance. As there is a paucity of detailed petrologic description of pseudotachylite in the literature, and as the Nason terrane occurrences provide contrasting geochemical/petrologic settings, these aspects are emphasized.

GEOLOGIC SETTING

The North Cascade Mountains form a roughly linear belt extending from central Washington to southern British Columbia, and they are composed dominantly of pre-Tertiary crystalline rocks. The pseudotachylite described in this paper occurs in the northern part of the Nason terrane (Fig. 1), defined by Tabor *et al.* (1987). This terrane is composed of the dominantly pelitic Chiwaukum Schist and a number of mainly late Cretaceous tonalite to quartz diorite plutons.

During the late Cretaceous and early Tertiary, a number of deformational events occurred between the peak of regional metamorphism and cooling of the terrane (Magloughlin 1986b). The first of these produced a foliation expressed by the dimensional preferred orientation of micas and, to a lesser extent, a compositionally defined transposition foliation. This foliation was folded to a generally steeply-dipping orientation during the next deformational event which also

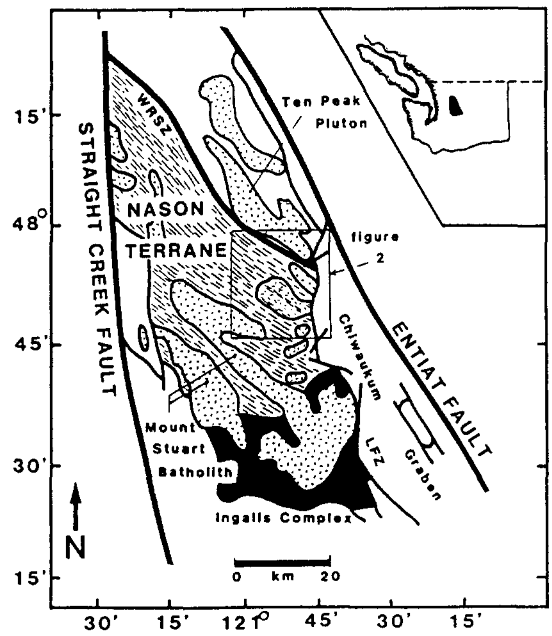

Fig. 1. Location map of the Nason terrane, North Cascade Mountains, Washington. WRSZ = White River shear zone (Magloughlin 1986b). LFZ = Leavenworth fault zone. After Tabor *et al.* (1987).

produced tight to isoclinal folds with a southwest vergence (Van Diver 1964, Magloughlin 1986b). Most of the pseudotachylite-bearing zones were developed parallel to this foliation. A suite of peraluminous trondhjemite pegmatites dated at about 83 Ma are affected by the folding event but not by the earlier deformation, providing a maximum age for the folding (Magloughlin & Brasaemle 1988).

The Nason terrane cooled during the late Cretaceous and early Tertiary, and the present erosion surface, at least in the vicinity of the Mount Stuart Batholith, passed through the 100°C isotherm by about 55 Ma, based upon apatite fission track dates (Erikson 1976). As this would place the majority of the terrane in the upper part of the brittle regime, and it seems unlikely pseudotachylite would form at such shallow levels, 55 Ma may place a younger age limit on the time of pseudotachylite formation. This also would give a minimum depth of formation of 4 km, assuming a geothermal gradient of 25°C km^{-1}.

FIELD DESCRIPTION

Introduction

Rather than being confined to a major fault or shear zone, the Nason terrane pseudotachylite is widespread. About 10 isolated bedrock localities have thus far been discovered and sampled (Fig. 2).

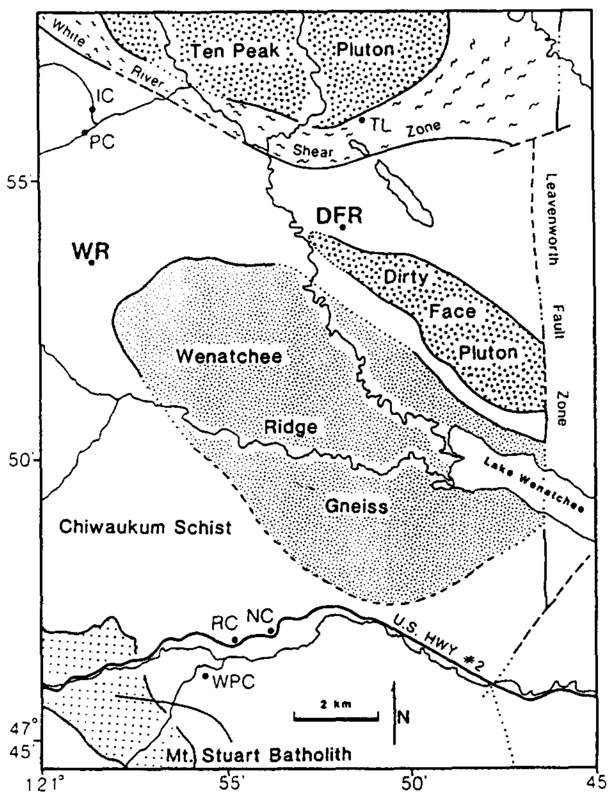

Fig. 2. Lithologic map of the northeast corner of the Nason terrane (see Fig. 1), showing the distribution of the known pseudotachylite localities. Pseudotachylite sites are DFR = Dirty Face Ridge; WR = Wenatchee Ridge; TL = Twin Lakes; IC = Ibex Creek; PC = Panther Creek; RC = Royal Creek; NC = Nason Creek; WPC = White Pine Creek.

The pseudotachylite is most common in graphitic pelitic schist, and is less common in semi-pelitic (i.e. less aluminous, more siliceous) schist. It has also been found within quartzite, amphibolite, epidote–biotite–hornblende tonalite, biotite–hornblende diorite and hornblende–quartz diorite. Glassy samples are black with a pearly luster, while holocrystalline pseudotachylite is black to slightly bluish.

Typical occurrences of pseudotachylite involve several to dozens of veins, usually ranging in thickness from a few mm to several cm. Pseudotachylite zones are much more continuous along strike than individual veins, and typically range from a few meters to at least tens of meters in length. Normally, pseudotachylite occurs as single narrow veins or zones, and excellent exposure permits the conclusion that no large-scale fault is present. At two locations (WR and DFR sites, Fig. 2), however, significant fault zones are present. At the DFR site, northwest of Lake Wenatchee, pseudotachylite is present sporadically along at least the lowest 500 vertical meters of exposure. The pseudotachylite is especially common in a 10 m wide single fault zone that occurs subparallel to the foliation. Pseudotachylite was first recognized near the crest of Wenatchee Ridge, in an area of about 60% tonalite gneiss sills and 40% interlayered pelitic schist. The interlayering generally ranges from a few tens of cm to several meters. The greatest concentrations of pseudotachylite occur in thick concordant veins flanked by gneiss (Fig. 5a). Here, a fault zone about 15 m thick contains abundant pseudotachylite.

