Geochemistry of the Late Mesoproterozoic Mount Eve granite suite: Implications for Late to post-Ottawan tectonics in the New Jersey–Hudson Highlands

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ABSTRACT

The Mount Eve granite suite is a postorogenic, A-type granitoid suite that consists of several small plutonic bodies occurring in the northwestern New Jersey-Hudson Highlands. Mount Eve granite suite rocks are equigranular, medium- to coarsegrained, quartz monzonite to granite, consisting of quartz, microperthite, and oligoclase, with minor hornblende, biotite, and accessory zircon, apatite, titanite, magnetite, and ilmenomagnetite. Whole-rock analyses indicate that Mount Eve granite is metaluminous to slightly peraluminous (ASI or aluminum saturation index, A/CNK or $Al_2O_3/(CaO + Na_2O + K_2O) = 0.62$ to 1.12) and has A-type compositional affinity defined by high K₂O/Na₂O (1.4 to 2.8), Ba/Sr (3 to 12), FeO₄/(FeO₄+MgO) (0.77 to 0.87), Ba (400 to 3000 ppm), Zr (200 to 1000 ppm), Y (30 to 130 ppm), Ta (2.5 to 6 ppm), total rare earth elements or REE (300 to 1000 ppm), low MgO (<1 wt%), Cr and Ni (both <5 ppm); and relatively low Sr (200 to 700 ppm). Variably negative Eu anomalies (Eu/Eu* = 0.13 to 0.72, where Eu/Eu* is the chondrite-normalized ratio of measured Eu divided by the hypothetical Eu concentration required to produce REE pattern with no Eu anomaly) and systematic decreases in Sr, Ba, Zr, Hf, Nb, and Ta, with constant total REE content and increasing Ce/Yb and SiO₂ contents, suggest crystallization of feldspars + zircon + titanite \pm apatite. Possible modes of origin include dry melting of charnockitic gneisses or Fe-rich mafic to intermediate diorites within the Mesoproterozoic basement. Two possible tectonic mechanisms for generation of Mount Eve granite include (1) residual thermal input from a major lithospheric delamination event during or immediately after peak Ottawan orogenesis (1090–1030 Ma) or (2) broad orogenic relaxation between peak Ottawan and a late (1020–1000 Ma) high-grade, right-lateral transpressional event.

Keywords: granite, A-type, Grenville, New Jersey Highlands, tectonics

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INTRODUCTION

Within the Grenville Province of the central and northern Appalachians and the Adirondack Highlands (Fig. 1), there are several examples of weakly to undeformed, late- to postorogenic plutonic rocks that were emplaced sporadically over a period of ~50 to 100 million years and that postdate the major pulse of deformation and metamorphism associated with the Ottawan orogeny (1090–1030 Ma, as defined by Rivers, 1997; McLelland et al., 1996, 2001). These rocks not only place important constraints on the lower age limit for the main pulse of Ottawan orogenic events, but also provide clues to tectonic processes occurring during final stages of the Grenville orogenic cycle. In the Adirondack Highlands, regional lithospheric delamination associated with orogenic collapse of overthickened crust has been proposed to explain large volumes of syn- to Late Ottawan granitoid rocks (Lyon Mountain Gneiss; Whitney and Olmstead, 1988) emplaced during the interval between 1060 and 1045 Ma (McLelland et al., 2001). Younger suites of volumetrically minor and sporadically distributed granitoids were also emplaced in the Adirondacks (McLelland et al., 1996, 2001), the Green Mountains (Ratcliffe et al., 1991), and the New Jersey–Hudson Highlands (Drake et al., 1991; Gates and Krol, 1998; Gates et al., 2001a) during the interval between 1035 and 960 Ma. These younger plutonic suites have received much less attention in the past because of their relatively small volumes and limited areal extent. However, interest in these rocks recently has been renewed due to the important role they play in constraining the



Figure 1. Regional map showing the location of Middle Proterozoic (Grenville-age) basement in eastern North America. Labeled areas include the (1) Long Range massif; (2) Adirondack massif; (3) Green Mountains massif; (4) Berkshire massif; (5) Reading Prong; (6) Honey Brook upland; (7) Baltimore Gneiss antiforms; (8) Blue Ridge Province, including the Shenandoah (8a) and French Broad (8b) massifs; (9) Goochland terrane; (10) Sauratown Mountains anticlinorium; and (11) Pine Mountain belt. Map from Tollo et al. (2004) with modifications after Rankin et al. (1989b).

timing of culminating events of the Ottawan orogeny (e.g., McLelland et al., 2001). Recent recognition of Late to post-Ottawan, high-grade, ductile transpressional shear zones in the central Adirondack Highlands and the New Jersey–Hudson Highlands (Gates, 1995, 1998) has also raised the possibility that this younger plutonic activity could be related to localized crustal extension associated with ductile shearing rather than regional-scale lithospheric delamination.

The Mount Eve granite suite is composed of thirty small (0.2 to 5 km²), stocklike bodies of undeformed quartz monzonite to granite (Drake et al., 1991) that intrude high-grade Middle Mesoproterozoic basement gneisses of the New Jersey-Hudson Highlands portion of the Reading Prong (Figs. 1 and 2). One of the larger plutons has a U-Pb zircon crystallization age of 1020 ± 4 Ma (Drake et al., 1991), and thus is part of the Late to post-Ottawan plutonic granitoid suite mentioned earlier. Present knowledge of the Mount Eve granite suite comes from geologic mapping by Offield (1967), Drake et al. (1991), and Volkert and Drake (1999). Previously published data for the Mount Eve granite suite include two major-element analyses reported in Drake et al. (1991). This paper presents a more detailed study of the geochemistry of the Mount Eve granite suite in order to elucidate its petrogenesis and implications for Late to post-Ottawan tectonics within this region of the Grenville Province. Based on new data presented here, it has been found that the Mount Eve granite suite has strong A-type chemical affinities and represents partial melting of metaigneous Mesoproterozoic basement gneisses. The restricted spatial extent, small volumes (~2 to 5 km3), and temporal association with other volumetrically minor granitoid rocks exposed elsewhere in the New Jersey-Hudson Highlands supports a production mechanism for the Mount Eve granite suite that is related to the onset of a high-grade, dextral transpressional shearing event that occurred during the waning stages (ca. 1020-1000 Ma) of Grenville orogenesis.

REGIONAL GEOLOGIC SETTING

The Mount Eve granite suite is located in northwestern New Jersey and southeastern New York ~60 km northwest of New York City (Fig. 2) in the Mesoproterozoic New Jersey-Hudson Highlands. The New Jersey Highlands, along with the physically contiguous Hudson Highlands of New York state and similar rocks extending into eastern Pennsylvania, are collectively called the Reading Prong, which is one of the largest of several Grenville-age (1300 to 1000 Ma) basement massifs within the core of the Appalachian orogenic belt of eastern North America (Figs. 1 and 2; Rankin, 1975). These basement massifs lie outboard (east) of the main Grenville Province in eastern Canada and record variable amounts of post-Mesoproterozoic metamorphic and deformational overprint (e.g., Rankin et al., 1989a; Gates and Costa, 1998). The New Jersey-Hudson Highlands display evidence of only brittle deformation concentrated along narrow, reactivated Mesoproterozoic shear zones due to Late Paleozoic compression and Mesozoic rifting (Gates, 1995, 1998), and thus have a well-preserved record of Grenville-age metamorphism and deformation.

