An evaluation of Rb-Sr dating of pseudotachylyte: Structural-chemical models and the role of fluids

JERRY F. MAGLOUGHLIN*

Department of Earth Resources, Colorado State University, Fort Collins, CO 80523, U.S.A.

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Rb-Sr geochronometry has been used in several studies in an effort to date pseudotachylyte and therefore the fault hosting the pseudotachylyte and the tectonism that produced the faulting. The usual procedure has been the “thin-slab” technique, which in metamorphic rocks involves construction of an isochron using whole rock analyses of adjacent but compositionally different slices of rock, and is based on the assumption of isotopic equilibrium between the slices. In attempts to date pseudotachylyte, analyses have been obtained using a pseudotachylyte vein and the immediately adjacent host rock. Such studies commonly yield: 1) apparent ages with high errors owing to small a small range of Rb/Sr values or to “scatterchron” data; 2) host rocks not plotting on the same isochron or scatterchron defined by the pseudotachylyte; 3) apparent dates that are inconsistent with other estimates of the time of faulting; or 4) apparent ages that are not independently constrained. These studies commonly fail to record the type of pseudotachylyte vein utilized; injection veins are commonly larger and more obvious targets for collecting but are likely to yield geologically meaningless dates.

A Rb-Sr geochronometric study of pseudotachylyte from the North Cascade Mountains, Washington, reveals: 1) an apparent age older than the likely age of the pseudotachylyte; 2) pseudotachylyte and host rock chemical and isotopic characteristics indicating that the pseudotachylyte was not the result of bulk melting of normal schist; and 3) metasomatism prior to pseudotachylyte formation likely affected both the protolith and what is now the host rock.

In light of previous studies, the new data, and related information regarding fault-related metasomatism, three closed system models and one open system model for pseudotachylyte formation are proposed. These models make specific predictions regarding apparent whole rock-pseudotachylyte dates, microstructural features, and the relationship between the whole-rock pseudotachylyte date and the whole rock-biotite Rb-Sr dates in the same rock. The models suggest pseudotachylyte-host rock dating is unlikely to produce real ages of pseudotachylyte formation. Worse, because many pseudotachylytes apparently form during cooling and uplift, the technique will instead yield a seemingly reasonable but geologically meaningless date. Certain approaches to the problem, including a microstructural analysis coupled with a whole rock-biotite age on the same rock, may yield an actual age of pseudotachylyte formation, but the assumptions made heretofore about the behavior of the Rb-Sr system at the time of pseudotachylyte formation are questionable.

INTRODUCTION

Pseudotachylyte is a rock locally present within fault and shear zones, formed as a result of friction-induced melting (Magloughlin and Spray, 1992). At present, it is the only definite evidence of paleoseismicity in such rocks (e.g., Cowan, 1999), and therefore provides direct physical evidence of discrete structural events that likely occurred during protracted tectonic processes. Unlike other fault rocks that evolve during ongoing, progressive deformation, potentially over tens of millions of years or more, pseudotachylyte forms in a geologically instantaneous event. Melting on
the fault surface occurs in seconds, and quenching of the melt typically takes seconds to hours. Consequently, successful geochronologic analysis of pseudotachylyte has the potential to date not merely a tectonic episode but a single, discrete fault slip episode within an extended tectonic event, and thus is a valuable exercise.

Several workers have attempted to date pseudotachylyte using the Rb-Sr “thin-slab” technique (Maddock, 1986; Thoeni, 1988; Peterman and Day, 1989; Kamineni et al., 1990; Boeckeler, 1994; Adams and Su, 1996). This technique has been used in high grade metamorphic rocks (and also in certain fault rocks), where small-scale lithologic heterogeneities between layers having different Rb/Sr ratios offer the possibility of obtaining a “metamorphic isochron”, if Sr achieves isotopic homogeneity between layers at the time of metamorphism (e.g., Hofmann, 1979; Peucat and Martin, 1985; Thoeni and Hoinkes, 1987; Adams and Su, 1996). In most cases where the thin slab technique has been applied to pseudotachylyte, it has been concluded that geologically reasonable dates have been obtained. In some cases, fault movement and therefore regional tectonic events have been constrained solely on this evidence. However, most previous studies have not considered in detail the basis of such dating, nor the relationship of such dates to real geologic events. Furthermore, there has been little consideration of the geologic mechanisms operative within fault zones and shear zones such that the requisite conditions for obtaining a valid Rb-Sr date might be established. The purpose of this paper is to explore these questions and to consider whether Rb-Sr apparent dates on pseudotachylyte are meaningful.

