TRACE-ELEMENT SIGNATURES AND TECTONIC AFFINITIES OF PROTEROZOIC A-TYPE GRANITES AND RHYOLITES IN CENTRAL WISCONSIN

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ABSTRACT

New major-, trace- and rare-earth-element data for early Proterozoic A-type metaluminous granites and rhyolites exposed in east-central Wisconsin confirmed the genetic relationship of these rocks. Rhyolite exposed in Berlin, Wisconsin, has major- and trace-element chemistries and rare-earth-element patterns similar to that of the granite exposed at Redgranite, Wisconsin. Variation between the two suites is consistent with small amounts of fractional crystallization. We interpreted the Berlin rhyolite to represent the extrusive equivalent of the granite of Redgranite. One rhyolite sample, collected from a shear zone, has consistently lower values for rare-earth elements; this variation could represent variation in the degree of fractionation within the rhyolite or alteration that accompanied shearing.

New trace-element data also distinguished among the tectonic environments in which metaluminous granites and rhyolites of Wisconsin formed. Our data showed that the granite of Redgranite and the Berlin rhyolite have geochemical signatures that are consistent with extensional settings, and their metaluminous character supports generation by low-pressure melting of calc-alkaline crust. Comparison of Wisconsin rocks with other Proterozoic A-type granites confirmed that those of this study were likely generated during post-collisional extension of continental crust. The ages of the units (approximately 1,750 Ma) support the interpretation of these as post-orogenic granitic magmas. Therefore, we interpreted the Berlin rhyolite and the granite at Redgranite, Wisconsin, to represent post-collisional, A2-type rhyolites and granites generated during the collapse of crust that was thickened during the Penokean Orogeny.

INTRODUCTION

Numerous granite and rhyolite outcrops dispersed throughout east-central Wisconsin are important (if somewhat enigmatic) keys to understanding Wisconsin's Proterozoic history. In the early 1980s, Smith (1978, 1983) completed a geochemical study of these "inliers," attributing them to post-orogenic magmatism. His interpretation was based mainly on their ages in relation to the Penokean Orogeny. Uranium–lead isotope analyses of zircons from granite and rhyolite outcrops in Wisconsin suggest that the ages of these rocks fall in the most recent pulse of Geon 17 post-Penokean magmatism at approximately 1,750 Ma (Van Wyck, 1995; Van Schmus and others, 2001; Holm and others, 2005). In central and southern Wisconsin, rocks associated with this pulse are the rhyolite beneath the Baraboo quartzite, 1,754 ± 44 Ma; Baxter Hollow granite, 1,752 ± 15 Ma (Van Wyck, 1995); Observatory Hill rhyolite, 1,759 ± 2 Ma; and Montello granite, 1,746 ± 3 Ma (Van Schmus and others, 2001; Holm and others, 2005). These ages indicate that they are younger than the calc-alkaline intrusive rocks associated with the main Penokean Orogeny (1,890–1,820 Ma, Sims and others, 1989) and older than the more extensive A-type magmatism of the Stettin syenite complex (1,565 ± 4 Ma, Van Wyck and others, 1994), Wausau syenite (1,520 Ma, Van Schmus, 1976) and the Wolf River batholith (1,470 Ma, Van Schmus and others, 1975; Dewane and Van Schmus, 2003) to the north. The Geon 17 igneous rocks are distinct from other Proterozoic igneous rocks and key to interpretation of the geologic history of Wisconsin.

Our study of the northernmost of the A-type granites of east-central Wisconsin continues the work of Smith (1978, 1983) and other workers (for example, Van Schmus, 1978, 1980; Anderson and others, 1980). Our intention was to characterize two suites of the Geon 17 A-type igneous rocks in central Wisconsin using trace- and rare-earth-element geochemistry. To understand their relationship, we used petrogenetic modeling to investigate the role of fractional crystalli-

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zation as a possible origin of geochemical differences between the two suites. We employed important trace-element ratios to infer the tectonic regime that was present during the early Proterozoic and compared A-type rocks of central Wisconsin to other Proterozoic A-type granites of known tectonic affinities. The new high-precision trace-element data presented in this paper helped us place the granites and rhyolites in a post-collisional (extensional) regime during the post-Penokean geologic history of central Wisconsin.

GEOLOGIC SETTING

The Penokean Orogeny was a major collisional event in the Early Proterozoic (1,870–1,820 Ma) of Wisconsin (Van Schmus, 1976, 1980; Maass, 1983; Sims and others, 1989). Voluminous calc-alkaline and alkaline plutonism and large-scale structural elements characterized this mountain-building event (Maass, 1983; Southwick and Morey, 1991; Holm and Lux, 1996; Van Wyck and Johnson, 1997). By 1,820 Ma, Penokean accretion terminated and was followed by an approximately 20 Ma period of magmatic quiescence in Wisconsin. Magmatism flared up again, beginning with a pulse at approximately 1,800 Ma; this pulse was followed by two other recognized post-Penokean pulses at 1,775 and 1,750 Ma (Van Schmus and others, 2001; Holm and others, 2005). During the three Geon 17 pulses, granites and rhyolites with A-type chemistries were generated and are preserved in central Wisconsin as isolated outcrops extending from Redgranite in the north to southern Sauk County (south of Baraboo; fig. 1). Recent workers in the Penokean and post-Penokean rocks of Minnesota suggested that Geon 17 rocks are associated with renewed subduction beneath Laurentia following Penokean accretion (Holm and others, 2005). Between 1,775 and 1,750 Ma, the angle of the subducting slab is thought to have steepened, altering horizontal stresses, changing the tectonic regime from compressional to extensional, and facilitating the collapse of overthickened Penokean crust (Holm and others, 2005).

In Wisconsin, magmatism associated with Penokean collapse ceased by approximately 1,750 Ma (Holm and others, 2005) and was followed by an extended period of cooling and exhumation of Penokean rocks and deposition of the Baraboo quartzite (Holm and others, 1998; Medaris and others, 2003). Extensive A-type magmatism was renewed in Wisconsin at approximately 1,565 Ma with the intrusion of the Stettin syenite (1,565 Ma, Van Wyck and others, 1994), the Wausau syenite (1,520 Ma, Van Schmus, 1976), and the more voluminous Geon 14 intrusions that stretch from California to Scandinavia and include the Wolf River batholith in Wisconsin (Anderson, 1983). Although outside the scope of this paper, this later pulse of Proterozoic A-type magmatism represents an important chapter in the Proterozoic history of the entire North American continent and may have hydrothermally altered or reheated the post-Penokean igneous rocks addressed here.

The early Proterozoic granite of Redgranite (Smith, 1983; called Waushara granite by Weidman, 1898) and Berlin rhyolite (Buckley, 1898; Weidman, 1898) are two of the numerous Proterozoic A-type igneous rocks that crop out in east-central Wisconsin (fig. 1; Smith, 1978). Erosion has exposed such granites and rhyolites in central and eastern Wisconsin; they are elsewhere unconformably overlain by Cambrian sandstone and Pleistocene glacial deposits (Smith, 1983). Bedrock beneath the sandstone and glacial deposits, sampled in deep water wells, is similar in composition to those rocks exposed at the surface (Smith, 1978), and the dispersed outcrops have been interpreted to be genetically related: granites as part of the same composite pluton and rhyolites as the extrusive equivalents (fig. 1; Smith, 1983).

Previous workers (Smith, 1978, 1983; Van Schmus, 1978) interpreted Geon 17 rhyolites and granites in east-central Wisconsin to be co-magmatic on the basis of similar age and proximity to one another (fig. 1). Since the early 1980s, several studies of trace-element characteristics of A-type granites (for example, Pearce and others, 1984; Whalen and others, 1987; Eby, 1990, 1992) have refined our understanding of similar granites and their tectonic settings. However, few modern geochemical techniques have been used to correlate the trace-element geochemistry or tectonic setting of Geon 17 granites and rhyolites in central Wisconsin. Our study was designed to further correlate dispersed rhyolites and granites and to explore the tectonic environment in which they were emplaced. Characterization of the geochemical signatures of the Berlin rhyolite and the granite of Redgranite will expand our understanding of the early Proterozoic geologic history of Wisconsin.