Rocks of the New Jersey–Hudson Highlands consist of a complex assemblage of paragneiss, orthogneiss, marbles, and intrusive granitoid rocks that were highly deformed and metamorphosed at upper amphibolite- to hornblende-granulitefacies conditions during Grenville orogenesis (Volkert and Drake, 1999). The oldest rocks (of unknown age) in the region are a suite of quartzofeldspathic orthogneiss that include very light-colored, biotite-hornblende-quartz-plagioclase gneiss, charnockitic (orthopyroxene-bearing) quartz diorite, and interlayered amphibolite, collectively called the Losee metamorphic suite (Volkert and Drake, 1999). These rocks are interpreted to represent a continental volcanic-plutonic arc suite of calc-alkaline rocks (Volkert and Drake, 1999). Rocks of the Losee metamorphic suite are lithologically and chemically very similar to tonalitic and charnockitic gneisses found in the southern Adirondacks (McLelland and Chiarenzelli, 1990) and to the Mount Holly Complex in the Green Mountain massif in Vermont (Ratcliffe et al., 1991), which have been dated at ca. 1350 to 1300 Ma. A thick sequence of supracrustal paragneiss, the age of which is not well constrained but is older than 1100 Ma, is interpreted to unconformably overly the Losee metamorphic suite (Volkert and Drake, 1999). These rocks consist of a heterogeneous package of quartzofeldspathic gneiss, calc-silicate rocks, quartzite, and marble. Although there are few constraints with which to construct a detailed depositional history for the supracrustal sequence, Volkert and Drake (1999) used detailed geochemical data to suggest that these rocks were deposited in an evolving system of continental- to oceanic-arc extensional basins. Amphibolite occurs interlayered with all Late Mesoproterozoic rocks of the New Jersey Highlands (Volkert and Drake, 1999), and the geochemical data available support the interpretation that most amphibolite is of metaigneous origin, representing metamorphosed mafic volcanics with minor occurrences of metamorphosed dikes and plutonic rocks.

Two A-type granitoid suites intrude the Losee metamorphic suite and associated supracrustal paragneisses: the Vernon Supersuite (Volkert and Drake, 1998; Volkert et al., 2000) and the Mount Eve granite suite (Drake et al., 1991). The Vernon Supersuite granitoids underlie ~50% of the New Jersey Highlands and consist of the Byram intrusive suite and the Lake Hopatcong intrusive suite. Conventional multigrain U-Pb geochronology by thermal ionization mass spectrometry (TIMS) on air-abraded zircon fractions extracted from a single sample of the Byram intrusive suite yield upper-intercept ages ranging from 1088 ± 41 Ma to 1122 ± 53 Ma (Drake et al., 1991). Volkert et al. (2000) obtained whole-rock Rb-Sr isochron ages of 1116 \pm 41 Ma (⁸⁷Sr/⁸⁶Sr_i = 0.70389) for the Byram intrusive suite and 1095 ± 9 Ma (87 Sr/ 86 Sr₁ = 0.70520) for the Lake Hopatcong intrusive suite based on six individual samples from each suite collected from various localities. The Vernon Supersuite rocks all possess well-developed, high-grade metamorphic



fabrics (e.g., gneissic layering) and field relations (e.g., concordant contacts and fold phases and geometries similar to those of surrounding Mesoproterozoic rocks) that indicate these rocks are pre- or syntectonic plutons deformed and metamorphosed during the Ottawan orogeny (Volkert et al., 2000). These granitoids are chemically similar to other plutonic rocks of A-type chemical affinity with ages of 1180-1060 Ma from other parts of the Grenville orogen, including southeastern Canada (Easton, 1986; Lumbers et al., 1990; Davidson 1995), the Adirondacks (Wasteneys et al., 1999; McLelland et al., 2001), the northern Blue Ridge (Tollo and Aleinikoff, 1996; Hughes et al., 1997), and the surrounding Hudson Highlands (Drake et al., 1991; Verrengia and Gorring, 2002). Rocks of Late to post-Ottawan age (<1030 Ma) are volumetrically minor in the New Jersey-Hudson Highlands, but consist of the Mount Eve granite (1020 ± 4) Ma; Drake et al., 1991), the Canada Hill granite $(1010 \pm 4 \text{ Ma};$ Aleinikoff and Grauch, 1990), the Lake Tiorati diorite (1008 \pm 4 Ma; Gates et al., 2001a), and a suite of very late, crosscutting pegmatite dikes (ca. 1000-915 Ma; Gates and Krol, 1998). Similar plutonic activity of Late to post-Ottawan age has been documented elsewhere in the Adirondacks (ca. 1035 Ma, Lyonsdale Bridge pegmatite; 935 Ma, Cathead Mountain leucogranite; McLelland et al., 2001) and in the Green Mountain massif (ca. 960 Ma, Stamford Hill rapakivi granite; Ratcliffe et al., 1991).

THE MOUNT EVE GRANITE SUITE

The Mount Eve granite suite consists of about thirty (0.2 to 5 km² each) stocklike bodies of pink to light-gray, massive, medium- to coarse-grained quartz monzonite to granite (International Union of Geological Sciences classification [Streckeisen, 1973], based on modal data from Drake et al., 1991). Based on normative feldspar content calculated from wholerock major-element analyses reported here, all Mount Eve granite suite samples are classified as granites (Fig. 3). Classification based on normative feldspar was used because detailed point counting of the samples reported in this paper was not undertaken. These intrusive rocks crop out over a over small area (~40 km²) in the northwestern part of the New Jersey-Hudson Highlands extending ~20 km from near Glenwood, New Jersey, northward to Big Island, New York (Fig. 2). Drake et al. (1991) obtained a U-Pb upper-intercept age of 1020 ± 4 Ma on three air-abraded zircon separates from one sample collected near Mount Eve, New York (Fig. 2), using conventional multigrain TIMS techniques. Except for magmatic flow fabrics documented by Drake et al. (1991) near intrusive contacts, rocks of



Figure 3. Plot of normative anorthite (An)–albite (Ab)– orthoclase (Or) for the Mount Eve granite suite samples analyzed in this study (filled squares) and two analyses from Drake et al. (1991) (unfilled squares). Diagram after O'Connor (1965).

the Mount Eve granite suite lack a penetrative deformation fabric or evidence for metamorphic recrystallization (Fig. 4). Mapping by Drake et al., (1991) and Volkert and Drake (1999) clearly demonstrates that the granitoid intrusions are discordant to compositional layering, foliation, and folds developed in the surrounding Mesoproterozoic (Grenville-age) country rocks at both outcrop and map scales. Abundant small (<10–15 cm) lenticular xenoliths of amphibolite and quartzofeldspathic gneiss also occur locally in the granitoid intrusions (Figs. C8 and C9 *in* Drake et al., 1991). The U-Pb zircon age and field relations clearly indicate that the Mount Eve granite suite was intruded after the main pulse (or pulses) of high-grade metamorphism and deformation that affected the Mesoproterozoic basement.