Pseudotachylite vein and zone classification

From the study of hundreds of veins from the various localities, a classification scheme of pseudotachylite veins and groups of veins (zones) from the Nason terrane has been established. This scheme is purely descriptive. Figure 3 displays vein types I–VI.

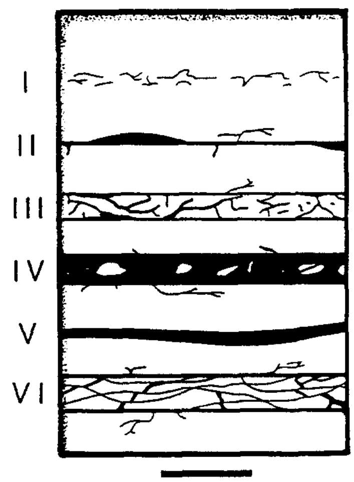

Fig. 3. Pseudotachylite veins and zones in the Nason terrane. Types I–VI are described in the text. Fine lines in VI are small-scale faults or cataclasite zones offsetting pseudotachylite veins. The scale bar is approximately 10 cm.

Type I zones are uncommon. They are up to 10 cm wide extending parallel to the foliation. Individual veins of pseudotachylite are up to several mm thick and 10 cm long. While these zones have a tabular shape, individual veins are non-planar and change orientation sharply. Individual veins commonly do not interconnect on two-dimensional outcrops.

Type II veins are among the most common. An essential feature is a planar principal vein, continuous for meters to tens of meters along strike, displaying repeated variations in thickness from 1 mm or less to several cm. The lengths of type II veins are commonly tens of meters or greater, and virtually all are parallel to the foliation. Thin veins branch off the main vein and intrude the host rock. Accompanying most type II veins are plano-convex lenses of pseudotachylite on either side of the main vein. These may be up to several tens of cm long and commonly several cm thick, and form some of the larger volumes of pseudotachylite. A simple model for the formation of these plano-convex lenses (PCLs) is presented below.

Type III occurrences vary from about 1 cm to about 1 m in thickness (Figs. 3 and 5b). Individual type III zones may vary somewhat in thickness but this commonly continues for tens of meters along strike. The external boundaries of the zone are extremely sharp and planar. There is typically a small amount of pseudotachylite along these boundaries, but most form branching networks within the zone. Individual veins commonly connect the two margins of the zone. These are the 'paired shears' of Grocott (1981).

Very similar to type III zones are type IV, which are of the same general scale (Figs. 3 and 5a). These two types are probably intergradational, and borrowing from the terminology of conglomeratic rocks, may be referred to as clast (type III) and matrix (i.e. pseudotachylite) dominated (type IV). Grocott (1981) described a similar transition from type III to type IV zones.

Type V veins are non-planar and commonly gently sinuous; they branch out from types II, III and IV, range up to several cm thick, and may extend for many meters in length. They have very sharp margins which lack cataclasite. These veins are dilational, and are comparable to the 'injection veins' of Sibson (1975) and Grocott (1981). They are the only type that occurs at all orientations relative to the foliation. All other veins and zones in the northern Nason terrane are typically parallel to sub-parallel to the foliation.

Based upon their similar geometry, dominantly foliation-parallel orientation, and the common truncation of veins by cataclasite zones, type VI zones are reactivated type III zones (Fig. 3). They are considered separate from other types in that multiple generations of pseudotachylite may occur. Cutting the zones and offsetting pseudotachylite veins are narrow anastomosing slip surfaces, commonly polished and highly reflective, with shallow grooves and displaying slickenlines (Fleuty 1975). Petrographically, these slip surfaces appear as faults and cataclasite zones.

Model of PCL formation

A simple model is suggested here for the formation of plano-convex lenses (PCLs) of pseudotachylite described above (Fig. 4). Prior to the formation of the pseudotachylite, the incipient fault zone is envisaged as a network of thin cataclasite zones. These anastomose about the mean orientation of the fault, forming asperities. When rapid slip begins, the fault adopts the energetically favorable planar shape, and the most favorable location, namely the mean orientation of heavily fractured zone, which has the greatest density of cataclasite and has experienced the most strain softening. The asperities will become sheared off and intensely fractured as the first pseudotachylite is generated (Fig. 4a). The melt will quickly intrude the intensely fractured former asperity as a result of the increase in volume of the melt relative to the pre-existing rock. The cataclasite matrix within the former asperity, being extremely fine-grained and reactive, may melt (Fig. 4b). The net effect will be a volume increase within the former asperity, which may help to wedge some of the xenoliths toward the opposite wall of the fault and toward the trailing edge of the former asperity into the progressively narrower zone below the two walls of the fault. This results in fracturing and mechanical reduction facilitating further melting (Fig. 4c). Ultimately, most of the material previously occupying the former asperity is either melted or is mechanically reduced in size and fed out into the vein (Fig. 4d).

PETROGRAPHY

In thin section, the pseudotachylite varies from colorless to dark brown to yellow brown. Its opacity and optical behavior range from opaque to colorless and isotropic.

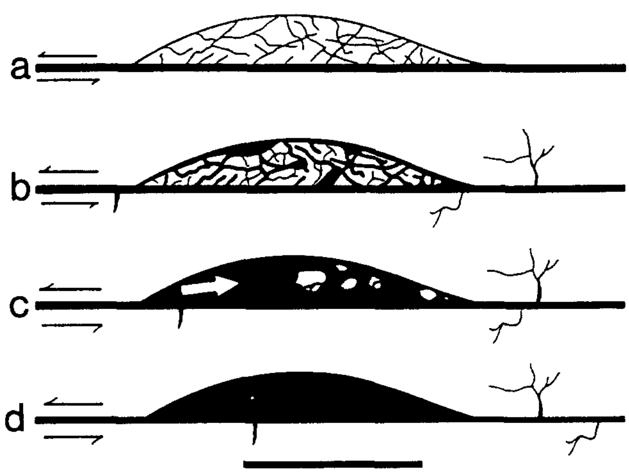

Fig. 4. Schematic model describing the formation of the plano-convex lenses (PCLs) of pseudotachylite. (a) A cataclasite zone is isolated during initial slip on the main fault; (b) melt intrudes the fractured asperity; (c) assimilation of porphyroclasts, frictional melting, and mechanical size reduction occur; (d) final appearance. The scale bar is approximately 10 cm.