For ease of discussion, I use the term “protolith” to refer to the volume of rock, including all pre-melting metasomatic modifications of whatever origin, in which extensive frictional melting occurs. From field and microscale observations and chemical considerations, it appears that the protolith can undergo moderate melting, where much material survives as clasts in the pseudotachylyte, to near total melting. A difficulty exists in that the protolith is by definition extensively destroyed during melting, and owing to probable variations in the protolith along the fault, and flow of and mixing within the melt, the resultant pseudotachylyte cannot automatically be assumed chemically equivalent to any particular protolith. The lithic clasts within the pseudotachylyte might in some cases yield a better approximation of the protolith than would the immediately adjacent rock.

In the thin slab technique, in order to obtain an isochron, Rb-Sr analyses of pseudotachylyte are commonly paired with a “whole rock” analysis, normally obtained through analysis of rock immediately adjacent to the pseudotachylyte vein. For better distinction, I will refer to this as the “host rock”. For a Rb/Sr spread to exist in order for an isochron to be defined, the host rock and pseudotachylyte must be chemically different (e.g., different mica-plagioclase ratios). The validity of the thin slab approach therefore depends upon Sr isotopic equilibrium between the host rock and pseudotachylyte at the time of melting.

**Previous Rb-Sr Dates on Pseudotachylyte**

Maddock (1986) analyzed pseudotachylyte from a concordant fault vein, along with the host rock from the Outer Hebrides Fault in Scotland. He found that the pseudotachylytes were enriched approximately 10–40% in $^{87}$Rb/$^{86}$Sr relative to the host rock, yielding a scatterchron and apparent date of $2640 \pm 210$ Ma ($2\sigma$). This apparent date is consistent with the probable age of the host rocks (Maddock, 1986), but is far older than other estimates of the time of faulting, including mid-Paleozoic (Kelley et al., 1994), and late Proterozoic (Magloughlin et al., 2001).

Thoeni (1988) applied the Rb-Sr thin slab technique to two samples of pseudotachylyte from the eastern Alps. He used 9 thin slabs across each vein to generate scatterchrons (MSWD = 5.24 and 2.26); the adjacent host rock in each case did not fall on the scatterchron. Thin slabs within the pseudotachylyte veins ranged considerably in
Evaluation of Rb-Sr dating of pseudotachylyte

$^{87}\text{Rb} / ^{86}\text{Sr}$ values (ca. 4–16 and 4–10), possibly reflecting the mm-cm scale color banding, but did fall within the range of the host rocks (Thoeni, 1988). Thoeni interpreted the results to indicate that at the time the pseudotachylyte formed, variations in Rb/Sr were preserved across the thin slabs and color bands within the pseudotachylyte, but at the same time, Sr achieved isotopic homogeneity across the same thin slabs and color bands, and thus the apparent dates of 73 ± 3 and 79 ± 5 Ma (2σ) represent the time of pseudotachylyte formation and faulting. Significantly, these apparent dates fall within the range of biotite-whole rock Rb-Sr dates (see discussion below), and also among K-Ar and $^{40}\text{Ar} / ^{39}\text{Ar}$ white mica dates from the same region. Analyses of the adjacent rock (host rock) did not plot along the isochron, and were not included in the regression. Thoeni was unable to explain the large range in $^{87}\text{Rb} / ^{86}\text{Sr}$ values yet apparent Sr isotopic homogenization at the same scale.

Peterman and Day (1989) analyzed pseudotachylyte, the immediately adjacent host rock, and “far-field” country rock from two locations near Rainy Lake, Minnesota (U.S.A.) and Ontario (Canada). In both locations, they found pseudotachylyte enriched in Rb (strongly) and in Sr relative to the immediately adjacent rock. Based on the $^{87}\text{Rb} / ^{86}\text{Sr}$ enrichment of the pseudotachylyte relative to the host, the apparent lack of thermal overprinting since about 2.5 Ga, and the assumption of (1) Sr isotopic equilibrium between the pseudotachylyte and immediately adjacent rock at the time of formation and (2) subsequent closed system behavior, Peterman and Day (1989) obtained a pooled apparent date of 1947 ± 23 Ma. They interpreted this date as indicating the time of pseudotachylyte formation, and attempted to correlate this apparent age with other tectonic events in the North American craton.

