^{40}Ar-^{39}Ar geochronometry of pseudotachylytes by vacuum encapsulation: North Cascade Mountains, Washington, USA

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ABSTRACT

To determine a reliable means of dating pseudotachylytes, we obtained total gas ages, plateau ages and argon-retention ages on samples from the North Cascade Mountains, Washington. Quartz ampoule vacuum-encapsulation analysis of small grains (a few milligrams) from six samples allowed evaluation of ^{39}Ar loss through recoil during irradiation, and laser ablation on four samples allowed textural control. In microlitic samples, recoil-loss ^{39}Ar ranges from 0.2% to 8.4%. The ''total gas'' ages incorporating this ^{39}Ar are inconsistent, but retention ages are much more internally consistent, and within analytical error they match or nearly match plateau ages from most of the microlitic samples at 54–55 Ma. Samples analyzed by laser ablation suggest one episode of faulting and pseudotachylyte formation at 55–59 Ma, and an earlier episode at ca. 80 Ma. The partly glassy pseudotachylyte yielded laser-ablation, total gas, and retention ages of ca. 65 Ma. The microlitic pseudotachylytes indicate formation close to 55 Ma, with possible older faulting and pseudotachylyte formation at ca. 81–84 Ma. The good consistency among the retention ages, the laser ages with highest precision, and especially the plateau dates, combined with the ages falling within the anticipated time span, provides confidence in the geologic reality of the ages. Nevertheless, it is clear that large clasts and crystal fragments within these particular veins did not completely degas or may have an anomalous inherited radiogenic ^{40}Ar component.

Keywords: pseudotachylyte, ^{39}Ar/^{40}Ar, Cascade Range, faults, faulting.

INTRODUCTION

Pseudotachylyte forms in a wide variety of lithologies at typical depths of a few kilometers (Maddock et al., 1987; Karson et al., 1998) down to depths of tens of kilometers (Clarke and Norman, 1993; Austrheim and Boundy, 1994). Melting is generally considered an essential part of pseudotachylyte formation (Sibson, 1975; Maddock, 1983; Magloughlin and Spray, 1992). Spray (1995) proposed that melting is a transitional process as a result of cataclasis promoted by increasingly high strain rates. White (1996) combined observational data and calculations to demonstrate the likelihood of melting-generating plastic instabilities in the middle crust. Ray (1999) proposed several scenarios in which cataclastic material and melts could become intermixed. Whatever the exact mechanisms by which they are produced, pseudotachylytes in this study involved friction melting (Magloughlin, 1989), and preexisting cataclasite was at least partially a source for the pseudotachylyte melts (Magloughlin, 1992).

It is widely accepted that pseudotachylyte is produced during episodes of fast slip, likely associated with seismicity (Sibson, 1975; McKenzie and Brune, 1972), and possibly even in major, deep-focus earthquakes (Kanamori et al., 1998). Once formed, pseudotachylyte is similar to other silicate liquids, penetrating a short distance (centimeters to meters) into the surrounding rock, and quenching quickly as a function of melt temperature, host-rock temperature, and vein thickness.

Several studies have produced approximate age estimates on pseudotachylyte formation by using fission track geochronometry (Seward and Sibson, 1985), Rb-Sr geochronometry (Peterman and Day, 1989; Kamineni et al., 1990), and ^{40}Ar-^{39}Ar geochronometry (e.g., Reimold et al., 1990). On a sample from the Outer Hebrides, Scotland, a reliable age was obtained using over a dozen laser-ablation spot (~50 μm) analyses near the center of one vein (Kelley et al., 1994). This approach provided information on the spatial distribution of apparent ages, but it could not directly address the issues of argon loss due to thermal resetting or recoil loss of ^{39}Ar from the extremely fine grained microlites in the pseudotachylyte matrix. In a similar study of one sample from East Greenland, the youngest spot analyses were used to produce an isochron age inferred to correspond to an intrusive episode, whereas the remainder of the spot analyses yielded a scattering of older ages (Karson et al., 1998).