Virtually all of the pseudotachylite is apparently holocrystalline, while only two samples are glass. This is based upon petrographic observations and electron imagery. With the microprobe under a small beam width (10 μm) and even with low sample currents (10 nA), the glassy samples degrade and a hole quickly develops, a behavior typical of glass. Other samples of similar composition survive 50 nA sample currents for many minutes with no damage. However, no TEM analysis has been done to attempt to verify the glassy nature of these samples. The glassy samples are from the DFR and WPC sites; the latter contains the only vesicles that have been found (Fig. 6a). Vesicular pseudotachylite is rare; for a compilation of other sources see Maddock *et al.* (1987). This site is also the most southerly site, which is significant as peak metamorphic pressures decrease greatly and cooling occurred progressively earlier from north to south across the terrane (Magloughlin 1986b). Assuming the pseudotachylites formed within a period of perhaps 10 million years, the rocks farthest south should have been relatively the shallowest. It is reasonable, therefore, that vesicles be present, if anywhere, in the southernmost occurrence.

Microphenocrysts are present in some samples, and a variety of dendritic and spherulitic textures involving gedrite, plagioclase and biotite exist. The microphenocrysts are set in a still finer-grained apparently cryptocrystalline matrix which is not optically resolvable at 1000 ×. Besides microporphyritic textures, microglomeroporphyritic textures (Williams *et al.* 1982) and a type of pilotaxitic texture analogous to porphyritic-spinifex texture in ultrabasic rocks (Bard 1986, p. 69) are present in some samples. Biotite and/or plagioclase microphenocrysts have been noted by Sibson (1975), Passchier (1982), Maddock (1986) and Swanson (1988).

Excellent examples of flow banding marked by a relatively darker material (very dark brown to black) is present in many samples as straight, contorted, or concentric ribbons, isolated blobs, and a coating on virtually all cataclasite fragments (Figs. 6b & c). Microprobe analysis of this material so far indicates its composition is very similar to the host pseudotachylite. This material, believed to be cataclasite matrix, is discussed further below.

Inclusions

The most abundant inclusions in the pseudotachylite are of quartz; they vary from angular to rounded, and are either monocrystalline or polycrystalline. Quartz is invariably strained, displaying deformation bands, undulose extinction, etc. Rutile and zircon are common and typically less than 10 μm in diameter. Kyanite and garnet have been noted in a few samples. Plagioclase xenocrysts are uncommon, and biotite and muscovite xenocrysts very uncommon.

Cataclasite inclusions are nearly as common as quartz. They are typically enveloped by a thin layer of opaque material. Iron sulfide is common within this material (Fig. 6d). Opaque inclusions, thought to be cryptocrystalline cataclasite matrix, are generally abundant as small globular to irregular knots and concentrations, generally less than 0.01 mm across. They are commonly concentrated around quartz. Relatively undeformed fragments of the host rock are not uncommon, especially tonalite gneiss fragments at the WR site.

In veins of types I, II and V the inclusions are very small relative to the vein size, normally less than 0.5–1.0 mm. In vein types I, IV and V, the inclusions commonly show at least a slight concentration toward the center of the vein.

Vein microstructure

The larger (1 to several cm thick) veins typically show darker, in some cases opaque, margins. The margins of the main veins are sharply defined and the pseudotachylite here is inclusion-poor to inclusion-free relative to the central portions of the vein. In this respect they differ from cataclasite margins described below. This may be a quench feature.

In some samples, dilational veins cut both host and pseudotachylite and contain chlorite ± hematite (Fig. 5d). Where present, the hematite forms a central stripe within the vein.

Veins of two different generations in cross-cutting relations are unusual, but have been noted in pelitic schist and amphibolite. They are commonly of a different color, and at the contact the truncating vein has the usual dark margin (Fig. 5c). Pseudotachylite xenoliths of a previous generation have been noted in some veins.

What are interpreted as pressure-solution seams are present in a number of samples as thin, black, sinuous bands (Fig. 5c). These cut both the host and the pseudotachylite. Their dominant orientation is parallel to the foliation and margins of the veins. They are not densely spaced and are typically fairly short (a few mm) in the pseudotachylite, end abruptly, and may be perturbed by and anastomose around inclusions, especially quartz. Pressure-solution seams are commonly concentrated near vein margins and good examples also occur between xenoliths or between a xenolith and a vein margin.

In addition to forming ubiquitous xenoliths, cataclasite is present in many samples in sub-millimeter, subconcordant to concordant zones (pre- or post-dating the pseudotachylite) or along the margins of the pseudotachylite vein (pre-dating the pseudotachylite). It is much darker than the pseudotachylite, commonly black, and far richer in angular, strained quartz fragments and strained, mechanically anisotropic minerals (biotite, muscovite). Cataclasite zones are commonly found cutting pseudotachylite veins in type VI occurrences, and pseudotachylite clasts have been noted within the cataclasite.

Obvious mixing occurs in some veins between pseudotachylite and the adjoining cataclasite (Fig. 6b). For example, cataclasite forms a 0.5 mm thick margin on either side of a 1 cm thick glassy vein (Fig. 6c) and the cataclasite is clearly drawn out into the vein in the