METHODS

Hand-sized samples (RGQ01-2, RGQ01-3, RGQ01-5, and RGQ01-6) were collected from abandoned quarries at Redgranite and Berlin, Wisconsin. The Redgranite quarry is part of a park located in the center of the town of Redgranite, Wisconsin (lat: 44°02′40″N, long: 89°05′55″W). Samples from Redgranite were chosen on the basis of freshness and spatial

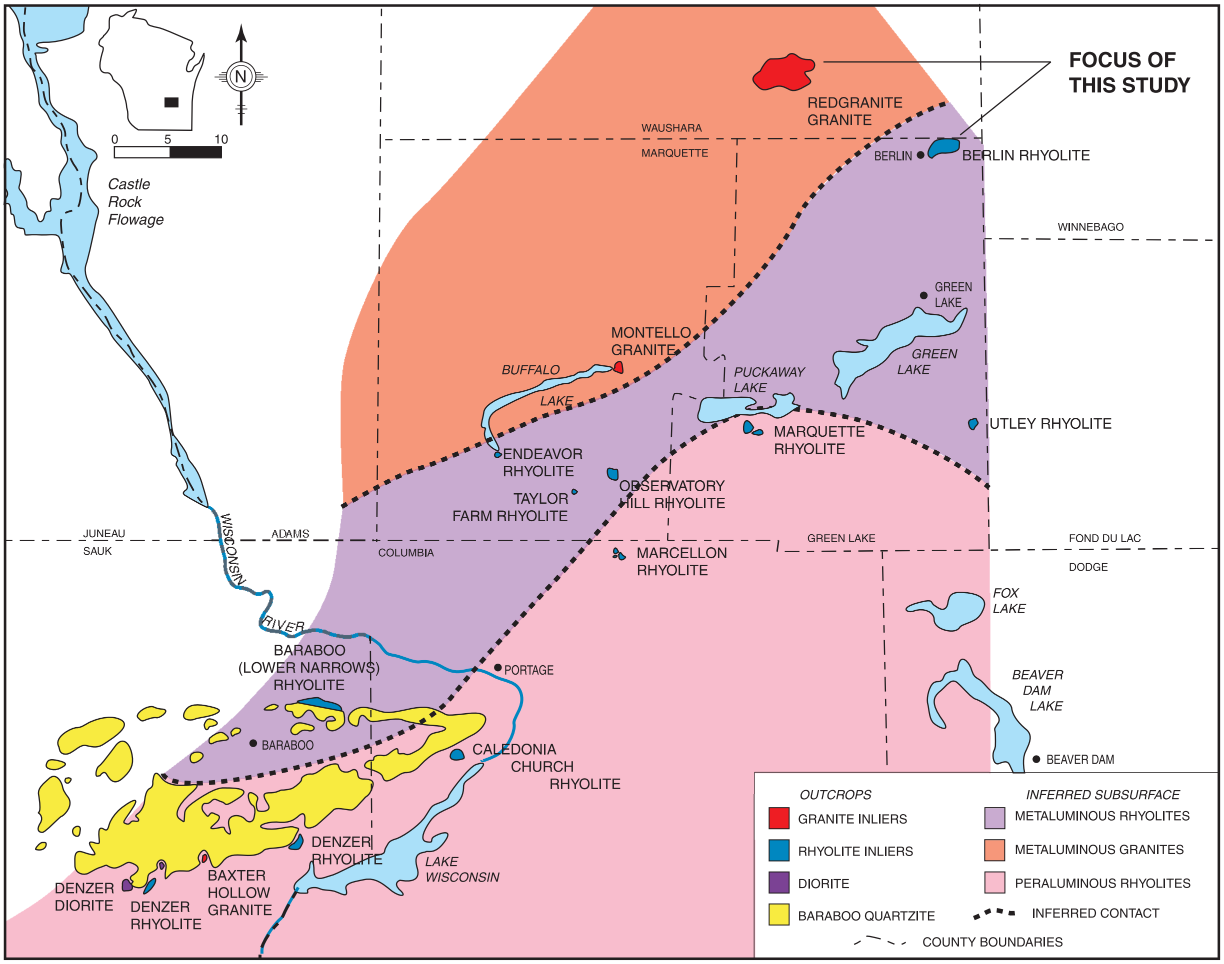


Figure 1. *Map showing granite and rhyolite outcrops in central Wisconsin (after Smith, 1983). Also mapped are the inferred contacts of metaluminous granites and metaluminous and peraluminous rhyolites in the subsurface, outcrops of known related diorites, and the Baraboo quartzite. Locations from which we collected granite and rhyolite for this study are indicated in the northeastern part of the map.*

distribution (taken at approximately 200 m intervals around the perimeter of the quarry). Recognized shear zones in the Redgranite quarry were avoided to minimize the effects of alteration and shear. Berlin rhyolite samples were collected from an abandoned quarry on the north–northwestern edge of Oakwood Cemetery along State Highway 91 in Berlin, Wisconsin (lat: 43°58′22″N, long: 88°55′55″W). Samples of the rhyolite were chosen as representative of the rock types exposed in this quarry and were part of a larger petrographic study to understand the effects of shearing (Hocker, 2002). Two fresh samples (BQS-12 and BQS-31) were collected at 20 to 30 m intervals along the north and east walls of the quarry to represent unsheared, unaltered rhyolites. The third sample (BSH-2-1) from Berlin was collected from a narrow (9 to 18 cm) shear zone within the rhyolite (tens of meters from other samples) to determine whether shearing and strain affected the geochemistry of the samples.

Redgranite and Berlin samples were analyzed by inductively coupled mass-spectrometry (ICP-MS) at Actlabs–Skyline in Tucson, Arizona, for major-, trace- and rare-earth-element geochemistry. Samples run for major- and selected trace elements were analyzed on a combination simultaneous sequential Thermo Jarrell-Ash ENVIRO II ICP or a Spectro Cirros ICP. All other trace- and rare-earth elements were spiked with an internal standard, and samples were analyzed using a Perkin Elmer SCIEX ELAN 6000 ICP-MS and proprietary sample-introduction methodologies. (Further information about geochemical preparation and analysis methods may be found on the Actlabs Web site: http://www.actlabs.com/methods_usa.htm.)

RESULTS

Hand-sample and thin-section analyses

The granite and rhyolite sampled for this study are part of the metaluminous suites defined by Smith (1983; fig. 1). Samples collected from Redgranite were texturally homogeneous, reddish-gray, fine-grained, and distinctly lacking in mafic minerals. We determined the modal mineralogy for the granite of Redgranite to be 30 to 40 percent quartz (0.2–1 mm), 45 to 55 percent perthitic alkali feldspar (0.2–5 mm), and 3 to 10 percent plagioclase (0.5–2 mm; table 1). Accessory minerals included primary apatite (1–2%; 0.05–0.1 mm), zircon–xenotime (1–2%; 0.1–0.2 mm), biotite (1–5%; 0.2–0.5 mm), and magnetite–ilmenite (1–3%; 0.3–0.5 mm) with secondary chlorite, sericite, hematite, and titanite composing the remainder of the rock (up to 4–6 modal percent; table 1). Quartz in Redgranite samples was significantly recrystallized (grains were small [0.2–1 mm] and showed irregular boundaries and undulatory extinction); alkali feldspar present in the groundmass was similar in size and morphology to recrystallized quartz and was also present as larger phenocrysts (2–5 mm) that showed perthitic texture. Grain boundaries on larger alkali feldspar grains also showed grain-boundary recrystallization. Biotite grains were significantly altered to chlorite, and magnetite–ilmenite grains generally had hematite and titanite rims in varying proportions (table 1). The alkali feldspar in the granite at Redgranite had a stippled appearance in plane-polarized light, suggesting that it was slightly altered to sericite–kaolinite (no more than 1–2% of each grain was altered).

