Timing of Iapetus Ocean rifting from Ar geochronology of pseudotachylytes in the St. Lawrence rift system of southern Quebec

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ABSTRACT

Laser ablation $^{40}Ar/^{39}Ar$ step-heating analyses for encapsulated and unencapsulated pseudotachylytes from a Neoproterozoic normal fault belonging to the St. Lawrence rift system (Canada) preserve the absolute timing of rifting and initial opening of the Iapetus Ocean. The total gas and retention ages for encapsulated pseudotachylytes from the Montmorency fault (Quebec City) are 610.3 ± 4.6 Ma and 619.0 ± 2.5 Ma. Ten unencapsulated analyses from two pseudotachylyte veins with varying matrix/clast ratios yield total gas ages of 634.7 ± 1.6–663.9 ± 1.8 Ma. These ages show an excellent linear relationship with the proportion of clast inclusions, resulting in lower intercept ages (i.e., no host rock) of 613.3 and 614.2 Ma. These statistically indistinguishable ages constrain major seismic faulting along the St. Lawrence rift system and significantly improve prior estimates for late Neoproterozoic rifting of Iapetus. The upper intercepts, reflecting host-rock ages, match cooling ages of Grenville basement in the area. We conclude that the time of major continental rifting along the northern Laurentian margin and initiation of the Iapetus Ocean occurred at 613–614 Ma, coeval with emplacement of the 615 Ma Long Range dikes of Labrador. This study also demonstrates that Ar geochronology of pseudotachylytes using varying clast/matrix ratios is a robust method to date ancient faulting.

INTRODUCTION

Since Wilson's (1966) proposal for a proto-Atlantic (Iapetus) Ocean along the eastern margin of Laurentia during the Paleozoic, geologists have variably constrained the timing and history of the creation of this ocean basin in the northern Appalachians (Bond et al., 1984; Williams and Hiscott, 1987; Kamo et al., 1989; Aleinikoff et al., 1995; Cawood et al., 2001). The breakup and end of the Mesoproterozoic supercontinent Rodinia resulted in the formation of two oceans (Pacific and Iapetus) and the formation of Gondwana. Based on paleomagnetic data from the late Precambrian, there are two major competing hypotheses for the formation of Iapetus. Depending on the position of Laurentia (high or low latitude), either Baltica or Amazonia rifted away during the late Neoproterozoic to create an ocean basin. Through the recognition of similar Mesoproterozic terranes along the eastern margin of Laurentia and Amazonia, it is generally accepted that Amazonia rifted from Laurentia during a series of extensional events that are loosely constrained as 620–570 Ma (Keppie et al., 2001; Miller and Barr, 2004). However, due to lack of suitable lithologies and overprinting tectonic events (e.g., the Ordovician Taconic orogeny of the Appalachians) there were no well-constrained radiometric fault ages for late Neoproterozoic rifting between Laurentia and Amazonia; we address this with pseudotachylyte dating in the St. Lawrence rift system.

In the Quebec Appalachians, a system of normal faults containing pseudotachylytes separates ca. 1 Ga Grenville basement rocks from Cambrian–Ordovician sediments of the St. Lawrence Lowlands (Philpotts and Miller, 1963; Tremblay et al., 2003). The area has a long history of faulting, including evidence for frictional melt events preserved in basement rocks (Philpotts and Miller, 1963). Pseudotachylytes are seismically generated melts (e.g., Sibson, 1975) that can be used to determine the time of major faulting. The occurrence of pseudotachylytes indicates dynamic rupture and slip during coseismic displacement (e.g., Swanson, 1992). Radiogenic dating of pseudotachylytes has the potential of accurately determining the age of coseismic brittle faulting, but is hindered by incomplete melting and associated resetting of the host rock (Magloughlin et al., 2001; Warr et al., 2007). This study presents new $^{40}Ar/^{39}Ar$ geochronology ages for pseudotachylytes from the Montmorency fault in the northern Appalachians in southern Quebec, using recently developed approaches that overcome most of the past limitations of pseudotachylyte dating, including sample encapsulation and clast/matrix determinations. These new results accurately constrain the late Neoproterozoic (Ediacaran) age of rifting between Laurentia and Amazonia, and thus the initiation of the Iapetus Ocean in this area. Beyond regional implications, this work demonstrates the reliability of multiple subsample dating to determine the absolute ages of melt matrix and incorporated host material in fault rocks.