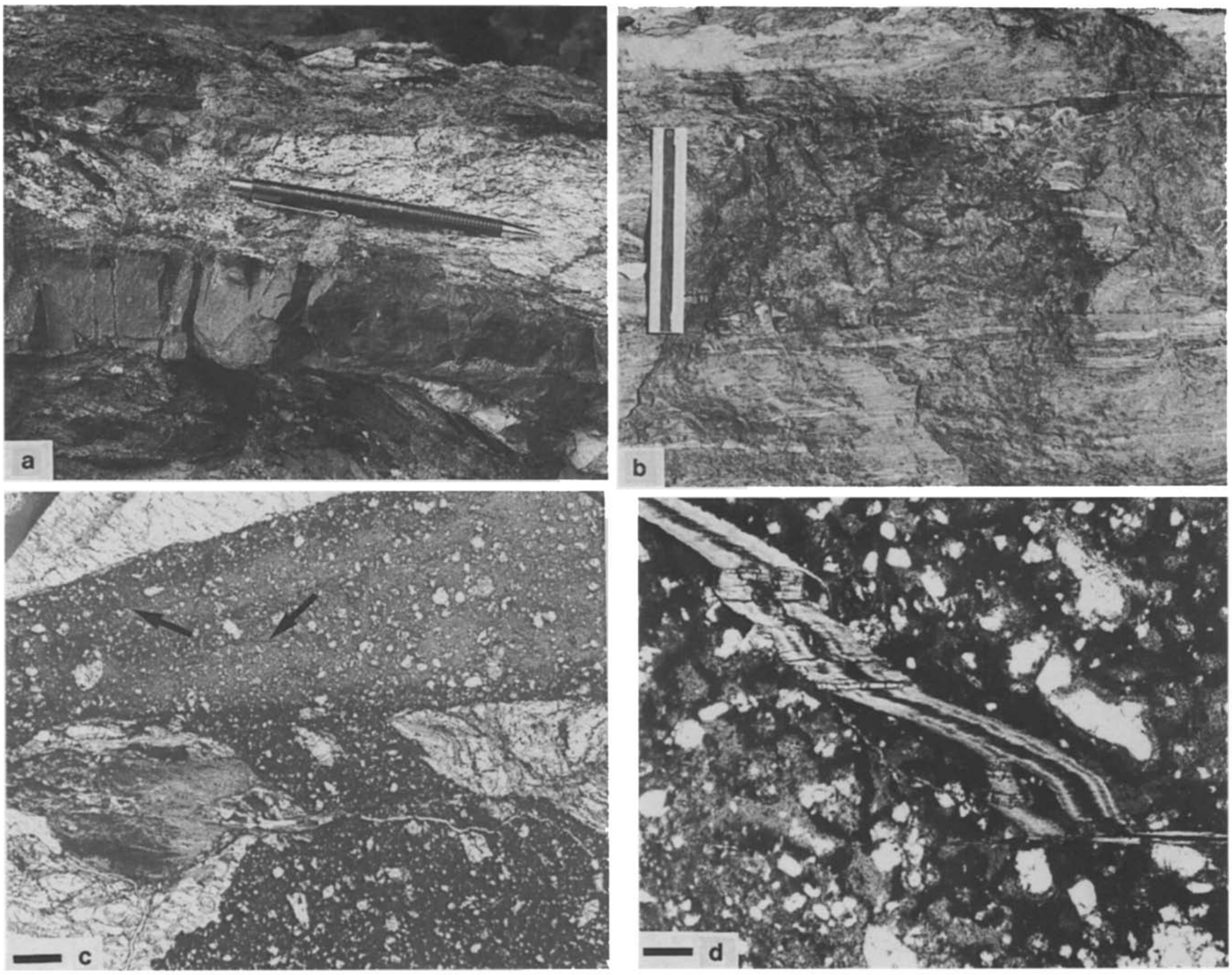

Fig. 5. (a) & (b) Outcrop photographs of pseudotachylite veins and zones; view approximately 45° down-dip toward the northeast. (a) Thick type IV vein at a contact between pelitic schist and tonalite gneiss (WR site). Asymmetry of the foliation indicates that the vein occurred along a zone of sinistral slip. (b) Type III zone, DFR site. The scale is 15 cm long. (c) & (d) Photomicrographs of pseudotachylite veins. (c) Pseudotachylite (bottom) truncated by a later pseudotachylite vein (right to left, at top), in plane-polarized light. Slightly darker margins are visible in top vein. Arrows point to pressure solution seams. The scale bar is 1 mm. (d) Chlorite fiber-filled crack–seal vein, in cross-polarized light. The central dark band within the vein is hematite. The scale bar is 0.2 mm.