In discussing their results, Peterman and Day (1989) invoked significant mobility of Rb and Sr, and suggested that Sr achieved isotopic equilibrium between the host schist and pseudotachylyte vein immediately following pseudotachylyte formation, but the system remained closed to later re-equilibration. They used three observations to support elemental mobility: 1) the presence of concordant quartz lenses in the fault zone(s); 2) small-scale chemical variations in a pseudotachylyte vein present between a biotite schist and a quartz-plagioclase vein; and 3) higher Sr and Rb concentrations in the pseudotachylyte than in the host rock. Objections can be raised to all three points, including the timing of the quartz vein formation, and the fact that several of the elements involved (their figure 3) showed relationships opposite to those expected if diffusion had been extensive. An additional objection is that within foliated rocks, faults are likely to nucleate along structural anisotropies, such as contacts between mica-rich and feldspar-rich domains. Mica-rich domains are inherently weaker and more prone to melting. Thus, the protolith, and consequently the friction melt and pseudotachylyte, commonly will not be chemically representative of the bulk rock on a regional or even outcrop scale, and this provides a non-diffusion based explanation for point (3). Likewise, for mechanical reasons, the rock immediately adjacent to a pseudotachylyte vein is likely to be quartz and/or feldspar rich, and chemical comparison of this host rock to the pseudotachylyte is likely to show an apparent depletion of Rb and possibly Sr of the host rock, as observed in the Peterman and Day samples. A similar effect may be described by O’Hara (1992) and discussed further in Adams and Su (1996).

Kamineni et al. (1990) report a Rb-Sr host rock-pseudotachylyte apparent isochron from the Sydney Lake Fault Zone in the western Superior Province of North America. Two pseudotachylytes and host rocks were used (no specific information on the pseudotachylytes or the methodology is given), yielding an apparent age of 2183 ± 74 Ma. The pseudotachylytes yielded $^{87}\text{Rb} / ^{86}\text{Sr}$ values (4–11 times higher than those of the host rocks. Kamineni et al. (1990) used these data to support a model of widespread transcurrent faulting along subprovince boundaries in the Superior Province, postulating a tectonic link between separate orogens, and to support the timing of tectonism.
for which little direct geologic evidence exists.

Boeckeler (1994) analyzed pseudotachylytes from the Great Common Fault Zone in New Hampshire and Maine, where fault movement likely occurred between the early Devonian and Triassic. He obtained a Rb-Sr scatterchron of 298 ± 31 Ma, interpreted as reflecting tectonism postdating the Acadian orogenic event.

Adams and Su (1996) analyzed thin slabs from a pseudotachylyte (although some uncertainty exists regarding the nature of these particular fault rocks), and obtained $^{87}\text{Rb}/^{86}\text{Sr}$ values on the slabs of approximately 7–10, yielding an apparent age consistent with thin slab ages on ultramylonites. However, these samples have higher Rb and lower Sr than nearby samples of gneiss (O’Hara, 1992), a relationship that could have resulted from removal of lithic clasts from the pseudotachylyte prior to analysis. In other words, one possible origin for this apparent isochron is through mixing between quartzofeldspathic and mica-rich materials.

In summary, most previous published studies produced geologically plausible apparent ages that are generally post-tectonic with respect to the most recent major tectonometamorphic event. In general, most studies appear to assume that co-linearity of pseudotachylyte analyses on the isochron diagram is produced by Sr isotopic equilibration across domains in the pseudotachylyte having variable Rb/Sr ratios, the latter produced by unexplained mechanisms, even though linearity can be produced by mixing and other mechanisms (e.g., Field and Råheim, 1979; Wendt, 1993). Mixing as a mechanism has generally not been considered or has been discounted, despite the fact that pseudotachylytes commonly show much higher Rb/Sr values than their host rocks, values likely intermediate between the values for the whole rock and a high Rb/Sr mineral such as mica. Host rock analyses were either not obtained, or were included or not included in the isochrons depending upon whether they were co-linear with the pseudotachylyte analyses. Finally, the ages obtained through these methods commonly have been used in an attempt to establish or constrain fault movement, and even tectonism affecting major orogens.

**Rb-Sr Analysis of Pseudotachylyte from the Nason Terrane, Washington**

To provide an additional test of this method, Rb-Sr analysis was carried out on two pseudotachylyte veins and their host rocks in a setting where independent knowledge of the age of the pseudotachylyte is available. The samples are from the Nason Terrane (Washington, U.S.A.; Tabor et al., 1987), where pseudotachylytes have been described previously (Magloughlin, 1989, 1992, 1993). Pseudotachylyte occurs in a variety of host rocks and is widely distributed, forming fault veins and injection veins from less than 0.5 mm to 25 cm thick, and extending from as little as a few mm to over one hundred meters along strike. The most common host rocks are graphitic garnet biotite schist, including the two samples described below. $^{40}\text{Ar}/^{39}\text{Ar}$ analyses indicate an age of about 55 Ma for these pseudotachylytes (Magloughlin et al., 2001).

**Analyses**

Both samples (Fig. 1) were obtained from a locality a few km northwest of Lake Wenatchee,
in Chelan County, Washington. Sample 1 is a pseudotachylyte breccia forming a zone several cm wide, consisting of a black pseudotachylyte matrix and about 50% angular to rounded clasts of the host schist. Sample 2 is a black pseudotachylyte vein 0.5–1 cm thick, with a waxy to vitreous luster, and with inclusions smaller than ~0.5 mm. Both samples appear internally homogeneous and thus a single pseudotachylyte analysis of the vein material was obtained for each. The immediately adjacent host schist was used for the “host rock” analysis.

