Age, origin, and significance of brittle faulting and pseudotachylyte along the Coast shear zone, Prince Rupert, British Columbia

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ABSTRACT

Northwest-striking brittle faults containing cataclasite, fault gouge, and, in one location, pseudotachylyte are common in the vicinity of the Coast shear zone near Prince Rupert, British Columbia. The pseudotachylyte locality, found in a dextral strike-slip fault zone along the Coast shear zone, contains spherulites, alkali feldspar microlites, and amygdules, suggesting that the pseudotachylyte crystallized rapidly from a melt phase within 5 km of the surface. ^{40}Ar/^{39}Ar incremental heating of the pseudotachylyte matrix yielded a weighted mean plateau of 29.8 ± 0.6 Ma and an inverse isochron of 29.8 ± 1.5 Ma with an ^{40}Ar/^{36}Ar intercept of 296.0 ± 15.2. These results show that pseudotachylyte associated with brittle faulting can be dated precisely, and imply that some dextral coast-parallel displacement occurred across the Coast shear zone in the Oligocene and that the majority of exhumation in the Coast Mountains at the latitude of Prince Rupert (~54°N) was accomplished by 30 Ma.

Keywords: British Columbia, Coast Mountains, pseudotachylite, brittle deformation, dating.

INTRODUCTION

The Coast shear zone has long been recognized as an important structural feature in the Coast Mountains of British Columbia and southeastern Alaska (e.g., Brew and Ford, 1978). Most previous work has focused on the high-temperature deformational history of the shear zone (e.g., Klepeis et al., 1998; Andronicos et al., 1999; Rusmore et al., 2001), the Coast shear zone as a terrane boundary (e.g., Crawford et al., 1987; Hollister and Andronicos, 1997; Cowen et al., 1997), or as a geophysical discontinuity in the crust and upper mantle (Morozov et al., 1998). The purpose of this study is to focus attention on the more recent brittle deformational history of the Coast shear zone.

The Coast shear zone is a 2–11-km-thick zone of well-foliated, steeply to moderately dipping, upper amphibolite facies rocks that extends for at least 1200 km along the Coast Mountains (Rusmore et al., 2001) (Fig. 1). Reflection and refraction seismic data show an ~2 km step in the Moho across the shear zone that separates significantly different seismic velocities in the deep crust and upper mantle, suggesting that the shear zone might mark the boundary between different lithospheric blocks (Morozov et al., 1998). At the surface, the Coast shear zone separates rocks with significantly different postaccretionary histories (Crawford et al., 1987, 2000; Hollister and Andronicos, 2000; Rusmore et al., 2001), and some suggest that the Coast shear zone may form the structure along which significant coast-parallel translation occurred between 90 and 50 Ma (e.g., Cowen et al., 1997).

The Cenozoic development of topography in the Coast Mountains has variously been attributed to the Miocene passage of the Anahim hotspot (Parrish, 1983), extension-driven uplift associated with the formation of the Queen Charlotte basin in the Miocene (Rohr and Currie, 1997), and recent isostatic uplift caused by Pleistocene alpine and continental glaciation (Farley et al., 2001). It is clear that a spatial, kinematic, and temporal understanding of post–50 Ma brittle deformation along the Coast shear zone is important for understanding the timing of Coast Mountains uplift and exhumation.

Evenchick et al. (1999) described early Miocene (or perhaps younger) normal faults and other brittle features immediately north of the present study area. In this paper we describe a suite of brittle faults and associated pseudotachylyte from the Coast shear zone. Microstructural evidence and ^{40}Ar/^{39}Ar incremental-