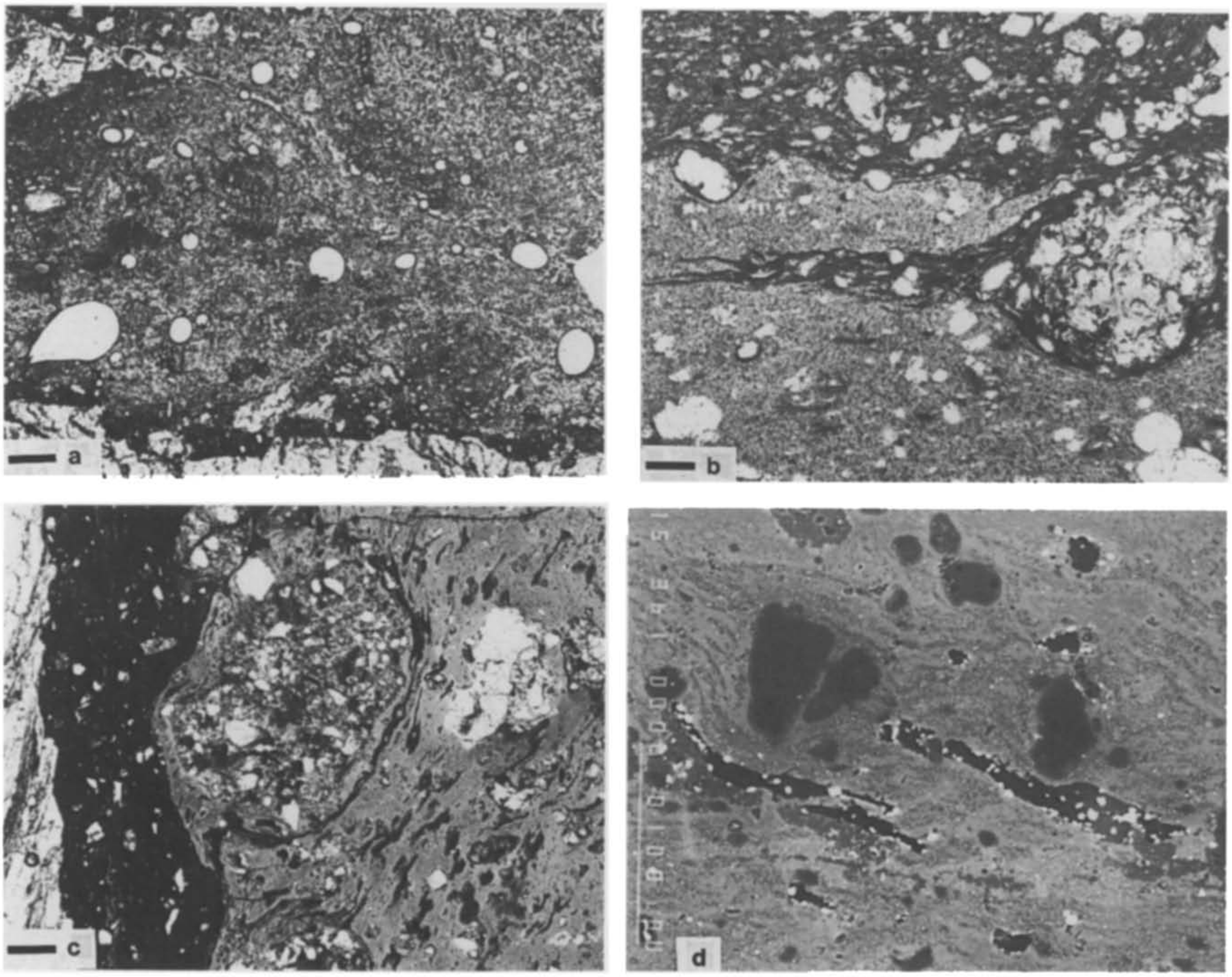

Fig. 6. (a)–(c) Plane-polarized light photomicrographs of pseudotachylite; the scale bars are 0.2 mm. (d) Back-scattered electron image of pseudotachylite; the scale bar is 100 μm. (a) Vesicular pseudotachylite, WPC locality. (b) Cataclasite porphyroclast and flow banding in microlitic pseudotachylite, DFR locality. (c) Margin of a glassy pseudotachylite vein, DFR locality. On the left is the host schist; the dark band is a cataclasite margin; on the right is glass with xenocrysts, xenoliths, and tendrils of dark cataclasite drawn out from the cataclasite margin. (d) Quartz xenocrysts (dark grey) and Fe-sulfide studded cataclasite bands (black) in pseudotachylite showing faint flow banding.

inferred direction of flow, in a pattern symmetrical about the center of the vein.

Host

The pseudotachylite host rock is commonly extremely deformed and retrogressively metamorphosed. Microfaulting and microfracturing are common. Narrow (0.1 mm) cataclasite zones are common, especially in quartz rich hosts. Quartz and plagioclase display chaotic undulose extinction. Biotite and kyanite show accordion-like kink bands. Garnet is intensely fractured and locally partly replaced by oxides, chlorite and white mica. Fine-grained white mica partially replaces garnet, plagioclase, kyanite, and staurolite. It is important to note, however, that such textures typically associated with the pseudotachylite and pseudotachylite-bearing fault zones, are very *non-penetrative* across the terrane. Indeed, some samples containing pseudotachylite even a few meters or less from the nearest obvious zone of intense deformation show mineralogy and deformation textures typical of those developed throughout the region.

In the tonalite gneiss host at the WR site, coarse-grained muscovite is bent, highly kinked, or recrystallized. Some large plagioclase crystals (>5 mm) are almost completely altered to fine grained white mica. Muscovite and biotite are completely recrystallized; these are essentially mica pseudomorphs after mica.

CHEMISTRY

Introduction

Eight pseudotachylite samples were selected for microprobe analysis, four from the Wenatchee Ridge site and four from the Dirty Face Ridge site. The samples are from various pseudotachylite zones spaced at least several meters apart. Analysis was performed on the JEOL superprobe, using WDS (wavelength dispersive spectrometry) mode, at the University of Washington. The beam current was typically 20 nA, with a beam width of 20 μm, and synthetic glass and natural minerals were used as standards. An average of about nine randomly located points per sample were analyzed. Individual points were selected using reflected light, transmitted light, and backscattered electron imagery to ensure avoidance of inclusions, areas of poor polish, or alteration. Raster scan analysis was generally not possible due to abundant inclusions; furthermore, of interest here is the composition of the pseudotachylite alone (without inclusions), in an effort to understand what materials actually melted during pseudotachylite production.

The two sites studied vary by only one known parameter. At the DFR site, only pelitic schist is present, while at the WR location, the pelitic schist is interlayered with closely spaced tonalite sills. Field evidence strongly suggests that the pseudotachylite formed within the pelitic schist, but at Wenatchee Ridge, intrusion of pseudotachylite into the tonalite and abundant tonalite xenoliths within the pseudotachylite raise the possibility of either participation of the tonalite in the melting or assimilation of some tonalite into the melt. To investigate this possibility, the spot pseudotachylite compositions have been compared with 'end member' pelitic schist and tonalite compositions obtained from bulk chemical analysis.

Host rock

Seven samples of tonalite orthogneiss, including several from the vicinity of the Wenatchee Ridge site, have been analyzed using the ICP (inductively coupled plasma) instrument at the University of Washington (Table 1). In the Wenatchee Ridge area, the tonalites of the Wenatchee Ridge Orthogneiss (WRO) are petrologically fairly uniform, with slightly varying modal abundances of muscovite and biotite (Magloughlin 1986b). Orthoclase is very uncommon, and where present, seldom exceeds one modal percent. Plagioclase varies in composition from calcic albite to calcic oligoclase. The bulk chemical analyses show that the $CaO : Na_2O$ ratio varies considerably, reflecting the range in plagioclase compositions. Of most importance to the present discussion is the uniformly high SiO_2, the fairly consistent Al_2O_3, and the very low values of Fe_2O_3, MgO, MnO and TiO_2. This is a chemically simple gneiss, suited as an end member in the following discussion.

Bulk chemistry and selection of a schist 'end member' is complicated by ubiquitous quartz veins, which range in width from millimeters to centimeters. A number of bulk chemical analyses are available (Ort & Tabor 1985), but the silica content varies greatly reflecting the 'contaminating' quartz veins. Based upon the observation that quartz is ubiquitous in the pseudotachylite and that all other phases—save a few refractory phases (rutile, zircon) present in trace amounts—are virtually absent, it has been inferred that quartz did not participate in the melting to the same extent as other phases. Thus, selection of a quartz-poor sample which contains the typical metamorphic assemblage (quartz–plagioclase–biotite–aluminosilicate–staurolite–muscovite–Ti oxide–graphite) is justified. Toward this end a sample free of quartz veins (TC-1) was selected and the analysis is given in Table 2. Important to note are the high TiO_2, FeO, MgO and Al_2O_3 values, and the low SiO_2 value. Obviously selection of a single sample is not as satisfactory as using a suite, but it is justified by the pronounced bulk chemical uniformity of the Chiwaukum Schist (Magloughlin 1986b), at least in the northern half of the terrane.