The Mount Eve granite suite contains microcline or microcline microperthite, quartz, and oligoclase as the dominant mineral phases. Ferromagnesian minerals typically include both hornblende and biotite. Preliminary electron microprobe data indicate that both the hornblende (hastingsite, according to the classification of Leake et al., 1997) and the biotite are Fe-rich, with Fe/(Fe + Mg) ratios of 0.7 to 0.9, well within the ranges for hornblende and biotite from other Proterozoic A-type granites (Anderson, 1983). The Fe-Ti oxide minerals are magnetite and ilmenomagnetite. Zircon, apatite, allanite, and titanite are common accessory minerals. Titanite has been confirmed by electron microprobe analysis. Primary fluorite has not been observed. The assemblage of titanite + quartz + magnetite and the lack of primary fluorite suggest that parental Mount Eve granite suite magmas were relatively low in magmatic fluorine (<1 wt%; Price et al., 1999) and crystallized under conditions of moderate oxygen fugacity (Wones, 1983).

Figure 2. Location map showing Middle Proterozoic basement of the New Jersey–Hudson Highlands (inset, lower right) and approximate location (heavy lined rectangle in inset, lower right) of geologic map showing the region where the Mount Eve granite suite is exposed. Maps modified from Drake et al. (1991) and Heleneck and Mose (1984), respectively. Abbreviations include NY—New York; PA—Pennsylvania; NJ—New Jersey; CT—Connecticut; NYC—New York City.



Figure 4. Photographs showing the lack of penetrative deformation fabric in the Mount Eve granite suite. Hammer handle in A is 28 cm long; coin (dime) in B is 1.7 cm in diameter.

GEOCHEMISTRY

Fifteen representative samples from four plutons from the type locality at Mount Eve, near Pine Island, New York, and south of Pochuck Mountain, New Jersey, were collected for this study (Fig. 2). Whole-rock major-element compositions indicate that the entire suite is comprised of alkali-rich felsic grani-

toids with no associated mafic or intermediate rocks (Table 1). The SiO₂ content ranges from 65 to 72 wt%, the Al₂O₃ content ranges from 13.5 to 15.5 wt%, and the total alkali (Na₂ + K_2O content ranges from 8.5 to 10.5 wt% (Table 1; see appendix for analytical methods). Most of the suite is metaluminous (ASI or aluminum saturation index, A/CNK or molar Al₂O₂/(CaO + $Na_2O + K_2O < 1.0$, although a few samples are mildly peraluminous in composition (A/CNK~1.1; Fig. 5, A). The Mount Eve granite suite has very high K₂O contents (4.8 to 7.5 wt%) and high K_2O/Na_2O ratios (1.3 to 2.8) that reflect the high modal abundance of K-feldspar in these rocks. For most samples, CaO and MgO contents are generally low (<3 wt% and <0.9 wt%, respectively). Total Fe (as Fe₂O₃) contents and molar FeO_t/(FeO_t+MgO) ratios are high (3 to 5.4 wt% and 0.77 to 0.88, respectively), and most samples plot within the tholeiitic field for granitoid rocks (Fig. 5, B). These major-element characteristics (high K2O/Na2O, K2O/MgO, total Fe, and molar FeO_t/(FeO_t+MgO) and low CaO and MgO) are broadly similar to those of A-type granitoids (Collins et al., 1982; Whalen et al., 1987; Eby, 1992). However, the Mount Eve granite suite has slightly lower FeO_t/(FeO_t+MgO) ratios compared to other Meso- and Neoproterozoic A-type granitoids from the New Jersey Highlands (Vernon Supersuite; Volkert et al., 2000; Fig. 5, B), the northern Blue Ridge (Tollo and Aleinikoff, 1996; Tollo et al., this volume), and the Adirondack massif (Whitney and Olmsted, 1988; McLelland and Whitney, 1990).

Chondrite-normalized rare-earth-element (REE) patterns for the Mount Eve granite suite are characterized by moderate to steep negative slopes (La/Yb = 6 to 40) and generally modest negative Eu anomalies (Eu/Eu* = 0.62 to 0.91, where Eu/Eu* is the chondrite-normalized ratio of measured Eu divided by the hypothetical Eu concentration required to produce REE pattern with no Eu anomaly; Fig. 6). A few samples with noticeably deeper Eu anomalies (Eu/Eu $^* < 0.4$) also have relatively high SiO₂ (~71.5%) and lower Al₂O₃, CaO, Sr, and Ba compared to the rest of the suite (Table 1 and Fig. 6). This suggests a significant role for feldspar in the petrogenesis of these samples through more extensive crystal fractionation of both plagioclase and K-feldspar, as discussed later. Relative to average I-type, calc-alkaline, and peraluminous S-type granitoids, A-types typically have high concentrations of REE, Zr, Nb, Ta, Ga, F, Sn, Zn, and Y and low concentrations of Ba and Sr (Loiselle and Wones, 1979; Whalen et al., 1987; Eby, 1990). The rocks of the Mount Eve granite suite have high concentrations of REE and high-field-strength elements (HFSE) that clearly distinguish them from I- or S-type granites and are similar to those of the older A-type Vernon Supersuite granitoids from the New Jersey Highlands (Fig. 7, A and B) when plotted on the granitoid tectonic discrimination diagrams of Pearce et al. (1984). Most samples of the Mount Eve granite suite plot in the "within-plate granite" field (Fig. 8, A-C), as do many A-type granitoid suites (e.g., Whalen et al., 1987; Eby, 1990). Two samples of Mount Eve granite plot near the boundary of the "volcanic arc" and "ocean ridge" granite fields on the Yb versus Ta diagram (Fig.

