Gunbarrel mafic magmatic event: A key 780 Ma time marker for Rodinia plate reconstructions

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ABSTRACT

Precise U-Pb baddeleyite dating of mafic igneous rocks provides evidence for a widespread and synchronous magmatic event that extended for >2400 km along the western margin of the Neoproterozoic Laurentian craton. U-Pb baddeleyite analyses for eight intrusions from seven localities ranging from the northern Canadian Shield to northwestern Wyoming–southwestern Montana are statistically indistinguishable and yield a composite U-Pb concordia age for this event of 780.3 ± 1.4 Ma (95% confidence level). This 780 Ma event is herein termed the Gunbarrel magmatic event. The mafic magmatism of the Gunbarrel event represents the largest mafic dike swarm yet identified along the Neoproterozoic margin of Laurentia. The origin of the mafic magmatism is not clear, but may be related to mantle-plume activity or upwelling asthenosphere leading to crustal extension accompanying initial breakup of the supercontinent Rodinia and development of the proto–Pacific Ocean. The mafic magmatism of the Gunbarrel magmatic event at 780 Ma predates the voluminous magmatism of the 723 Ma Franklin igneous event of the northwestern Canadian Shield by ~60 m.y. The precise dating of the extensive Neoproterozoic Gunbarrel and Franklin magmatic events provides unique time markers that can ultimately be used for robust testing of Neoproterozoic continental reconstructions.

Keywords: mafic magmatism, geochronology, dike swarms, rifting, Rodinia.

INTRODUCTION

Growing recognition and documentation of large-volume mafic magmatic events indicate that they are a common feature in the geologic evolution of Earth. Such events have been attributed to a variety of geodynamic processes, including triple-junction rifting, continental breakup, the generation of oceanic and continental flood-basalt provinces, giant radiating dike swarms, and magmatic underplating. Many large-scale mafic magmatic events are thought to have originated from mantle plumes, but the origin and even the existence of mantle plumes remain subjects of debate. The occurrence of such large-scale magmatic events on Earth is significant because of potential causal relationships between various geophysical, biological, and climatological processes. Recent advances in isotopic methods have led to precise dating of many mafic magmatic events and have shown that many large-scale magmatic events occurred during relatively short intervals of time (i.e., a few million years or less). Precise dating of mafic magmatic events is important for continental reconstructions because they provide unique time markers that can sometimes be correlated between previously adjacent continental blocks that have since been dispersed by plate tectonic processes. Precise dating of mafic rocks, combined with paleomagnetic studies, provides robust constraints for testing proposed ancient continental configurations, such as those that have recently been proposed for the Neoproterozoic supercontinent Rodinia.

In this paper we present new U-Pb baddeleyite age determinations from Neoproterozoic mafic dikes and sheets exposed along the U.S. and Canadian segments of the northern Cordillera and the northwestern Canadian Shield. These dates are statistically indistinguishable and provide evidence for a widespread and essentially synchronous mafic magmatic event at 780 Ma along the western margin of the Laurentian craton that provides a key time marker for potential Rodinia reconstructions. The exact origin of this event is difficult to determine, but likely heralded the early breakup and rifting of the supercontinent Rodinia.

U-Pb RESULTS

Baddeleyite for U-Pb dating was obtained from mafic dikes, sheets, and sills from seven localities extending from Great Bear Lake in the northern Northwest Territories of Canada to southwestern Montana and northwestern Wyoming (Fig. 1). Analytical methods and results are listed in Table DR1[1]). The U-Pb analyses from 16 baddeleyite fractions from 8 mafic sheets give essentially identical $^{207}Pb/^{206}Pb$ dates ranging from 775 to 782 Ma; most analyses are <2% discordant. Except where otherwise indicated, uncertainties in isotopic ages are reported at the 95% confidence level. The age results are first discussed in terms of their local geologic context; subsequent discussion focuses on regional relationships.