Results

The overall average chemical compositions (with standard deviations) of pseudotachylite samples from the DFR and WR sites are given in Table 2. With the exceptions of MnO, Na_2O and K_2O, the average composition of the WR pseudotachylites is closer to the aver-

Table 1. Bulk chemical analyses of tonalite gneiss. Chemical analyses were done by ICP emission spectrometry on a Baird PS-1 polychromator instrument in the Department of Geological Sciences, University of Washington by Dr A. J. Irving. Methods used were similar to those of Thompson & Walsh (1983). Sample preparation techniques involved lithium metaborate fusion for major elements, and dissolution in hydrofluoric–perchloric acids (plus fusion of residue with NaOH) for trace elements. Synthetic matrix-matched solutions and U.S. Geological Survey rock standards were used for instrument calibration, and other rock standards were routinely analyzed as samples. Analytical precision is 1% relative for Si, Ti, Al, Fe, Mn, Mg, Ca, Na, Sr, Ba, and 3–5% relative for K

	Sample						
	253-1	290-2	347-1	364-1	102-3	105-15	105-17
SiO_2	69.78	74.97	73.68	74.81	70.50	69.54	72.84
TiO_2	0.44	0.08	0.36	0.17	0.43	0.15	0.08
Al_2O_3	15.74	15.54	13.25	15.02	15.09	18.10	16.41
Fe_2O_3	2.26	0.44	3.21	0.59	1.74	0.69	0.25
MnO	0.04	0.01	0.10	0.01	<0.01	<0.01	<0.01
MgO	0.95	0.17	0.72	0.30	0.94	0.46	0.17
CaO	4.35	1.70	3.23	2.05	4.48	1.62	1.61
BaO	0.03	0.11	0.04	0.08	0.15	0.15	0.06
SrO	0.10	0.05	0.02	0.07	0.08	0.06	0.07
Na_2O	5.68	5.40	4.34	5.35	2.50	6.03	7.07
K_2O	0.51	1.77	1.15	1.53	2.09	2.08	0.83
LOI	—	—	—	—	1.08	0.90	0.37
Total	99.88	100.25	100.10	99.98	99.08	99.78	99.76

age composition of the WRO than is the average of the DFR samples. For each oxide, the standard deviation is larger for the WR analyses than for the DFR analyses, indicating greater dispersion of the data. There is a close compositional similarity between the schist and the DFR samples. The WR samples are also similar in composition to the schist, but the discrepancies in the CaO and K_2O values are larger.

In Figs. 7(a)–(e), plots are shown of selected oxides vs SiO_2. The scales for each pair of plots (WR and DFR) are identical. There is roughly a five times greater concentration of TiO_2, MnO, MgO and FeO in the schist than in the average orthogneiss. If there is an effect due to the proximity of the meta-tonalite sills, it should be most obvious with these oxides.

For the DFR samples, the data cluster symmetrically around the pelitic schist value. For the WR samples, the data again cluster near the pelitic schist value, but trail off toward the tonalite value. In the case of TiO_2, the data may hint at a hyperbolic pattern such as would be produced by mixing (Faure 1986, p. 149).

Figures 8(a) & (b) are AFM diagrams on which are shown spot analyses of pseudotachylite samples from the two sites. Also shown is the average biotite analysis from the Chiwaukum Schist, as well as the schist analysis and the average of the tonalite gneiss analyses from Table 2.

In the case of the WR data, there is a well defined linear trend between the schist and the tonalite. The analyses from each sample plot along the length of the trend; no single sample is responsible for the observed pattern.

Table 2. ICP analyses of pelitic schist (sample TC-1) and Wenatchee Ridge Orthogneiss (Table 1), and microprobe analyses of pseudotachylite from the Dirty Face Ridge and Wenatchee Ridge sites. $\bar{x}$ = mean, S.D. = sample standard deviation. Pseudotachylite data include 27 spot analyses on four samples from DFR, and 44 spot analyses on four samples from WR

	Hosts		Pseudotachylite	
Oxide	Schist TC-1	Gneiss ($\bar{x}$ ± S.D.)	DFR ($\bar{x}$ ± S.D.)	WR ($\bar{x}$ ± S.D.)
SiO_2	54.07	72.30 ± 2.34	57.15 ± 2.51	57.89 ± 5.24
TiO_2	0.83	0.24 ± 0.16	0.93 ± 0.30	0.72 ± 0.44
Al_2O_3	20.41	15.59 ± 1.47	20.19 ± 1.40	19.18 ± 1.94
FeO	7.07	1.18 ± 1.00	6.17 ± 1.02	5.89 ± 2.08
MnO	0.10	0.02 ± 0.03	0.11 ± 0.02	0.11 ± 0.04
MgO	3.30	0.53 ± 0.34	2.98 ± 0.76	2.66 ± 1.00
CaO	4.66	2.72 ± 1.29	3.55 ± 0.81	1.53 ± 0.97
Na_2O	4.08	5.20 ± 1.44	4.77 ± 1.30	3.98 ± 2.65
K_2O	2.61	1.42 ± 0.61	2.39 ± 0.96	4.68 ± 3.56
Total	97.13	99.83 ± 0.37	98.23 ± 0.94	96.64 ± 1.77

Discussion of melting mechanisms

The similarity between the compositions of the pseudotachylite and the schist is good evidence for near-total melting of the modally major minerals in the pelitic (i.e. non-quartz vein) component of the schist. The slightly elevated silica values of the pseudotachylite relative to the schist (TC-1) must result either from the schist being more siliceous at the two pseudotachylite sites, or from a minor incorporation of vein quartz, or both.

The CaO and K_2O values are about 2% lower and 2% higher, respectively, in pseudotachylite from the WR site than in TC-1. It appears that most of this effect is due to a single sample of pseudotachylite which was especially K_2O-rich and CaO-poor. This pseudotachylite may have had a particularly pure (i.e. plagioclase-poor) schist parent; all other oxide values are similar to the other pseudotachylites. Na_2O is slightly higher and CaO slightly lower in the pseudotachylite from DFR relative to TC-1. If this difference is significant, it may stem from the fact that the rocks in the DFR area experienced the