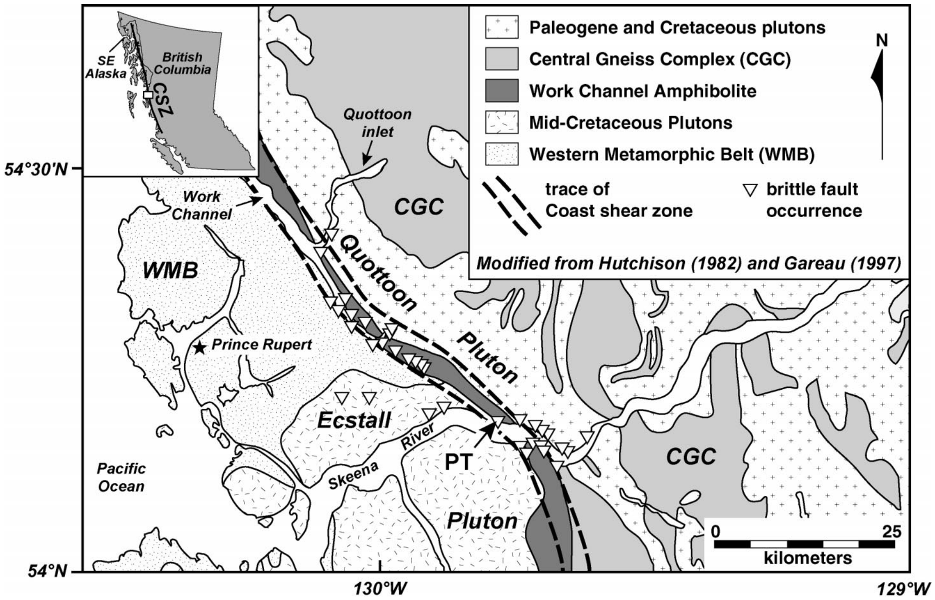

Figure 1. Simplified geologic map of Prince Rupert area showing Coast shear zone (CSZ) and distribution of brittle fault rocks. PT marks location of pseudotachylyte quarry (54°13.377′N, 129°46.430′W).

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heating data from the fine-grained matrix indicate that the pseudotachylyte was seismogenically produced in the uppermost crust (<5 km) at 30 Ma. These results place new constraints on the timing and style of brittle faulting in the Coast Mountains, indicate that some coast-parallel displacement was accommodated within the Coast shear zone, and suggest that the high-grade metamorphic rocks of the Coast Mountains were effectively exhumed by the Oligocene.

GEOLOGIC SETTING

In the Prince Rupert area, the Coast shear zone separates the high-grade migmatitic supracrustal rocks and associated Cretaceous and Eocene plutonic rocks of the Central Gneiss Complex from the rocks of the Western Metamorphic Belt (Fig. 1). The Central Gneiss Complex was metamorphosed, deformed, and intruded by quartz diorite and tonalite plutons throughout the Late Cretaceous and Eocene. The 55–60 Ma Quottoon pluton intruded the Coast shear zone during east-side-up shearing, and the Kasiks sill was emplaced near the end of exhumation of the gneiss complex at 53 Ma (Hollister and Andronicos, 2000). Exhumation of the Central Gneiss Complex was followed by rapid cooling to below the Ar-Ar biotite closure temperature (∼300 °C) by 50 Ma (Crawford et al., 1987).

In the southern part of the map area (Fig. 1), the western margin of the Coast shear zone is defined by the well-foliated margin of the Ecstall pluton. The 91 Ma Ecstall pluton intruded the high-grade rocks of the Western Metamorphic Belt at a depth of ∼30 km. These rocks were then exhumed and cooled through the Ar-Ar biotite closure temperature by ca. 70 Ma (Crawford et al., 1987; Butler et al., 2002). The Work Channel amphibolite (Fig. 1) is predominately composed of well-foliated migmatitic amphibolite cut by amphibole-bearing leucosomes (Lappin and Hollister, 1980). Locally, and within the Coast shear zone, these rocks display subsolidus mylonitic fabrics that are parallel to the strike (∼330°) of the shear zone.

BRITTLE FAULTS AND FAULT-RELATED ROCK

In the Prince Rupert area the Coast shear zone is a lineament defined by the Work Channel and a topographic low that extends across the Skeena River to the south (Fig. 1). Outcrops are rare within the lineament. However, recent improvements along the Work Channel access road and road metal quarries along Highway 16 have exposed brittle fault-related rocks, including pseudotachylyte. We measured more than 300 fault surfaces and associated slickenline orientations along and near the Coast shear zone in the Prince Rupert area (Fig. 1). Of these, we were able to determine the slip directions on 194 faults (Fig. 2). The majority (55%) of normal faults occur west of the Coast shear zone, and dextral and reverse faults dominate the central region of the shear zone (Fig. 3). We were not able to directly determine the relative timing of the different fault types in the field.

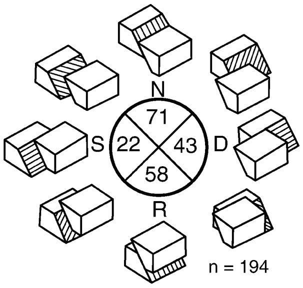

Figure 2. Quadrant diagram showing numbers of normal (N), reverse (R), dextral (D), and sinistral (S) faults measured in Prince Rupert area.