The Berlin rhyolite (with the exception of sample BSH-2-1; see next paragraph) shows little visual variation in outcrop and is a reddish-brown ash-flow porphyry; we found similar proportions (10–15 modal percent each) of sub- to anhedral, pink, alkali feldspar phenocrysts (1–4 mm) and elongate “cigar-like” features (Smith, 1978; Tellock and Brinkmann, 1982) in a dark gray, quartzofeldspathic recrystallized groundmass. In thin section, the groundmass for the Berlin rhyolite consisted predominantly of fine-grained quartz (15–20 modal percent) and alkali feldspar (45–50 modal percent). Feldspar phenocrysts were sub- to anhedral in thin section, and grain-boundary migration recrystallization (Passchier and Trouw, 1996) was visible along the edges of the phenocrysts as fine, irregularly shaped quartz and feldspar grains. Few plagioclase grains (2–5 modal percent) were apparent; they were generally fine grained and recrystallized. In thin section, very fine-grained (0.05–0.5 mm) blue-green amphiboles (riebeckite?) defined a weak foliation and composed 5 to 10 modal percent of the rhyolite in most samples. Anhedral opaque minerals (magnetite–ilmenite) were also present in small amounts (up to 1 mm; 1–4 modal percent) and were altered in places to titanite. Elongate cigar-like features were present throughout the rhyolite and appeared to be predominantly ribbons of recrystallized quartz and alkali feldspar. These features have been variably interpreted to represent lapilli (Smith, 1978; Tellock and Brinkmann, 1982) or the result of shearing (Hocker, 2002).

One Berlin rhyolite sample (BSH-2-1), collected from a narrow shear zone, was lighter in color and showed shear indicators (such as pressure shadows) in outcrop (Hocker, 2002). Shear-zone orientations in this locality are parallel or subparallel to layering and foliation (strike: 65°–70°; dip: 77°N to near vertical; Tellock and Brinkmann, 1982). Major minerals were similar to those in unsheared Berlin rhyolite; quartz and alkali feldspar were similar in size and composed 80 to 90 modal percent of the rock. In thin section, however, mineralogical differences included the near absence of blue-green amphiboles and the presence of biotite as an alteration product of amphibole and magnetite (table 1). Plagioclase was also much less abundant than in other Berlin samples, composing only 1 to 2 percent of the modal mineralogy. Elongated ribbons of quartz and K-feldspar were more abundant in this sample and they defined the foliation.

Geochemical analyses

Results of geochemical analyses for the granite of Redgranite and Berlin rhyolite samples are shown in table 2. In general, the results confirmed visual estimates of homogeneity for both suites. Standard deviations for major elements show variations of less than 1 weight percent of the total sample, with only SiO_2 in Redgranite varying by more than 1 percent (table 2). Trace-element values for Proterozoic Wisconsin granites and rhyolites generally vary no more than 20 percent from one another (table 2). Rare-earth elements vary by 0 to 10 percent. Trace-element values for sample BSH-2-1 are consistently lower than other Berlin samples, in a few cases varying as much as 35 percent (table 2).

Elemental variations between granite of Redgranite and Berlin rhyolite samples are also relatively small; sheared Berlin rhyolite shows the greatest variation. In general, values for immobile elements, such as the high-field strength elements and middle to heavy rare-earth elements, are similar between the two unaltered suites of samples. Large ion lithophile elements are the only values that vary significantly between the two suites (table 2). These observations are reinforced in rare-earth and extended trace-element spider diagrams for these samples (figs. 2 and

Table 1. Modal* and normative mineralogy of samples

Modal mineralogy (volume %)

	Redgranite samples				Berlin samples		
Mineral	**RGQ01-2**	**RGQ01-3**	**RGQ01-5**	**RGQ01-6**	**BQS-31**	**BQS-12**	**BSH-2-1**
Quartz (fine grained)	—	—	—	—	15–20	15–20	15–20
Quartz (coarse grained)	35–40	30–35	35–40	35–40	10–15	10–15	10–15
Alkali feldspar (fine grained)	—	—	—	—	45–50	45–50	45–50
Alkali feldspar (perthitic, coarse grained)	50–55	45–50	50–55	50–55	10–15	10–15	10–15
Plagioclase	3–5	8–10	3–5	5–7	2–4	3–5	1–2
Biotite	3–5	1–2	1–2	2–3	—	—	3–5 (alteration)
Sodic amphibole	—	—	—	—	7–10	5–7	2–4
Apatite	1–2	1–2	1–2	1–2	<1	<1	—
Magnetite/ilmenite	1–2	2–3	2–3	2–3	1–3	1–3	2–4
Chlorite (alteration)	1–2	2–3	2–3	2–3	<1	<1	<1
Hematite (alteration)	<1	<1	<1	1–2	1–2	1–3	2–4
Titanite (alteration)	<1	1–2	<1	<1	—	—	—
Zircon/xenotime	<1	1–2	<1	<1	—	—	—
Fluorite	1–2	1–2	1–2	1–2	—	—	—

Normative mineralogy (wt %)

	Redgranite samples				Berlin samples		
Normative mineral	**RGQ01-2**	**RGQ01-3**	**RGQ01-5**	**RGQ01-6**	**BQS-31**	**BQS-12**	**BSH-2-1**
Quartz	31.29	38.22	29.59	32.08	29.38	29.36	31.93
Orthoclase	29.08	29.73	32.27	32.44	27.42	26.30	26.59
Albite	27.59	23.78	27.84	27.92	35.74	37.57	35.96
Anorthite	1.80	0.44	0.89	0.87	0.00	0.05	0.03
Diopside	0.35	1.25	1.51	1.44	1.35	0.50	0.00
Hypersthene	7.40	5.12	5.50	4.21	3.91	4.17	4.37
Magnetite	1.14	0.87	0.95	0.75	0.19	0.68	0.68
Ilmenite	0.30	0.33	0.35	0.35	0.26	0.26	0.27
Apatite	0.04	0.04	0.04	0.04	0.02	0.04	0.02
Corundum	0.00	0.00	0.00	0.00	0.00	0.00	0.32
Acmite	0.00	0.00	0.00	0.00	0.95	0.00	0.00

*Modal mineralogy estimated visually by thin-section examination.

3), showing slight variation between Redgranite and unaltered Berlin samples; these Berlin samples generally exhibit consistently lower values for large ion lithophile and some of the rare-earth elements. The sheared Berlin sample exhibits significant variation in rare-earth elements from both unaltered suites (fig. 2), showing greater depletion in light and middle rare-earth elements than in heavy rare-earth elements.

Petrogenetic modeling

Petrogenetic models, like those of Anderson and Cullers (1978), use trace- and rare-earth elements and their distribution coefficients to distinguish processes that may have generated geochemical variations among samples. For our models, we used the distribution coefficients for rhyolites published in Rollinson (1993; data from Arth, 1976; Pearce and Norry, 1979; Nash

Table 2. Geochemical analyses for samples of granite of Redgranite and Berlin rhyolite

