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Isotopic dating of Meso- and Neoproterozoic mafic magmatism in the southern Tobacco Root Mountains, Southwestern Montana

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Abstract

New isotopic dating of mafic dikes in the southern Tobacco Root Mountains of southwestern Montana provides evidence for two distinct episodes of subparallel Proterozoic mafic magmatism separated by about 700 m.y. Previously published geochemical data from dikes in the southern Tobacco Root Mountains had identified three geochemical groups (termed groups A, B, and C) with apparent Rb–Sr ages of 1455 Ma (group A) and 1100–1120 Ma (groups B and C). Sm–Nd dating of a geochemical group A dike yields an age of 1448 ± 49 Ma that is interpreted to represent the emplacement age of the dikes. This age is similar to published U–Pb dates from mafic sills that intrude the nearby Mesoproterozoic Belt Supergroup and Laramide basement-cored uplifts of the Archean Wyoming Province. Paleomagnetic results from groups A and B dikes are similar, suggesting that the were emplaced at about the same time. We suggest that the mafic magmatism recorded by the southern Tobacco Root Mountains group A/C dikes at about 1450 Ma probably corresponds to continental extension that accompanied development of the Mesoproterozoic Belt Basin. U–Pb dating of baddeleyite from the group B dikes provides evidence for a younger magmatic event with an age of 782.4 ± 4.9 Ma (95% confidence; ±7.1 Ma incorporating uranium decay constant errors). This date is similar to isotopic dates from Neoproterozoic mafic dikes and sills exposed elsewhere in uplifts of the Rocky Mountain foreland and that intrude the Mesoproterozoic strata of the Belt Supergroup. Geochronologic data from elsewhere in the northern Cordillera and Canadian Shield indicate that the group B dikes in the southern Tobacco Root Mountains are part of a regional 780 Ma magmatic event that extended for more than 2400 km along the western margin of Laurentia. The origin of the magmatic event is not clear, but may be related to a mantle plume and crustal extension accompanying initial breakup of the supercontinent Rodinia and development of the proto-Pacific Ocean. No evidence of ca. 1100 Ma mafic magmatism in this part of the northern Cordillera was found.

Keywords: Geochronology; Mafic dikes; Uranium–lead; Samarium–neodymium; Rodinia; Laurentia; Paleomagnetism; Proterozoic

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1. Introduction

Proterozoic mafic dikes are a common feature of the basement-cored uplifts of the Laramide foreland

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province of Wyoming and Montana. In southwestern Montana, west- and northwest-striking dikes are found in, and parallel to subparallel, to a pervasive zone of Laramide-age (Late Cretaceous–early Tertiary) reverse or thrust faults that cut the Archean crystalline basement. These dikes are thought to have been emplaced parallel to normal faults that formed during northeast-southwest-directed extension accompanying development of the Helena embayment of the Mesoproterozoic (ca. 1470 to 1400 Ma) Belt-Purcell Basin (Harrison et al., 1974; Wooden et al., 1978; Schmidt and Garihan, 1986; Evans et al., 2000).

In southwestern Montana, geochemical analyses of dikes from the Ruby Range and southern Tobacco Root Mountains (Fig. 1) identified three distinct groups with Rb–Sr ages of 1455 ± 125 Ma (group A), 1120 ± 185 (group B), and 1130 ± 130 (group C) (Wooden et al., 1978). The 1450 Ma age is similar to dates from mafic sills that intrude sedimentary rocks of the Belt-Purcell Supergroups (Höy, 1989; Hunt, 1962; Zartman et al., 1982; Anderson and Davis, 1995; Sears et al., 1998), but the 1100 Ma age does not correlate with known magmatic events in the northern Cordillera. As part of a broader study of the paleomagnetism and geochronology of mafic dikes in the foreland uplifts of the Wyoming Craton, we report Sm–Nd and U–Pb dates from dikes in the southern Tobacco Root Mountains. These dates provide evidence for two widespread episodes of mafic magmatism along the western margin of the Laurentian craton at about 1450 and 780 Ma. The 1450 Ma dikes appear to be related to extension accompanying development of the Mesoproterozoic Belt Basin, whereas the 780 Ma dikes appear to be related to a major episode of mafic magmatism along the western margin of Laurentia that may be related to the breakup of the supercontinent Rodinia.

