Shawinigan arc magmatism in the Adirondack Lowlands as a consequence of closure of the Trans-Adirondack backarc basin

Jeff Chiarenzelli[1,*], Sean Regan[1], William H. Peck[2], Bruce W. Selleck[2], Brian Cousens[3], Graham B. Baird[4], and Catherine H. Shrady[1]

[1]*Department of Geology, St. Lawrence University, Canton, New York 13617 USA*
[2]*Department of Geology, Colgate University, Hamilton, New York 13346, USA*
[3]*Department of Earth Sciences, Carleton University, 1125 Colonel By Drive, Ottawa, Ontario K1S 5B6, Canada*
[4]*Department of Earth Sciences, University of Northern Colorado, Greeley, Colorado 80639, USA*

ABSTRACT

The Antwerp-Rossie metaigneous suite (ARS) represents arc magmatism related to closure of the Trans-Adirondack backarc basin during Shawinigan collisional orogenesis (ca. 1200–1160 Ma). The ARS is of calc-alkaline character, bimodal, and lacks intermediate compositions. Primarily intruding marble and pelitic gneiss, the ARS is spatially restricted to the Adirondack Lowlands southeast of the Black Lake fault. On discrimination diagrams, the ARS samples plot primarily within the volcanic arc granite fields. Incompatible elements show an arc-like signature with negative Nb, Ta, P, and Zr and positive Cs, Pb, La, and Nd anomalies relative to primitive mantle. Neodymium model ages (T_{DM}, depleted mantle model) range from 1288 to 1634 Ma; the oldest ages (1613–1634) and smallest epsilon Nd (ε_{Nd}) values are found in proximity to the Black Lake fault, delineating the extent of Laurentia prior to the Shawinigan orogeny. The epsilon Nd values at crystallization (1200 Ma) plot well below the depleted mantle curve. Geochemical and isotopic similarities to the Hermon granitic gneiss (HGG) (ca. 1182 Ma) and differences from the Hyde School Gneiss–Rockport Granite suites (1155–1180 Ma) suggest that arc plutonism rapidly transitioned into A-type AMCG (anorthosite-mangerite-charnockite-granite) plutonism. Given the short duration of Shawinigan subduction, apparently restricted extent of the ARS (Adirondack Lowlands), location outboard of the pre-Shawinigan Laurentian margin, intrusion into the Lowlands supracrustal sequence, bimodal composition, and recent discovery of enriched mantle rocks in the Lowlands, it is proposed the ARS formed as a consequence of subduction related to closure of a backarc basin that once extended between the Frontenac terrane and the Southern Adirondacks.

INTRODUCTION

The Mesoproterozoic Grenville Province is a portion of one of the Earth's major orogenic belts that extends for thousands of kilometers and across several continents, often invoking Himalayan analogues (Gates et al., 2004). Our understanding of the Grenville is hampered by its age, complexity, and deep exhumation. While considerable progress has been made in understanding the events that collectively have shaped the Grenville Province (Rivers, 2008), many fundamental questions about the orogen remain unanswered (McLelland et al., 2010). This is particularly true in the Central Granulite terrane (McLelland et al., 1996), where granulite facies overprinting, widespread and voluminous AMCG (anorthosite-mangerite-charnockite-granite) magmatism, and intense deformation have obscured the geologic history. This has resulted in the relatively recent discovery of the Shawinigan orogeny (ca. 1200–1140 Ma) in southern Quebec (Corrigan, 1995; Rivers, 2008) and in the Adirondacks (Heumann et al., 2006; Bickford et al., 2008).

The Adirondack Lowlands is a small part of the Adirondack region and the Central Metasedimentary Belt of the Grenville Province, widely known for abundant marble and mineralization related to Zn-Pb and talc mines. Because of this mining history, it is one of the best-studied areas in the Grenville Province. In addition, it is at lower grade than the adjacent Adirondack Highlands (Mezger et al., 1991; Streepey et al., 2001), contains considerably less volume of AMCG plutonic rocks, and lacks an Ottawan overprint (Heumann et al., 2006; Rivers, 2008). Thus the Adirondack Lowlands presents a window into the events that preceded the Ottawan phase of the Grenville orogeny, and contains supracrustal rock deposited before, and perhaps during, the Shawinigan orogeny (Rivers, 2008).