The same locality yielded a Rb-Sr biotite-whole rock date of $65.5 \pm 2.2$ Ma, and a zircon fission track date of $60.5 \pm 5$ Ma (Magloughlin, 1993, 1995). The biotite-whole rock date is somewhat younger than other whole rock-mica ages from the area; two three-point isochrons (Magloughlin, 1995) and two precise two-point isochrons (Magloughlin, 1993) all yield ages in the 79.5–89 Ma range. These ages are interpreted to yield the approximate time of cooling through $\sim 300^\circ$C. A hornblende separate from the pseudotachylyte locality gave a $^{40}\text{Ar}/^{39}\text{Ar}$ age of $88.1 \pm 0.8$ Ma (Magloughlin and Dunlap, unpublished data).

The Rb-Sr analyses for this study were made at the University of British Columbia; the techniques were similar to those given in Magloughlin (1995) and owing to instrumental limitations, yielded relatively low-precision $^{87}\text{Sr}/^{86}\text{Sr}$ analyses (Table 1). In sample 1, the $^{87}\text{Rb}/^{86}\text{Sr}$ of the pseudotachylyte is 43% higher than the $^{87}\text{Rb}/^{86}\text{Sr}$ of the host schist, and the apparent age has a large $2\sigma$ error, $43 \pm 86$ Ma (Fig. 2a). The pseudotachylyte from sample 2 has a $^{87}\text{Rb}/^{86}\text{Sr}$ about five times higher than the host and more than twice the value of any whole rock sample (25 analyses) of Chiwaukum Schist analyzed (Magloughlin, 1993, 1995). The pseudotachylyte-host pair defines an apparent age of $64 \pm 5$ Ma ($2\sigma$) (Fig. 2a). The pseudotachylyte contains 263 ppm Rb. Whole-rock samples of Chiwaukum Schist contain 17–96 ppm Rb (25 analyses), whereas biotite in the schist (the only modally significant Rb-bearing mineral) contains 167–310 ppm Rb (6 analyses) (Magloughlin, 1993, 1995).

**Discussion of Nason Terrane pseudotachylytes**

Little interpretation is possible from sample 1. The pseudotachylyte in sample 2 has a much
higher Rb/Sr ratio than its host schist, and thus the elevated Rb/Sr value cannot be explained by total melting of typical schist. The pseudotachylyte displays no evidence for recrystallization or alteration, and thus later infiltration of Rb-rich fluids is unlikely. The only modally significant Rb-rich mineral in the host rock is biotite. Chiwaukum Schist biotite has $^{87}$Rb/$^{86}$Sr values of 6 to 32 (Magloughlin, 1993, 1995).

Two models may explain both the enrichment of Rb in the pseudotachylyte and the similarity between the host rock-pseudotachylyte date and the host rock cooling dates. In the first, either the pseudotachylyte or its protolith became enriched in Rb as a result of pre-, syn-, or post-melting processes. Following pseudotachylyte formation, the pseudotachylyte remained open to Sr exchange with the immediately adjacent host rock, closing to further exchange at approximately 64 Ma. However, there is little evidence for alteration of the vein and therefore for an intergranular diffusion either to serve as a means of post-melting Rb enrichment, or to aid Sr diffusion. Whether or not there is a fluid phase to allow relatively fast intergranular diffusion rather than volume diffusion, at temperatures near 300°C, it is unreasonable that the pseudotachylyte and the host rock should remain open to Sr exchange on the scale of several cm, only to close to further Sr exchange at about the same time as sub-mm-scale biotite within the schist. A variation on this model is that the pseudotachylyte coincidentally formed at the time of biotite Rb-Sr closure, with Rb enrichment and Sr isotopic equilibrium established within the protolith or at the time of pseudotachylyte formation. This variation is similar to the scenario implied by Peterman and Day (1989). In the present case, however, mineralogic evidence suggests that the temperature was considerably below 300°C (Magloughlin, 1993); moreover, the pseudotachylyte is likely 10 million years younger than the Rb-Sr biotite-whole rock age (Magloughlin et al., 2001).