GEOLOGIC SETTING AND PSEUDOTACHYLYTE DESCRIPTION

Along the eastern margin of Laurentia, U-Pb dating of rhyolites and mafic dikes indicates that Neoproterozoic rifting in the northern Appalachians occurred between 620 and 570 Ma (Kamo et al. 1989; Aleinikoff et al., 1995; Cawood et al., 2001). In the Quebec Appalachians, the St. Lawrence rift system is a set of Neoproterozoic normal faults associated with the opening of the Iapetus Ocean (Fig. 1) (Kumarapeli, 1985). It represents a half-graben structure consisting of listric faults that dip beneath

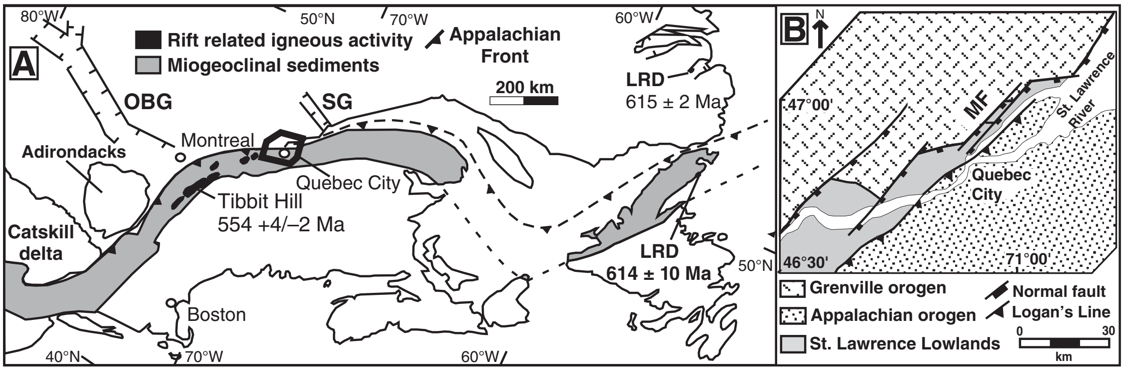

Figure 1. A: Appalachian orogen in New England and Canada with locations of Appalachian front and Ottawa-Bonnechere (OBG) and Saguenay grabens (SG), failed arms of St. Lawrence rift system (SLRS) (modified from Cawood et al., 2001). Also shown are distributions of miogeoclinal sediments and 615 Ma rift-related Long Range mafic dikes (LRD; Kamo et al., 1989). B: Generalized geologic map showing location of normal and transfer faults, including Montmorency fault (MF), of SLRS near Quebec City (modified from Tremblay et al., 2003).

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the platform cover sequence and younger Appalachian fold-thrust belt (Tremblay et al., 2003; Allen et al., 2009). The main system of northeast-southwest–trending faults occurs at the contact between Mesoproterozoic rocks of the Grenville basement and Cambrian–Ordovician strata of the St. Lawrence Lowlands. The Ottawa-Bonnechere and Saguenay grabens were characterized as failed rift arms of a rift-rift-rift triple junction that extended into the Grenville basement (Kumarapeli, 1985; Fig. 1A). Fault rocks of the St. Lawrence rift system consist of cataclasites and breccias with several areas containing pseudotachylytes and foliated fault gouge.

Samples were collected from the Montmorency fault, north of Quebec City. The Montmorency fault is a northeast-southwest–trending, steeply dipping normal fault that separates Grenville gneisses to the northwest from Paleozoic sediments to the southeast (Fig. 2A). Surface exposure of the hanging wall of the Montmorency fault reveals a tilted sequence of Ordovician sandstones and shales of the Utica Formation and an interbedded sequence of limestones and shales of the lower Trenton Group in fault contact with Mesoproterozic gneisses and granitoids of the Laurentides Park Complex. However, drill cores collected from hanging-wall sediments near the Montmorency fault reveal Middle to Late Cambrian passive margin–related Potsdam group sandstones, unconformably overlying Mesoproterozic basement (Dykstra and Longman, 1995). The deposition of these mature quartz-rich sandstones indicates a predominantly shallow subtidal setting (Lewis, 1971), and thickness variations indicate that faults were active during deposition (Dykstra and Longman, 1995). Thus the surface juxtaposition of Ordovician sediments in contact with Precambrian basement reflects early Paleozoic activity along the fault system (Sabourin 1973; Harland and Pickerill, 1982; Tremblay et al., 2003).