			TABLE ·	I. WHOLE	-ROCK C	DMPOSIT	IONS OF	THE MOU	NT EVE (BRANITE (SUITE				
Sample	EVE-1	EVE-2	EVE-3	EVE-4	EVE-5	EVE-6	EVE-7	PO-1	PO-2	PO-3a	PO-3b	PO-4	PO-5a	PO-5b	PO-6
Major elements															
SiO2#	67.35	67.14	66.11	65.10	67.24	71.47	65.74	68.02	71.57	68.94	71.35	65.59	69.94	67.00	65.76
Tio ₂	0.79	0.70	0.71	0.67	0.66	0.23	0.80	0.51	0.47	0.43	0.49	0.66	0.40	0.58	0.67
Al ₂ O ₃	14.53	14.51	14.19	14.52	14.21	13.51	14.53	14.51	13.60	14.62	14.29	15.28	15.50	14.65	15.28
Fe ₂ O ₃ T	5.31	4.10	3.09	3.17	3.60	3.13	5.11	3.18	3.18	3.52	3.21	4.72	3.13	4.83	4.72
MnO	0.10	0.08	0.10	0.11	0.08	0.05	0.10	0.02	0.02	0.02	0.03	0.07	0.02	0.05	0.07
OgM	0.74	0.73	0.82	0.73	0.60	0.38	0.89	0.82	0.82	0.61	0.44	0.78	0.54	0.80	0.83
CaO	2.72	3.17	4.61	6.71	2.54	1.52	2.58	1.58	0.86	0.56	1.25	2.78	1.02	2.00	1.72
Na ₂ 0	3.66	3.80	2.60	3.68	3.21	2.88	3.87	2.70	2.76	2.77	3.42	3.47	3.89	3.25	3.48
K20	5.21	5.28	7.26	4.76	6.48	7.36	6.10	6.84	5.91	6.94	5.99	6.31	5.49	6.01	6.41
P ₂ O ₅	0.20	0.14	0.06	0.24	0.12	0.02	0.16	0.14	0.12	0.09	0.09	0.15	0.08	0.16	0.15
Total	100.61	99.65	99.55	99.68	98.74	100.56	99.87	98.33	99.30	98.51	100.55	99.81	100.02	99.33	99.09
Trace elements [§]															
a	81	164	39	105	96	242	65	121	115	53	102	76	73	82	91
3 5	256	205	116	267	00 761	152	0 D D D D D	12-	2.06	107	202	105	197	16.1	0
20,00	## V IV				107	400 6 F L	007	107	072	121	007	000	101	+0-	200
	N.A.	N.A	N.A.	N.A.	0.02 r	0.10	30.4	21.12	20.0 2	10.4	24.Z	29.0	10.0	20.4	30.0 20.0
Nd	138	135	67	107	170	189	170	108	95	68	95	131	73	82	132
Sm	36.9	40.0	16.6	28.7	36.6	33.0	36.6	22.2	17.4	12.2	17.9	28.5	15.0	16.7	28.3
Eu	7.01	7.65	3.65	5.31	7.03	1.39	7.66	4.78	2.18	3.31	4.83	5.23	3.23	3.91	5.76
Gd	N.A.##	N.A.	N.A.	N.A.	32.4	31.3	32.5	20.4	16.4	9.7	15.8	25.0	14.2	16.3	25.5
Tb	4.47	4.86	2.12	3.36	4.97	4.01	4.91	3.10	2.27	1.37	2.27	3.82	2.22	2.49	3.98
Dv	N.A.	N.A.	N.A.	N.A.	26.7	18.2	25.0	16.6	11.3	6.5	11.5	20.1	11.3	12.3	19.4
Ho	NA	A.N	N.A.	A N	5.16	3.33	4.93	3.07	2.08	1.25	2.19	3.90	2.26	2.48	3.96
Er	٩N	AN	٩N	٩Z	12.34	7.63	11.34	7.02	4.78	3.35	5.44	9.33	5.55	5.93	9.35
i E	٩Z	AN	٩N	٩Z	1.75	0.94	1.55	0.93	0.60	0.49	0.79	1.32	0.79	0.79	1.24
Yh	11.1	11.1	6.0	6	11.8	6.1	10.5	2.8	3.7	3.4	2.5	8.7	5.4	5.5	9.6
Lu :	1.54	1.49	0.79	1.23	1.71	0.87	1.52	0.80	0.51	0.50	0.78	1.29	0.76	0.83	1.25
Sr	410	448	681	660	399	197	441	441	176	409	487	500	307	385	442
Ba	2195	2102	2219	1594	2176	459	2328	2442	985	2250	2246	2160	1468	1825	2160
Cs	0.44	0.44	1.22	1.36	0.85	1.34	0.47	2.95	1.97	1.13	0.95	0.76	1.29	1.03	0.98
Rb	N.A.	N.A.	N.A.	N.A.	170	201	127	189	159	248	167	135	208	164	180
D	2.8	4.7	5.2	8.5	4.3	2.4	2.1	1.2	1.1	4.1	3.8	3.7	3.3	3.8	4.4
Th	3.6	9.7	5.7	14.9	5.9	27.2	3.3	12.0	14.5	8.2	8.2	5.7	10.1	9.5	8.9
×	122	122	57	92	129	82	119	78	54	30	56	98	57	63	96
Zr	1084	1028	1044	1262	916	238	1163	675	415	639	561	807	490	757	826
Щ	24.4	22.5	23.2	26.2	18.6	6.7	23.3	15.2	10.2	14.6	12.6	18.9	11.0	16.7	18.1
dN	N.A.	N.A.	N.A.	N.A.	64	24	51	29	20	44	44	38	32	27	40
Та	3.2	3.3	2.4	2.6	4.0	0.6	3.2	1.4	0.5	2.3	2.0	2.8	2.3	1.3	2.6
Sc	6.5	6.1	5.9	6.4	6.5	4.5	7.3	5.2	10.3	6.2	3.5	7.0	1.8	8.8	7.6
ŭ	ი	ю	N	ю	e	ი	5	N	4	N	ო	5	N	ო	4
ĪZ	14	15	9	12	12	ო	15	7	7	9	ω	13	9	10	11
Co	4	ო	0	ო	ო	0	4	0	ო	0	ო	4	0	4	5
>	N.A.	N.A.	N.A.	N.A.	12	4	15	6	22	11	10	22	10	16	19
ASI ^{††}	0.87	0.82	0.69	0.62	0.84	0.87	0.82	0.99	1.09	1.12	0.99	0.87	1.09	0.95	0.97
K ₂ O/Na ₂ O	1.42	1.39	2.79	1.29	2.02	2.55	1.57	2.53	2.14	2.51	1.75	1.82	1.41	1.85	1.84
FeO _t ((FeO _t + MgO) ^{\$\$} Eu/Eu ^{*###}	0.87 0.63	0.84 0.63	0.77 0.72	0.80 0.62	0.84 0.62	0.88 0.13	0.84 0.67	0.78 0.68	0.78 0.39	0.84 0.91	0.87 0.87	0.84 0.59	0.84 0.67	0.84 0.72	0.84 0.65
Total iron expresed a	sseu in wei s Fe O	gru percent	, irace eleir	ienis in par	rs per millio	_									

· τοιαι που expressed as re₂O₃. ^SAll trace elements were analyzed by instrumental neutron activation analysis or inductively coupled plasma mass spectrometry, except Sr, Ba, Y, and Zr, which were analyzed by inductively

##N.A,—not analyzed. ¹¹ ASI—alumina saturation index, A/CNK or molar AI₂O₃/(CaO + Na₂O + K₂O) ⁵⁸FeO₁/(FeO₁ + MgO)—molar FeO₁ + MgO), where FeO₁ is total iron expressed as FeO (Fe₂O₃ × 0.9). ^{5##}Eu/Eu*—the chondrite-normalized ratio of measured Eu divided by the hypothetical Eu concentration required to produce a rare-earth-element pattern with no Eu anomaly.



Figure 5. Plots of SiO₂ (wt%) versus (A) ASI or aluminum saturation index, A/CNK or molar $Al_2O_3/(CaO + Na_2O + K_2O)$; (B) FeO₁/(FeO₂ + MgO) for the Mount Eve granite suite (filled squares) and for the ca. 1100 Ma Vernon Supersuite (unfilled field; Volkert et al., 2000) of the New Jersey Highlands; and (C) FeO_t/(FeO_t + MgO) for granitoids and granitic gneisses from the Adirondacks, including the 1103-1093 Ma Hawkeye suite (diagonal striped field; J. McLelland, personal commun.) and the 1060-1045 Ma Lyon Mountain Gneiss (open field with small ticks; Whitney and Olmsted, 1988), and also granitoids from the northern Blue Ridge Province, including the 1060 ± 5 Ma Old Rag granite suite (gray shaded field; Tollo et al., this volume) and the Neoproterozoic (765-680 Ma) A-type suite (black shaded field; Tollo and Aleinikoff, 1996; Tollo et al., 2004). The dividing line separating the fields of tholeiitic and calc-alkaline affinity is from Anderson (1983). FeO, refers to total iron expressed as FeO. Plots B and C modified after Frost et al. (2000).