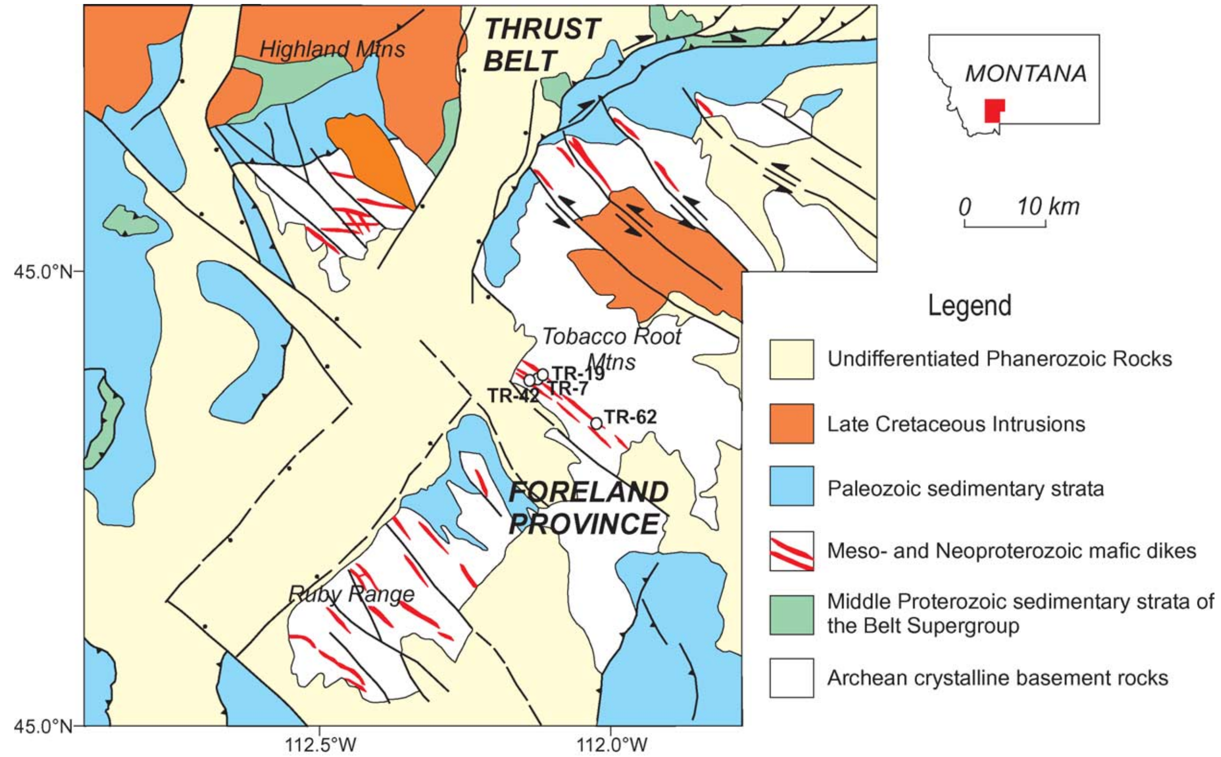

Fig. 1. Tectonic map of southwestern Montana showing the location of the Tobacco Root Mountains, the Cordilleran fold and thrust belt, the Rocky Mountains foreland province, and the distribution of Meso- and Neoproterozoic diabase dikes. The circles show the approximate locations of the dikes dated in this study. Modified from Schmidt and Garihan (1986) and Schmidt et al. (1988).

2. Geology of diabase dikes in the southern Tobacco Root Mountains

Unmetamorphosed Proterozoic mafic dikes exposed in the southern and northern parts of the Tobacco Root Mountains cut Archean and early Paleoproterozoic crystalline basement rocks of the Wyoming Province (Fig. 1) (Mueller et al., 2004; Vitaliano et al., 1979; Mogk and Henry, 1988). The mafic dikes trend N70°W, are nearly vertical, and cut the northeast-trending metamorphic foliation of the basement rocks. The dikes range from about 1 to 110 m in thickness, and are up to 10 km long. Geochemical studies by Wooden et al. (1978) identified three groups of dikes based on major and trace element geochemistry (Fig. 2). Descriptions of the dikes presented below are based on descriptions by Wooden et al. (1978) and observations made during this study.

Group A dikes are 2 to 7 m wide, fresh to somewhat altered and are fine to medium-grained (≤1 to 2 mm average grain size) diabase consisting primarily of clinopyroxene (augite) and plagioclase. These dikes are chemically undifferentiated, display moderate iron-enrichment, and are among the most primitive of the dikes in the southern Tobacco Root Mountains (Wooden et al., 1978). A Rb–Sr isochron age, based on chemically similar samples from the nearby Ruby Range, yields 1455 ± 125 Ma. Group C dikes yield somewhat similar geochemical results but were considered younger than the group A dikes due to a poorly defined Rb–Sr age of 1130 ± 130 Ma. Paleomagnetic data indicate that the A and C dikes have identical magnetization directions. Assuming these are thermoremanent magnetizations acquired during dike emplacement, the paleomagnetic data suggest that the dikes, although geochemically distinct, were emplaced at about the same time (Harlan et al., 1996a, 1997). Differences in the geochemistry of these dike groups, however, indicate that the A and C dikes reflect different source compositions and/or post-melting processes and crustal contamination (Wooden et al., 1978).

Group B dikes are thick (typically 10 to 110 m), have well-defined chill margins, and are composed of clinopyroxene and plagioclase, but also contain primary hornblende and biotite. A striking feature of these dikes is the presence of graphic intergrowths of quartz and plagioclase. The coarse grain size of these dikes, abundance of hydrous minerals, graphic intergrowths, and thickness usually distinguish them from groups A and C dikes. These dikes are strongly iron-enriched and are quartz normative (Wooden et al., 1978). The Rb–Sr data from the group B dikes are scattered, and define an apparent age of 1120 ± 185 Ma. Despite the large analytical errors associated of the Rb–Sr dates, and the caveat that these dates be confirmed by other isotopic methods (Wooden et al., 1978), many work-

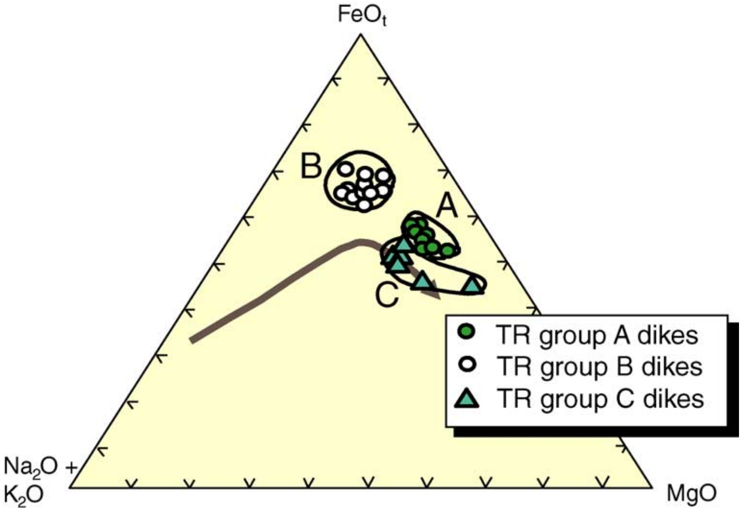

Fig. 2. Diagram showing the three geochemical groups for dikes in southwestern Montana. Modified from Johnson and Swapp (1989) and Wooden et al. (1978).