PSEUDOTACHYLYTE

The pseudotachylyte occurs in diorite in the central region of the Coast shear zone (Fig. 1). Gareau (1997) mapped the diorite as part of the 91 Ma Ecstall pluton. These rocks are cut by a 1–2-m-wide, near-vertical brecciated fault zone that strikes northwest. Slickenfiber lineations are subhorizontal and indicate dextral slip on fault surfaces (Fig. 3). A moderate penetrative foliation in the diorite is subparallel to the fault zone. Veins of pseudotachylyte are parallel and perpendicular to fault surfaces (Fig. 4A), and range from a few millimeters to 7 cm in width; larger veins contain visible clasts of host rock in the matrix. The pseudotachylyte is black to dark brown and appears cherty on fresh surfaces.

Microstructures

Pseudotachylyte veins typically contain 15%–25% subangular to rounded xenocrysts of plagioclase, quartz, and lithic clasts of cataclasite (Fig. 4B). Amygdules are present in some of the larger pseudotachylyte veins, and are filled by calcite and/or K-feldspar ± chlorite ± sphene ± prehnite (Fig. 4C). In thin section, pseudotachylyte veins consist of an ultrafine-grained opaque groundmass that contains finely disseminated magnetite, alkali feldspar microlites, and biotite (Fig. 4D).

Pseudotachylyte veins that occur along fault surfaces appear to have formed in association with cataclasis, because cataclasite fragments are observed in the pseudotachylyte, and flow bands in the pseudotachylyte follow uneven cataclasite margins and appear to sweep cataclasite fragments into the matrix (Fig. 4B). In addition, pseudotachylyte veins are cut by microfaults and clasts of pseudotachylyte occur within the cataclasite.

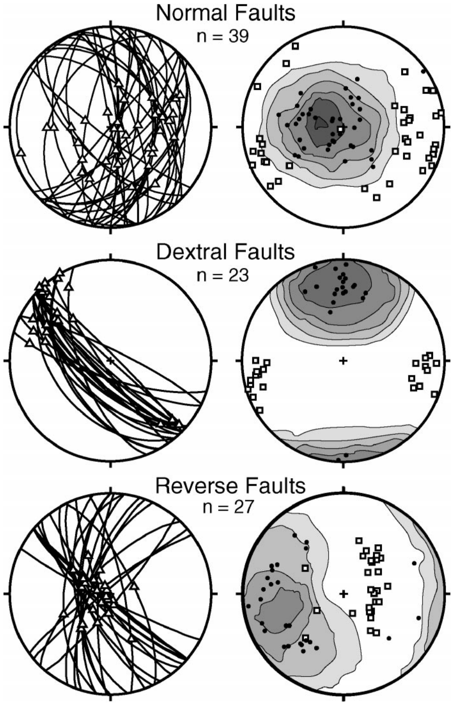

Figure 3. Stereograms of fault orientations (great circles) and shortening (P) and extension (T) axes from Coast shear zone (CSZ). Kamb contours (2σ) for P-axis orientations (filled circles) are shown. T axes are squares and slickenfiber lineations are triangles. Normal faults are from locations in Ecstall pluton (see Fig. 1), and dextral and reverse faults are from central region of CSZ (dashed lines in Fig. 1).

Melt Origin of the Pseudotachylyte

The sharp boundaries of the pseudotachylyte veins suggest that they were intruded as melts along and across brittle fault surfaces (Fig. 4). A melt origin for these veins is supported by the presence of spherulites and microlites that typically form during rapid cooling of a melt phase (Magloughlin and Spray, 1992). In addition, the rounded xenocrysts of plagioclase and quartz suggest that these grains were thermally eroded by a melt phase, and the amygdules (originally vesicles) show that a dissolved vapor phase exsolved from the melt during cooling. The absence of biotite and hornblende xenocrysts in the pseudotachylyte matrix suggests that these minerals were preferentially assimilated into the melt. Although these minerals have a higher melting point than quartz or feldspar, their lower fracture toughness makes them more susceptible to cataclasis and preferential melting (Maddock, 1992; Spray, 1992).