An alternative explanation more consistent with textural and mineralogic observations (Magloughlin, 1992) follows. During the development of cataclasite zones as a precursor to pseudotachylyte-generation, biotite is preferentially mechanically and chemically degraded and forms a disproportionately high fraction of the cataclasite and ultracataclasite matrix. During pseudotachylyte generation, it is also more susceptible to melting than, for example, the framework silicates. Biotite is almost completely absent as crystal fragments in pseudotachylyte from the Cascades and elsewhere (Magloughlin, 1992, 1993; Spray 1992) whereas plagioclase is much more commonly present. It is thus very likely that the lithologic precursor and melt are more enriched in biotite, or more depleted in the main Sr-bearing mineral plagioclase, than the bulk schist. Upon formation, the melt should therefore fall on a mixing line between the bulk schist and biotite. Owing to the typically high Rb/Sr value of biotite, even a slight enrichment in “biotite component” of the melt would allow a fairly precise apparent date to be obtained on the host rock-pseudotachylyte (matrix) pair. The nearly identical host rock-pseudotachylyte apparent date and whole rock-biotite date from the same outcrop supports this (Fig. 2b). This model and the model of selective biotite contribution to the melt are further supported by the composition of a pseudotachylyte vein analyzed by Spray (1993). Spray analyzed the matrix to a Nason Terrane pseudotachylyte (his sample number NT-5), and

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sr, ppm</th>
<th>Rb, ppm</th>
<th>$^{87}$Rb/$^{86}$Sr</th>
<th>$^{87}$Sr/$^{86}$Sr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, host</td>
<td>298</td>
<td>39.6</td>
<td>0.385 ± 0.015</td>
<td>0.70621 ± 0.00026</td>
</tr>
<tr>
<td>1, pseudotachylyte</td>
<td>272</td>
<td>51.6</td>
<td>0.549 ± 0.022</td>
<td>0.70631 ± 0.00012</td>
</tr>
<tr>
<td>2, host</td>
<td>241</td>
<td>57.0</td>
<td>0.685 ± 0.027</td>
<td>0.70749 ± 0.00018</td>
</tr>
<tr>
<td>2, pseudotachylyte</td>
<td>220</td>
<td>263</td>
<td>3.464 ± 0.139</td>
<td>0.71003 ± 0.00022</td>
</tr>
</tbody>
</table>

Table 1. Rb-Sr analyses of pseudotachylyte and host rock. Errors are 2σ.
the chemical composition, including water content, is close to that of a typical metamorphic biotite. Observations of pseudotachylyte grading into biotite-rich regions in the host rocks and lithic clasts (Magloughlin, 1993, 1998) also suggest a pseudotachylyte composition similar to biotite.

However, in a pseudotachylyte vein formed within chemically homogeneous rock, analyses of the bulk pseudotachylyte (no mechanical removal of clasts) paired with host rock will not in this scenario yield a Rb-Sr separation. A Rb-Sr separation would be obtained through any of the following processes: 1) the pseudotachylyte or its precursory cataclasite zone forms within a relatively higher Rb/Sr zone, which is likely because biotite-rich layers are mechanically weaker and favor fault nucleation and slip; 2) low Rb/Sr, plagioclase-rich clasts are filtered out during migration of the melt; 3) a clast-poor portion of the pseudotachylyte is selected for analysis; 4) clasts relatively enriched in plagioclase are removed prior to chemical analysis, producing a pseudotachylyte (melt) enriched separate, as is commonly the practice (e.g., Adams and Su, 1996).

In summary, the second model requires: 1) enrichment of the melt in Rb/Sr via precursory deformational processes or melting processes; and 2) either an initial difference in Rb/Sr between the pseudotachylyte-generating layer and the adjacent layers, or some process to remove some fraction of the plagioclase-bearing clasts in the analyzed “pseudotachylyte”. We can evaluate this latter process by considering the Rb and Sr concentrations in biotite and plagioclase, in a model rock in which all of the Rb and Sr are contained in these two minerals. From available Rb-Sr analyses (Magloughlin, 1993, 1995) on biotite, and microprobe data on SrO and CaO in plagioclase (Magloughlin, unpublished data), Rb concentrations of approximately 200 and 20, and Sr concentrations of 20 and 100 are reasonable values for biotite and plagioclase, respectively. For these values (and more extreme values are possible) removal of only 20% of the plagioclase can yield approximately 20% $^{87}$Rb/$^{86}$Sr separation between the protolith and the clast-depleted melt; pairing protolith-melt would yield a moderately precise apparent date. As the protolith is a mixture of plagioclase and biotite, the protolith-clast-depleted-melt apparent date will be identical to the plagioclase-prototolith-biotite date. With increasing removal of clasts, the composition of the pseudotachylyte migrates away from the protolith along the isochron toward biotite, allowing an increasingly precise apparent date to be obtained.

**MECHANICAL, MELT, AND FLUID EFFECTS ON THE Rb/Sr VALUE OF PSEUDOTACHYLYTE**

Several mechanical and melting processes could have a significant effect on the Rb/Sr and Sr isotopic characteristics of pseudotachylyte, and thus are important in evaluating whether Rb-Sr dates are valid. As described above, the melt tends to be enriched in Rb/Sr owing to easier mechanical and chemical destruction of the biotite during cataclasis, relative to plagioclase, and also its faster melting following melt generation. This allows mechanical separation of the lithic clasts and plagioclase crystal fragments and produces a bulk pseudotachylyte with an elevated Rb/Sr. But several other processes may influence the composition of pseudotachylytes.