	Redgranite samples						**Berlin samples**				
	RGQ01-2	**RGQ01-3**	**RGQ01-5**	**RGQ01-6**	**Mean**	**St Dev**	**BQS-31**	**BQS-12**	**BSH-2-1**	**Mean***	**St Dev***
Major-element analyses (in wt %)											
SiO_2	73.43	76.97	73.27	75.30	74.74	1.75	74.64	74.39	75.89	74.52	0.18
Al_2O_3	11.35	10.23	11.65	11.69	11.23	0.68	11.97	12.14	12.2	12.06	0.12
Fe_2O_3	5.74	4.38	4.80	3.80	4.68	0.82	3.33	3.42	3.41	3.38	0.06
MnO	0.06	0.05	0.05	0.05	0.05	0.01	0.06	0.04	0.02	0.05	0.01
MgO	0.08	0.09	0.08	0.08	0.08	0.01	0.04	0.04	0.04	0.04	0.00
CaO	0.47	0.40	0.55	0.53	0.49	0.07	0.32	0.15	0.02	0.24	0.12
Na_2O	3.26	2.81	3.29	3.30	3.17	0.24	4.35	4.44	4.25	4.40	0.06
K_2O	4.92	5.03	5.46	5.49	5.23	0.29	4.64	4.45	4.50	4.55	0.13
TiO_2	0.16	0.18	0.18	0.18	0.18	0.01	0.14	0.14	0.14	0.14	0.00
P_2O_5	0.02	0.02	0.02	0.02	0.02	0.00	0.01	0.02	0.01	0.02	0.01
LOI	-0.68	-0.65	-0.41	-0.19	-0.48	0.23	-0.15	-0.32	-0.18	-0.23	0.12
TOTAL	98.8	99.52	98.95	100.25			99.34	98.92	100.3		
$\frac{Al_2O_3}{CaO+Na_2O+K_2O}$	0.98	0.95	0.95	0.95			0.94	0.98	1.03		
Trace-element analyses (in ppm)											
Y	63	67	77	71	70	6.0	61	59	40	60	1.4
Sc	3	2	3	2	3	0.6	—	—	—	—	—
Be	3	4	5	5	4	1.0	4	3	2	4	0.7
Co	2	—	1	1	1	0.3	—	1	1	1	—
Cu	34	19	13	14	20	9.8	16	—	10	16	—
Zn	48	45	75	65	58	14.3	71	50	—	60	15.2
Ga	22	18	22	22	21	2.2	25	24	26	24	0.5
Ge	2	1	2	2	2	0.2	1	2	2	2	0.4
Rb	171	152	181	182	172	13.7	109	103	104	106	4.6
Sr	48	32	28	27	34	9.8	9	7	8	8	1.3
Y	64	65	75	73	69	5.8	61	59	43	60	1.8
Zr	274	300	339	307	305	26.8	374	359	397	366	10.9
Nb	36	33	39	36	36	2.4	28	25	29	27	2.1
Mo	3	—	4	3	3	0.5	6	—	—	6	—

	Redgranite samples						Berlin samples				
	RGQ01-2	RGQ01-3	RGQ01-5	RGQ01-6	Mean	St Dev	BQS-31	BQS-12	BSH-2-1	Mean*	St Dev*
Trace-element analyses (in ppm)											
Ag	—	0.8	0.6	—	0.7	0.1	—	—	—	—	—
Sn	10	10	8	12	10	1.5	10	5	9	7	4.069
Sb	3.4	1.9	1.8	1.0	2.0	1.0	—	0.7	0.6	0.7	—
Cs	2.3	1.4	2.1	2.5	2.1	0.5	0.6	—	0.6	0.6	—
Ba	397	359	392	408	389	21.2	106	103	109	104	2.03
Hf	9.4	9.7	11.6	9.9	10.2	1.0	10.2	9.9	10.2	10.0	0.25
Ta	3.1	2.8	3.4	3.0	3.1	0.3	2.0	2.0	2.0	2.0	0.00
W	1	2	2	2	2	0.7	—	—	—	—	—
Tl	1.0	0.9	1.6	1.4	1.3	0.3	0.5	0.5	0.9	0.5	0.03
Pb	92	56	93	52	73	22.3	11	20	22	15	6.11
Th	32.5	26.8	32.9	31.6	31.0	2.8	17.9	17.5	17.3	17.7	0.28
U	7.6	7.8	9.5	9.0	8.5	0.9	5.9	5.3	5.0	5.6	0.44
Rare-earth element analyses (in ppm)											
La	96.6	74.9	88.7	89.5	87.4	9.1	69.9	71.9	37.8	70.9	1.4
Ce	191.7	153.0	181.0	180.7	176.6	16.5	141.8	141.7	90.4	141.8	0.0
Pr	20.5	16.7	19.6	19.7	19.1	1.7	15.7	15.7	8.4	15.7	0.0
Nd	71.6	60.8	71.1	70.4	68.5	5.1	57.9	59.1	30.9	58.5	0.8
Sm	12.8	11.2	13.0	12.6	12.4	0.8	10.9	11.0	5.9	10.9	0.0
Eu	0.69	0.58	0.70	0.67	0.66	0.06	0.36	0.38	0.23	0.37	0.01
Gd	10.9	9.8	11.9	11.4	11.0	0.9	10.1	10.1	5.2	10.1	0.0
Tb	2.0	1.9	2.2	2.1	2.1	0.2	1.8	1.7	1.1	1.8	0.0
Dy	11.5	11.3	13.2	12.6	12.1	0.9	10.4	10.3	7.0	10.3	0.0
Ho	2.3	2.4	2.8	2.6	2.5	0.2	2.2	2.1	1.6	2.2	0.0
Er	6.8	7.1	8.3	7.7	7.5	0.6	6.4	6.3	5.1	6.4	0.1
Tm	1.11	1.14	1.38	1.28	1.23	0.12	1.03	1.00	0.88	1.02	0.02
Yb	7.0	7.1	8.6	7.8	7.6	0.7	6.4	6.5	5.9	6.5	0.0
Lu	1.02	1.06	1.24	1.16	1.12	0.10	0.98	0.97	0.89	0.97	0.01

*Mean and standard deviation calculated for unaltered/unsheared samples only.

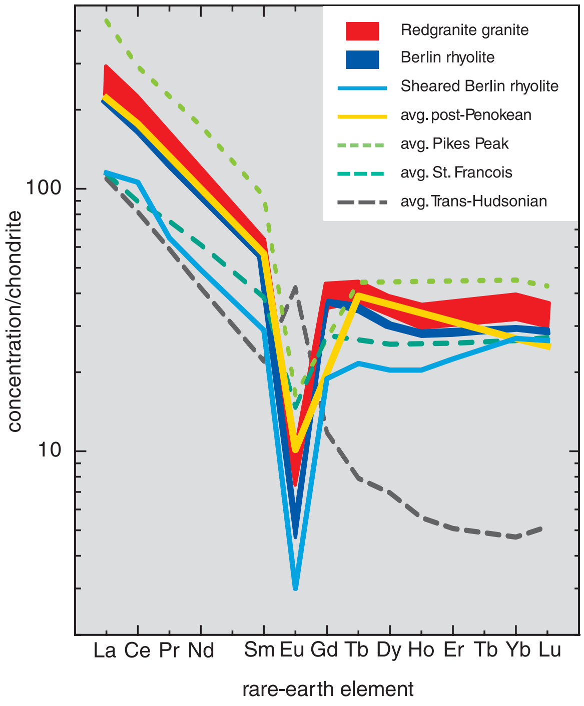


Figure 2. *Rare-earth-element spider diagram showing similarities among samples from the same suite and between samples from the two suites collected for this study. The red field covers the range of data for the granite of Redgranite; the dark blue field covers range of data for the Berlin rhyolite. Results for the Berlin rhyolite collected from a shear zone (sample BSH-2-1) are plotted separately (solid light blue line) for comparison and to illustrate the distinctiveness of this sample. Also plotted for comparison are published data for post-Penokean rocks (from Anderson and others, 1980), and three Proterozoic granitic–rhyolitic suites from a variety of tectonic settings, including continental rift (St. Francois, from Menuge and others, 2001), extensional–post-orogenic (Pikes Peak, from Smith and others, 1999) and continental arc rocks (Trans-Hudsonian, from Hollings and Ansdell, 2002). All samples are normalized to chondrite (Sun and McDonough, 1989).*

and Crecraft, 1985). On the basis of mineralogical differences, we modeled fractionation of plagioclase, apatite, and biotite using the equation for Rayleigh fractionation (Rollinson, 1993):

$$\frac{C_L}{C_O} = F^{(D-1)}$$

where C_L is the concentration in the remaining liquid, C_O is the concentration in parent magma, F is the fraction of melt remaining, and D is the distribution coefficient. In figure 4 we present four models of fractionation, two using an average of the Redgranite samples as the source (C_O) and two using an average of the two Berlin rhyolite samples that are most similar. Each of the source rocks was modeled for two values of F: F = 0.95 and F = 0.8 (that is, 5–20% crystallization).