In this study, we have used ^{40}Ar-^{39}Ar geochronometry on pseudotachylytes from northwest-striking sinistral faults within a small region to address the following questions: (1) Are ^{40}Ar-^{39}Ar ages obtained from pseudotachylytes geologically meaningful? This is an important initial question because the fault rocks have proved difficult to date and because of the small number of ^{40}Ar-^{39}Ar studies of pseudotachylyte thus far, and the relatively good geologic constraints on the age of these pseudotachylytes. (2) Are there differences among total-gas ages, argon-retention ages (Dong et al., 1995), and plateau ages? If so, which of these provide the best means of dating pseudotachylytes? (3) Do large clasts within pseudotachylyte veins preserve older (prefaulting) ages or serve as ''sinks'' for Ar released from the material that formed the

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TABLE 1. SAMPLE LOCATIONS

Sample No.	Location	UTM coordinates
N115-5	West side of Dirty Face Ridge, NW of Lake Wenatchee	NG 5307200 659200
N115-25	West side of Dirty Face Ridge, NW of Lake Wenatchee	NG 5307200 659200
WR388-3, -R	West side of Dirty Face Ridge, NW of Lake Wenatchee	NG 5307200 659200
N235-2	Longfellow Mountain	NG 5311840 644560
N245-2	Near Rock Lake, Nason Ridge	NG 5296700 652160
N253-3	Near Lake Ethel, Chiwaukum Mountains	NG 5290550 658200

Note: Host rocks to these pseudotachylytes are mostly garnet biotite schists; samples N115-5, WR388-3, and N235-2 also contain hornblende.

melt? An answer to this question has important implications for whether pseudotachylytes can be dated routinely, depending upon the abundance, age, and K content of the omnipresent clasts.

GEOLOGIC SETTING AND SPECIMENS

The specimens studied are from the Nason terrane (Tabor et al., 1987) in the North Cascade Mountains of Washington State. The Nason terrane consists of Cretaceous plutonic rocks and amphibolite-facies metamorphic rocks, metamorphosed at ca. 90–95 Ma. Pseudotachylyte and cataclasite are in close association in widespread, typically narrow (<1 m), foliation-parallel, high-angle sinistral fault zones. The faults are generally northwest-striking, and where it can be determined, display sinistral offsets. Prior to this study, there were no direct dates on this faulting episode. Individual veins range up to 25 cm thick. The samples are from four localities (Table 1).

The samples are from sharply bounded, millimeter- to centimeter-scale veins and consist of dark pseudotachylyte with small, abundant crystal fragments (mostly quartz) and lithic clasts of cataclasite. Crystal fragments other than quartz are uncommon. The pseudotachylyte is generally similar in composition to biotite and has as much as $\sim$7 wt% K_2O (Magloughlin, 1992). The host rocks to the pseudotachylyte veins are mostly garnet-biotite and biotite-hornblende schists. Therefore, the pseudotachylytes (i.e., the matrix, excluding inclusions) are Si-depleted equivalents of the host rocks in which the K content is mostly or exclusively derived from the melting of biotite (bulk compositions given in Magloughlin, 1989). One sample contains two generations of pseudotachylyte, an earlier dark brown vein (1%–2% K_2O) and a later light brown vein (3%–6% K_2O), consistent with origination of the melts from more amphibole-rich and biotite-rich rocks, respectively.

Regionally, glassy pseudotachylytes are very uncommon but are present (Magloughlin, 1992). The pseudotachylyte is normally microlitic (Fig. 1) and consists of amphibole, biotite, and in some cases pyroxene microlites in a finer-grained matrix of plagioclase-like composition. One specimen (N115-25B) is partly glassy and partly spherulitic.

The pseudotachylytes lack any thermal overprint, indicating that they are postmetamorphic and are thus younger than 85 Ma (Magloughlin, 1993). The terrane was unroofed and sedimentary deposition began at ca. 50 Ma (Erikson and Williams, 1976); pseudotachylyte ages are thus constrained to 85–50 Ma.