8, C). Given the limited volumes and map extent of the Mount Eve granite suite, it is unlikely that these few rocks were generated in a different tectonic setting or involved melting of significantly different crustal source rocks. These two samples have the largest negative Eu anomalies and highest SiO_2 contents (Fig. 6), and thus their relatively low Ta concentrations are



Figure 6. Rare-earth-element (REE) plots of Mount Eve granite suite samples. Normalization factors are based on Leedy chondrite (Masuda et al., 1973) and are La (0.378), Ce (0.978), Pr (0.15), Nd (0.716), Sm (0.23), Eu (0.0866), Gd (0.311), Tb (0.0589), Dy (0.39), Ho (0.087), Er (0.255), Tm (0.039), Yb (0.249), and Lu (0.0387). PO-2 and EVE-6 are high-SiO₂ samples with the lowest Eu/Eu* values (Table 1), where Eu/Eu* is the chondrite-normalized ratio of measured Eu divided by the hypothetical Eu concentration required to produce REE pattern with no Eu anomaly.

attributed to crystal fractionation processes, as discussed later. According to the classifications of Eby (1992), most Mount Eve samples are A₂-type granites (Figs. 9, A and B), indicating their derivation from crustal sources that previously had been generated in a subduction zone or continent-continent collision tectonic environment. This is further supported by the fact that the Mount Eve samples analyzed in this study fall mainly within the compositional range between average continental crust and island-arc basalt (Fig. 10). As noted by previous workers (e.g., Whalen et al., 1987; Eby, 1992; Landenberger and Collins, 1996; Förster et al., 1997), the trace-element discrimination diagrams of Pearce et al. (1984) more accurately reflect the chemistry of crustal source rocks than they identify tectonic settings. With this in mind, the trace-element data for the Mount Eve granite suite indicate derivation from crustal sources that were affected by previous convergent orogenic processes (e.g., the Ottawan orogeny) and were subsequently partially melted during a post-Ottawan crustal heating event.

Trace-element abundances in the Mount Eve granite suite show systematic variation that can be attributed to crystal fractionation of mainly plagioclase and K-feldspar, and accessory zircon and titanite (Figs. 11–13). Strontium and barium concentrations show a progressive decrease with increasing SiO_2 (Fig. 11, A and B), and the two samples with the highest SiO_2 and lowest Sr and Ba also have the lowest Eu/Eu* ratios (Fig. 12, A and B), indicating that feldspars were important crystallizing phases in the Mount Eve suite magmas. In general, the data set more closely parallels fractional crystallization vectors for K-feldspar (Fig. 12, B and C); however, Rb/Ba–Rb/Sr sys-



Figure 7. Plots of (A) Zr + Nb + Ce + Y versus FeO_t/MgO and (B) Zr versus Ce for the Mount Eve granite suite (filled squares) compared to the A-typeVernon Supersuite granitoids from the New Jersey Highlands (unfilled field; Volkert et al., 2000). FeO_t refers to total iron expressed as FeO. Diagrams modified after Whalen et al. (1987).

tematics (Fig. 12, D) suggest a mixture of plagioclase and K-feldspar crystallization. Therefore, it is likely that both plagioclase and K-feldspar were important crystallizing phases in the Mount Eve granite suite.

Accessory minerals such zircon, allanite, and titanite are common in granitoid rocks and can exert a strong control on trace-element systematics of granitic liquids due to their large



Figure 8. Plots of (A) Y + Nb versus Rb, (B) Y versus Nb, and (C) Yb versus Ta for the Mount Eve granite suite (filled squares) from the study area. Diagrams modified after Pearce et al. (1984). Dashed line in Figure 8, B, is the upper limit of oceanic granites from anomalous ridge segments. PO-2 and EVE-6 are high-SiO₂ samples with the lowest Eu/Eu* values (Table 1), where Eu/Eu* is the chondrite-normalized ratio of measured Eu divided by the hypothetical Eu concentration required to produce REE pattern with no Eu anomaly.



Figure 9. Plots of (A) Nb–Ce–Y and (B) Y/Nb versus Sc/Nb showing the distribution of Mount Eve granite (filled squares) relative to fields (dashed lines in Figure 9, B) for the A_1 and A_2 subtypes of A-type granitoids. Diagrams modified after Eby (1992).

affect on bulk distribution coefficients for HFSE (Zr, Hf, Nb, and Ta) and REE (Mahood and Hildreth, 1983; Sawka, 1988). In the Mount Eve samples, Zr and Hf both show decreasing trends with increasing SiO₂, indicating that zircon played an important role during crystallization (Fig. 11, C and E). Ta and Nb also show large decreases with increasing SiO₂, which most likely represents the combined effect of fractionation of small amounts of titanite \pm Fe-oxides (Fig. 11, D and F). The ubiqui-



Figure 10. Plot of Y/Nb versus Yb/Ta for Mount Eve granite suite rocks (filled squares). Crosses indicate composition of average continental crust (C) and lower crust (LC), from Taylor and McLennan (1985). Boxes show fields for oceanic-island and island-arc basalts. Diagram modified after Eby (1990).

tous presence of titanite identified in thin section and by electron microprobe suggests that it was probably a significant phase controlling HFSE variations in the Mount Eve suite. Further evidence for crystal fractionation of both zircon and titanite is displayed by systematic increases in Hf/Ta, Th/Ta, and La/Sm with increasing Ce/Yb (Fig. 13, A–C, respectively). Fractional crystallization vectors in Figure 13, A–C, show that this trace-element variation is consistent with the combined effect of zircon and titanite crystallization using distribution coefficients from Mahood and Hildreth (1983) and Sawka (1988) for these mineral phases. Allanite is essentially precluded from this assemblage because it would have depleted the fractionating granitic liquids in light REE and Th, and thus Ce/Yb would show systematic decreases with Th/Ta and Hf/Ta, which are not observed.

PETROGENETIC MODELS

Several different models for the petrogenesis of A-type granites have been proposed that reflect the wide range of chemical variations observed in these rocks. These models can be grouped into three major categories: (1) those that involve extensive fractional crystallization from basaltic parents (Loiselle and Wones, 1979; Turner et al., 1992), (2) those that involve a combination of mantle and crustal sources via mixing and/or assimilation-fractional crystallization (AFC) processes (e.g., Barker et al., 1975; Foland and Allen, 1991), and (3) those that invoke partial melting of various crustal lithologies, including anhydrous lower crustal granulites (Collins et al., 1982; Whalen et



Figure 11. Plots of (A) Sr, (B) Ba, (C) Zr, (D) Ta, (E) Hf, and (F) Nb versus SiO_2 for the Mount Eve granite suite (filled squares). Decreasing Sr and Ba with increasing SiO_2 indicates feldspar crystal fractionation, and decreasing Zr, Hf, Ta, and Nb with increasing SiO_2 indicates zircon + titanite (\pm Fe-oxide) crystal fractionation. Small, unfilled oval represents the estimated parental magma for the Mount Eve granite suite. PO-2 and EVE-6 are high-SiO_2 samples with the lowest Eu/Eu* values (Table 1), where Eu/Eu* is the chondrite-normalized ratio of measured Eu divided by the hypothetical Eu concentration required to produce REE pattern with no Eu anomaly.

al., 1987; Landenberger and Collins, 1996), underplated mafic rocks and their differentiates (Frost and Frost, 1997), and intermediate granitoid rocks ranging from tonalite to granodiorite (Anderson, 1983; Sylvester, 1989; Creaser et al., 1991).