ers have cited them. Paleomagnetic directions obtained from the group B dikes are significantly different from those of the groups A and C dikes, and from Late Cretaceous to Recent expected directions for southwestern Montana (Fig. 3). A paleomagnetic pole determined from the group B dikes (Harlan, 1993) is inconsistent with poles from well determined ca. 1100 or 1450 Ma rocks elsewhere in North America, but is similar to poles obtained from well-dated Neoproterozoic (ca. 780 and 723 Ma) igneous rocks elsewhere in the northern Cordillera (Park et al., 1994; Harlan et al., 1997) and poles from Neoprotoerozoic sedimentary rocks from the Ghuar Group (ca. 800 to 740 Ma) of the Grand Canyon Supergroup (Weil et al., 2004). The paleomagnetic data reported by Harlan et al. (1996a, 1996b) and Harlan et al. (1997) strongly suggest that the southern Tobacco Root Mountains group B dikes may be Neoproterozoic in age.

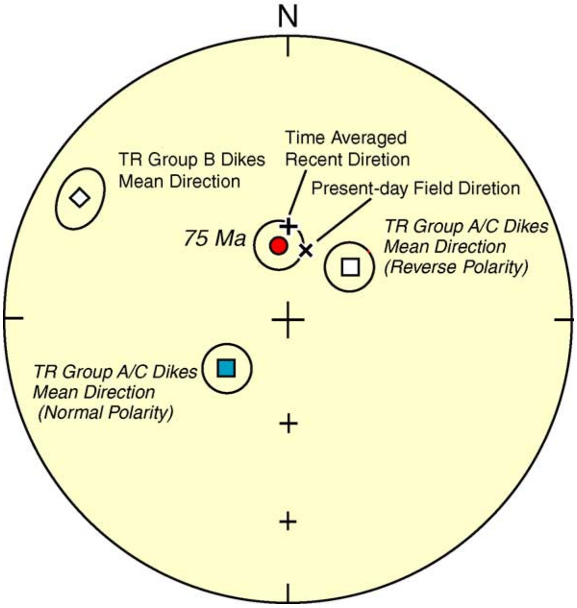

Fig. 3. Equal area projection showing in situ paleomagnetic mean directions and their α_{95} cones of confidence for group A/C (ca. 1450 Ma) (squares) and group B (780 Ma) (diamond) dike swarms from the southern Tobacco Root Mountains. Also shown are Late Cretaceous (75 Ma) reference, present-day, and time averaged directions for southwestern Montana. Open symbols are projections on the upper hemisphere and represent reverse polarity directions in present-day coordinates; filled symbols are projections on the lower hemisphere and represent normal polarity magnetizations. The group A/C and group B dike swarms are parallel to subparallel but yield magnetizations that are distinctly different from each other and significantly different from Cretaceous/Tertiary or Recent field directions. The group A/C dikes contain a dual polarity remanent magnetization, thus both normal and reverse polarity mean directions are shown. A paleomagnetic pole calculated from these rocks is similar to poles from ca. 1450 Ma rocks from elsewhere in North America. The group B dikes contain a magnetization that is of shallow negative inclination; a paleomagnetic pole calculated from these rocks is similar to poles derived from Neoproterozoic igneous rocks elsewhere in the Cordillera. The time averaged and present day directions are of normal polarity and are plotted on the lower hemisphere. Paleomagnetic data from Harlan (1993). Figure modified from Harlan et al. (1996a).

3. Sm–Nd and Rb–Sr analysis of the Tobacco Root Mountains group A dikes

Although the Tobacco Root group A dikes contain trace quantities of very fine-grained baddeleyite (LeCheminant, written communication, 1994) we could not easily separate this material for U–Pb dating. Consequently, we prepared mineral separates from a single group A dike for analysis by the Sm–Nd whole-rock-mineral isochron method (Bernard-Griffiths and Gruau, 1989). Paleomagnetic samples from this site give a well-defined, reverse polarity magnetization similar to that shown in Fig. 3. The Sm–Nd technique can be an effective technique for dating mafic rocks because the spread in Sm/Nd ratios in individual minerals is typically great enough that a reasonable isochron can be fit to the data. Because of the relative insensitivity of the Sm–Nd system to subsequent thermal perturbations, Sm–Nd dates from mafic dikes commonly record the crystallization age of mafic dikes (Hanes, 1987). The separates used in the analysis consisted of pure (>99%), unaltered plagioclase and clinopyroxene splits of differing density and/or magnetic characteristics, a whole rock split, and a mixture of intergrown hornblende and pyroxene; results of the analyses are shown in Table 1. The least radiogenic Sr and Nd values are found among the plagioclase splits ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7029–0.7030$; $^{143}\text{Nd}/^{144}\text{Nd} = 0.5121–0.5122$). The most radiogenic Nd is found among the pyroxene splits ($^{143}\text{Nd}/^{144}\text{Nd} = 0.5133–0.5134$) whereas the pyroxene + hornblende sample contains the most radiogenic Sr ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7077$). The whole-rock split has intermediate values of both $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$.