Magmatic rocks can provide considerable insight into the timing and nature of tectonic events and processes in the crust and mantle. Here our intent is to document the age, field relations, petrography, chemistry, Nd isotopic systematics, and tectonic setting of the Antwerp-Rossie metaigneous suite (ARS) in the context of our evolving understanding of the polyorogenic Grenville Province (Grenville orogenic cycle of McLelland et al., 1996; Elzivirian, Shawinigan, and Grenvillian orogenies of Rivers, 2008). Foremost among these considerations is that the metaplutonic rocks of the ARS are currently the oldest known intrusive rocks in the Adirondack Lowlands. They were, along with the supracrustal sequence they intrude, deformed and metamorphosed during the Shawinigan orogeny. A more complete understanding of the ARS provides the context for, and constraints on, the Shawinigan orogeny in the Adirondack Lowlands and south-central Grenville Province that set the stage for the great volumes of massif anorthosite and related granitic rocks intruded during its waning stages.

GEOLOGICAL SETTING AND SHAWINIGAN OROGENSIS IN THE ADIRONDACK LOWLANDS

The Adirondack Lowlands currently expose a wide variety of supracrustal rocks metamorphosed to mid-upper amphibolites facies and variably deformed during the Shawinigan orogeny (Fig. 1; Corrigan, 1995; Rivers, 2008). In descending stratigraphic and/or structural

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[*]E-mail: jchiaren@stlawu.edu.

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stacking order, the upper marble, subdivided into 16 units (deLorraine and Sangster, 1997), is sequentially underlain by fine-grained aluminous rocks of the Popple Hill Gneiss (Carl, 1988) and equivalent major paragneiss of Engel and Engel (1953), and then the lower marble. Much of our knowledge of the Adirondack Lowlands stratigraphy comes from exploration related to the sedimentary exhalative Balmat sphalerite deposits, which are hosted in the upper marble. Basement to the supracrustal rocks is currently not recognized (cf. Carl and Van Diver, 1975; Wasteneys et al., 1999) and supracrustal rocks may be allochthonous or underlain by oceanic crust (Chiarenzelli et al., 2010). This sequence was intruded by several igneous suites ranging in age from ca. 1150 to 1200 Ma, synchronous with the production of substantial volumes of leucosome in pelitic gneisses at 1160–1180 Ma (Heumann et al., 2006). The thermal effects of the orogeny and subsequent AMCG plutonism outlasted deformation associated with the Shawinigan orogeny.

In contrast to the Adirondack Lowlands, the Adirondack Highlands are dominated by granulite facies metaigneous rocks with thin screens of highly dismembered and intruded supracrustal rocks similar in nature to those exposed in the Adirondack Lowlands (Heumann et al., 2006; Wiener et al., 1984). The boundary between the Lowlands and the Highlands (Carthage-Colton mylonite zone; Figs. 1 and 2) has long been recognized as a fundamental, if enigmatic, shear zone (Mezger et al., 1992; Streepey et al., 2001). Work by Selleck et al. (2005) affirmed its late history as an orogenic collapse structure that followed an earlier oblique-reverse ductile history (Baird, 2006). By compiling paleobarometric and temperature data, Rivers (2008) confirmed its orogen-wide significance and proposed that the Adirondack Lowlands are part of the orogenic lid to the 1020–1090 Ma Ottawan phase of the Grenvillian orogeny (Fig. 1). This interpretation fits well with existing knowledge of the distribution of Ottawan igneous rocks, structures, and metamorphic effects and mineral growth, that for the most part appear to be minor or absent in the Adirondack Lowlands, but occur widely in the Highlands and adjacent areas of the Central Granulite terrane and elsewhere in the Grenville Province (McLelland et al., 2010; Rivers, 2008).

Geochronological studies of the Adirondack Lowlands are numerous, and recent studies involve the extensive use of sensitive high-resolution ion microprobe (SHRIMP) analyses because of the complex nature of zircons recovered from high-grade rocks (McLelland et al., 2010). Most relevant to this discussion are U-Pb zircon and monazite ages that essentially restrict