The Hottah mafic intrusions (Fraser, 1964) occur as northeast-striking, gently southeast dipping gabbro sheets that intrude the 1880–1840 Ma Great Bear magmatic arc, Northwest Territories, Canada (Fig. 1). The sheets are associated with nearly vertical diabase dikes extending across the Wopmay fault that disappear rapidly within the western margin of the Archean Slave craton. Together, the gently dipping sheets and northeast-striking mafic dikes are called the Hottah sheets (Fraser, 1964; Fahrig and West, 1986). The Hottah sheets are typically coarse-grained tholeiitic subalkaline gabbro that locally grade into more felsic compositions. Baddeleyite was recovered from three sheets: the Gunbarrel, the Calder, and the Faber Lake gabbros. The Gunbarrel gabbro, named for Gunbarrel Inlet on the southeast side of Great Bear Lake (Fig. 1), extends for >50 km and is as thick as 200 m. It cuts rocks of the Great Bear magmatic zone and postdates folding and major faulting in the area. The Calder gabbro is a northwest-dipping sheet that cuts both the plutonic rocks of the Great Bear magmatic zone and Dumas Group sedimentary rocks (Fig. 1). This sheet is 50 m thick and extends across the entire width of the Wopmay orogen to the western margin of the Slave craton. The Faber Lake gabbro is a poorly mapped sheet that extends for 30 km and disappears below Paleozoic cover to the southwest (Fig. 1).

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[1]GSA Data Repository item 2003159, U-Pb baddeleyite results for Gunbarrel igneous events, is available online at www.geosociety.org/pubs/ft2003.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