Table 1
Sm–Nd and Rb–Sr data for whole rock and mineral/density separates from a reverse polarity geochemical group A dike, southern Tobacco Root Mountains, Montana

Fraction	Rb (ppm)	Sr (ppm)	Sm (ppm)	Nd (ppm)	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	^{147}Sm/^{144}Nd	^{143}Nd/^{144}Nd
TR-42 (Sample location: 45.420925°N, 112.1561°W)								
PL-001	2.29	296.9	0.473	2.083	0.0224 ± 3	0.702917 ± 27	0.1371 ± 1	0.512250 ± 15
PL-003	2.66	264.1	0.222	1.069	0.0291 ± 3	0.702967 ± 23	0.1255 ± 1	0.512137 ± 19
PL-005	2.48	263.5	0.686	3.056	0.0273 ± 3	0.702995 ± 21	0.1355 ± 4	0.512224 ± 16
PX-007	0.42	24.6	1.038	2.447	0.0493 ± 5	0.704005 ± 34	0.2562 ± 3	0.513360 ± 17
PX-008	0.58	41.3	1.000	2.426	0.0409 ± 5	0.703715 ± 21	0.2490 ± 7	0.513295 ± 15
PX-009[a]	4.38	55.3	3.940	12.954	0.2293 ± 30	0.707675 ± 21	0.1837 ± 2	0.512709 ± 14
PX-010	0.28	11.1	0.966	2.239	0.0726 ± 9	0.704426 ± 23	0.2605 ± 3	0.513459 ± 19
WR-014	3.46	118.4	2.245	7.772	0.0844 ± 11	0.704376 ± 20	0.1744 ± 2	0.512600 ± 15

Analytical procedures for Rb–Sr and Sm–Nd analyses were similar to those reported by Stille et al. (1986, and references therein). Samples were dissolved in an HF-HNO$_3$ mixture in screw-cap PFA Teflon bombs at approximately 100 °C for 3 to 4 days. Rubidium, strontium, and the REE were extracted from the sample using cation exchange resin in 2.5 M HCl. Samarium and neodymium were isolated from the other REE using cation exchange in 0.2 M 2-methyllactic acid (Lugmair et al., 1975). Analytical blanks for the procedure were 1–4 ng (10^{-9} g) for all four elements.

Isotopic data were obtained by thermal ionization mass spectrometry using a VG 54R single-collector mass spectrometer. Isotopic data for rubidium were obtained using triple Re filaments and those for Sr using single oxidized Ta filaments. Samarium and Nd isotopic data were obtained using triple filaments with a Re center filament and Ta side filaments. All elements were run as the metal. Six analyses of the La Jolla Nd standard gave a mean ^{143}Nd/^{144}Nd = 0.511851 ± 0.000013 ($2\sigma_m$) and five analyses of Sr standard SRM 987 gave a mean ^{87}Sr/^{86}Sr = 0.710251 ± 0.000020 ($2\sigma_m$). The data were reduced using ISOPLOT v. 2.75 (Ludwig, 1994).

PL is plagioclase, PX is clinopyroxene, and WR is whole rock.

[a] This separate consists of intergrown hornblende and clinopyroxene.

The samarium–neodymium data yield an apparent age of 1448 ± 49 Ma (2σ) (Fig. 4). Although there is some scatter in the data, as indicated by the mean square of weighted deviates (MSWD) of 5.3, this age represents our best estimate for the crystallization age of this dike. This result is consistent with the previously published estimate of Wooden et al. (1978) for the age of the group A dikes based on the whole-rock Rb–Sr isochron from the Ruby Mountains. Because the paleomagnetic data from the group C dikes is essentially identical to that of the group A dikes, we suggest that the group C dikes were probably emplaced at about 1450 Ma. In subsequent discussion, we refer to the groups A and C dikes collectively as the A/C dikes.

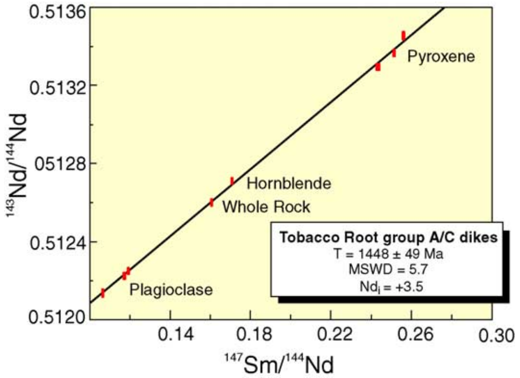

Fig. 4. Samarium–neodymium diagram showing data obtained for mineral/density fractions from a reverse polarity group A dike from the southern Tobacco Root Mountains. The best-fit age (T) is interpreted to represent the age of emplacement of the groups A and C dikes. MSWD: mean square of weighted deviates.

The positive initial $\varepsilon_{\mathrm{Nd}}$ value of +3.5, indicates that the sample was derived primarily from a depleted-mantle source. However, the calculated mantle separation age (T_{DM}; DePaolo, 1981) of 1650 Ma suggests that either the parental magma was contaminated with some light-rare-earth enriched crust at the time of emplacement, or that the sample was derived from a source that had been extracted from the mantle at or prior to 1650 Ma.

Rubidium–strontium data plotted on a conventional ^{87}Rb/^{86}Sr versus ^{87}Sr/^{86}Sr evolution diagram (not shown) are quite scattered (MSWD = 265) and do not yield reliable age information. A best-fit line through the data indicates an apparent age of 1740 ± 440 Ma

Table 2
Calculated initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ values for sample TR-42 assuming an emplacement age of 1448 Ma

Sample	Initial $^{87}Sr/^{86}Sr$	Initial $^{143}Nd/^{144}Nd$
PL-001	0.702452 ± 0.000027	0.510946 ± 0.000015
PL-003	0.702362 ± 0.000024	0.510943 ± 0.000019
PL-005	0.702428 ± 0.000022	0.510935 ± 0.000016
PX-007	0.702981 ± 0.000035	0.510922 ± 0.000018
PX-008	0.702865 ± 0.000023	0.510926 ± 0.000017
PX-009[a]	0.702911 ± 0.000065	0.510961 ± 0.000014
PX-010	0.702918 ± 0.000029	0.510980 ± 0.000019
WR-014	0.702623 ± 0.000031	0.510941 ± 0.000015

[a] This separate consists of intergrown hornblende and pyroxene.

and an initial $^{87}Sr/^{86}Sr = 0.7024 \pm 0.0004$ (Model 1 solution of Ludwig, 1994). Data for pyroxene fractions consistently plot above the best-fit line, whereas that for the proxene + hornblende fraction plots distinctly below the best-fit line. The results indicate that the Rb–Sr systems of the mineral fractions have not remained closed since crystallization of the rock.