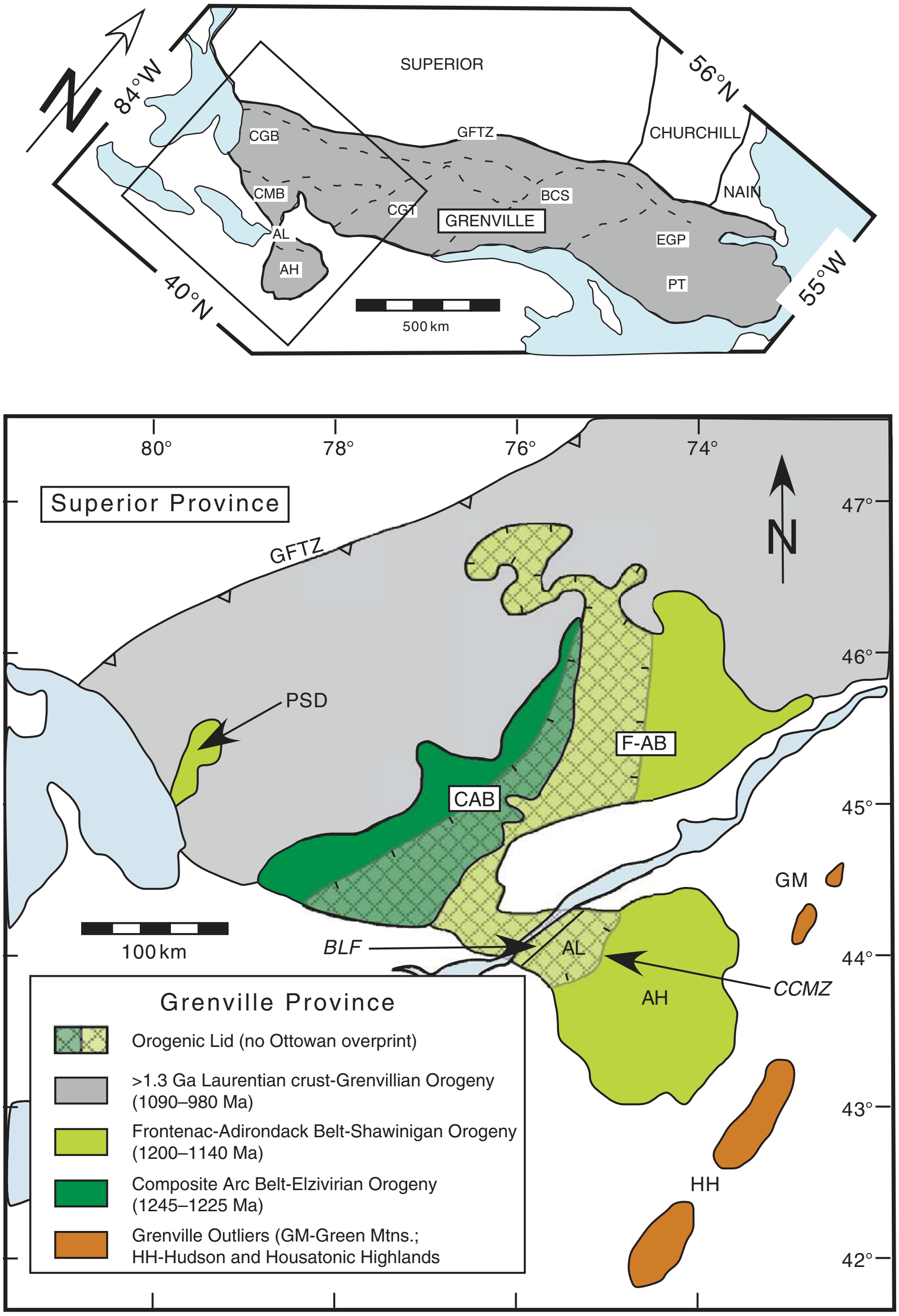


Figure 1. General location map showing subdivisions of the Grenville Province after McLelland et al. (1996). Inset shows simplified tectonic map of the south-central Grenville orogen displaying areas affected by Shawinigan orogenesis. Boundaries are drawn after Rivers (2008). Abbreviations: AH—Adirondack Highlands; AL—Adirondack Lowlands; BCS—Baie Comeau segment; BLF—Black Lake fault; CAB—composite arc belt; CCMZ—Carthage-Colton mylonite zone; CGB—Central Gneiss Belt; CGT—Central Granulite terrane; CMB—Central Metasedimentary Belt; EGP—eastern Grenville Province; F-AB—Frontenac-Adirondack belt; GFTZ—Grenville Front tectonic zone; GM—Green Mountains; HH—Hudson and Housatonic Highlands; PSD—Parry Sound domain; PT—Pinware terrane.