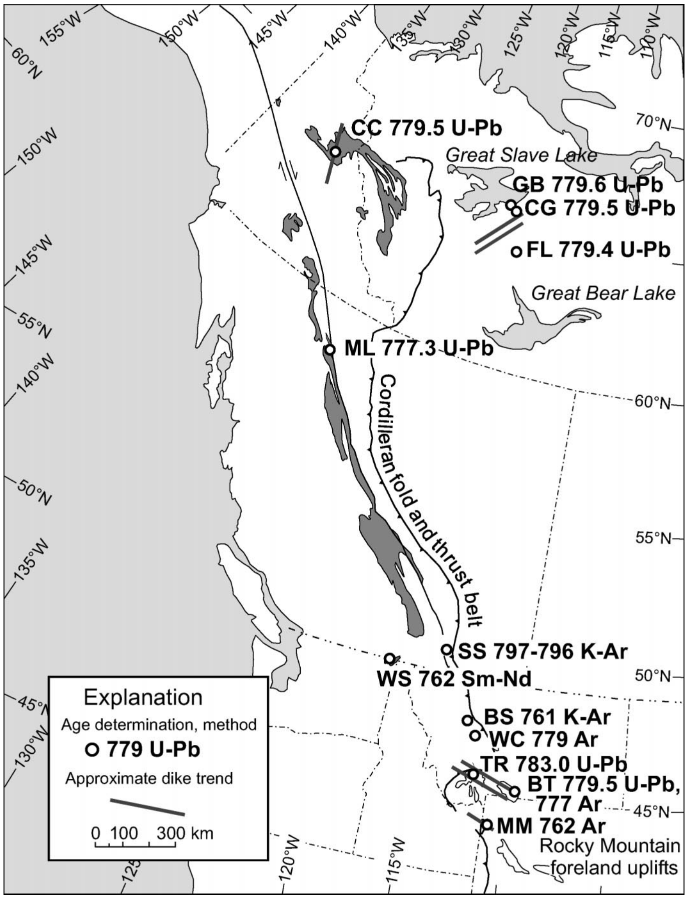

Figure 1. Location map showing distribution of Neoproterozoic dikes and sills with ages of 800–763 Ma. Dark shaded areas are locations of Neoproterozoic sedimentary and volcanic strata. Northwest Territories: CC—Concajou Canyon sill; GB—Gunbarrel gabbro; CG—Calder gabbro; FL—Faber Lake gabbro. British Columbia: ML—Muncho Lake diabase dike. Alberta: SS—sill intruding Siyeh Formation in Purcell Supergroup. Washington: WS—volcanic rocks at base of Windermere Supergroup. Montana: BS—Belt Supergroup sill; WC—gabbro sill in Belt Supergroup strata near Wolf Creek; BT—Christmas Lake dike, Beartooth Mountains; TR—Tobacco Root Mountains. Wyoming: MM—mafic dike at Mount Moran, Teton Mountains. U-Pb, K-Ar, Ar, and Sm-Nd represent apparent ages generated by uranium-lead, potassium-argon, $^{40}Ar/^{39}Ar$, and samarium-neodymium methods, respectively.

Because all the baddeleyite analyses for the three Hottah sheets are <2.4% discordant, we report weighted-average $^{207}Pb/^{206}Pb$ dates for each intrusion. Two baddeleyite analyses from the Gunbarrel gabbro give a mean date of 779.6 $\pm$ 1.4 Ma (mean square of weighted deviates [MSWD] = 0.24), three baddeleyite fractions from the Calder gabbro yield a mean date of 779.5 $\pm$ 1.8 Ma (MSWD = 0.17), and two fractions from the Faber Lake gabbro (also called the Camsell River gabbro sill) gave a mean date of 779.4 $\pm$ 2.3 Ma. A weighted mean $^{207}Pb/^{206}Pb$ date for the Hottah sheets, based on the seven analyses, is thus 780.0 $\pm$ 1.0 Ma (MSWD = 0.26). Because baddeleyite is a primary crystallizing phase in mafic magmas (Heaman and LeCheminant, 1993), this age represents the best estimate of the age of emplacement of the Hottah sheets.

Farther north and west, in the Mackenzie Mountains (Fig. 1), the regionally extensive 18–60-m-thick Concajou Canyon sill is exposed over a distance of ~200 km (Park, 1981). The sill intrudes the upper part of the Proterozoic Tsezotene Formation of the Mackenzie Mountains Supergroup and is part of a regionally extensive suite of mafic rocks that intrudes the sedimentary section up to the level of the Neoproterozoic Little Dal Group. Sills and north- to northwest-striking dikes related to the sill may be cogenetic with undated basalt lavas that cap the Little Dal Group. The Little Dal Group represents the final stages of deposition in the Mackenzie Mountains Supergroup and corresponds to the onset of widespread crustal extension (Armstrong et al., 1982). Two baddeleyite analyses from the Concajou Canyon gabbro sill give a weighted mean $^{207}Pb/^{206}Pb$ date of 779.5 $\pm$ 2.3 Ma (MSWD = 0.21). This date is identical to (1) a U-Pb zircon date of 777.7 +2.5/−1.8 Ma obtained by Jefferson and Parrish (1989) from a fault-bounded quartz diorite plug that is interpreted to be overlain by the pre-Windermere Coates Lake Group and (2) less precise Rb-Sr mineral isochron dates of 766 $\pm$ 24 and 769 $\pm$ 27 Ma of Armstrong et al. (1982).

In the Muskwa Ranges of British Columbia (Fig. 1), the 25–30-m-wide, northeast-striking (010°) Muncho Lake diabase dike cuts deformed siltstones of the Mesoproterozoic or Neoproterozoic Tuchodi Formation and is unconformably overlain by Silurian carbonate rocks. Elsewhere, dikes of presumed similar age have either northeast or northwest strikes and are overlain by sedimentary strata of the Neoproterozoic Windermere Supergroup (sequence C). A single baddeleyite analysis from the Muncho Lake diabase gave a $^{207}Pb/^{206}Pb$ age of 777.3 $\pm$ 3.0 Ma (2σ).