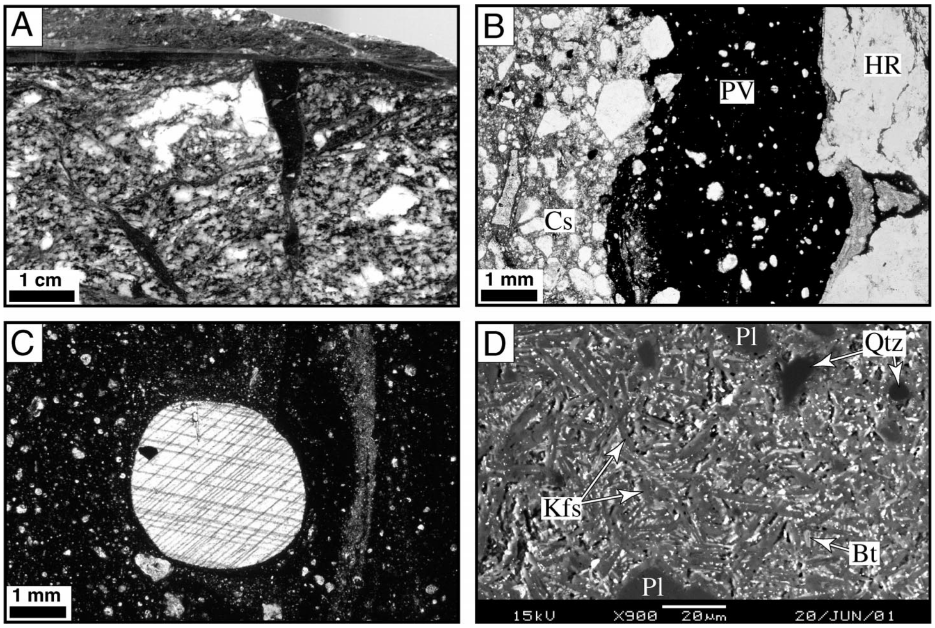

Figure 4. Pseudotachylyte microstructures. A: Slab with pseudotachylyte veins (black) cutting diorite host rock. B: Photomicrograph (plane polarized light, PPL) of cataclasite (Cs), pseudotachylyte vein (PV), and diorite host rock (HR). C: Photomicrograph (PPL) of calcite-filled amygdule in pseudotachylyte. D: Backscattered electron image of alkali feldspar (Kfs) microlites, rounded lithic clasts of plagioclase (Pl) and quartz (Qtz), and finely disseminated biotite (Bt) and magnetite (bright white points and clusters).

^{40}Ar/^{39}Ar DATING OF PSEUDOTACHYLYTE MATRIX

Approximately 5 mg of black pseudotachylyte matrix was degassed in 25 increments at the University of Wisconsin Rare Gas Geochronology Laboratory; 23 increments comprising $>$97% of the gas released were concordant in age at the 95% confidence level, defining a weighted mean plateau of 29.8 $\pm$ 0.6 Ma with a mean square of weighted deviations of 1.7 (Fig. 5A). These 23 analyses define an inverse isochron of 29.8 $\pm$ 1.5 Ma (Fig. 5B) with $\Sigma/(n - 2)$ of 1.8 and an ^{40}Ar/^{36}Ar intercept of 296.0 $\pm$ 15.2 that is indistinguishable from atmosphere. The two lowest temperature steps yielded apparent ages younger than that of the plateau, possibly reflecting minor argon loss due to diffusion or alteration (Fig. 5A). There is no evidence of excess argon, nor does ^{39}Ar recoil (e.g., Magloughlin et al., 2001) appear to have been a problem for this sample. We interpret the isochron as a conservative estimate of time elapsed since solidification of the pseudotachylyte.

SIGNIFICANCE

A complicated suite of brittle faults is present along and near the Coast shear zone at the latitude of Prince Rupert, British Columbia (Figs. 1–3). Pseudotachylyte associated with a suite of dextral faults in the central region of the shear zone provides compelling evidence for seismic faulting (Sibson, 1975; Magloughlin and Spray, 1992) ca. 30 Ma (Fig. 5). In addition, the presence of rapid quench textures and amygdules in the pseudotachylyte (Fig. 4) implies that this portion of the Coast shear zone was relatively cool and within 5 km of the surface at this time (Sibson, 1975; Maddock et al., 1987). Apatite fission-track dates of 36–39 Ma (Harrison et al., 1979) from within the study area support this conclusion.

These results place important constraints on the cooling and exhumation history of the Coast Mountains. Coast shear-zone fabrics affect the eastern margin of the 91 Ma Ecstall pluton and the western margin of the 55–60 Ma Quottoon pluton (Fig. 1; Hollister and Andronicos, 1997). Geobarometry from the Ecstall and Quottoon plutons indicates that they crystallized at depths of $\sim$30 and $\sim$20 km, respectively (Butler et al., 2002; Metcalf and Davidson, 1997). The core of the Ecstall pluton cooled through the biotite closure temperature ($\sim$300 °C) by 55 Ma (Butler et al., 2002), and the Quottoon pluton cooled through $\sim$300 °C by 45 Ma (Harrison et al., 1979). Apatite fission-track dating (Harrison et al., 1979; Parrish, 1983) and (U-Th)/He dating (Farley et al., 2001) suggest that the Coast Mountains underwent two episodes of relatively rapid uplift between 35 and 40 Ma and after 10 Ma with little or no exhumation between 30 and 10 Ma. Our ^{40}Ar/^{39}Ar results from the pseudotachylyte near Prince Rupert appear to support this exhumation history and imply that most of the exhumation (from a depth of $\sim$30 km to $<$5 km) was accomplished by 30 Ma (see also Harrison et al., 1979).