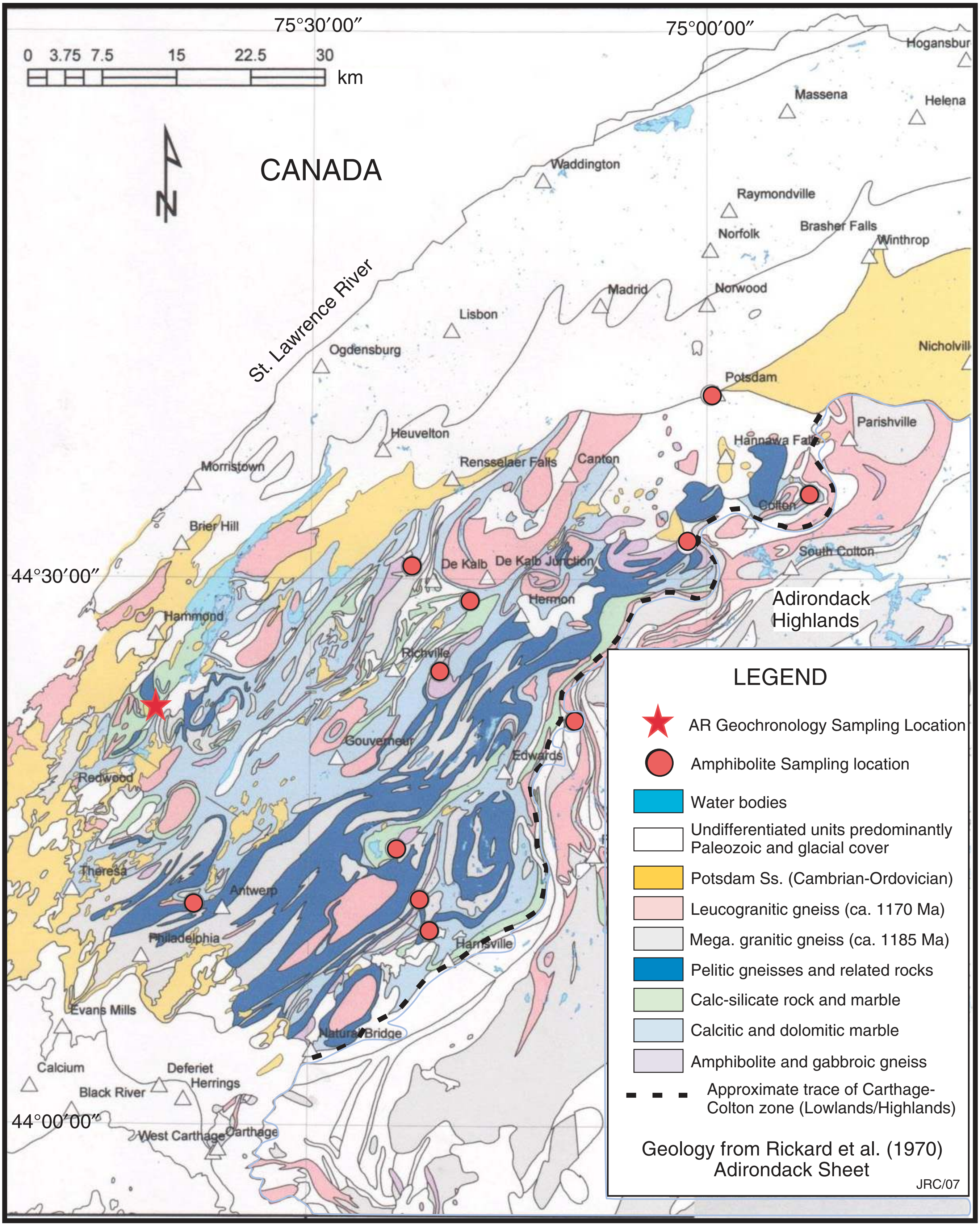


Figure 2. Simplified geologic map of the Adirondack Lowlands after Rickard et al. (1970). Red star indicates location of the Split Rock diorite sample utilized for U-Pb zircon geochronology in this study.

known igneous activity to ca. 1150–1200 Ma. Relatively undeformed AMCG rocks in the Adirondack Lowlands indicate that Shawinigan deformation ceased by 1155–1160 Ma, while thermal effects, recorded by titanite and monazite U-Pb ages, lasted another 50 m.y. or more (Mezger et al., 1991). Studies of metamorphic zircon in ultramafic and mafic rocks (Chiarenzelli et al., 2010; Selleck, 2008) and those recovered from anatectic leucosomes developed within the Popple Hill Gneiss (Heumann et al., 2006) yield Shawinigan ages that essentially overlap those interpreted as crystallization ages of the ARS. This work has confirmed the lack of Ottawan metamorphic effects and indicates that igneous and metamorphic ages are contemporaneous with the ca. 1140–1200 Ma Shawinigan igneous and associated thermotectonic events. Titanite geochronology yields slightly younger, but not Ottawan, ages that likely represent isotopic closure due to cooling (1103–1159 Ma; Mezger et al., 1991; Heumann et al., 2006). These data suggest that the Adirondack Lowlands were little affected by the Ottawan event and dropped down along the Carthage-Colton mylonite zone late enough to escape overprinting (Selleck et al., 2005). Thus the Adirondack Lowlands are an exemplary place to study Shawinigan orogenesis within the south-central Grenville orogen.