**Lithologic contacts—Two different lithologies, simple mixing**

Commonly, pseudotachylyte-bearing fault zones develop along lithologic contacts within regionally metamorphosed and foliated rocks. In the North Cascade Mountains, for example, they commonly develop along schist-metatonalite and schist-quartz vein contacts (Magloughlin, 1989). Assume a simple case where Sr isotopic equilibrium is achieved between two lithologies having different Rb/Sr values, separated by a contact (the question of the scale of probable isotopic exchange is another issue). At some point, isotopic exchange ceases and the two lithologies define two points on an isochron diagram with a slope that increases over time. When friction melting occurs along the contact at some time after the cessation of iso-
topic exchange, and in a simple case where the pseudotachylyte is formed from contributions by both lithologies, then the pairing of the pseudotachylyte with either lithology, in an effort to obtain an isochron, yields an apparent age (an inherited isochron) that is older than the actual age of the pseudotachylyte.

**Fluids and contacts/fault zones**

Lithologic contacts, fault zones, and shear zones are good pathways for fluids, and extensive metasomatism could occur prior to pseudotachylyte generation, especially if the pseudotachylyte is preceded by cataclasite formation (Magloughlin, 1992). Many examples of such zones acting as fluid conduits have been described (Winchester and Max, 1984; Smalley et al., 1988; Dipple et al., 1990; Gates and Speer, 1991). Removal or addition of alkalis and Sr, potentially aided by recrystallization, neomineralization, and mineral dissolution, has the potential to change greatly the Rb/Sr of the protolith relative to the unaltered rock. Indeed, Rb (or K) gain and Sr (or Ca) loss appear to be likely at least in certain lithologies based on field and experimental studies (Orville, 1963; Winchester and Max, 1984; Smalley et al., 1988; Hamamoto et al., 1994). Sr isotopic exchange between the fluid and the protolith can also lead to initial slopes of the pseudotachylyte-host rock isochron. For example, prior to melting, if a protolith (such as a fault rock or a permeable lithologic layer) is initially in Sr isotopic equilibrium with host rock having a different Rb/Sr, fluid flow along the fault zone exchanging Sr with the protolith could change the $^{87}\text{Sr}/^{86}\text{Sr}$ of the protolith. Upon pseudotachylyte formation, the pseudotachylyte would already have a higher or lower $^{87}\text{Sr}/^{86}\text{Sr}$ than the immediately adjacent host rock, and thus an isochron pairing the two would have an initial non-zero slope thus yielding a geologically meaningless apparent date.

**Post-faulting fluids**

Fluids migrating along the fault zone after pseudotachylyte generation could also affect Rb-Sr dates, but this may be less likely than pre-generation alteration. Pseudotachylyte-bearing fault zones do not seem to be commonly reactivated by extensive later faulting. This may be the result of strain hardening owing to the solidification of the melt along the main fault and within all connected open fractures. Consequently, within and close to the generation zone (Grocott, 1981; Magloughlin and Spray, 1992), there may be relatively few connected fractures to serve as fluid pathways. In addition, alteration of the pseudotachylyte by extensive fluid flow should be associated with cross-cutting veins containing low-temperature minerals; alteration of minerals stable at high temperature to minerals appropriate to lower temperature; and growth of new low-temperature minerals in the pseudotachylyte groundmass (e.g., Thoeni, 1988; Magloughlin, 1989). Where carbonates have precipitated, for example to form amygdules (Maddock et al., 1987; Thoeni, 1988; Kropf et al., 1993), significant shifts in Rb/Sr or $^{87}\text{Sr}/^{86}\text{Sr}$ or both can be expected.

**Volume diffusion**

One notion put forth to defend the validity of Rb-Sr pseudotachylyte-host rock dates is that Sr could, through volume diffusion, equilibrate isotopically between the pseudotachylyte and host rock, presumably just after pseudotachylyte formation. However, volume diffusion is unlikely to contribute to isotopic homogeneity owing to the minimal distance over which it is likely to operate. Using literature values (Margaritz and Hofmann, 1978) of $D$ for K and Na (as proxies for Rb) and for Sr in obsidian and basalt at temperatures from 800–1300°C, and the simple equation

$$x(\text{cm}) = \sqrt[D* t(\text{sec})]$$

we find that even for unusually thick veins and the improbable situation of a melt remaining at high temperature for more than an hour or so, diffusion would only allow mobility of 20–300 µm for Sr, and up to 1 mm for Na. Thus, even within
the melt itself, diffusion is very unlikely to produce isotopic homogenization.