Published geochemical data for comparison

Average geochemistry for other post-Penokean granites in Wisconsin (Anderson and others, 1980), two A-type granite–rhyolite suites from elsewhere in the United States (approximately 1.4 Ga, Pikes Peak, Colorado, Smith and others, 1999; approximately 1.1 Ga, St. Francois Mountains, Missouri, Menuge and others, 2001) and two suites of continental arc granites (approximately 1.8 Ga, Penokean orogen, Wisconsin, Van Wyck, 1995; approximately 1.8 Ga, Trans-Hudsonian orogen, Canada, Hollings and Ansdell, 2002) were used for comparison and were chosen on the basis of their Proterozoic ages and tectonic settings. Average rare-earth and trace-element values (normalized to chondrite; Sun and McDonough, 1989) for these suites are shown in figures 2 and 3. In figures 5, 6, and 7, we include trace-element values for published A-type granites that have major-element chemistries similar to the granite of Redgranite and the Berlin rhyolite.

DISCUSSION

Comparison of rhyolite and granite chemistry

Trace- and rare-earth-element data for suites from the granite of Redgranite and unaltered Berlin rhyolite suggest that the rock suites are chemically similar. On trace- and rare-earth-element diagrams (figs. 2 and 3), the suites of granite and rhyolite from Wisconsin follow the same general trends, showing negative anomalies in trace elements, such as Ba, K, Sr, P, Eu, Sm, and Ti. Europium and Sr depletions for both suites may be interpreted to be the result of residual plagioclase or plagioclase fractionation in the source of these high-silica rocks; lower values in the Berlin rhyolite may represent fractionation of a magma similar to that of the rocks at Redgranite prior to eruption. Barium and K anomalies suggest variable fractionation of alkali feldspar or biotite in these suites. Phosphorus, Sm, and Ti anomalies may indicate apatite (P) and biotite or amphibole (Sm and Ti) fractionation–re-

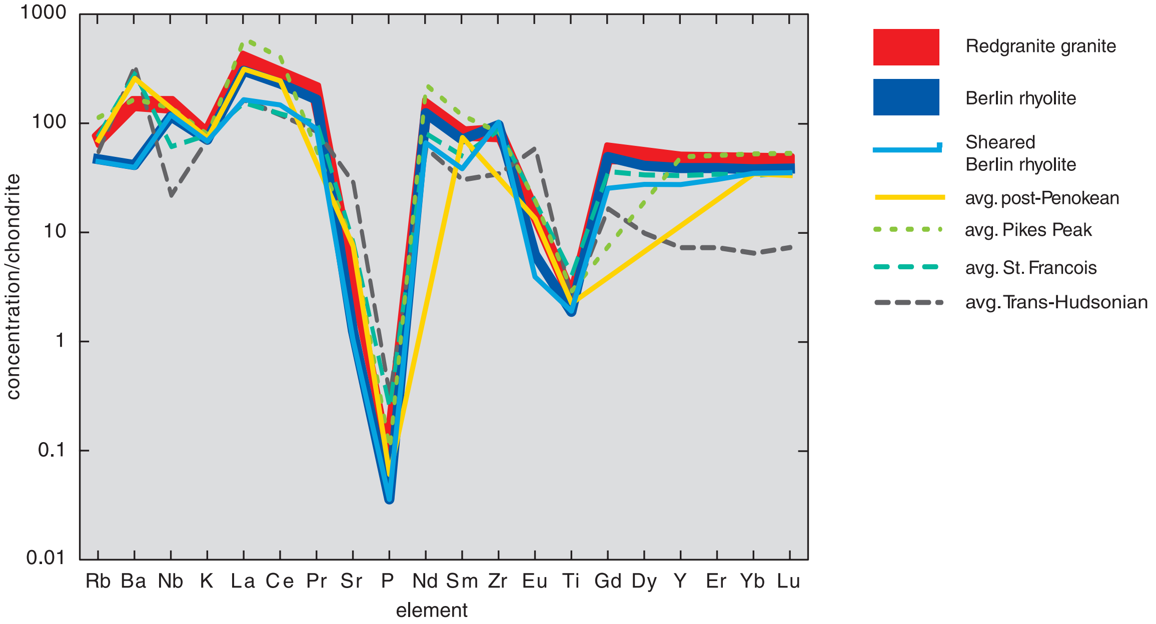


Figure 3. *Extended trace-element spider diagram showing similarities and differences among suites collected for this study. Granite of Redgranite, Berlin rhyolite, and sheared Berlin rhyolite are plotted separately as in figure 2. Average trace-element values for Proterozoic granite–rhyolite suites from post-Penokean rocks (from Anderson and others, 1980) and a variety of tectonic settings, including continental rift (St. Francois, from Menuge and others, 2001), extensional–post-orogenic (Pikes Peak, from Smith and others, 1999) and continental arc rocks (Trans-Hudsonian, from Hollings and Ansdell, 2002) are plotted for comparison. All samples are normalized to chondrite (Sun and McDonough, 1989).*

sidua in the source of Wisconsin granitoids.

Large ion lithophile elements, such as Rb, Ba, Nb, and K, show marked differences between the two suites; Berlin rhyolite is depleted in these elements relative to Redgranite rocks. Rare-earth elements are also consistently lower in the rhyolite relative to the granite. Differences in Rb, Ba, and K can be explained by slight variations in the modal proportions of potassium-bearing minerals such as K-feldspar and biotite in both suites. Rare-earth-element compositions may be controlled by the fractionation of biotite or other accessory minerals that preferentially take up these elements, such as apatite, zircon, or allanite (Rollinson, 1993); a larger Eu anomaly suggests fractionation of plagioclase. In thin section, examination of unaltered rhyolite revealed a smaller fraction of plagioclase, apatite, and primary biotite than in the granite, supporting this interpretation.

To test the hypothesis that fractional crystallization of a single parent magma was the main mechanism by which variations in these magmas were generated, we performed petrogenetic modeling on average compositions of the granite of Redgranite and the Berlin rhyolite. Because these rocks are so similar in major- and trace-element compositions, we modeled only slight fractionation (5% and 20%) of the granite to generate the compositional variations observed in Berlin rhyolite (fig. 4A). Variations in plagioclase and biotite contents are marked between the granite and rhyolite; also, the lack of apatite in the rhyolite suggests that it might be a fractionating phase. We modeled the fractionation of apatite, biotite, and plagioclase (5%, 25%, and 70% of the total fractionated solid, respectively; for example, Scaillet and others, 1995) on the basis of the mineralogy of the samples and on experimental data from high-silica granites (Piwinskii, 1968; Piwinskii and Wyllie, 1968; Scaillet and others, 1995). The trace-element values for the Berlin rhyolite fall within the modeled values for 5- to 20-percent fractionation of the granite of Redgranite (fig. 4A).