Among the various intrusive rocks in the Adirondack Lowlands, those of the ARS (ca. 1200 Ma) are the oldest recognized (Buddington, 1939; Fig. 2). In addition, the ARS is restricted in geographic occurrence to the Adirondack Lowlands primarily southeast of the Black Lake fault. It is absent from adjacent areas of the Frontenac terrane and Adirondack Highlands, whereas the younger Rockport Granite and similar rocks of the Hyde School Gneiss (ca. 1170 Ma) and other 1155–1180 Ma granitoids with A-type affinities are found across the entire area (Carl and deLorraine, 1997; Marcantonio et al., 1990; McLelland et al., 1992; Peck et al., 2004; Wasteneys et al., 1999). This suggests that the Black Lake fault may have developed along a fundamental boundary that existed just prior to the 1155–1180 magmatism that spans it (Peck et al., 2009). The ARS may be related to the Hermon granitic gneiss (HGG) (Carl and deLorraine, 1997), which has similar distribution, geochemical properties, Nd systematics, and yielded a younger U-Pb zircon SHRIMP II age of 1182 ± 7 Ma (Heumann et al., 2006). Thus the distribution of these rock types yields important clues and temporal constraints on the assembly of the Central Metasedimentary Belt that have been used to suggest that the ARS formed above the leading edge of Laurentia during Shawinigan subduction (McLelland et al., 1996, 2010; Peck et al., 2004; Wasteneys et al., 1999; Rivers and Corrigan, 2000).

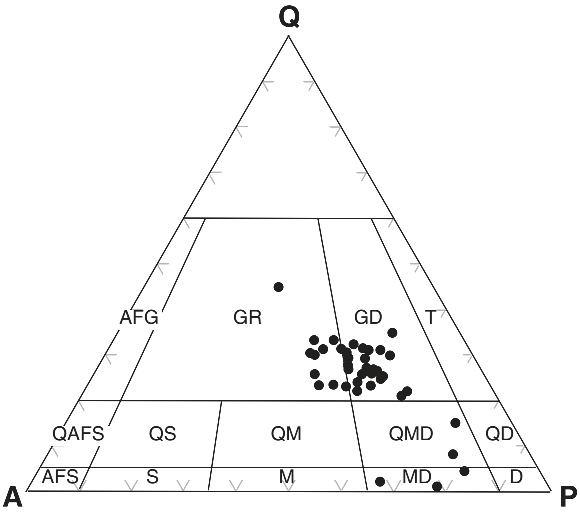
RESULTS

The ARS is of limited spatial distribution but intrudes a wide variety of lithologies that form the Adirondack Lowlands supracrustal sequence. It intrudes mostly marble, but also intrudes amphibolites, pelitic gneisses, schists, and contains xenoliths of quartzite (Fig. 3). The ARS was originally mapped by Buddington (1934, p. 60), who wrote: "…these masses appear to have been intruded in irregular sill or lens-like form conformable to the bedding of the Grenville formation." The ARS consists predominantly of medium- to fine-grained, gray, equigranular, and relatively undeformed felsic plutonic rocks, despite upper amphibolite facies metamorphism. Because the ARS often crosscuts foliation in the supracrustal rocks or contains strongly foliated xenoliths, the supracrustal rocks were deformed prior to its intrusion. The age of this foliation is unknown and may predate the Shawinigan orogeny or, more likely, occurred early in its deformational history.

Petrographic investigation of 15 samples and those investigated by Carl and deLorraine (1997) yield a compositional range of granitic to gabbroic, most samples plotting within the granodiorite field (Fig. 4). The mineralogy of the suite consists of alkali feldspar, quartz, plagioclase, hornblende, augite, magnetite, and

Figure 3. Photograph of granite of the Antwerp-Rossie suite intruding marble (upper part) and with xenoliths of quartzite (lower part).

Figure 4. Plutonic rock classification chart of Streckeisen (1973). A—Alkali feldspar; P—plagioclase; Q—quartz. Abbreviations: AFG—alkali-feldspar granite; GR—granite; GD—granodiorite; T-tonalite; QAFS—quartz alkali-feldspar syenite; QS—quartz syenite; QM—quartz monzonite; QD—quartz diorite; AFS—alkali-feldspar syenite; S—syenite; M—monzonite; MD—monzodiorite; D—diorite.



biotite. Trace minerals include apatite, zircon, and monazite. Some of the zircons and monazites show pronounced zoning. Alkali feldspars show extensive perthitic lamellae, minor deformation twinning, and plagioclase has normal zoning. Quartz demonstrates undulatory extinction, and sometimes displays a myrmekitic relationship with plagioclase. Primary pyroxenes are common, but are typically replaced by secondary minerals such as epidote and calcic amphiboles, possibly due to alteration during the waning stages of metamorphism or during subsequent hydrothermal events. Ophitic to subophitic textures are observed in the mafic members of the suite.