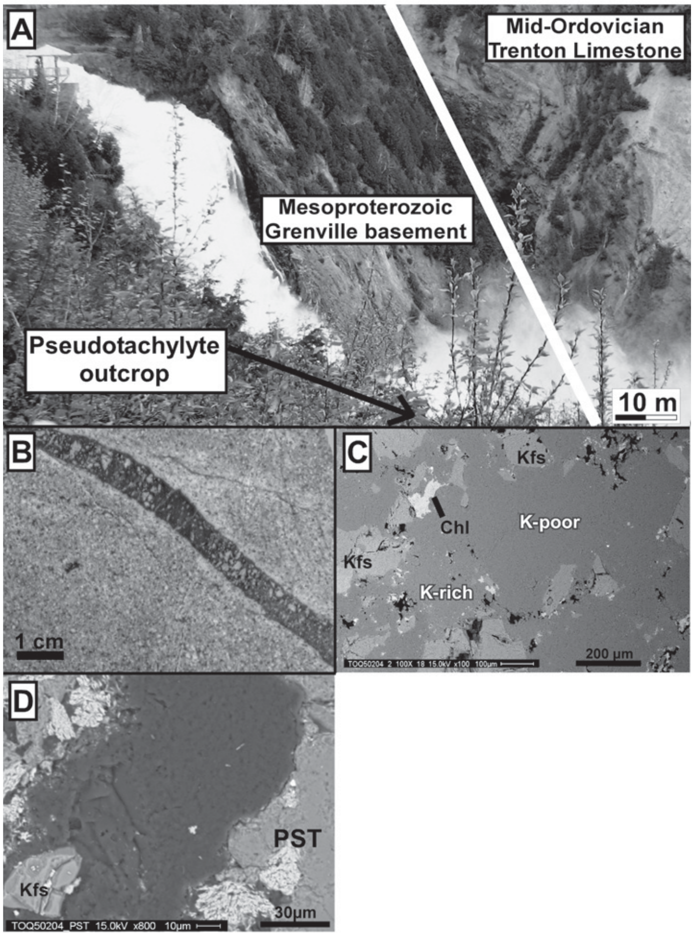

Figure 2. A: Field exposure of steeply dipping Montmorency fault (MF) at Montmorency Falls, north of Quebec City. B: Pseudotachylyte vein found in gneissic host rock of Grenville basement. C: Representative scanning electron microscope image (100× magnification) of pseudotachylyte vein displaying potassium-rich and silica-rich matrix and potassium feldspar (Kfs) clasts (Chl—chlorite). D: Silica-rich chilled margin of pseudotachylyte (PST) with potassium feldspar clast.

In the footwall of the Montmorency fault, Grenville basement contains remarkably well-preserved dark brown and black pseudotachylyte veins (Fig. 2B). These pseudotachylytes typically cut the gneissic foliation of the granitic gneiss wall rock. Matrix compositions reflect the dominant mineralogy of the host rock of quartz + potassium feldspar, and have a heterogeneous distribution of potassium (Fig. 2C). Evidence for friction-induced melting for the formation of these pseudotachylytes is seen in the glassy appearance of the pseudotachylytes and their silica-rich chilled margins on both sides (Figs. 2B and 2D), which are characteristic of rapid quenching from high temperatures (Magloughlin, 1992). Clasts, identified by sharp angular edges, found within the pseudotachylyte matrix include alkali feldspar and quartz with trace amounts of mica and iron oxide. A minor amount of retrograde chlorite is observed around alkali feldspar clasts and feldspar-rich matrix areas.

METHOD

Pseudotachylytes from the Montmorency fault contain an abundance of alkali feldspar and quartz clasts that affect ^{40}Ar/^{39}Ar dating by producing ages between those of the host rock and melt formation. The incorporation of clasts in pseudotachylyte veins has often given geologically ambiguous ages from ^{40}Ar/^{39}Ar analyses (e.g., Müller et al., 2002; Di Vincenzo et al., 2004), signifying that clasts are not equilibrated with the matrix or are completely outgassed. To mitigate the effects of clast inclusions, Warr et al. (2007) developed a method that compares the relative abundance (in percent) of clasts within the matrix of a given area in a vein with the age of that sample. Extrapolating the relative abundance of clasts to zero (i.e., all matrix), the age of vein formation is dated; conversely, extrapolating to 100% clasts records the (cooling) age of the host rock. Determining the proportions of clast inclusions was achieved by measuring their total area in a 500X scanning electron microscope (SEM) image. A description of how the relative abundances were determined is provided in the GSA Data Repository[1].

^{40}Ar/^{39}Ar Geochronology

In this study, two complementary ^{40}Ar/^{39}Ar geochronology techniques were used to determine the timing of major displacement on the Montmorency fault: encapsulation dating and multiple subsample dating. Laser ablation ^{40}Ar/^{39}Ar step-heating analyses were performed on a VG1200S mass spectrometer with 20 s heating times at successively higher powers, following the procedure of Lo Bello et al. (1987).