Loiselle and Wones (1979) proposed that extensive fractional crystallization of tholeiitic basalts would produce felsic magmas with high FeO/MgO and low oxygen fugacity and water content, characteristic of some A-type granites. This mechanism has been proposed to explain the Red Bluff granitic suite in West Texas (Shannon et al., 1997), the Sybille Intrusion of the Laramie anorthosite complex (Scoates et al., 1996), and the Topsails igneous suite of Newfoundland (Whalen et al., 1996). However, this mechanism is not likely to have formed the Mount Eve granite suite because there is no field evidence for the large volumes of associated mafic rocks and the continuum of compositions that would be expected to have resulted from



Figure 12. Plots of (A) Sr and (B) Ba versus Eu/Eu*, (C) Sr versus Ba, and (D) Rb/Sr versus Rb/Ba for the Mount Eve granite suite (filled squares). Arrows indicate the direction and magnitude of Rayleigh-type crystal fractionation of plagioclase (Pl; 20%) and K-feldspar (Kfs; 20%) using distribution coefficients from Mahood and Hildreth (1983) and Nash and Crecraft (1985). Small, unfilled oval represents the estimated parental magma for the Mount Eve granite suite.. Mineral abbreviations are after Kretz (1983). PO-2 and EVE-6 are high-SiO₂ samples with the lowest Eu/Eu* values (Table 1), where Eu/Eu* is the chondrite-normalized ratio of measured Eu divided by the hypothetical Eu concentration required to produce REE pattern with no Eu anomaly.

such a mechanism. Furthermore, the high concentrations of Sr and modest Eu anomalies in Mount Eve granite suite preclude extensive fractionation of a gabbroic mineral assemblage from a basaltic parent. Although more difficult to completely dismiss, similar arguments can be made against mechanisms involving mixing and/or AFC of mantle-derived basaltic magmas with crust-derived felsic melts (e.g., Barker et al., 1975) to produce the parental magmas of the Mount Eve granite suite. As in the previous model, the expected wide spectrum of spatially associated and demonstrably comagmatic rocks (e.g., gabbro to granite) is not observed. However, this does not entirely preclude mixing and AFC processes. The parental magmas to the Mount Eve granite suite could have been produced by mixing and/or crustal AFC from magmas derived from partial melting



Figure 13. Plots of (A) Hf/Ta, (B) Th/Ta, and (C) La/Sm versus Ce/Yb for the Mount Eve granite suite (filled squares). Arrows indicate the direction and magnitude of Rayleigh-type crystal fractionation of allanite (Aln; 2%), zircon (Zrc; 2%), and titanite (Ttn; 2%) using distribution coefficients from Sawka (1988). Small, unfilled oval represents the estimated parental magma for the Mount Eve granite suite. Mineral abbreviations are after Kretz (1983). PO-2 and EVE-6 are high-SiO₂ samples with the lowest Eu/Eu* values (Table 1), where Eu/Eu* is the chondrite-normalized ratio of measured Eu divided by the hypothetical Eu concentration required to produce REE pattern with no Eu anomaly.

of mafic to intermediate crust (see discussion later). This mechanism is difficult to address without Sr and Nd isotope data on the Mount Eve granite suite, as well as proposed crustal source rocks.

Given the relatively narrow chemical variations and the lack of associated mafic to intermediate rocks, partial melting of crustal rocks is interpreted to have been the dominant petrogenetic process that formed the parental magmas of the Mount Eve granite suite. Supracrustal metasedimentary sequences in the New Jersey-Hudson Highlands are ruled out because they generally lack the appropriate compositions to have produced Atype granites. Dehydration partial melting of micas within aluminosilicate-rich metapelites within the Hudson Highlands has been proposed to have been responsible for forming the highly peraluminous S-type Canada Hill granite (Heleneck and Mose, 1984; Ratcliffe, 1992). In contrast, metaigneous crustal lithologies, commonly cited as possible source rocks for A-type granites (e.g., Collins et al., 1982; Anderson, 1983; Clemens et al., 1986; Whalen et al., 1987; Sylvester, 1989; Creaser et al., 1991; Frost and Frost, 1997), are abundant in the New Jersev-Hudson Highlands (except for tholeiitic ferrodiorites). In particular, rocks of the Losee metamorphic suite (amphibolite, intermediate charnockite, tonalitic gneiss) constitute a large volume of the New Jersey Highlands basement and are considered here as the most representative of possible crustal source rocks for the Mount Eve granite suite. As discussed earlier, geochemical data suggest that the Losee rocks represent a continental-arc sequence, and thus would be appropriate source rocks for A2subtype trace elements with the characteristics of those in the Mount Eve granite suite (Fig. 9). In the following sections we explore this hypothesis by comparing the experimental data available for the partial melting of starting materials that are representative of potential source rocks within the Losee metamorphic suite with the least chemically evolved samples of the Mount Eve granite suite (~65–68 wt% SiO₂). Based on the evidence for crystal fractionation within the Mount Eve granite suite, we suggest that the least evolved samples are the best approximation to parental Mount Eve magmas, and therefore best reflect the chemical characteristics of the crustal source(s) from which they were derived.

Partial Melting of Tonalitic to Granodioritic Source Rocks

Partial melting of tonalitic to granodioritic source rocks has been proposed by several workers to explain the origin of A-type granites (Anderson, 1983; Sylvester, 1989; Creaser et al., 1991; Patiño Douce, 1997; Smith et al., 1999). Figure 14, A–D, shows the major-element composition of experimentally produced partial melts of tonalitic to granodioritic sources (e.g., Carroll and Wyllie, 1990; Skjerlie and Johnston, 1993; Patiño Douce, 1997) compared to the major-element compositions of rocks of the Mount Eve granite suite. The majority of the least chemically evolved Mount Eve samples have much lower SiO₂ and higher



Figure 14. Plots of (A) CaO, (B) Al_2O_3 , (C) K_2O , and (D) Na_2O versus SiO_2 for the Mount Eve granite suite samples in this study (filled squares) compared to experimental partial melts of fluid-absent tonalite/granodiorite (gray field; Skjerlie and Johnston, 1993; Patiño Douce, 1997); H_2O -undersaturated tonalite (open field with small ticks; Carroll and Wyllie, 1990); basalts and mafic amphibolites (unfilled field; Beard and Lofgren, 1991; Rushmer, 1991; Rapp and Watson, 1995); Grenville mafic charnockitic (open field with dashed outline; Beard et al., 1994); and ferrodiorite (circle with cross; Scoates et al., 1996). Small, unfilled oval represents the estimated parental magma for the Mount Eve granite suite.

CaO contents then liquids derived from the fluid-absent melting of tonalitic or granodioritic sources. Hydrous partial melting of tonalitic compositions (Carroll and Wyllie, 1990) produces melts with the appropriate SiO₂, CaO, and MgO contents, but the Al₂O₃ and Na₂O contents are much higher and the K₂O content lower than those of the parental Mount Eve Granite magmas. Overall, these comparisons suggest that partial melting of more mafic rocks was most likely involved in the petrogenesis of parental magmas to the Mount Eve Granite suite.