Carl and deLorraine (1997) performed a survey of the geochemistry of major plutonic rock suites in the Adirondack Lowlands as a tool to characterize and distinguish between them. The major element chemistry presented therein is used in conjunction with the 15 major and trace element geochemical analysis presented herein (Table 1). A histogram displaying SiO_2 content illustrates a bimodal distribution among the suites, including a mafic and larger felsic mode (Fig. 5). Only 1 of the 42 samples analyzed in the Carl and deLorraine (1997) study and ours plots between ~52.5 and 62.5 wt% SiO_2. On Harker diagrams, the ARS rocks show linear trends with increasing SiO_2, especially when plotted against CaO, MgO, Fe_2O_3, MnO, P_2O_5, and TiO_2 (Fig. 6). It is interesting that they are also on trends defined by other igneous suites in the Adirondack Lowlands, including those of the HGG (Carl and deLorraine, 1997). The ARS rocks have a mild calc-alkaline signature and corresponding trend on an AFM (alkalies, FeO, MgO) diagram (Fig. 7).

Rare earth element (REE) diagrams show light REE enrichment and depleted heavy REE typical of a garnet-bearing source (Fig. 8). A negative europium anomaly is present in one sample, but the rest have linear flat sloping trends. The large ion lithophile elements such as Cs, Pb, La, and Nd show enrichment, while the high field strength elements Nb, Ta, P, and Zr illustrate depletion (Fig. 9). Lead and Cs are enriched between 100 and 1000 times that of the primitive mantle values (Sun and McDonough, 1989). On tectonic discrimination diagrams plotting Y versus Nb and Y + Nb against Rb (Pearce et al., 1984), the ARS occurs in the volcanic arc granite field (Figs. 10 and 11).

We selected 12 representative samples from throughout the ARS exposure for Nd isotopic analysis, including a single sample of Hermon gneiss for comparison. Depleted mantle model ages (T_{DM}) and epsilon Nd (ε_{Nd}) values at 1200 Ma are shown in Figure 12. Neodymium concentrations range from 20.67 to 73.34 ppm and Sm ranges from 3.4 to 14.91 ppm. Corrected $^{143}Nd/^{144}Nd$ ratios range from 0.511931 to 0.512363 and $^{147}Sm/^{144}Nd$ ratios vary from 0.0831 to 0.1280 (Table 2). The ε_{Nd} values range from 1.52 to 5.42, yielding a wide variance of model ages (T_{DM}) from 1.288 to 1.634 Ga, based on a depleted mantle source (e.g., DePaolo, 1981). The average model age is 1.510 Ga, ~300 m.y. before the U-Pb zircon crystallization age (see following). The three oldest ages of 1.617 Ga (SPR-1), 1.634 Ga (SPR-28), and 1.613 Ga (SPR-31) all occur at or in very close proximity to the Black Lake fault and also have the lowest ε_{Nd} values present in the suite. The whole-rock samples provide a poorly constrained Sm-Nd isochron age of 1.03 Ga (Fig. 13). On an Nd evolution diagram, the slope of individual samples, including the Balmat gabbros and/or amphibolites (potentially correlative to mafic members of the ARS; Chiarenzelli et al., this volume) and HGG, are approximately similar (Fig. 14). No trend is seen when ε_{Nd} is plotted against SiO_2, suggesting that crustal contamination of the ARS was minimal (Fig. 15).

Several studies, using various techniques, have been carried out to define the age of the ARS (e.g., whole-rock Rb-Sr isochron, Carl et al., 1990; U-Pb zircon multigrain, McLelland et al., 1992; U-Pb zircon SHRIMP, Wasteneys et al., 1999). The current study utilized the U-Pb zircon SHRIMP reverse geometry (RG) technique on zircons separated from the Split Rock diorite body (Carl and deLorraine, 1997) located just southeast of the Black Creek fault (Universal Transverse Mercator zone 18T, NAD 27, 444594mE, 4916887mN). The age is within analytical error of the other studies (Table 3; Fig. 16). Analytical details are given in the Appendix. Figure 16 shows large, well-zoned zircons lacking rims and cores when imaged using backscattered electrons and cathodoluminescence. The 6 spots (~20 µm) on 3 zircons yielded a $^{207}Pb/^{206}Pb$ age of 1203 ± 13.6 Ma. Three of the analyses show slight reverse discordance; however, the calculated age is in agreement with previous studies.