Similar rare-earth-element patterns between the granite and rhyolite samples suggested that the Berlin rhyolite is comagmatic with the granite of Redgranite and represents the granite's extrusive equivalent. Modeling indicated that slight differences in trace- and rare-earth-element values probably represent varying degrees of fractionation in the source magma prior

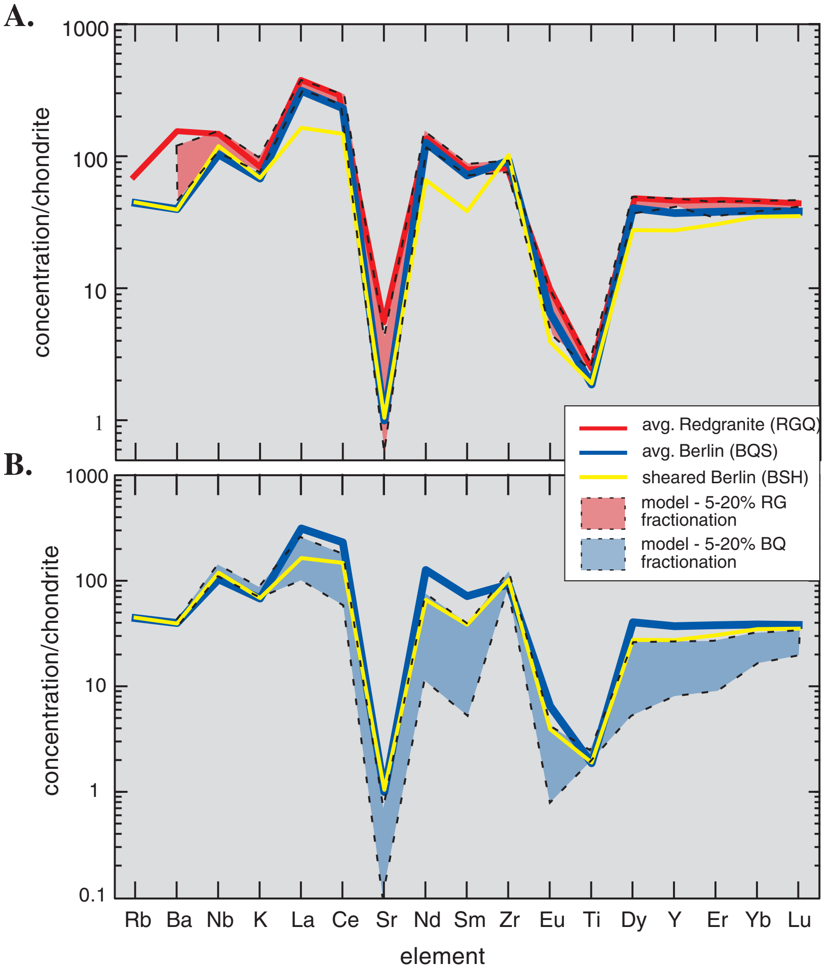


Figure 4. *Results of trace-element modeling of fractionation. A: Models of compositions produced (orange field in dashed line) by 5- to 20-percent fractionation of average Redgranite granites (red line; RGQ samples). Fractionating minerals included plagioclase, biotite, and apatite (based on modal mineralogy). Note the overlap of Berlin samples (blue line) with the compositions generated particularly by 5-percent fractionation (upper dashed line), suggesting small amounts of fractionation of granite produce rhyolite. B: Models of compositions produced (blue field in dashed line) by 5- to 20-percent fractionation of average Berlin samples (blue line; unsheared Berlin rhyolite samples [BQS]). Fractionating minerals included biotite, amphibole, apatite, and plagioclase (based on differences in modal mineralogy). The models generate compositions similar to the sheared rhyolite sample (BSH) through small amounts of fractional crystallization.*

to eruption and confirmed the hypothesis that Berlin rhyolite and Redgranite granites are related.

Origin of variations within the Berlin rhyolite

The rhyolite sample collected from the shear zone (BSH-2-1; Hocker, 2002) is chemically and mineralogically distinct from other rhyolites in this study. Although most trace-element concentrations are similar to unsheared Berlin rhyolite, the shear-zone sample has rare-earth-element values consistently lower than those of the Redgranite and the other Berlin samples collected for this study. Because the pattern is similar (fig. 2) and mobile elements such as Rb are not significantly depleted in the shear-zone sample relative to the other samples (fig. 3), it is difficult to interpret differences. We present two possibilities:

- Lower rare-earth-element values represent differing degrees of fractionation within Berlin rhyolite, with sample BSH-2-1 representing a more fractionated liquid.
- Fluids present during shearing have leached rare-earth elements from accessory minerals along grain boundaries as they dissolve and recrystallize (for example, Condie and Sinha, 1996; Rolland and others, 2003).

The shear-zone sample from Berlin (BSH-2-1) is visually lighter and has mineralogy distinct from the other Berlin samples, and the shear zone is parallel to layering foliation (Tellock and Brinkmann, 1982). Layering in this area is close to vertical (dipping 77°–90°; Tellock and Brinkmann, 1982; Hocker, 2002); thus, lateral variations in composition may represent different ash flows. Consequently, we tested the hypothesis that this sample represents eruption of a slightly more fractionated rhyolite using trace-element modeling. Our modeling simulated fractionation of the average fresh compositions exposed at Berlin and is based on differences in modal mineralogy (table 1) and fractionating phases in experiments (Piwinskii, 1968; Piwinskii and Wyllie, 1968; Scaillet and others, 1995). It was designed to illustrate the effects of 5- to 20-percent fractionation of biotite (10%), amphibole