METHODOLOGY

Two ^{40}Ar-^{39}Ar analytical methods were used. The first approach involves laser ablation of small areas within 4-mm-diameter, 80-μm-thick disks cut from thin sections of the veins and adjacent rock. This method is similar to that used by Kelley et al. (1994) and Karson et al. (1998). ^{39}Ar lost from the material by recoil cannot be captured, but good control on spatial and textural variations within the sample is possible. We analyzed several textural and mineralogical features within the veins, particularly the matrix, while avoiding lithic clasts. We also analyzed fine-grained parts of lithic clasts of cataclasite, which contain quartz, plagioclase, and severely strained and/or partially melted amphibole and/or biotite. Although mafic crystal fragments are very uncommon within the pseudotachylytes, we identified and analyzed two small amphibole fragments and three small biotite fragments. Four disks from three samples were analyzed using $\sim$0.1 s laser pulses to vaporize $\sim$50-μm-diameter spots per pulse. Four to seven spot analyses were obtained from each disk. Because of the thinness of the disks, several pulses were combined for some of the analyses. Analytical techniques are similar to those of Boundy et al. (1996).

A second experimental approach used was a quartz ampoule vacuum-encapsulation technique (Dong et al., 1995). This method enables an evaluation of recoil loss of reactor-produced ^{39}Ar from the sample during neutron irradiation. Normally, ^{39}Ar that escapes during irradiation is lost, and, especially in fine-grained materials, erroneous ages can result. Samples are sealed in quartz ampoules under a high vacuum and after irradiation placed in a glass manifold attached to a laser-fusion system. The recoil fraction is collected initially by breaking open the ampoule with a steel ball. For the recoil fraction, the ^{40}Ar/^{36}Ar ratio had an atmospheric value, and the ^{40}Ar blank was typically 2 to 8×10^{-10} mL at standard temperature and pressure (1 to 4×10^{-14} mol). Subsequent gas fractions typically approached a blank level of 2 to 10×10^{-12} mL (1 to 5×10^{-16} mol). After the recoil fraction is collected and analyzed, a 5 W argon-ion continuous laser was focused onto the sample within the ampoule for step-heating analysis, typically involving 20 s heating times at successively higher power.

Figure 1. Backscattered-electron image of typical pseudotachylyte from Nason terrane. Sample consists of large, slightly dendritic crystals of amphibole (am); medium gray biotite crystals (bi); small, bright, blocky Fe sulfide crystals (su); and dark matrix with a calcic plagioclase composition (ma). Some of the small bright crystals ($<$1 μm) may be clinopyroxene. Most of the K in such samples resides in biotite. Sample N246-4b.

Vacuum encapsulation combined with laser step-heating allows the construction of an age spectrum and the possibility of obtaining a plateau age. Because the recoil ^{39}Ar is also captured, it can be included with the remainder of the gas to calculate a total-gas age that is equivalent to a K-Ar age. However, it may not always be appropriate to reintegrate this gas fraction. Omitting this fraction yields an "argon-retention age," which may yield more reasonable and consistent ages owing to the natural loss of radiogenic Ar from sites near the surface of ultrafine crystals and crystal defects (Dong et al., 1995). In such materials, the total-gas age is a minimum age for the growth of the crystals or the onset of Ar retention upon cooling. In this second experimental approach, we used several milligrams of 150 to 250-μm-diameter grains of unaltered

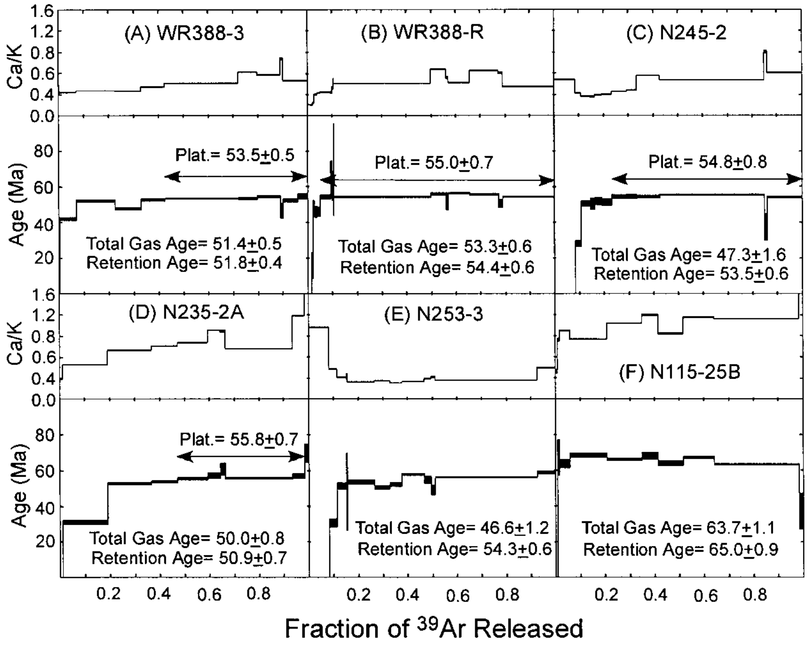

Figure 2. Age spectra for six vacuum-encapsulated samples. A–D: Plateau ages also shown; their MSWD values are 1.5, 2.4, 2.4, and 1.0, respectively. Errors boxes are 1 σ. Errors stated are 2 σ.