TIMING AND NATURE OF SHAWINIGAN MAGMATISM

Table 4 summarizes the geochronological studies conducted on the ARS and rocks thought to be related to it. With few exceptions, the ages from both Rb-Sr and U-Pb systems are within analytical error of one another. The age of the Split Rock diorite reported herein as 1203 ± 13.6 Ma and is used for Nd model age and ε_{Nd} calculations. Buddington (1934, 1939) noted that mafic rocks were the oldest members of the suite, and thus it is possible that granitic members of the suite are slightly younger. In addition, one of us (Selleck, 2008) identified tonalitic and gabbroic rocks of similar age to the east in Pierrepont. Lupulescu et al. (2010) documented pegmatite bodies intruding the Adirondack Lowlands supracrustal sequence, also of similar age. These studies expand both the geographic range and the known rock types associated with Shawinigan magmatism in the area.

The ARS is bimodal in composition (Fig. 5), with a gap at 52.5–62.5 wt% SiO_2. Most samples are granitic and are between 67.5 and 72.5 wt% SiO_2. Four samples contain <55 wt% SiO_2 and likely represent an earlier related mafic pulse (Buddington, 1934, 1939) of the suite. Samples of the Gray's School syenite, tentatively assigned to the HGG (Carl and DeLorraine, 1997), fall into the 52.5–62.5 wt% SiO_2 gap, as do younger rocks of tonalitic composition in the Hyde School Gneiss (McLelland et al., 1992). Previous studies (Carl and deLorraine, 1997; Wasteneys et al. 1999) suggested that the ARS consists of volcanic arc granites, based on major and trace element characteristics. Figures 11 and 12 display data from Carl and deLorraine (1997) and this study that are in good agreement and compatible with models in which the ARS is arc related and formed above a subduction zone, perhaps on the leading edge of Laurentia (McLelland et al., 1996; Wasteneys et al., 1999; Peck et al., 2004). An extensive discussion of the geochemical features of igneous rocks from the Adirondack Lowlands and their interpretation was made by Carl and deLorraine (1997) and Carl (2000), and will not be repeated here.

Incompatible trace elements from the ARS have abundances suggestive of subduction-related magmas (Fig. 9). High field strength elements such as Nb, Ta, P, and Zr have negative anomalies relative to other elements when normalized to primitive mantle, while the large ion lithophile elements, including Cs, Pb, La, and Nd, have positive anomalies. These characteristics are typical of arc magmas derived from subducted sediments and metasomatized lithospheric mantle (Cousens et al., 1994; Dostal et al., 1998; Tian et al., 2008). Only a single sample shows a negative Eu anomaly (Fig. 8) indicative of the fractional crystallization and removal of plagioclase.

The Sm-Nd isotopic systematics of select samples were analyzed to constrain the origin of the ARS (Figs. 13 and 14). They yield ε_{Nd} values that range from 1.52 to 5.42 and show little correspondence with whole-rock geochemistry (Fig. 15). The samples have lower ε_{Nd} values at 1200 Ma than the Mesoproterozoic depleted mantle curve, which suggests that the rocks of the suite, especially mafic varieties, were not derived from a depleted mantle source.