Although there appears to be general agreement as to the timing of exhumation in the Coast Mountains, the mechanism for uplift and erosion is a matter of some debate. Plate reconstructions (Engebretson et al., 1985; Stock and Molnar, 1988; Norton, 1995) at the latitude of Prince Rupert ($\sim$54°N) show that motion between the Pacific plate and North America changed from mostly convergent to transform by 45 Ma. In the reconstruction by Stock and Molnar (1988), the North American margin would have undergone extension from ca. 40 to 20 Ma. Hyndman and Hamilton (1993) noted a dramatic increase in basaltic volcanism in the Queen Charlotte Islands area at this time, and suggested that extension resulting in the volcanism and formation of the Queen Charlotte basin (Rohr and Dietrich, 1991) is linked to larger scale plate motions. However, Rohr and Currie (1997) noted that the North American margin was largely a transform margin throughout the formation of

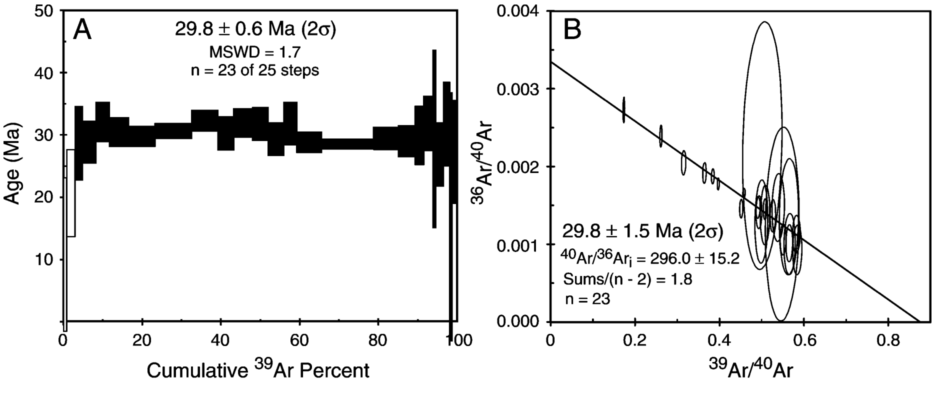

Figure 5. Age spectrum (A) and inverse isochron (B) from laser incremental heating of pseudotachylyte matrix. Filled plateau steps comprising $>$97% of gas released were used in isochron regression. Uncertainty for each analysis is shown at $\pm 2\sigma$. MSWD—mean square of weighted deviations. Analytical procedures and data-reduction methods were described by Singer and Brown (2002).

the Queen Charlotte basin, and suggested that the formation of the basin was coincident with uplift of the Coast Mountains due to gravitational collapse of the Paleogene arc beginning ca. 25 Ma and lasting throughout the Miocene. Farley et al. (2001) noted that this model is inconsistent with the relatively low rates of exhumation from 30 to 10 Ma implied by the apatite fission-track and (U-Th)/He dates. Farley et al. (2001) favored more recent uplift of the Coast Mountains and suggested that most of the present-day topography formed in the past 2.5 m.y.

Our results show that seismogenic dextral strike-slip faulting occurred at 30 Ma. Shortening and extension (P-T) axes calculated for the different fault sets (Fig. 3) show that these faults are not kinematically compatible and must have formed at different times. The timing and orientation of the dextral faulting are consistent with plate motion models (e.g., Norton, 1995) that show that the North American margin at the latitude of Prince Rupert at 30 Ma was dominated by dextral transform motions. The reverse faults might be relatively young, and could coincide with the relatively recent uplift of the Coast Mountains suggested by Farley et al. (2001). This interpretation is supported by the plate model of Norton (1995) that shows the North American margin under compression for the past 5 m.y.

This study highlights the presence of brittle faulting near and along the Coast shear zone and shows the potential for precisely dating these structures. A few previous studies (e.g., Stowell and Hooper, 1990; Haeussler, 1992; Evenchick et al., 1999; McClelland and Mattinson, 2000; Miller et al., 2000) presented orientation data for brittle faults near the Coast shear zone, but for the most part, the brittle deformation history of this important crustal scale structure has been underappreciated.

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