Models and discussion

A generalized model for the behavior of the Rb-Sr system during pseudotachylyte formation in biotite-rich rocks is shown in Fig. 3. This is for situations where: 1) the initial rock is homogeneous; 2) the Rb is concentrated in a single high Rb/Sr mineral, or several mineral species if their closure temperatures are very similar; 3) there is a low Rb/Sr, Sr-rich mineral resistant to assimilation by the melt. These criteria are likely to be commonly met owing to the presence of biotite and plagioclase in many pseudotachylyte host rocks. The first three (Figs. 3a–c) are consistent with microstructural observations and differ in the time of pseudotachylyte formation relative to biotite closure in the Rb-Sr system. These are also closed system models, consistent with the common observation that pseudotachylytes contain high temperature dendritic crystallites or low Rb/Sr, Sr-rich mineral resistant to assimilation by the melt. These criteria are likely to be commonly met owing to the presence of biotite and plagioclase in many pseudotachylyte host rocks. The first three (Figs. 3a–c) are consistent with microstructural observations and differ in the time of pseudotachylyte formation relative to biotite closure in the Rb-Sr system. These are also closed system models, consistent with the common observation that pseudotachylytes contain high temperature dendritic crystallites or

Fig. 3. Models for the formation of pseudotachylyte veins in biotite-bearing rocks for the Rb-Sr system. Three closed-system scenarios occur if the pseudotachylyte is generated at ambient temperatures exceeding the closure temperature of biotite (a), at the closure temperature of biotite (b), and below the closure temperature of biotite (c). An open system model (d) occurs after biotite closure, and can produce a date younger than the biotite-whole rock date. Left side figures show the isochron situation at the time of pseudotachylyte formation; right side figures show the isochron situation at some later time. Abbreviations: wr = whole rock, bio = biotite, pst = pseudotachylyte.
microlites that would be easily altered mineralogically and texturally as a result of open system behavior.

In (a), the pseudotachylyte forms while the temperature of the country rock exceeds the biotite closure temperature, and because the pseudotachylyte behaves as a new whole rock closed system, it begins to evolve on the isochron diagram. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of biotite simply increases along with the host rock with which it remains in isotopic equilibrium until the closure temperature is reached, at which time the whole rock-biotite isochron begins to attain a positive slope. This results in a date from the host rock-pseudotachylyte pair that exceeds that of the whole rock-biotite pair, and could result if the pseudotachylyte were relatively deep in origin, forming at temperatures above about 300–350°C. Such a situation might be demonstrated by evidence showing plastic deformation of quartz (and possibly feldspar) accompanying pseudotachylyte formation, and possibly pseudotachylytes that are subsequently plastically deformed (Passchier, 1982). However, at very elevated temperature, the possibility develops of ongoing isotopic exchange between the pseudotachylyte and host, and thus the host rock-pseudotachylyte age would underestimate the true age of formation.

In (b), pseudotachylyte generation occurs at the same time as biotite closure, and thus the whole rock, biotite, and pseudotachylyte are collinear. This coincidence of pseudotachylyte formation at the approximate time of biotite closure might be recorded texturally by both brittle and plastic microstructures intimately associated with the pseudotachylyte; but these textures are both strain rate and fluid dependent.

In (c), pseudotachylyte formation occurs after biotite closure, and again, the three are both initially and remain collinear. Texturally, this situation might be represented by evidence of pseudotachylyte formation accompanying cataclastic behavior of quartz, accompanied by low temperature metamorphic retrogression. In (a), the whole rock-pseudotachylyte pairing would produce the actual age of the pseudotachylyte if the “whole rock” analyzed were chemically identical, with respect to the Rb-Sr system, to that which formed the pseudotachylyte. The difficulty is that the “whole rock” is destroyed in the pseudotachylyte formation process, and a common observation is that pseudotachylyte fault veins are sharply bounded and appear to have formed from a very specific lithologic layer. In geochemically non-homogeneous rocks such as most schistose metasedimentary rocks, the rock presently adjacent to the pseudotachylyte cannot be assumed to be representative of the whole rock from which the pseudotachylyte formed; in highly homogeneous rocks, this assumption might be valid. The pseudotachylyte paired with lithic clasts contained within the pseudotachylyte would yield a valid date if the clasts are chemically representative of the $^{87}\text{Sr}/^{86}\text{Sr}$ of the whole rock that formed the pseudotachylyte.