pseudotachylyte, typically from the centers of veins, for six samples. These were hand separated under a binocular microscope to exclude grains with visible impurities.

RESULTS

The results of the laser step-heating experiments (Fig. 2 and Table 2) were that four of the six samples had <1.5% ^{39}Ar loss, but two samples had over 8% of their total ^{39}Ar in the initial recoil gas fraction. The total-gas ages vary, but the retention ages are much more consistent, with five of six samples being between 50.9 and 54.4 Ma. Four samples yielded reasonable plateau ages composed of ~50%–95% of the gas that cluster tightly between 53.5 and 55.8 Ma. The partly glassy sample (N115-25B) yielded somewhat older ages (Table 2). The WR388 samples (one rock) had low recoil loss and showed good agreement with the plateau ages. N235-2A yielded a plateau at 55.8 ± 0.7 Ma, while N253-3 did not yield a plateau but had a retention age very similar to the plateau ages.

Four samples analyzed by laser ablation (Table 3) yielded spot ages equivalent to argon-retention ages. Small gas yields on some spots led to relatively large errors, but several spots yielded good precisions. For N245-2V, the weighted average of all laser spot ages is 54.6 ± 2.6 Ma, in excellent agreement with the retention and plateau ages. The laser-ablation analyses for N115-25B display moderate variability, but with the exception of the oldest spot, they are in agreement within error with the step-heating age, at ca. 65 Ma. The cataclastic fragments yielded older ages.

The results for the matrix of N115-5A and the dark brown (more calcic) pseudotachylyte of N115-5B are less consistent but may suggest an age of ca. 81–84 Ma, whereas the microstructurally younger light brown (more K-rich) pseudotachylyte in N115-5B yielded ages slightly older than the four plateau ages. Again, the cataclastic fragments yielded anomalously old ages (Table 3).

DISCUSSION AND CONCLUSIONS

The pseudotachylyte ages by both methods, laser ablation and vacuum encapsulation, fall within the geologically constrained age range, from which we can make several important observations. The generally low recoil loss and retention ages that are more consistent than the total-gas ages suggest that the retention ages offer a more appropriate approach for these particular rocks, and also that laser-ablation ages, if large inclusions are avoided, ought to yield realistic ages for these and possibly other pseudotachylytes having similar textures and mineralogies. This latter suggestion is supported by the good agreement between the laser and vacuum-encapsulation ages for N245-2A.

TABLE 2. VACUUM-ENCAPSULATED STEP-HEATING RESULTS

Sample	Total gas age (±2σ)	^{39}Ar recoil loss (%)	Retention age (Ma)	Plateau age (Ma)	MSWD	Gas in plateau (%)
WR388-3	51.4 ± 0.5	0.2	51.8 ± 0.4	53.5 ± 0.5	1.49	68
WR388-R	53.3 ± 0.7	1.5	54.4 ± 0.5	55.0 ± 1.1	2.40	95
N245-2	47.3 ± 1.6	8.4	53.5 ± 0.6	54.8 ± 0.8	2.40	77
N235-2A	40.0 ± 0.8	1.0	50.9 ± 0.6	55.8 ± 0.7	0.95	51
N253-3	46.6 ± 1.2	8.1	54.3 ± 0.5	n.p.		
N115-25B	63.7 ± 1.1	0.7	65.0 ± 0.8	n.p.		

Note: n.p. = no plateau.