Quartz Tube Vacuum Encapsulation

One sample was analyzed using a quartz vacuum-encapsulation technique described by Dong et al. (1995) and Magloughlin et al. (2001). With this method, the total gas age represents a minimum age for growth of crystals and the beginning of Ar retention upon cooling; the calculated retention age provides a maximum age for the sample (Magloughlin et al., 2001). By measuring the total gas and retention ages of a pseudotachylyte sample, we are able to bracket the age of melt formation. The major benefit of this technique is the extremely small sample size (<100 µm), which enables the use of small areas that are essentially free of clasts.

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[1] GSA Data Repository item 2012117, methods, Table DR1, and Figures DR2–DR3, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Multiple Subsamples

In contrast to the small sample size method, subsample analysis allows the inclusion of clasts for dating, but requires that the clast/matrix ratio is determined for at least three samples from a single vein. We analyzed 10 1-mm-sized samples, containing variable amounts of clast inclusions, from 2 pseudotachylyte veins.

RESULTS

Encapsulation Dating

The result for the encapsulated sample by laser step heating yields a total gas age of 610.3 ± 4.6 Ma and a retention age of 619.0 ± 2.5 Ma (Fig. DR1 in the Data Repository), thus constraining vein formation to between 610 and 619 Ma. Based on the criteria provided by McDougall and Harrison (1999), no plateau age can be interpreted from the age spectrum, which has a humped-back geometry. Young ages at low temperatures possibly represent ^{40}Ar loss due to minor chlorite alterations near potassium feldspar clasts and feldspar-rich matrix areas (Fig. DR1).

Subsample Dating

The proportion of clast and matrix was determined for 10 samples from 2 pseudotachylyte veins that exhibit average clast proportions between 9% and 20% (Fig. 3A; Table DR1). The clasts include potassium feldspar and quartz with trace amounts of mica and opaque minerals.

The 10 ^{40}Ar/^{39}Ar total gas ages for the 2 veins range from 663.53 ± 2.23 Ma for the most clast-rich sample, to 634.98 ± 2.22 Ma for the most clast-poor sample (Figs. DR1 and DR2). All Ar release spectra have similar staircase-shaped degassing patterns (Fig. 3B), which is typical for analyses of mixed phases with varying ages (McDougall and Harrison, 1999). Similar to the encapsulated sample, no plateau age can be interpreted from these spectra, as expected with this approach (Magloughlin et al., 2001). All samples have complex degassing spectra indicative of veins that contain a mixed population with a considerable amount of inherited Ar, which is largely present in potassium feldspar clasts with only a minor amount from incorporated mica clasts.

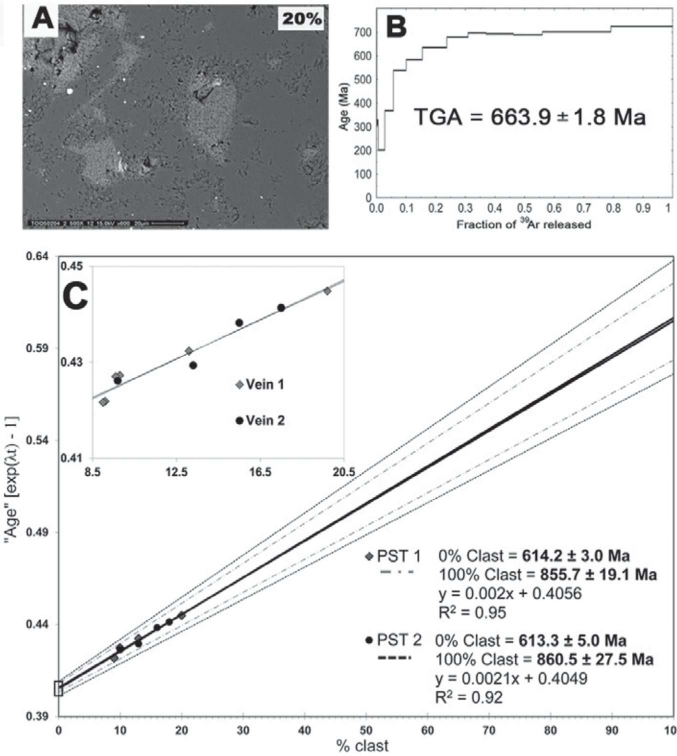

Figure 3. A: Backscattered electron image (500× magnification) of unencapsulated sample with 20% clast content. B: Degassing spectra for unencapsulated sample with 20% clast content (TGA—total gas age). C: Total gas age versus percent clast correlation plot with corresponding regression lines for two pseudotachylyte veins. Inset shows close-up and minimal scatter of data. Plot ages expressed as $\exp(\lambda t - 1)$, where λ is decay constant and t is total gas age.