Apparent initial $^{87}Sr/^{86}Sr$ ratios at 1448 Ma range from 0.7024 for plagioclase to 0.7029 for the pyroxene and pyroxene + hornblende fractions (Table 2). The initial ratios for plagioclase are consistent with the Sm–Nd data and indicate that the rock was derived primarily from a depleted-mantle source with a small "continental" contribution. The higher apparent initial ratios for the pyroxene fractions indicate a source that was only slightly depleted. The pyroxene fractions are characterized by much lower Rb and Sr contents (Table 2), which makes these minerals more susceptible to post-crystallization open-system behavior. Consequently, we suggest that the initial $^{87}Sr/^{86}Sr = 0.7024$ from the plagioclase fractions more closely represents the true initial $^{87}Sr/^{86}Sr$ at the time of emplacement.

4. U–Pb dating of the Tobacco Root Mountains group B dikes

Samples from three dikes previously identified as belonging to geochemical group B based on paleomagnetic analysis were processed for U–Pb dating. Zircon and baddeleyite were found in all three samples (TR7, TR19, and TR62), although baddeleyite in sufficient quantities for dating was obtained only from samples TR7 and TR19. Zircons obtained from the group B dikes consisted of prismatic to equant, clear to slightly pink grains and fragments, and commonly had numerous cracks and fractures. The presence of crystal faces and/or prismatic terminations suggests that the zircons are of igneous origin. The baddeleyite consisted of tiny (≤200 μm) red-brown, translucent, striated and bladed crystals and crystal fragments. Methods used in the U–Pb analyses are similar to those described in Harlan et al. (2003a). Analytical data are listed in Table 3.

Zircons from the group B dikes were not air abraded and give highly discordant (55 to 80%) analyses indicating substantial Pb loss since crystallization, whereas baddeleyite analyses are much less discordant (Fig. 5A). Using all the zircon and baddeleyite analyses, we obtain a model-2 regression with an upper intercept age of 787 ± 11 Ma (MSWD = 26), and a lower intercept age of 105 ± 19. The excessive scatter in the zircon analyses presumably is the result of Pb loss associated with Laramide igneous activity and/or uplift of the Tobacco Root Mountains in Late Cretaceous time and/or problems with zircon inheritance.

The four baddeleyite analyses alone (Fig. 5B) provide an essentially identical, but analytically more precise model 1 upper intercept age of 782.4 ± 4.9 Ma (MSWD = 0.23). Incorporating errors in uranium decay constants for comparison with other isotopic dating systems yields a slightly larger error of ±7.1 Ma. Because baddeleyite is a primary igneous phase in mafic dikes and thus is largely unaffected by inheritance (Heaman and LeCheminant, 1993), we consider the upper intercept age given by the baddeleyite analyses to be the best estimate of the crystallization and emplacement age for the group B dikes.

5. Discussion

Isotopic data presented here provide evidence for two discrete Proterozoic mafic magmatic events separated by about 700 m.y. Sm–Nd dating and the paleomagnetic data indicate that the group A/C mafic dikes were emplaced at about 1450 Ma. This age is similar to dates from mafic sills in the nearby Mesoproterozoic Belt Basin located immediately north and northwest of the Tobacco Root Mountains, which have yielded dates of 1433 ± 10 Ma, 1445 ± 11 Ma, 1468 ± 2 Ma,

Table 3
U–Pb isotopic data for zircon and baddeleyite from group B diabase dike samples, southern Tobacco Root Mountains, Montana