In the foreland uplifts of the Wyoming province of southern Montana and northwestern Wyoming, numerous northwest-trending mafic dikes intrude Archean crystalline basement rocks that compose the core of the ranges. At least some of these dikes are Mesoproterozoic, but some northwest-striking dikes in two uplifts yield Neoproterozoic isotopic dates. In the Beartooth Mountains (Fig. 1), baddeleyite from the 10-m-wide, northwest-striking, subvertical Christmas Lake dike yielded a $^{207}Pb/^{206}Pb$ baddeleyite date of 779.5 $\pm$ 3.0 Ma; a smaller fraction yielded a less-well-determined date of 768.7 $\pm$ 16.8 Ma. The two $^{207}Pb/^{206}Pb$ dates are identical to a $^{40}Ar/^{39}Ar$ hornblende plateau date of 777 $\pm$ 4 Ma from the same dike reported by Harlan et al. (1997). (The $^{40}Ar/^{39}Ar$ dates cited in Harlan et al. [1997] were recalculated from their published values by using the revised age of 523.1 Ma for the international hornblende standard MMhb-1 [Renne et al., 1998].) In the southern Tobacco Root Mountains, ~200 km to the west (Fig. 1), northwest-striking mafic dikes of geochemical group B (Wooden et al., 1978) yielded two baddeleyite fractions from each of two dikes that gave mean $^{207}Pb/^{206}Pb$ dates of 781.7 $\pm$ 3.8 (MSWD = 0.34) and 776.7 $\pm$ 4.6 Ma (MSWD = 0.71). Because the baddeleyites from the southern Tobacco Root Mountains are somewhat discordant, a conventional U-Pb discordia upper intercept of 782.4 $\pm$ 4.9 Ma (MSWD = 0.23) is probably the best estimate of the emplacement age of the Tobacco Root group B dikes. These dates indicate that at least some of the northwest-striking dikes that cut foreland uplifts of the Wyoming province are Neoproterozoic. In the Tobacco Root Mountains, the 780 Ma dikes were emplaced parallel to subparallel to an earlier Mesoproterozoic (ca. 1.45 Ga) dike swarm (Wooden et al., 1978; Harlan et al., 1996) probably related to extension accompanying development of the Belt basin.

DISCUSSION AND CONCLUSIONS

Together, the $^{207}Pb/^{206}Pb$ baddeleyite dates from the mafic sheets described here, extending from near the present-day Arctic Ocean to northwestern Wyoming, yield statistically identical $^{207}Pb/^{206}Pb$ ages ranging from 782 to 775 Ma, with no systematic variation of ages along the breadth of the exposures. The dates provide evidence for a regionally extensive short-lived mafic magmatic event extending for >2500 km along the western margin of the Laurentian craton. Because the ages are statistically indistinguishable, the 16 $^{207}Pb/^{206}Pb$ dates from the 8 mafic sheets are pooled to yield a composite age of 779.4 $\pm$ 0.8

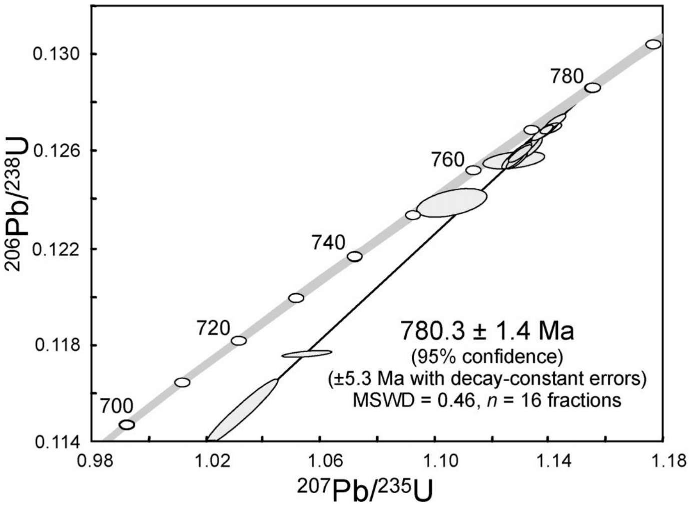

Figure 2. U-Pb concordia plot for baddeleyite analyses from mafic sills and dikes of Gunbarrel magmatic event. MSWD—mean square of weighted deviates.