Partial Melting of Mafic Amphibolites

Several workers have discussed the origin of A-type granites by partial melting of mafic source rocks (e.g., Frost and Frost, 1997; Smith et al., 1999). Figure 14, A–D, illustrates that experimentally generated partial melts of basalt and amphibolite can produce intermediate to felsic liquids (Beard and Lofgren, 1991; Rushmer, 1991; Rapp and Watson, 1995) that are similar to the compositions of the least evolved rocks of the Mount Eve granite suite, although their K₂O contents are much lower than those of the Mount Eve granite suite, and to most Atype granites in general. However, most of the partial-melt experiments have been carried out on low- and medium K mafic rocks (<1 wt% K₂O), and Beard and Lofgren (1991) suggest that the alkali content of the melts produced is related to the composition of the starting materials. Chemical data for New Jersev-Hudson Highlands amphibolites indicate a wide variety of basaltic protolith compositions (Volkert and Drake, 1999; Kula and Gorring, 2000; Harclerode et al., 2001), ranging from low-K (<0.4 wt%) tholeiitic basalts to medium-K (1.0 to 1.5 wt%) calc-alkaline basalts. Systematic geochemical investigation of amphibolites within the Losee metamorphic suite has yet to be undertaken, but preliminary data suggest that most are of the medium-K, calc-alkaline type (Kula and Gorring, 2000). Therefore, partial melting of Losee amphibolites could have generated intermediate to felsic A-type liquids with high K₂O and K/Na ratios similar to those of the Mount Eve granite suite. However, as pointed out by Smith et al. (1999), this possibility is difficult to assess because of a lack of experimental data for partial melts of K-rich mafic rocks.

Partial Melting of Charnockitic Gneisses

Other viable lithologies within the Losee metamorphic suite that may have partially melted to produce the Mount Eve granite include a suite of charnockitic intermediate metaigneous rocks ranging in composition from diorite to tonalite (Volkert and Drake, 1999). This suite of rocks is similar in composition to sources involved in petrogenetic models that invoke partial melting of dehydrated charnockitic lower crust to explain the petrogenesis of A-type granites (e.g., Collins et al., 1982; Whalen et al., 1987; Landenberger and Collins, 1996). Tollo and Aleinikoff (1996) suggested partial melting of charnockitic Grenville-age basement in the petrogenesis of parental magmas to metaluminous A2-type granites of the Robertson River igneous suite (e.g., Laurel Mills granite) in the Blue Ridge Province of Virginia. High-temperature partial melting experiments involving Grenville-age charnockitic rocks (~60-64 wt% SiO₂) conducted by Beard et al. (1994) produced high-SiO₂ (>70 wt%) granitoid melts, and thus these are not appropriate source rocks for parental Mount Eve magmas (Fig. 14, A-D). Volkert et al. (2000) proposed that orthopyroxene-bearing diorite (~55 wt% SiO_2) within the Losee metamorphic suite has the appropriate composition, and upon partial melting could have produced the parental syenitic liquids that formed the widespread and voluminous 1100 Ma A-type Vernon Supersuite magmas. This supports earlier conclusions that more mafic rocks (e.g., amphibolite, diorite) were probably more viable as source rocks for the generation of parental A-type magmas that resemble the least chemically evolved Mount Eve granite suite samples.

A more definitive assessment of the Losee metamorphic suite as the ultimate source of the Mount Eve magmas will necessitate the production of additional isotope and geochemical data on Losee rocks. Nevertheless, we consider the lithologic variability in the Losee metamorphic suite representative of the range of possible crustal sources that could have generated the parental Mount Eve granite magmas. Furthermore, as indicated earlier, it is likely that the parental Mount Eve magmas represent mixtures of partial melts from various source rock compositions in variable proportions. We propose a model similar to that of Frost and Frost (1997), where the metaluminous, relatively oxidized characteristics of the least evolved Mount Eve magmas could be explained as mixtures of intermediate and felsic partial melts derived from the Losee metamorphic suite. These parental magmas would then have crystallized a feldspar-dominated assemblage in the shallow crust to produce the more evolved high-SiO₂ varieties of the Mount Eve granite suite.

IMPLICATIONS FOR GRENVILLE TECTONICS

One of the principal tectonomagmatic events in the Grenville orogen during the late Mesoproterozoic was the Ottawan orogeny (ca. 1090–1030 Ma; e.g., McLelland et al., 1996, 2001). The Ottawan orogeny is thought to have been a Himalayan-style continental collision event with associated crustal thickening, high-grade metamorphism, ductile nappe-style folding in the southeast (e.g., in the Central Granulite Terrane, the Adirondack Highlands, and Appalachian massifs), and brittle northwestdirected thrusting farther west in the orogen (e.g., in the Grenville Front tectonic zone and the Central Metasedimentary Belt). Although the timing of peak Ottawan orogenesis varied spatially, this event severely affected most rocks older than ca. 1060 Ma throughout much of the Grenville orogen (e.g., McLelland, 1996, 2001; Aleinikoff et al., 2000). The age and field relations of the Mount Eve granite suite indicate that its origin is clearly related to post-peak Ottawan tectonic activity, and, as pointed out by Drake et al. (1991), place a lower limit of ca. 1020 Ma on penetrative Ottawan metamorphism and deformation in the New Jersey–Hudson Highlands. Tectonic activity within the Central Granulite terrane and the Adirondack sectors of the Grenville orogen during the interval between 1090 and 1000 Ma was generally characterized by rapid uplift, lithospheric delamination, and extensional collapse along low-angle normal faults within the overthickened core of the Ottawan orogen (McLelland et al., 1996, 2001; Corrigan and Hamner, 1997). Extrapolation of this mechanism to the New Jersey-Hudson Highlands region suggests that lithospheric delamination could have caused deep crustal melting to produce the Mount Eve granite suite. In this model, the A-type characteristics of the Mount Eve granite suite could be explained by partial melting of crustal rocks as hot asthenosphere impinged on the base of the crust subsequent to lithospheric delamination. Similar delamination models have been proposed for the syn- to Late Ottawan, mildy A-type granitoids of the Lyon Mountain Gniess suite (ca. 1060-1045 Ma) in the Adirondacks (McLelland et al., 1996; 2001) and the 1020 to 1010 Ma Labrieville, St. Urbain, and St. Ambroise anorthositegranite associations in Québec (e.g., Owens et al., 1994; Higgins and van Breemen, 1996). Such major lithospheric delamination in the New Jersey-Hudson Highlands would have been diachronous with syn- to Late Ottawan delamination events in the Adirondacks that produced the Lyon Mountain Gniess granitoid suite. However, a major problem with lithospheric delamination models for the Mount Eve granite suite concerns the small volumes and limited areal extent of the magmatism. Unless delamination was localized, larger volumes and a wider geographic distribution of post-tectonic, undeformed, A-type granitoid magmas would be expected within the New Jersey-Hudson Highlands. Rocks that fit this description have not been documented anywhere in the New Jersey-Hudson Highlands, and localized delamination of a small section of lithosphere beneath the Mount Eve area seems unlikely. These problems notwithstanding, it is possible that residual thermal input from major lithospheric delamination events that occurred in the Adirondacks during or immediately after peak Ottawan orogenesis (ca. 1090-1030 Ma) could have supplied heat to the base of the crust beneath the Mount Eve area. However, such processes do not explain why crustal melting was localized in the Mount Eve area.