Sample	Mineral analyzed	Weight[a] (μg)	U (ppm)	Pb (ppm)	$^{206}\mathrm{Pb}/^{204}\mathrm{Pb}$[b]	$^{207}\mathrm{Pb}/^{206}\mathrm{Pb}$[c]	$^{208}\mathrm{Pb}/^{206}\mathrm{Pb}$[c]	$^{207}\mathrm{Pb}/^{235}\mathrm{U}$[d]	$^{206}\mathrm{Pb}/^{238}\mathrm{U}$[d]	$^{207}\mathrm{Pb}/^{206}\mathrm{Pb}$[d]	Age (Ma)[e]
TR-7 (sample location: 45.4261 °N, 112.1340 °W)											
1(43)	Zr	N.D.	N.D.	N.D.	899.20	0.07661	0.34490	0.56505	0.06473	0.06331	719 ± 5
(9 zircon grains)					(0.375)	(0.534)	(0.2810)	(0.292)	(0.142)	(0.246)	
5(43)	Bd	N.D.	N.D.	N.D.	2454.5	0.06854	0.02464	1.1413	0.12689	0.06524	782 ± 4
(∼60 baddeleyite grains)					(0.229)	(0.560)	(4.00)	(0.257)	(0.147)	(0.205)	
1(47)	Zr	24	1355	120	1406.5	0.07227	0.28872	0.66138	0.07472	0.06420	748 ± 4.5
(1 large zircon; 24 mg)					(0.538)	(0.453)	(0.283)	(0.329)	(0.242)	(0.213)	
2(47)	Zr	82	1036	91	1315.2	0.07399	0.27288	0.65600	0.07451	0.06386	737 ± 2.5
(multiple–grain analysis)					(0.278)	(0.18)	(0.148)	(0.154)	(0.097)	(0.116)	
6(47)	Bd	N.D.	N.D.	N.D.	1401.8	0.07427	0.04099	1.0559	0.11759	0.06512	778 ± 13
(multiple–grain analysis)					(3.70)	(0.256)	(1.08)	(0.663)	(0.098)	(0.612)	
TR19 (sample location: 45.3689 °N, 111.9274 °W)											
2(43)	Zr	N.D.	N.D.	N.D.	336.10	0.10406	0.37274	0.65431	0.07429	0.06388	738 ± 5.5
(19 very small zircons)					(0.133)	(0.384)	(0.269)	(0.302)	(0.132)	(0.261)	
6(43)	Bd	N.D.	N.D.	N.D.	1990.4	0.06771	0.03487	1.1283	0.12563	0.06514	779 ± 7
(∼37 small baddeleyite grains)					(0.160)	(1.03)	(5.15)	(0.380)	(0.117)	(0.350)	
4(47)	Zr	N.D.	N.D.	N.D.	496.81	0.09048	0.36038	0.61177	0.07042	0.06301	708 ± 4
(multiple–grain analysis)					(0.099)	(0.268)	(0.178)	(0.412)	(0.365)	(0.185)	
5(47)	Bd	N.D.	N.D.	N.D.	3010.5	0.6854	0.04021	1.0331	0.11525	0.06502	775 ± 6
(multiple–grain analysis)					(3.51)	(0.279)	(1.23)	(1.010)	(0.964)	(0.280)	
TR62 (sample location: 45.3662 °N, 111.9035 °W)											
4(49)	Zr	58	3500	213	413.70	0.09365	0.45631	0.36182	0.04360	0.06019	610 ± 8
(multiple–grain analysis)					(0.609)	(0.239)	(0.147)	(0.438)	(0.149)	(0.386)	
5(49)	Zr	62	3518	229	527.66	0.08509	0.59199	0.35415	0.04349	0.05906	569 ± 17
(multiple–grain analysis)					(1.63)	(0.249)	(0.122)	(0.854)	(0.139)	(0.789)	

Zr = zircon; Bd = baddeleyite; N.D. = not determined.

[a] Sample weights and U–Th concentrations were determined for fractions containing grains large enough to be transferred to a microbalance. Errors on these weights and concentrations do not exceed 1.5%.

[b] Raw data, not corrected for laboratory blank or mass fractionation. Values in parentheses are two-sigma errors in percent. Instrumental biases were monitored through replicates of NBS Standard 983.

[c] Data corrected for laboratory blank and mass fractionation (0.13 ± 0.05% per a.m.u.). Blank values: (43) fractions: (31 pg: 206/204 = 18.795; 207/204 = 15.417; and 208/204 = 37.637); (47) fractions: (23 pg: 206/204 = 19.966; 207/204 = 15.426; and 208/204 = 37.649); (49) fractions: (61 pg: 206/204 = 18.3; 207/204 = 15.36; and 208/204 = 37.654).

[d] Radiogenic values corrected for laboratory blank, mass fractionation, and initial Pb (assuming Stacey and Kramer model Pb values at 780 Ma).

[e] $^{207}\mathrm{Pb}/^{206}\mathrm{Pb}$ age. Errors given at the 95% confidence level.