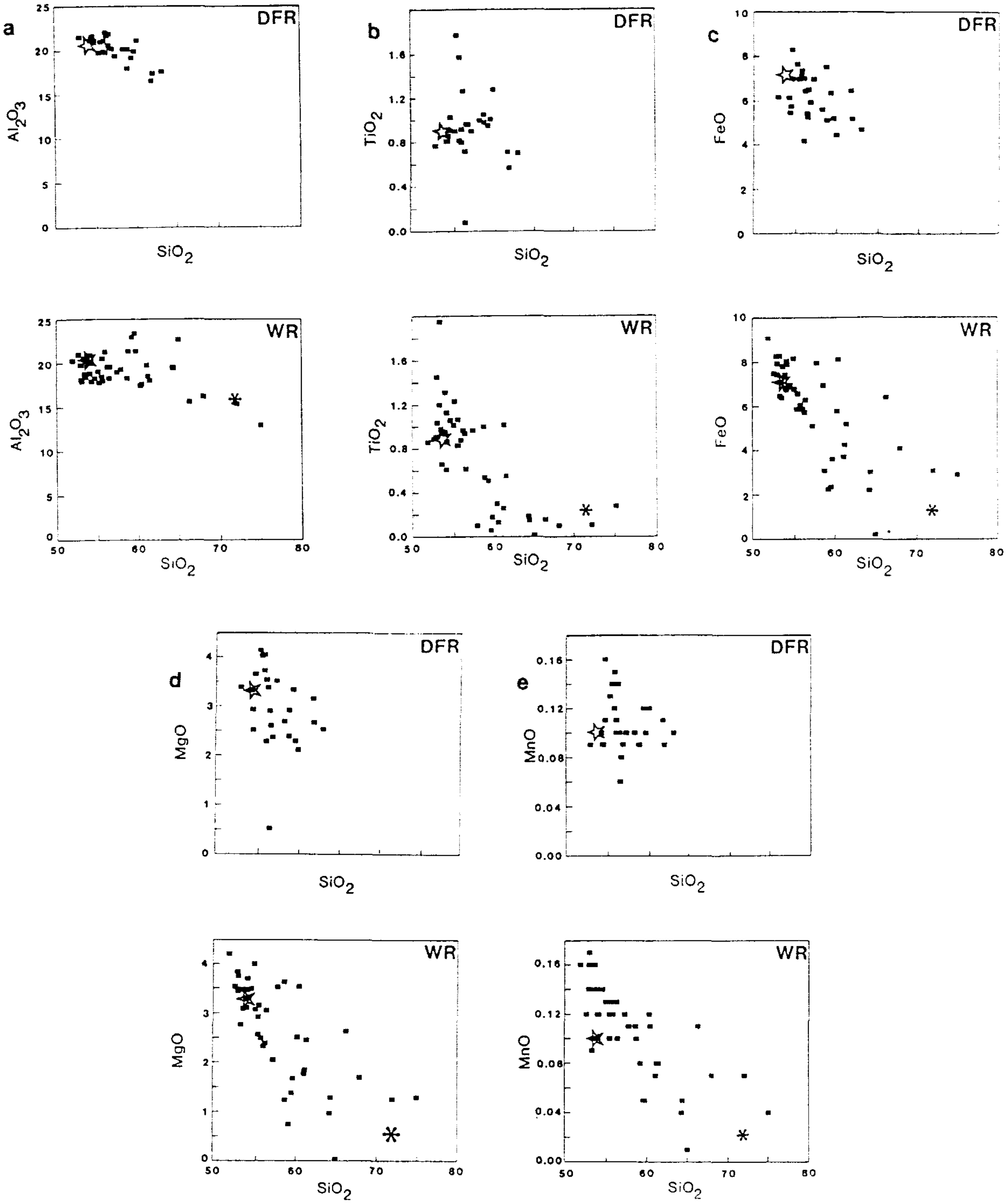

Fig. 7. Plots of selected oxides vs silica; in all cases data for the DFR pseudotachylites are at the top and data for the WR pseudotachylite are at the bottom. Asterisk = average tonalite value; star = schist value.

highest metamorphic pressures in the terrane; TC-1 is from a few km to the south where the rocks record lower metamorphic pressures (Magloughlin 1986b). In the DFR area, more CaO would thus be partitioned into garnet preferentially over plagioclase due to the elevated pressure (the GASP reaction and barometer, Ghent 1976). If garnet were a common xenocryst phase in the pseudotachylite, less CaO would be available to enter the melt. If this is indeed the cause of the observed variations, given constant parental composition, the CaO content in the pseudotachylite should increase from north to south across the terrane.

The only known difference between the DFR and WR sites is the presence of the tonalite sills at the WR site. The sites are only a few miles apart, and there is no evidence to suggest they were at very different temperatures or pressures at the time the pseudotachylite formed. Yet very different patterns are present in Fig. 7. For the DFR site, the scatter of the data about the TC-1 value, at least in the case of FeO, MgO and MnO, is symmetrical and thus may simply reflect variable parental bulk composition, not the operation of any particular melting or assimilation mechanism.

One possible model explaining the trends present in

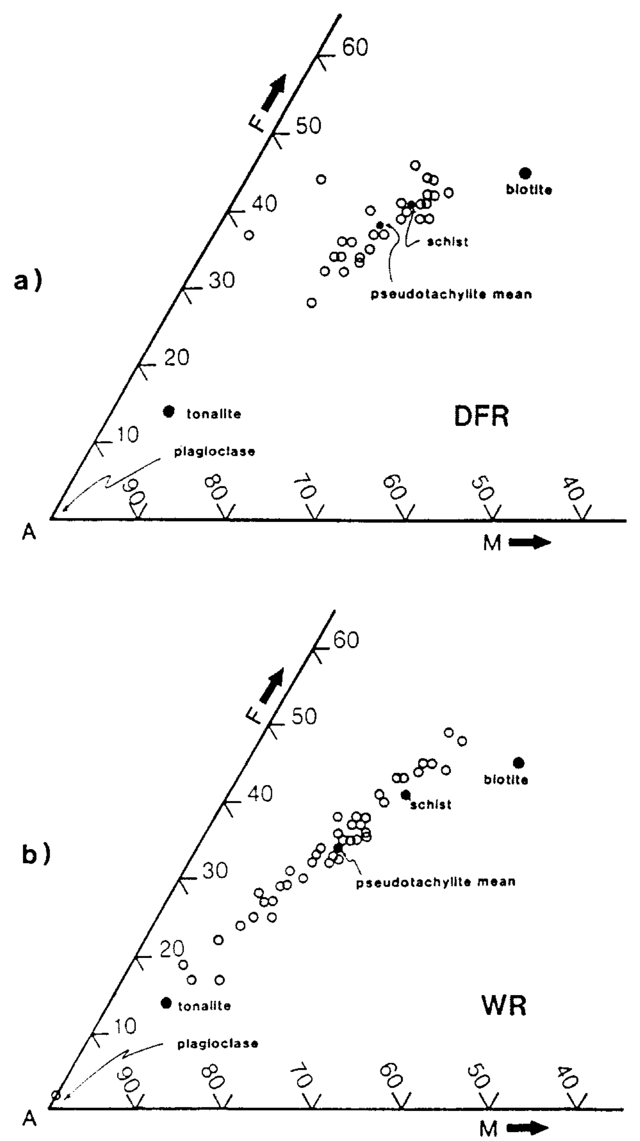

Fig. 8. Igneous AFM diagrams for spot analyses on pseudotachylite samples from the DFR (a) and WR (b) localities. Plagioclase plots at the A apex. The biotite analysis is the average of 99 spot analyses on 22 samples from throughout the terrane. The average tonalite and the schist values are from Table 2. In the WR plot, the pseudotachylite and schist means are coincident with individual spot analyses.