Figure 3C is a correlation plot between total gas age [represented by $\exp(\lambda t - 1)$, where λ = decay constant and t = total gas age] and proportion of clast for each of the 10 samples from 2 veins. Well-constrained linear regression analyses of six analyses from vein 1 and four analyses from vein 2 intercept the *y* axis (0% clasts) at 614.2 and 613.3 Ma, respectively; these ages are indistinguishable within error (Fig. 3C). At 100% clasts, the regression lines for veins 1 and 2 intersect at 856 and 861 Ma, respectively (Fig. 3C), reflecting early Neoproterozoic ages that match cooling ages of Grenville host rock in the region (800–900 Ma; e.g., Streepey et al., 2002).

DISCUSSION AND CONCLUSIONS

Pseudotachylyte Ar dating of the Montmorency fault using complementary methods yields ages that significantly refine previous tectonostratigraphic estimates for the timing of late Neoproterozoic continental rifting and Iapetus Ocean formation. Total gas and retention ages determined by vacuum encapsulation and multiple subsample dating provide an age of 613–614 Ma for the timing of fault-related friction melting.

As illustrated in Figure 3C, the timing of major faulting is obtained when the regression lines of multiple analyses intersect the *y* axis at 0% clasts. Also plotted in Figure 3C, represented by the black box, are the total gas and retention ages for the encapsulated sample of vein 1 that predicts the permissible age range. Ages at the upper end of the regression line, intersecting at 856 and 861 Ma, represent the ^{40}Ar/^{39}Ar closure ages of host-rock clasts that are typically feldspar rich in these samples. Potassium feldspar closure ages of ca. 850 Ma for the eastern Grenville Province have been reported by several authors (e.g., Cosca et al., 1991; Streepey et al., 2002), matching our results.

The ages obtained for the Montmorency fault significantly constrain the geological evidence for Ediacaran rifting and the breakup of Rodinia in the northern Appalachians (van Staal et al., 1998; Cawood et al., 2001). The results presented in this study match paleomagnetic reconstructions that require a pre-570 Ma opening of the Iapetus Ocean. The presence of pseudotachylytes demonstrates that the Montmorency fault was active during extensional faulting along the Laurentian margin in the late Neoproterozic at 613–614 Ma, coeval with the 615 Ma Long Range dikes of Labrador (Kamo et al., 1989). Based on paleomagnetic and sedimentologic data, continental breakup may have continued until ca. 570 Ma, when Iapetus seafloor spreading commenced (Williams and Hiscott, 1987; Cawood et al., 2001; Cawood and Nemchin, 2001). In Newfoundland, stratigraphic evidence for the timing of rifting began with the deposition of late Neoproterozic–early Cambrian Bradore Formation sandstone and conglomerate. Continued subsidence of an evolving passive margin places the rift-drift transition at the Precambrian-Cambrian boundary (Williams and Hiscott, 1987; Allen et al., 2009). The presence of an ocean basin outboard of the Iapetan margin by the late Ediacaran is also recorded in zircons from ocean island basalt seamount magmatism of the Tibbit Hill volcanics (554 Ma; Kumarapeli et al., 1989) in southern Quebec and the Skinner Cove volcanics (550 Ma; Cawood et al., 2001) in Newfoundland. Thus we interpret our pseudotachylyte ages as the initiation of rift faulting that led to the formation of Laurentia's Iapetus margin.

The ^{40}Ar/^{39}Ar pseudotachylyte age from this study combined with K-Ar analyses of brittle fault gouge and apatite fission-track analyses of Tremblay et al. (2007) illustrate a long, >400 m.y. deformation history along the Montmorency fault. The early phase of deformation, as presented in this study, took place at 613–614 Ma (Ediacaran), when coseismic normal faulting and extension occurred as the result of continental rifting over a hypothesized mantle plume (Burke and Dewey, 1973; Kumarapeli, 1985). Later deformation along the fault system occurred between 465 and 445 Ma and during Mesozoic exhumation (Tremblay et al., 2007; Tremblay and Roden-Tice, 2010), interpreted as normal fault reactivation from tectonic loading (Jacobi, 1981) and far-field tectonic activity from North Atlantic rifting. The fine-grained microstructure of pseudotachylyte veins and relatively low metamorphic grade in the region resisted resetting of the isotopic system, preserving the old ages. Beyond the regional implications, our study also illustrates a robust approach to pseudotachylyte dating that overcomes the limitations of previous efforts that were hampered by representative sample sizes and host-rock inclusions.

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