Ma (MSWD = 0.66). A slightly less precise, but statistically identical age is obtained by the regression of the individual points on a U-Pb concordia diagram, giving an upper intercept of 780.3 ± 1.4 Ma (MSWD = 0.43) (Fig. 2); we interpret this 780.3 Ma age to represent the best estimate for the age of this extensive magmatic event. This result demonstrates that the three distinct ca. 780 Ma dike swarms originally noted by Park et al. (1995) are clearly related to the same magmatic event. Collectively, we term this 780 Ma magmatic episode the Gunbarrel magmatic event, because of the exposures of the Gunbarrel gabbro along Gunbarrel Inlet, Great Bear Lake, Northwest Territories. This new age determination yields an enhanced and precisely determined age for the composite paleomagnetic pole of Park et al. (1995) and Harlan et al. (1997), a key paleomagnetic pole for Rodinia plate reconstructions.

Elsewhere within the U.S. Cordillera, several other mafic intrusions yield similar isotopic dates that suggest they may also be part of the Gunbarrel event. For example, a northwest-striking dike at Mount Moran in the Teton Range of northwestern Wyoming (Fig. 1) gave a $^{40}Ar/^{39}Ar$ age of ca. 772 Ma (Harlan et al., 1997). Similarly, mafic sills that intrude the Belt Supergroup in northwestern Montana (Fig. 1) gave a hornblende $^{40}Ar/^{39}Ar$ date of 779 ± 5 Ma (Harlan et al., 1997) and a K-Ar date of 761 ± 25 Ma (Mudge et al., 1968; recalculated with post-1977 decay constants), and a sill that intrudes the Purcell Supergroup in southwestern Alberta gave K-Ar hornblende dates of 797–796 Ma (Goble et al., 1999). We suggest that the Mount Moran dike and at least some of the widespread mafic sills that intrude the Belt and Purcell Supergroups are probably part of this same magmatic event. Together, these dates provide evidence for a widespread regional mafic magmatic event that occurred along the western margin of the Wyoming craton ca. 780 Ma. This event may also be correlative to the onset of mafic volcanism associated with the base of the northwestern Washington Windermere Group (Fig. 1), which yielded an Sm-Nd mineral isochron date of 762 ± 44 Ma (Devlin et al., 1988). The Gunbarrel magmatic event is geographically the largest mafic intrusive event yet recognized along the Neoproterozoic margin of Laurentia.

The exact cause of this mafic magmatism of the Gunbarrel magmatic event is enigmatic. LeCheminant and Heaman (1994) attributed the mafic magmatism to a major episode of crustal extension that affected the western margin of the North American continent. Alternatively, Park et al. (1994) suggested that the trends of dike swarms in northwestern Canada and Wyoming define part of a crudely radial pattern that may be associated with an ancient mantle plume. They argued that this plume produced a giant radiating-dike swarm, similar to those of the 1.27 Ga Mackenzie (LeCheminant and Heaman, 1989) and 0.72 Ga Franklin (Heaman et al., 1992) magmatic events. The proposed site of the plume was postulated to have been located west of the present coast of North America; other parts of the swarm were postulated to have been severed by subsequent Neoproterozoic–early Paleozoic rift events along the western margin of Laurentia. Park et al. (1995) proposed that the missing part of this dike swarm was the Neoproterozoic Gairdner dike swarm of Australia, but subsequent high-precision U-Pb dating of the Gairdner dike swarm (ca. 827 Ma) (Wingate et al., 1998) indicates that they cannot be part of the same magmatic episode that gave rise to the dikes of the Gunbarrel magmatic event. Additionally, the evidence for a Neoproterozoic giant radiating dike swarm is tenuous, as it is unclear whether the trend of the Neoproterozoic dikes in the southern Tobacco Root Mountains is a primary structural feature. Their orientation was probably controlled by dike intrusion along favorably oriented crustal fractures that developed during an earlier episode of intracontinental extension associated with development of the Mesoproterozoic Belt basin (Harlan et al., 1996).