the WR data of Fig. 7 involves partial melting. With partial melting, decreased ferro-magnesian oxide concentrations and elevated silica values would be expected. However, there are no known restites or obvious products of partial melting. The only effect along these lines may be differential absorption of minerals based upon their mechanical anisotropies. Highly anisotropic minerals (biotite, plagioclase, muscovite, chlorite) are virtually absent as xenocrysts; moderately anisotropic minerals (e.g. kyanite) are very rare; relatively isotropic minerals (zircon, rutile, garnet, quartz) are present in proportions similar to their occurrence in the pelitic schist. Of these, quartz and garnet are the only phases sufficiently abundant to produce a compositional effect on the pseudotachylite. Furthermore, given the time available for melting, anything close to equilibrium partial melting would not be expected.

A second model which could explain the observed trend at the WR site is fractional crystallization. If the melt cooled slowly while fractionating, a trend toward more siliceous, less ferromagnesian compositions could have resulted. This seems very unlikely as the time available for such action must have been short: the country rocks must have been at least several hundred and perhaps 500°C cooler than the melt. Significant widespread shear heating probably did not occur, as no major fault or shear zone was created and maintained. Furthermore, metamorphic thermobarometry on samples within the largest pseudotachylite-bearing fault zones and even on samples cut by pseudotachylite veins faithfully record peak metamorphic conditions of *ca* 600°C and 8 kb (Magloughlin 1986b). Finally, no significant systematic chemical zoning or spatial microlitic variations have yet been noted which might correlate with a differentiating melt.

A major argument against either of the preceding models is the chemical dissimilarity of the two sites. If a fundamental process were operative during melting and crystallization, it would be expected at each site and the trends should be similar.

The third model involves participation of the tonalite gneiss in the melting. In no case does the pseudotachylite form exclusively within the tonalite gneiss, but the constant proximity of the tonalite gneiss to the pseudotachylite generation zones at the WR site and the common tonalite xenoliths might predict that there would be some contribution from the tonalites to the pseudotachylite chemistry.

The AFM diagrams are here especially revealing. The well-defined linear pattern approximately between the points representing TC-1 and the mean tonalite for the WR site is a good argument for participation of the tonalite in the melting, especially when this pattern is compared with that for the DFR site.

It is interesting to note that the trend of the spot analyses in Fig. 8 passes 'above' biotite (i.e. on the 'F' side). Staurolite and garnet are the only other major Fe and Mg-bearing phases in the Chiwaukum Schist, and they have nearly identical Fe/Mg values. On the AFM diagram, they would plot just above the intersection of the pseudotachylite trend with the F–M join. It thus appears that garnet and staurolite must have participated significantly in the melting, and that these two minerals along with biotite control the F/M value of the pseudotachylite.

DISCUSSION

The link between cataclasite and pseudotachylite is demonstrated by: (a) ubiquitous cataclasite xenoliths in the pseudotachylite; (b) the common occurrence of pseudotachylite veins flanked by cataclasite margins; (c) textures illustrating arrested incorporation of cataclasite into the pseudotachylite; and (d) textures indicating oscillation between cataclasis and pseudotachylite generation. The pseudotachylite-bearing zones are dominantly parallel to sub-parallel to the foliation. Brittle failure along foliation planes is predicted for a large range of stress orientations (Borg & Handin 1966). The foliation apparently acted to localize the cataclasite zones, on which the pseudotachylite-forming faults nucleated. At the Wenatchee Ridge (WR) site, the development of cataclasite zones and subsequent pseudotachylite was further confined to narrow zones in the pelitic schist by the adjacent more competent tonalite gneiss.

The genetic link between cataclasis and pseudotachylite-generating slip is appealing. The development of cataclasite zones would produce significant strain softening. The ultra-fine-grained matrix to the cataclasite would be highly reactive under elevated temperatures. This material would also be water-rich via infiltration and disruption of crystal structures, especially of biotite. The influence of water is also shown by the abundant evidence for hydration reactions in the host rocks. So not only are the cataclasite zones preferred locations for rapid slip, but the ultra-fine-grained, water-rich material present would be a type of material very susceptible to melting. Finally, limited data suggest that the matrix of cataclasite adjacent to pseudotachylite veins, and the matrix of cataclasite xenoliths within the pseudotachylite, show a close chemical similarity to the pseudotachylite itself.

It has been suggested that the mechanical properties of minerals may control melting (Chyi *et al.* 1985, Spray 1988). This would dominantly influence the composition of the pseudotachylite. It is here suggested that the mechanical properties of the individual minerals first control the composition of the cataclasite matrix, via their varying susceptibility to cataclasis. The composition of this matrix in turn controls at least the initial composition of the pseudotachylite. This process may be analogous to experimentally generated friction melts, in which fine-grained materials form prior to the melt phase (Spray 1987).

CONCLUSIONS

In the Nason terrane, cataclasite zones apparently provided the strain-softened locations along which pseudotachylite zones developed, based upon clear textural and microstructural relations. The mechanical properties of the minerals controlled the composition of the cataclasite matrix, which in turn at least initially controlled the composition of the pseudotachylite. The cataclasite zones not only provided weakened zones for pseudotachylite-generating slip, but a water-rich and highly reactive material, the cataclasite matrix, which facilitated melting.

Comparison of the composition of the pseudotachylite with the composition of the pelitic schist indicates that the pseudotachylite formed from near-total melting of the pelitic (non-quartz vein) component of the schist. In the Wenatchee Ridge location, tonalite gneiss apparently either participated in the initial melting or was subsequently assimilated into the melt based upon apparent mixing relations.

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