TABLE 3. AGES DETERMINED BY LASER ABLATION ON SPOTS

Sample	Target	Age (Ma)
N245-2A	pst—patch	54.9 ± 4.6
	pst—patch	55.2 ± 3.2
	pst—patch	44.5 ± 13.1
	pst—matrix spot	56.6 ± 23.5
	pst—matrix spot	41.8 ± 28.2
N115-25B	pst—matrix spot	62.3 ± 2.5
	pst—matrix spot	70.9 ± 3.2
	pst—matrix spot	66.5 ± 2.1
	core of cataclastic lithic clast	120.0 ± 13.1
	rim of cataclastic lithic clast	78.9 ± 4.7
N115-5A	pst—matrix spot	79.5 ± 1.6
	pst—matrix spot	83.0 ± 3.8
	biotite*	61.0 ± 0.6
	amphibole*	98.0 ± 3.4
N115-5B	light brown pst—patch	57.3 ± 1.1
	light brown pst—patch	59.2 ± 1.2
	dark brown pst—patch	89.3 ± 6.2
	dark brown pst—patch	84.8 ± 4.4
	amphibole*	128.6 ± 11.6
	biotite*—in host at edge of vein	64.4 ± 1.9
	biotite*	99.6 ± 8.5

Note: Pst = pseudotachylyte. Patch refers to several individual spots vaporized and analyzed together in a single run. Matrix spot refers to a spot (single laser pulse) analysis of the pseudotachylyte itself, i.e. the cryptocrystalline material between any lithic clasts or crystal fragments. *The minerals listed refer to crystal fragments (~500–1500 μm) within the pseudotachylyte, except where noted.

Four of the six encapsulated samples yielded reasonable plateaus, and these ages agree at ca. 55 Ma. This result demonstrates that good plateau ages are possible for these complex rocks. The agreement between the laser-ablation analyses (N245-2A) and plateau ages from pseudotachylytes from three different localities indicates an important episode of faulting in the earliest Eocene. The younger pseudotachylyte in N115-5B may belong to this same episode of faulting, beginning slightly earlier, at 57–59 Ma.

The ages from N115-5A and the older pseudotachylyte in N115-5B may point to an earlier episode of faulting (ca. 81–84 Ma), while the region now exposed was deeper and at higher temperature following regional metamorphism. It is also possible that the scatter in these ages reflects some Ar loss during cooling, but more data are needed to confirm the existence of this event.

Sample N115-25B yielded a fairly uniform spectrum and laser-ablation ages that agree fairly well with the retention age, results that suggest an apparent time of formation at ca. 65 Ma. The partly glassy and spherulitic nature of this sample, however, leaves open the question of the validity of this apparent age. The age could correspond to devitrification of the sample, or it is also possible that the apparent age is too old because of incomplete resetting within the glassy regions. From Carroll and Stolper (1993), it is clear that silicate melts can accommodate significant quantities of argon. Quenching an inherited radiogenic component within glass could bias apparent ages to be too old. This possibility is consistent with experience gained from glassy impact-structure melt, which tends to be too old rather than too young (e.g., Bottomley, 1982; Bottomley and York, 1988).

Laser analysis of large cataclasite fragments and of the rare biotite and amphibole crystal fragments within the pseudotachylyte reveals reservoirs of ''older'' Ar. An abundance of such clasts, especially if they are Ar rich, would affect the ages obtained on large grains of pseudotachylyte, but this problem can be minimized by carefully selecting small pseudotachylyte grains (50–100 μm) for analysis. Moreover, the problem is minimized where the difference between the age of the host rocks and the age of the pseudotachylyte is small and where clasts are modally minor and K poor.

On the basis of these experiments, we advocate the vacuum-encapsulation method in order to evaluate the amount of ^{39}Ar lost to recoil, coupled with the laser approach to evaluate the spatial variability of ages and the role of crystal fragments and lithic clasts. In these particular samples, the retention ages are generally in good agreement with the plateau ages and indicate that the laser-ablation ages (though of lower precision) are reliable. However, these relationships may vary in other pseudotachylytes, especially those formed deeper in the crust and those with a more complex cooling history.

Regionally, these imply that this part of Washington was affected by significant and sometimes major earthquake activity, particularly between ca. 56 and 51 Ma. The numerous faults that produced the pseudotachylyte may have been related to a major dextral fault system active to the northeast from ca. 58 to 47 Ma, the Yalakom–Hozameen–Ross Lake Fault system (Umhoefer and Miller, 1996).

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