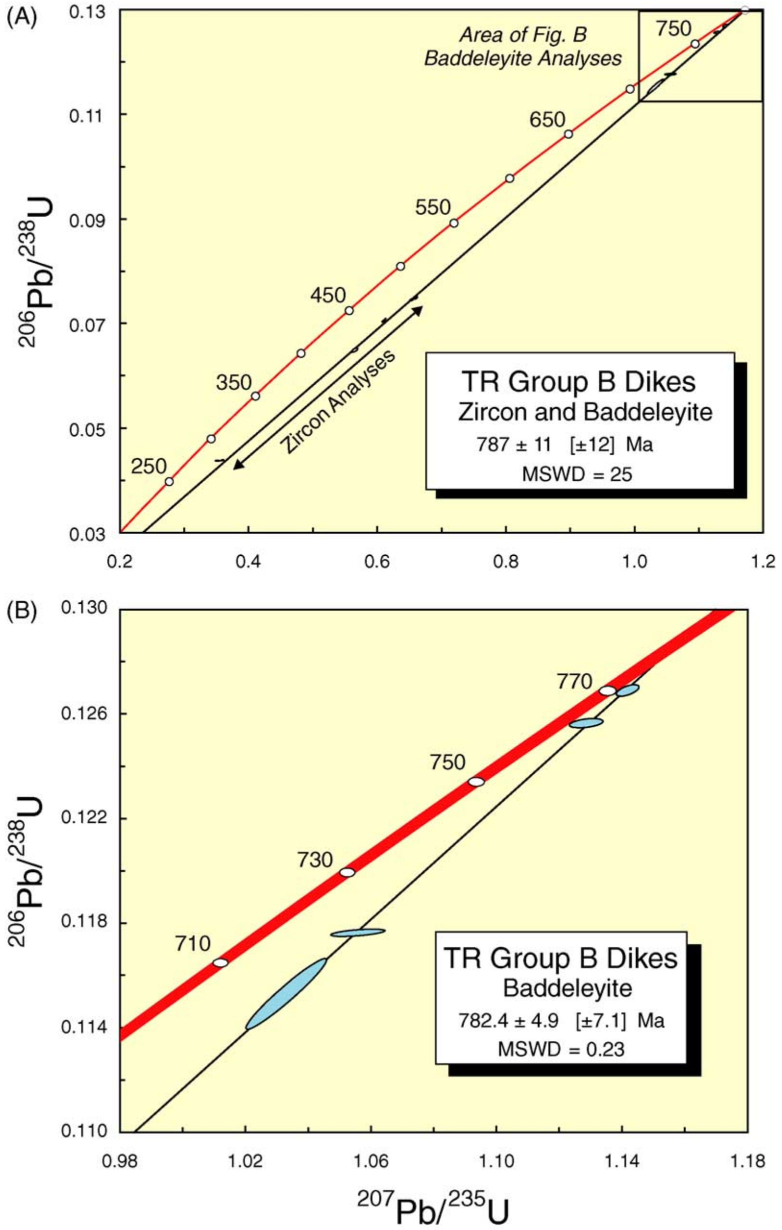

Fig. 5. (A) Concordia plot showing U–Pb results for seven zircon and four baddeleyite analyses from the southern Tobacco Root Mountains group B dikes. The error ellipses for individual analyses represent the analytical errors at $\pm 2\sigma$. (B) Enlargement of area shown in (A). The width of the concordia curve represents the error in the uranium-decay constant errors. Errors in regressions are given at 95% confidence. The error in brackets incorporates the error in the U–Pb age and errors in uranium-decay constants. MSWD: mean square of weighted deviates.

1469 ± 3 Ma, and 1457 ± 2 Ma (Zartman et al., 1982; Höy, 1989; Anderson and Davis, 1995; Sears et al., 1998). The 1450 Ma Sm–Nd age for the group A/C dikes is also similar to dates from NW-striking dikes exposed in Laramide-age basement-cored uplifts in central and northwestern Wyoming that have yielded U–Pb dates of 1467 Ma (Chamberlain and Frost, 1995). The mafic sills in the Belt Supergroup are thought to record rifting and subsidence accompanying development of the Belt Basin and we suggest that the group A/C dikes of the southern Tobacco Root Mountains and dikes father to the south and east may also be associated with this extensional event. The NW-trend of mafic dikes in southwestern Montana parallels a pervasive zone of NW-trending faults and fractures within the basement-cored uplifts (Schmidt and Garihan, 1986; Schmidt et al., 1988). These structures are thought to have formed in the Mesoprotoerozoic as down-to-the-north normal faults due to NE-SW directed extension and formation of Helena embayment of the Belt Supergroup (Harrison et al., 1974; Wooden et al., 1978; Schmidt and Garihan, 1986; Schmidt et al., 1988). These faults created a pervasive and long-lasting crustal weaknesses that controlled and localized subsequent tectonic activity in this area including the emplacement of Neoproterozoic mafic dikes (described below), inversion of the Mesoproterozoic normal faults as Laramide-age (Late Cretaceous–early Tertiary) basement-involved reverse faults, and Tertiary to Recent normal faults associated with post-orogenic collapse and/or Basin-Range extension (Schmidt and Garihan, 1986; Schmidt et al., 1988). The NW-trending structures also localized zones of Tertiary magmatic activity, elsewhere in southwestern Montana and northwestern Wyoming (Chadwick, 1970; Harlan et al., 1996b).

U–Pb dating of group B dikes in the southern Tobacco Root Mountains indicates that they were emplaced at 780 Ma, not ca. 1100 or 1450 Ma. The 780 Ma U–Pb date from the group B dikes is similar to isotopic dates from northwest-trending dikes elsewhere in basement-cored uplifts of the Rocky Mountain foreland and to some mafic sills that intrude the Middle Proterozoic Belt Supergroup. For example, a northwest-trending dike in the Beartooth Mountains, about 200 km to the east, yielded a whole-rock K–Ar isochron age of 750 ± 32 Ma (group IIIA dikes; Mueller and Rogers, 1973; Baadsgaard and Mueller, 1973; age recalculated using post-1977 decay constants). Subsequent high-precision dating of this dike has yielded baddeleyite U–Pb and hornblende ^{40}Ar/^{39}Ar dates of 779 Ma and 777 ± 4 Ma[1] dates, respectively (Harlan et al., 1997, 2003b), that are essentially identical to the 780 Ma group B U–Pb date from the southern Tobacco Root Mountains. Similarly, a northwest-trending dike at Mount Moran in the Teton Range of northwestern Wyoming gave a ^{40}Ar/^{39}Ar apparent age of about 772 Ma (Harlan et al., 1997, 2003b). Some mafic sills that intrude Middle Proterozoic Belt Supergroup strata in northwestern Montana also have yielded Neoprotoerozoic isotopic dates. For example, a sill near the Wolf Creek area gave a hornblende ^{40}Ar/^{39}Ar date of 779 ± 5 Ma (Harlan et al., 1997). In addition, a K–Ar date of 761 ± 25 Ma has been reported (location unspecified, J.D. Obradovich oral has communication cited in Mudge, 1972; recalculated using post-1977 decay constants). U–Pb sphene and zircon dates of 774 ± 3 Ma and 763 ± 12 Ma, respectively, have been obtained from sills elsewhere in the Belt Basin (J. Aleinikoff, written communication, 2003; Burtis et al., 2004). The similarity in isotopic dates suggests that are probably part of this same magmatic event. Together, these dates indicated a widespread regional magmatic event along the western margin of the Wyoming Craton at about 780 Ma. This magmatic event may be correlative to the onset of mafic volcanism associated with the Windermere Supergroup in northwestern Washington for which a Sm–Nd mineral isochron date of 762 ± 44 Ma has been reported (Devlin et al., 1988).