In (b), the whole rock-pseudotachylyte pair produces a true geologic age, but in (c), the apparent date is a maximum age of the pseudotachylyte formation. Unfortunately, (b) and (c) are chemically indistinguishable, and so if the whole rock-pseudotachylyte and whole rock-biotite dates agree, only a maximum time of formation can be determined. None of these three scenarios explain cases where the whole rock-pseudotachylyte date is younger than the whole rock-biotite date. This relationship requires either local, closed system rehomogenization or interaction with a fluid. In a local equilibrium model (Fig. 3d), time has elapsed since biotite closure. As a narrow shear zone or cataclasite zone develops, the central part of the zone becomes enriched in mica as quartz and feldspar are removed and then precipitated, possibly in the adjacent, less deformed host rock. This results in a decrease in the Rb/Sr value of the adjacent rock (fault rock host, Fig. 3d), whereas the central part of the shear zone is a new mica-rich fault-rock that would likely have a lower Rb/Sr value than biotite, owing to incomplete removal of low Rb/Sr phases (e.g., apatite, epidote, or plagioclase). Aided by fluids, Sr isotopic homogenization occurs between the fault rock and the adjacent host rock, result-
ing in a slight elevation of the $^{87}\text{Sr}/^{86}\text{Sr}$ of the host. When melting occurs, the melt may have the same Rb/Sr as the fault rock, or it may have a ratio between the fault rock and the host rock if some of the latter contributes to the melt. If the pseudotachylyte forms soon after the fault rock, rather than by reactivation in a later event, the now altered “fault rock host”, pseudotachylyte, and any vestiges of the fault rock will define an true isochron yielding the age of the pseudotachylyte, an age younger than the whole rock-biotite age. Whether or not the fault rock equilibrates with Sr in the infiltrating fluid is irrelevant to the age determination, as long as the fault rock and fault rock host remain in Sr isotopic equilibrium. However, if the infiltrating fluid has a lower or higher $^{87}\text{Sr}/^{86}\text{Sr}$ than the fault rock and only equilibrates or partly equilibrates with the fault rock, then a younger or older, geologically meaningless date may result. If the $^{87}\text{Sr}/^{86}\text{Sr}$ of the fluid is much lower than the host rock and fault rock, negative apparent dates are possible.

These models allow general predictions of the relationships among Rb/Sr and Sr isotopic values in host rocks and pseudotachylytes formed in various lithologies. The most common situation appears to be mica-bearing rocks with pseudotachylyte formed in the upper part of the crust without significant fluid involvement. In this setting, Rb-Sr pseudotachylyte-host rock apparent dates should be similar to whole rock-mica dates, or at the oldest, they will reflect whole rock-scale Sr isotopic closure (likely peak metamorphism in medium to high grade rocks). In a mica-bearing rock lacking a modally significant low Rb/Sr mineral, no significant spread in Rb/Sr values between the pseudotachylyte and host rock is likely. For rocks lacking a modally important high Rb/Sr mineral, such as may be the case in granulites, ultrabasic rocks, many amphibolites, and certain monomineralic rocks such as anorthosite, no significant difference in Rb/Sr between the host rock and pseudotachylyte is likely. Fluid involvement prior to or after pseudotachylyte generation could change these anticipated relations.

**Conclusions**

For the Nason Terrane samples, the whole rock-biotite and host rock-pseudotachylyte apparent dates agree within error. Thus, either scenarios (b) or (c) could apply. A situation equivalent to scenario (d) could also play a role; there is evidence for fluids accompanying pseudotachylyte formation (Magloughlin, 1992), and the host rocks in samples 1 and 2 have the among the lowest Rb/Sr ratios (and therefore the oldest model ages and lowest slopes on a Sr evolution diagram) of 25 whole rock schist samples (Magloughlin, 1993, 1995). Overall, the apparent age from sample 2 must represent the maximum possible time of pseudotachylyte formation, and the most probable true age for the pseudotachylyte (55 Ma, Magloughlin et al., 2001) suggests scenario (c) is the most likely.

The Peterman and Day (1989) example could be a model (d) situation, because the whole rock-pseudotachylyte apparent date is drastically younger than the whole rock-biotite apparent age and Peterman and Day present evidence for fluid involvement. In addition, the host rocks had anomalously old model ages compared to many other samples from the same unit. Microstructural study of the host rocks and the Rb-Sr analysis of any unmelted fault rock host would test whether model (d) is appropriate.

Previous Rb-Sr studies of pseudotachylyte have typically assumed that Sr attains isotopic equilibrium with the host rocks as a result of the melting process or through some other mechanism immediately after melting, but this attainment of Sr isotopic equilibrium between the pseudotachylyte and host rock does not seem very likely. In contrast, this study has described several possible structural-chemical models for pseudotachylyte formation within lithologies where many pseudotachylytes are found. Scenarios where a host rock-pseudotachylyte age represents the actual time of pseudotachylyte formation do exist theoretically, either through coincidence of fault slip at the time of isotopic closure in the dominant Rb-bearing mineral, or through
the pervasive influence of fluids prior to pseudotachylyte formation. The latter scenario might be possible to demonstrate. Otherwise, the results of Rb-Sr host rock-pseudotachylyte dating ought to be considered tentative at best.

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REFERENCES


Evaluation of Rb-Sr dating of pseudotachylyte