If the mafic dikes and sheets of the regionally extensive 780 Ma Gunbarrel magmatic event are related to a mantle plume and/or widespread crustal extension, then this event may have been a precursor to, or may have caused, the initial Late Proterozoic rifting of North America, the breakup of the supercontinent Rodinia, and the opening of the proto–Pacific Ocean. If so, the Neoproterozoic–earliest Paleozoic evolution of the Laurentian margin was probably a prolonged and diachronous multistage process in which various crustal fragments were severed from Laurentia during discrete rift events at 780 Ma, 750–720 Ma, and 570 Ma (Colpron et al., 2002), prior to the establishment of a passive continental margin in the latest Neoproterozoic or earliest Cambrian. Continents or crustal blocks proposed to have been located west of Laurentia prior to Neoproterozoic rifting include western Australia (Dalziel, 1991; Moores, 1991; Karlstrom et al., 1999; Meert and Torsvik, 2003), East Antarctica (Dalziel, 1993), South China (Li et al., 1995), North China (Piper and Rui, 1997), and Siberia (Sears and Price, 2000), or other as-yet-unidentified continents or continental fragments (Pisarevsky et al., 2003). Meert and Torsvik (2003) and Pisarevsky et al. (2003) have provided useful summary diagrams and discussions regarding the viability of various proposed Rodinia reconstructions.

The present lack of high-precision dating of mafic dike swarms in many Precambrian cratons precludes accurate identification of conjugate blocks that may have been adjacent to Laurentia and hinders precise Rodinia reconstructions. Precisely dated mafic magmatic events ca. 825 and 780 Ma have been identified in the Sibao area of the South China block and in eastern Australia (Wingate et al., 1998; Li et al., 1999; Zhou et al., 2002), and Li et al. (1999) proposed that the 830–820 Ma magmatism was caused by thermal instability related to a mantle superswell and that this plume event initiated the breakup of Rodinia. Zhou et al. (1999) further suggested that the 780 Ma mafic magmatism in the western Cordillera may have been a ''descendent'' of this mantle plume. Pisarevsky et al. (2003) suggested that the breakup of Rodinia may have begun ca. 820–800 Ma with rifting between the Australia-Mawson-Kalahari cratons and South China, followed by jump in position of magmatism resulting in rifting of South China from Laurentia ca. 780 Ma, coeval with the Gunbarrrel magmatic event. In contrast, Zhou et al. (2002) argued that the mafic magmatism in the South China block was the result of subduction-related processes along the Rodinia margin and that South China could not have been located between Australia and Laurentia ca. 830–820 Ma. The lack of Neoproterozoic dikes of 780 Ma age in Siberia suggests that Siberia was probably not adjacent to Laurentia during the Neoproterozoic. Recent high-precision U-Pb dating and paleomagnetic results demonstrate that if Australia was located in any position west of North America in the Neoproterozoic, as has been proposed for various Rodinia reconstructions, then rifting from Laurentia must have occurred well before 755 Ma (Wingate and Giddings, 2000).

Identification and precise U-Pb dating of widespread mafic magmatism at 780 Ma—the Gunbarrel magmatic event—together with mafic dikes associated with the younger, precisely dated 723 Ma Franklin igneous event (Heaman et al., 1992) provide unique time markers from the western margin of Laurentia that can be used to constrain the timing of breakup of Rodinia. If the Gunbarrel and Franklin magmatic events are part of radiating dike swarms associated with ancient mantle plumes or rift events, then coeval dike swarms should be present on conjugate rift margins of previously adjoining continents. High-precision U-Pb dating of such dikes on other continental blocks will help identify candidates for new continental reconstructions and/or aid refinement of currently proposed reconstructions. Ultimately, the precise time markers represented by these rocks may provide unique piercing points and/or paleomagnetic poles that can be used to evaluate the validity of competing paleocontinental reconstructions for Rodinia.

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