This 780 Ma mafic magmatic event identified in uplifts of the Rocky Mountain foreland and in sills of the Mesoproterozoic Belt Supergroup is correlative with mafic intrusions exposed elsewhere in the northern Cordillera and adjacent areas of the Canadian Shield. U–Pb dates in northeast-trending mafic gabbro dikes and subhorizontal sheets (the Hottah sheets) in the Great Bear magmatic zone in the northwestern Canadian Shield give baddeleyite dates of 780 ± 1 Ma (Harlan et al., 2003b; Park et al., 1995). Elsewhere, plugs and sills that intrude Neoproterozoic sedimentary strata in the Mackenzie Mountains give U–Pb ages of 777.7 +2.5/−1.8 Ma and 779.5 ± 2.3 Ma and a dike in the Muskwa Ranges gave a ^{207}Pb/^{206}Pb age of 777.7 +3.0 Ma (Jefferson and Parrish, 1989; Harlan et al., 2003b). Overall, the best estimate for the age of this mafic dike event is considered to be 780.3 ± 1.4 Ma

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[1] ^{40}Ar/^{39}Ar dates cited in Harlan et al. (1997) have been recalculated from their published values using the revised age for the international hornblende standard MMhb-1 of 523.1 Ma (Renne et al., 1998). The ^{40}Ar/^{39}Ar dates cited here do not incorporate errors in decay constants or uncertainties in the age of fluence monitors.

and this event has been termed the Gunbarrel magmatic event (Harlan et al., 2003b).

Together, isotopic dates from the Wyoming Province and the northern Cordillera provide evidence for a regionally extensive, precisely-dated, 780 Ma magmatic event that extended over 2400 km along the western margin of Laurentia, called the Gunbarrel magmatic event (Harlan et al., 2003b). The cause of this mafic magmatism, however, remains enigmatic. LeCheminant and Heaman (1994) attributed magmatism to a major episode of crustal extension along the western margin of North America. In contrast, Park et al. (1994) suggest that trends of dike swarms in northwestern Canada and Wyoming define parts of a crudely radial pattern associated with an ancient mantle plume. They argue that this plume produced a giant radiating dike swarm, similar to those of the 1.27 Ga Mackenzie (LeCheminant and Heaman, 1989) and 0.73 Ga Franklin (Heaman et al., 1992) magmatic events. The proposed location of the plume was postulated to be off the present coast of North America, with other parts of the swarm severed from the craton by subsequent Neoproterozoic and early Paleozoic rift events and development of an early Paleozoic passive continental margin along the western margin of Laurentia. The evidence for a giant radiating dike swarm is tenuous, however, as it is unclear whether the trend of the Neoproterozoic dikes in the southern Tobacco Root Mountains is primary as those dikes are parallel or subparallel to the older Mesoproterozoic group A/C dikes. Thus, it is likely that their orientation was controlled by the long-lived crustal fractures developed during the earlier episode of intracontinental extension associated during the development of the Mesoproterozoic Belt Basin (Harrison et al., 1974; Wooden et al., 1978; Schmidt and Garihan, 1986).

If the mafic dikes and sheets of this regionally extensive 780 Ma magmatic event are related to a mantle plume and widespread crustal extension, then this event may have been a precursor to, or a consequence of the initial Neoproterozoic 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 multi-stage process with discrete rift events at 780 Ma, 750 to 720 Ma, and 570 Ma (Colpron et al., 2002). Continents proposed to have been located west of Laurentia prior to rifting include: Western Australia (Dalziel, 1991; Moores, 1991; Karlstrom et al., 1999; Meert and Torsvik, 2003), East Antarctica (Dalziel, 1993; Weil et al., 1998), South China (Li et al., 1995), North China (Piper and Rui, 1997), and Siberia (Sears and Price, 2000, 2003), or other as yet unidentified continents or continental fragments (Pisarevsky et al., 2003). The identification and precise dating of a widespread mafic magmatic event at 780 Ma provides a unique time-marker that may be used to constrain the timing and breakup of Rodinia. Similarly, the precisely dated magmatic events at ca. 1450 Ma (mafic sills intruding the Belt Supergroup), ca. 1100 Ma (central Arizona diabase sheets) (Silver, 1978; Shastri et al., 1991; Heaman and Grotzinger, 1992), 780 Ma (Gunbarrel magmatic event), and 723 Ma (Franklin magmatic event; Heaman et al., 1992) may provide piercing points and paleomagnetic poles that can be used to evaluate the validity of competing paleocontinental reconstructions for Rodinia.

6. Conclusions

Geochronologic data from mafic dikes in the southern Tobacco Root Mountains of southwestern Montana provide evidence for two discrete mafic magmatic episodes characterized by the emplacement of northwest-striking dike swarms. A Sm–Nd mineral isochron from a geochemical group A dike yields an age of 1448 ± 49 Ma consistent with the whole rock Rb–Sr isochron reported by Wooden et al. (1978). Mafic magmatism at ca. 1450 Ma was likely related to extension during development of the nearby Mesoproterozoic Belt Basin. U–Pb dates from the southern Tobacco Root Mountains group B dikes document the presence of a Neoproterozoic magmatic event at 782.4 ± 4.9 Ma. These dikes were emplaced parallel to subparallel to the ca. 1448 Ma dikes of group A/C and were coeval to northwest-trending dikes in the other foreland uplifts of the Wyoming Province and some of the mafic sills that intrude the Belt Supergroup. Regionally, these dikes were part of a major episode of essentially synchronous 780 Ma mafic magmatism called the Gunbarrel magmatic event that extended for >2400 km along the western margin of Laurentia. The group B dikes may have been part of an ancient mantle plume related to the breakup of the Rodinian supercontinent, similar to that inferred for the Jurassic breakup of Pangea (Marzoli et al., 1999). No evidence was found for a mafic event at 1100 Ma along the western margin of the Wyoming Craton, as had been proposed from earlier Rb–Sr dating of mafic dikes in the southern Tobacco Root Mountains of southwestern Montana.

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