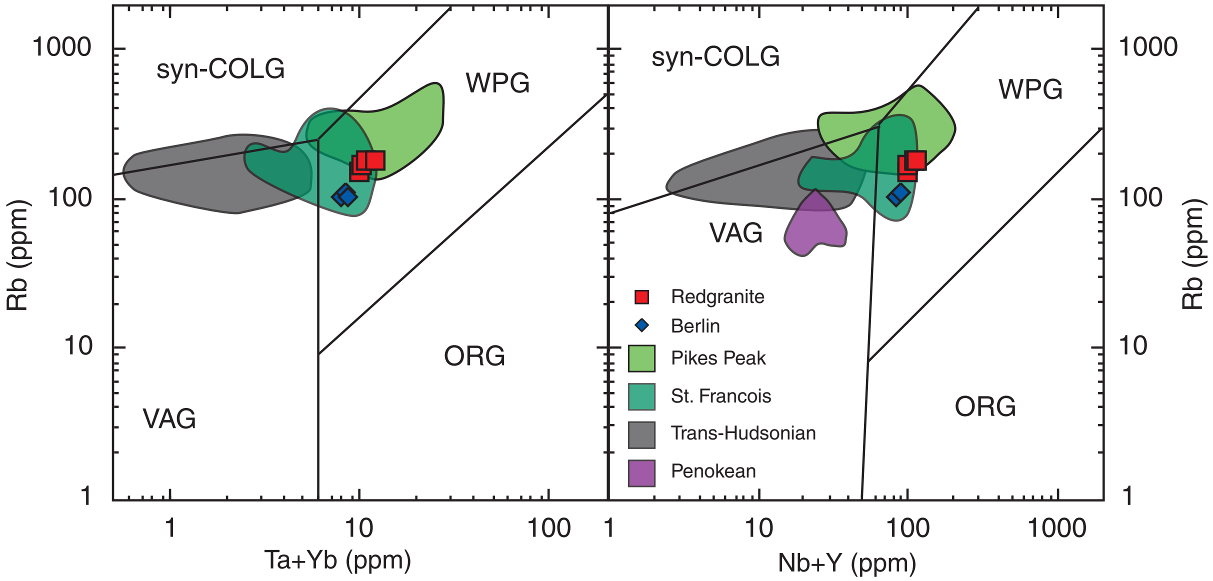


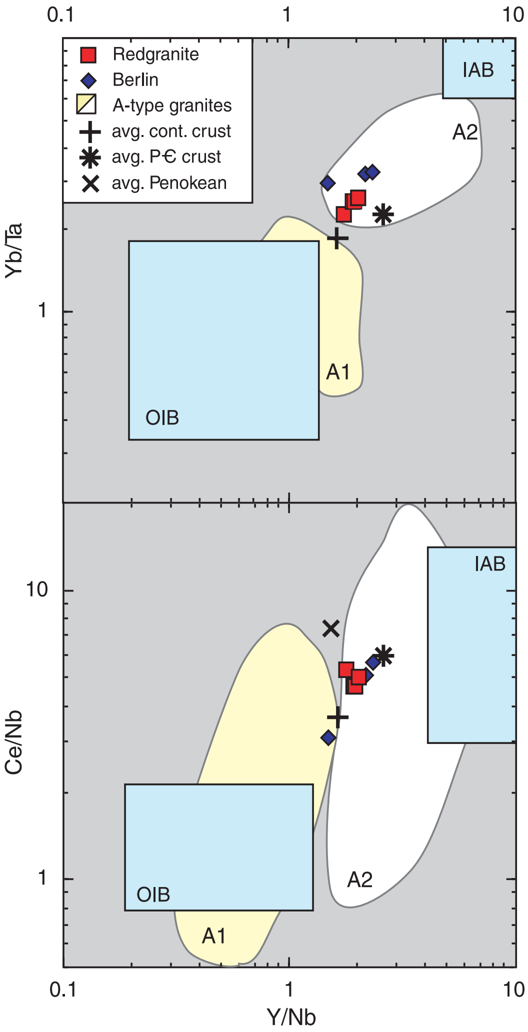
Figure 5. *Tectonic discrimination diagrams for A-type granites after Pearce and others (1984). Symbols for rocks from this study are red squares (Redgranite) and blue diamonds (Berlin rhyolite). Fields for published Proterozoic A-type granites (Pikes Peak, from Smith and others, 1999; St. Francois Mountains, from Menuge and others, 2001; Trans-Hudsonian arc rocks, from Hollings and Ansdell, 2002; Penokean rocks, from Van Wyck, 1995) are plotted for comparison. Note that all data for this study fall in the within-plate granite (WPG) field and that trace elements for Wisconsin data are most like other Proterozoic post-orogenic granites: St. Francois and Pikes Peak. Field abbreviations: VAG: volcanic arc granite; syn-COLG: syncollisional granite; ORG: ocean-ridge granite; WPG: within-plate granite. Data symbols are larger than analytical error.*

(15%), apatite (5%), and plagioclase (70%) (for example, Piwinskii, 1968) from an average of the two unsheared Berlin rhyolite samples (fig. 4B). Models of 5- to 20-percent fractionation of the modes listed above from unsheared rhyolite compositions generate patterns that are sufficiently similar to the Berlin shear-zone sample (fig. 4B), which suggests that fractionation may have generated the variation and that outcrops sampled may represent a sequence of comagmatic eruptions that recorded fractionation in the source magmas.

However, it cannot be overlooked that sample BSH-2-1 has experienced some deformation, demonstrated in shear sense indicators and significant recrystallization. Similarities in fluid mobile elements, such as Rb, between the sheared and fresh Berlin rhyolite samples suggest that hydrothermal alteration may not have played a significant role in changing the geochemistry of these rocks. Nonetheless, recent studies in quartzofelspathic rocks (Condie and Sinha, 1996; Rolland and others, 2003) suggested that fluids present during shearing may alter the rare-earth-element composition of similar rocks. Accessory minerals (such as zircon, xenotime, apatite, and possibly biotite or amphibole) that are rich in rare-earth elements may be dissolved or leached along grain boundaries as a result of shearing (for example, Condie and Sinha, 1996; Rolland and others, 2003). The lower rare-earth-element values (more so in light rare-earth elements than in heavy rare-earth elements; fig. 2) in the sheared rhyolite sample are consistent with this interpretation. However, with only three samples, it is difficult to evaluate the validity of either fractionation or shearing as a mechanism to generate variations within the rhyolite. More detailed work on structures, spatial relationships, and mineralogical differences of these rocks needs to be completed to determine the dominant mechanism that produced chemical differences.

Source and tectonic affinities of granite and rhyolite

The characterization of these A-type rocks as metaluminous (fig. 1; table 2; Smith, 1978, 1983) indicates that these rocks may represent partially melted arc-related (calc-alkaline) rocks associated with post-orogenic collapse. Experimental melting of calc-alkaline granitoids at low pressures produces chemical compo-



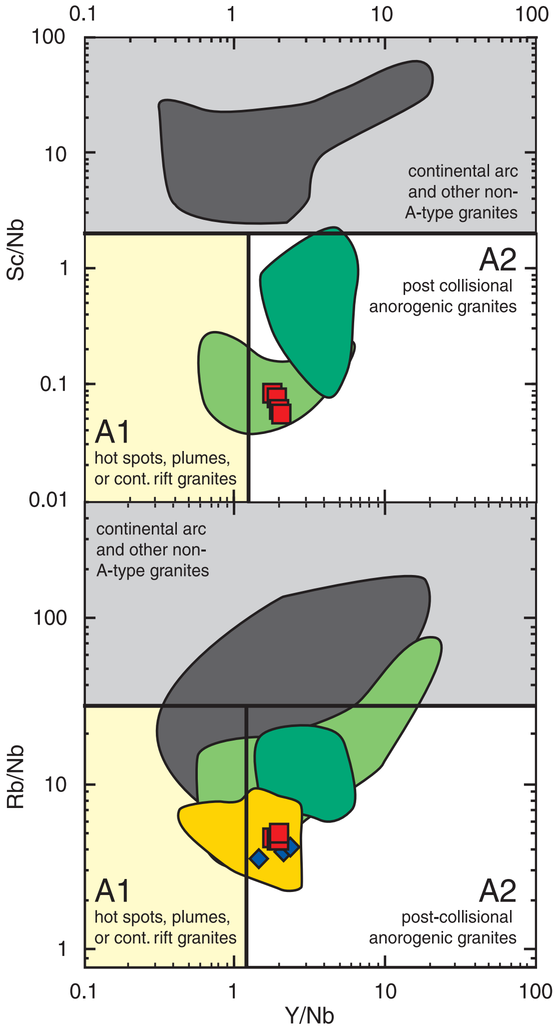


Figure 6. *Plots designed to discriminate source (after Eby, 1990). Wisconsin rocks are represented by filled squares (granite of Redgranite) and filled diamonds (Berlin rhyolite). Also plotted are continental crust (black cross; from Taylor and McLennan, 1985), average Penokean crust (black X; from Van Wyck, 1995), and average Precambrian continental crust (black asterisk; from Rudnick and Fountain, 1995). Gray fields represent A1- and A2- (labeled) type granites of Eby (1990) and are used for comparison. Wisconsin data fall in A2 field, between ocean-island basalt (OIB) and island arc basalt (IAB) fields on plots of Y/Nb vs. Yb/Ta and Y/Nb vs. Ce/Nb, among average crustal values, and are very similar to average Precambrian crust. Data symbols are larger than analytical error.*

Figure 7. *Diagram for discrimination between A-type granites after Eby (1992). On the diagram, solid line represents distinction between A1 and A2 granites: Y/Nb ratios of 1.2 (Eby, 1992). The A1 field (left) represents granites associated with hotspots, plumes, or continental rifts; the A2 field (right) represents granites associated with post-collisional or extensional settings (Eby, 1990, 1992). The long rectangular field represents granites associated with orogenic settings. Note that Wisconsin A-type granites are type A2 and are most like Pikes Peak (Smith and others, 1999). Data symbols are larger than analytical error.*

sitions similar to other metaluminous A-type granites (Patiño Douce, 1997). The generation of metaluminous A-type granite and rhyolite by low-pressure partial melting of arc-related granitoids is consistent with the geologic history of this part of Wisconsin and suggests that the rocks in this study may have been generated during the collapse of thickened Penokean crust.

To help understand the origin and tectonic setting for these A-type granites, we show them on several discrimination diagrams (figs. 5, 6, and 7). Diagrams that plot Rb against the sum of two incompatible elements (fig. 5) are designed to characterize the tectonic setting in which A-type granites may be emplaced (Pearce and others, 1984). Although some may argue that Rb can be relatively mobile during alteration, these diagrams have been reevaluated and still seem to give excellent results when used to discriminate tectonic setting of A-type granitoids (Förster and others, 1997). Two other diagrams (fig. 6) use trace-element ratios to distinguish between sources for two distinct A-type compositions—A1, a mixture of average crust (Taylor and McLennan, 1985; Rudnick and Fountain, 1995; Van Wyck, 1995) and mantle sources for ocean islands (OIB, fig. 6) and A2, a mixture of average crust and mantle sources for island arcs (IAB, fig. 6) (Eby, 1990). Ratios of Y, Sc, and Rb to Nb can also be used to distinguish among A-type rifting environments (fig. 7; Eby, 1992). On these diagrams (fig. 7), A1-type granitoids (Y/Nb <1.2) were generated in hotspots, plumes, or continental rift zones; A2-type granitoids (Y/Nb >1.2) are associated with post-collisional settings (Eby, 1990, 1992).