An alternative model to lithospheric delamination that might explain the localized nature of the Mount Eve granite suite is crustal heating due to broad orogenic relaxation between peak Ottawan orogenesis and the onset of the post-Ottawan, highgrade, dextral transpressional shearing event that occurred between ca. 1010 and 915 Ma (Gates, 1995, 1998; Fig. 15). This Late Grenville-age transpressional deformation is characterized by a group of vertical, anastomosing shear zones, 0.5 to 2 km wide, that overprint older high-grade fabric elements (Gates, 1998). A post-Ottawan escape-type tectonic event in the central Appalachians resulting from accretion to the north is interpreted to have produced this deformation (Gates et al., 2001b). Localized crustal heating due to upwelling asthenosphere associated with localized extension and/or transtension in the overall dextral transpressional regime could better explain the small volumes and limited areal extent of the Mount Eve granite suite (Fig. 15). This tectonic scenario is also consistent with the "within-plate" and A2-type trace-element compositions of the Mount Eve granite suite. The strike-slip environment could also explain the temporal association of two other intrusive igneous rock suites of post-Ottawan age within the Hudson Highlands: the Canada Hill granite (1010 ± 6 Ma; Aleinikoff and Grauch, 1990) and the Lake Tiorati diorite (1008 \pm 4 Ma; Gates et al., 2001a). Collectively, these rocks, along with the Mount Eve granite suite, consist of small, dispersed plutonic bodies that form a volumetrically minor, chemically diverse group that ranges from A- and S-type granites to calc-alkaline, I-type diorite. A similar transpressional tectonic model has been proposed by Speer et al. (1994) to explain the occurrence of small-volume, chemically diverse plutonic suites of Alleghanian age in the southern Appalachians. This type of model may explain similar small-volume occurrences of Late to post-Ottawan (ca 1030–930 Ma) granitoids elsewhere in the Grenville orogen, particularly in the Adirondacks (e.g., the Lyonsdale Bridge and Cathead Mountain pegmatites; McLelland et al., 2001) and the Green Mountain massif (e.g., the Stamford Hill rapakivi granite; Ratcliffe et al., 1991).

CONCLUSIONS

The Mount Eve granite suite is a relatively homogeneous suite of granitoid rocks that intruded Mesoproterozoic basement of the New Jersey-Hudson Highlands at ca. 1020 Ma during the waning stages of the Ottawan orogeny. The metaluminous to slightly peraluminous granitoids range from quartz monzonite to granite (Drake et al., 1991; Volkert and Drake, 1999) and typically contain Fe-rich hornblende \pm biotite and accessory zircon, titanite, apatite, magnetite, and ilmenomagnetite. The Mount Eve granite suite displays A-type chemical characteristics, including high concentrations of Zr, Y, and total REE; high FeO₂/MgO and K₂O/Na₂O; variably negative Eu anomalies; and low MgO, Cr, and Ni. Slight depletion in Nb relative to other HFSE and REE allows further classification of the Mount Eve granite suite into the A2 chemical subtype (Eby, 1992). Based on experimental and trace-element data, as well as regional geology, the parental Mount Eve granitoids were likely derived from relatively dry and oxidized partial melting of rocks similar to the metaigenous lithologies of the Losee metamorphic suite within the Mesoproterozoic basement. Covariations between key major and trace elements can be explained by crystal fractionation of feldspars and accessory phases (zircon and titanite) from relatively low-SiO₂ parental quartz monzonitic liquids



Figure 15. Schematic lithospheric cross-section during the late Middle Proterozoic in the New Jersey Highlands (1100–1000 Ma), modified from McLelland et al. (1996). The Mount Eve granite suite formed from broad lithospheric thinning and the onset of dextral transpressional shearing (e.g., Gates et al., 2001b). Small circles indicate dextral strike-slip motion; those with dots indicate blocks moving toward reader, and those with *xs* represent blocks moving away from reader.

to generate the syenogranites that are higher in SiO_2 and rich in K-feldspar.

The Mount Eve granite suite is part of a group of small-volume, chemically diverse plutonic rocks sporadically emplaced throughout the central and northern Appalachian basement massifs and the Adirondack Highlands between 1030 and 930 Ma. Mechanisms that might have produced the Mount Eve franite suite include (1) residual thermal heating of the base of the crust subsequent to major lithospheric delamination of an overthickened Ottawan orogen, or (2) localized extension and crustal melting due to the onset of Late to post-Ottawan dextral transpressional shearing superimposed on broad orogenic relaxation. The latter mechanism has particular advantages over the former model because it more easily explains the small volumes, limited areal extent, and chemical diversity of these rocks formed late in the Grenville orogenic cycle. Support for a transpressional origin also comes from the similarity of the Mount Eve granite suite in volume, distribution, and lithology to Alleghanian granitoids from the southern Appalachians that are proposed to have formed in a similar strike-slip transpressional tectonic environment.

APPENDIX—ANALYTICAL METHODS

Powders were prepared from samples weighing 10-15 kg by crushing in a hardened steel jaw crusher to a size of ~ 0.5 cm in diameter. The resulting chips were then thoroughly mixed, and a 50 g split was pulverized in an Al-ceramic shatter box that was used for major- and trace-element analysis. Major- and abundant trace-element (Sr, Ba, Zr, and Y) contents were determined at the Department of Earth and Environmental Studies, Montclair State University, by inductively coupled plasma optical emission spectrometry (ICP-OES) on a JY Ultima C system. Approximately 100 mg of sample were mixed with 400 mg of ultrahigh-purity lithium metatetraborate flux ((R)Spex-Certiprep) and fused in high-purity graphite crucibles at 1100 °C for 45 minutes. This technique achieves complete dissolution of the sample, including all accessory phases (e.g., zircon, titanite) based on visual inspection and replicate analyses of U.S. Geological Survey (USGS) standard G-2 and multiple aliquots of EVE-1 (see later). Molten samples were immediately dissolved in 50 ml of 7% HNO₃, and 6.5 ml of this solution was diluted in 50 ml of 2.5% HNO₃ (dilution factor of ~4000x) before ICP-OES analysis.

Experimental water was distilled and subsequently deionized with a Barnstead Nanopure system; the nitric acid used was of trace metal grade and from Fisher Scientific. All analyses were corrected for blank and flux contributions to the analytical signal (<1.5% for all elements). Calibration of instruments was achieved using eight USGS rock standards (BIR-1, DNC-1, BHVO-2, W-2, BCR-2, AGV-2, GSP-2, and G-2). Instrument drift (less than ±2% over the 2- to 3-hour run) was corrected by analyzing a matrix-matched drift monitor that was regularly spaced throughout each analytical run. Analytical precision and accuracy based on six complete dissolutions of USGS standard G-2 was better than 0.7% (26 standard deviation) for all major elements except Mg and P (1.5% and 2.5%, respectively). Loss on ignition was not determined.

Additional trace-element analyses (of REE, Sc, Cr, Ni, Co, V, Y, Nb, Ta, Hf, U, Th, Rb, and Cs) were performed either by instrumental neutron activation analysis (INAA) at Cornell University on powders or by inductively coupled plasma mass spectrometry (ICP-MS) using a Perkin-Elmer Elan 6000 at Binghamton University. INAA techniques and standards are as given in Kay et al. (1987). INAA precision and accuracy based on replicate analysis of an internal basalt standard (PAL; see Kay et al., 1987) and USGS standard G-2 are 2-5% (2 σ) for most elements and ±10% for U, Nd, and Ni. ICP-MS precision and accuracy based on replicate analysis of an internal basalt standard (PAL; see Kay et al., 1987) and USGS standard G-2 are ~5% (2 σ) for all elements analyzed. The same flux-dissolved solutions that were analyzed for major elements by ICP-OES were also analyzed by ICP-MS. Complete dissolution of accessory phases was confirmed by replicate analysis of five separate aliquots of EVE-1 that yielded similar precision to that for G-2, as stated above. All ICP-MS analyses were corrected for blank and flux contributions that were <1.5% of the total analytical signal for all elements.

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