Low pressure melting during extension may be initiated by a number of mechanisms in a variety of tectonic settings (for example, hotspots, plumes, continental rift zones, ocean ridges, and post-collisional zones; Pearce and others, 1984). The addition of the new data about granite of Redgranite and Berlin rhyolite on these diagrams confirmed the hypothesis that low-pressure melting–extension contributed to the generation of A-type granites in east-central Wisconsin. On diagrams of Pearce and others (1984), A-type granitoids from Wisconsin fall in the within-plate-granite field (WPG, fig. 5) and thus can be associated with either plume–hotspot related or post-orogenic extension (Pearce and others, 1984).

The distinction between generation of A-type granites in hotspot and post-orogenic settings can be made by distinguishing source (fig. 6) and tectonic affinity (fig. 7). Data from Redgranite and Berlin rocks plot in the A2-type granitoid field (fig. 6)—commonly associated with melting of crust and arc-related basalts (IAB, fig. 6; thought to represent crust generated during collision; Eby, 1990). Trace-element ratios from this study are very similar to average crustal compositions (Taylor and McLennan, 1985; Rudnick and Fountain, 1995; Van Wyck, 1995; fig. 6), suggesting that generation of A-type granites in Wisconsin involved extension and melting of a significant part of the pre-existing crust (Eby, 1990). Plots distinguishing tectonic setting for granitoids (fig. 7) further suggest the involvement of reworked thickened arc crust in the generation of the Wisconsin granites and rhyolites. Redgranite and Berlin samples collected for this study plot in the A2 field (fig. 7) and can be correlated with rifting in post-collisional tectonic settings (Eby, 1990, 1992).

The metaluminous character (table 1), similarity to average continental crust (fig. 6), and characterization of these rocks as the result of within-plate post-collisional extension (figs. 5 and 7) are consistent with the geologic history of eastern and central Wisconsin (for example, Holm and others, 2005). We interpreted the new data to indicate that low pressure melting of multiple crustal sources, particularly the extension of thickened crust that was generated during subduction and accretion associated with the Penokean Orogeny, contributed to the generation of these high-silica rocks.

Comparison of Wisconsin rocks to rocks of known tectonic affinities

Average trace- and rare-earth-element patterns and trace-element ratios for published A-type and arc suites (post-Penokean, Anderson and others, 1980; St. Francois, Menuge and others, 2001; Pikes Peak, Smith and others, 1999; Trans-Hudsonian, Hollings and Ansdell, 2002; and Penokean, limited data from Van Wyck, 1995) are plotted with geochemical analyses from this study in figures 2, 3, 5, and 7 to confirm our interpretation that these rocks formed in a post-collisional extensional regime. Normalized trace- and rare-earth-element values from this study overlap completely with average post-Penokean data (figs. 2 and 3), confirming previous characterization as post-Penokean. Discrimination diagrams also suggest correlation between granitoids from this study, published post-Penokean geochemistry, and other post-collisional granites (St. Francois and Pikes Peak; figs. 5 and 7). The rocks analyzed for this study show neither overlap with Penokean crustal values nor with other Proterozoic continental arc data (figs. 5, 6, and 7), confirming that these rocks were probably not directly associated with the Penokean Orogeny. Similarities in chemical composition between the granite of Redgranite, the Berlin rhyolite, other post-Penokean rocks and rocks from Pikes Peak batholith (thought to be the result of post-orogenic activity; Smith and others, 1999) support the conclusion that the post-Penokean A-type granitoids are likely post-orogenic and associated with extension.

It is interesting to note that on figure 5 many post-collisional A-type granitoids straddle the line between the areas shown as within-plate granites and volcanic arc granites (WPG and VAG). Published data from other post-orogenic A-type rocks (for example, post-Penokean, Anderson and others, 1980; Van Wyck, 1995; Pikes Peak, Smith and others, 1999) also straddle the division between the A1- and A2-type rocks (fig. 7; Eby, 1992). The proximity of the data for this study to the VAG field and the overlap of other post-collisional suites on A-type discrimination diagrams (figs. 5 and 7) emphasize the complexity of the geochemistry associated with A-type igneous rocks. The close relationship of A-type geochemistry to WPG and VAG settings suggests that Penokean (arc) crust may have melted to generate the A-type granitoids of this study, imparting components of its geochemistry to the resulting rocks (Patiño Douce, 1997). Additionally, although the bulk of geochemistry for post-collisional A-type rocks fall in the A2 field, some data from A-type granitoids “spill over” into A1 field (fig. 7). The straddling of data across the dividing line for distinct rifting environments may also suggest a complex evolution of post-collisional A-type granitoids—transitioning from collapse and extension of thickened arc crust (A2-type granitoids) to continental rift (A1 type) settings (Rogers and Greenberg, 1990).

CONCLUSIONS

The geochemistry of the Berlin rhyolite and the granite of Redgranite suggests that they are likely comagmatic and derived from the same source. Slight variations in some trace elements suggest that the Berlin rhyolite represents a more fractionated phase of the granite of Redgranite. Trace-element modeling of fractionation of the granite of Redgranite suggests that 5- to 20-percent fractionation can generate compositions similar to that of unaltered Berlin rhyolite. We concluded that Berlin rhyolite is likely the extrusive equivalent of the granite exposed in Redgranite.

Within the sampled exposure of Berlin rhyolite, one sample showed consistently lower values for many of the rare-earth and other immobile elements. These geochemical variations can be explained by one of two mechanisms: (1) varying degrees of fractionation within multiple flows or (2) hydrothermal alteration and/or shearing. Five- to 20-percent fractionation of unaltered Berlin rhyolite compositions can generate observed variations. However, because the sample with the most significant variation was taken in the proximity of a shear zone, it is also possible that shearing of high-silica rocks has produced significant decreases in rare-earth-element concentrations by alteration of rare-earth-element bearing minerals (for example, zircon, allanite, and so forth; Condie and Sinha, 1996; Rolland and others, 2003) and dissolution along grain boundaries (for example, Condie and Sinha, 1996). Although rare-earth-element bearing minerals are present in some of the samples, more work needs to be done to assess the contributions of alteration and/or fractionation to geochemical variations in the Berlin rhyolite.

The A-type granites in south and east-central Wisconsin likely had a complex tectonic history involving extension and melting (and possibly remelting) of crust. The metaluminous granitoids of Redgranite and Berlin rhyolite, like other metaluminous A-type granites, likely resulted from decompression melting of calc-alkaline rocks associated with collision (Patiño Douce, 1997). Tectonic discrimination diagrams support low pressure melting of thickened arc crust; the granite of Redgranite and Berlin rhyolite plot in the WPG (fig. 5; Pearce and others, 1984) and A2 (figs. 6 and 7; Eby, 1990, 1992) fields, commonly associated with post-orogenic or post-collisional extensional settings (Rogers and Greenberg, 1990). We concluded that melting during extension of thickened Penokean crust generated the A-type rocks of Redgranite and Berlin (Eby, 1990, 1992).

The Proterozoic history of central Wisconsin supports interpretation of these granitoids as post-orogenic and associated with collapse of crust thickened during Penokean accretion. Although subduction probably renewed immediately following the orogeny, the angle of the subducting slab steepened between 1,775 and 1,750 Ma (Holm and others, 2005). Slab rollback reduces horizontal stresses, and thus stresses in the overthickened Penokean crust may have shifted from dominantly compression to extension (Holm and others, 2005). Geon 17 granites and rhyolites of this area show a distinct change from the calc-alkalic (arc-like) activity of the Penokean Orogeny to post-collisional A-type volcanism and plutonism (Smith, 1983). It is likely that after the orogenic event associated with the Penokean, extension and rifting began to occur, generating the post-collisional A-type granite and rhyolite that crop out throughout south and east-central Wisconsin today.

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