TABLE 1. MAJOR AND TRACE ELEMENT ANALYSIS OF THE ANTWERP-ROSSIE SUITE

Sample	SPR 1	SPR 2	SPR8	SPR9	SPR11	SPR17	SPR21	SPR22	SPR24	SPR25	SPR27	SPR28	SPR29	SPR30	SPR31
SiO_2	60.38	72.36	72.6	70.87	70.67	64.73	50.03	51.7	78.84	69.73	64.72	51.8	70.35	70.92	53.34
TiO_2	0.58	0.3	0.29	0.56	0.30	0.78	0.59	1.04	0.21	0.37	0.54	1.09	0.36	0.39	1.92
Al_2O_3	16.06	15.26	14.91	14.91	15.27	15.94	16.3	14.13	11.08	15.43	15.85	16.84	15.05	14.75	16.58
Fe_2O_3	6.08	2.06	1.85	3.11	2.2	5.24	8.49	9.59	2.61	2.76	4.61	8.83	2.87	2.54	8.31
MnO	0.06	0.02	0.02	0.02	0.02	0.07	0.12	0.11	0.01	0.02	0.05	0.12	0.03	0.02	0.09
MgO	3.92	0.6	0.56	0.81	0.63	1.59	8.87	8.47	0.19	0.86	2.6	5.42	0.72	0.97	4.18
CaO	6.27	1.94	1.85	2.57	2.32	2.81	9.89	8.34	0.52	2.27	4.61	8.13	2.27	1.95	9.74
Na_2O	4.31	4.23	4.22	4.34	5.10	3.92	1.77	4.00	2.66	4.54	4.08	4.7	4.22	3.90	3.93
K_2O	1.39	3.86	3.85	2.69	3.22	3.77	1.89	1.42	4.83	3.42	2.38	1.48	3.02	3.83	3.06
P_2O_5	0.136	0.09	0.086	0.129	0.116	0.297	0.133	0.169	0.007	0.139	0.101	0.207	0.114	0.123	0.618
LOI	1.04	0.57	0.56	1.43	0.94	1.00	1.58	1.83	0.39	1.03	1.16	0.83	0.61	1.06	1.57
Total	101.3	100.2	100.3	101.4	100.8	100.2	99.7	100.8	101.4	100.6	100.7	99.5	99.6	100.5	103.3
Cs	0.3	1.4	1.6	2.8	0.6	5	1.5	1.1	1	<0.1	0.7	4	2	0.4	
Rb	16.9	84.2	89.2	77.3	43.5	96.6	44.2	62.9	34.8	77.7	62.3	51.9	91.1	25.36	
Sr	517	435	452	465	448	422	663	590	305	61	566	380	515	676	
Ba	333	601	635	562	662	932	481	978	163	174	902	314	708	726	
Ta	1.1	1.6	1.7	1.4	1.4	1.5	0.2	1.4	0.6	0.4	0.5	1.9	1.3	1.1	
Nb	5.85	9.15	8.79	9.91	6.89	13.73	2.52	7.03	7.27	7.85	4.9	10.71	8.27	18.03	
Pb	2.74	40.73	30.34	24.02	13.9	22.6	10.72	18.67	1.84	5.74	21.02	7.5	21.44	24.81	
Hf	1.13	4.24	4.71	4.88	3.38	3.79	1.44	2.77	2.16	8.69	2.27	1.96	4.16	3.94	
Zr	26.8	137	156.8	174.3	107.5	140.3	38.4	96.3	43.8	340.1	82.5	60.3	153.5	102.5	
Y	13.8	5.9	10.6	9.5	10.6	25.3	15.1	8.6	37.2	41.8	5.9	16.2	6.8	59.3	
Sc	12.6	2.6	4.1	4.9	4.8	8.3	26.1	4.3	35.3	0.4	2.6	10	3.9	20.4	
Cr	77	<1	1	2	2	8	69	3	278	<1	1	55	2	12	
Ni	29.8	1.2	2.2	2.2	1.9	5.6	60.4	1.8	62.4	<0.1	1.2	29.4	0.2	18.6	
Zn	33.2	63	127.8	76.3	28.2	108.9	63.3	56	48.4	5.1	36.3	46.7	49.2	193.5	
V	102	20	21	36	25	65	147	27	240	9	29	76	31	196	
Cu	2.28	1.82	13.71	1.7	5.81	5.22	27.09	2.19	5.24	0.51	1.02	2.71	1.92	9.75	
Th	2	20.8	8.6	3.5	1.1	15.5	3.5	8.5	1.1	11.4	6.9	8.6	8	6.4	
U	0.1	1.5	3.1	1.2	1	2.4	1.2	0.5	0.4	2.5	0.6	2.1	1.4	2.2	
Ga	21.33	22.2	23.48	24.23	21.91	23.33	16.31	20.31	22.08	21.09	20.83	23.38	23.14	25.36	
La	18.7	45.3	28.4	22.3	18	69.6	15.4	34.4	24.4	51.3	44.9	16.4	32.7	54.6	
Ce	33.12	79.23	53.66	39.73	32.32	130.5	30.58	63.13	61.52	107.7	78.4	33.41	59.58	118.1	
Pr	4.3	9.6	7.3	5.4	4.5	17.7	4.7	8.4	9.4	16	9.9	4.4	7.7	18.2	
Nd	16.8	32.2	26.6	21.4	17.8	64	19.8	30.5	38.4	63.1	31.3	16.9	27	70.3	
Sm	2.9	4.4	4.5	3.5	3.1	9.2	4.2	5	7	11.6	4	3.2	4	12.1	
Eu	0.8	1	0.9	1.1	1	1.8	1.3	1.2	1.9	1.2	1.1	0.7	1.2	2.3	
Gd	2.9	2.4	3.6	3.2	2.6	6.8	3.9	3.6	6.5	10	2.1	3	2.6	11.1	
Tb	0.5	0.3	0.5	0.4	0.4	1	0.5	0.4	1.1	1.7	0.3	0.5	0.4	1.9	
Dy	2.8	1.4	2.4	2.4	2.3	5.5	3	2.1	6.9	10	1.3	3.3	1.5	11.5	
Ho	0.6	0.2	0.4	0.4	0.5	1.1	0.6	0.4	1.5	2.1	0.2	0.7	0.3	2.5	
Er	1.5	0.6	1.1	0.9	1.1	2.7	1.6	0.9	4.3	5.5	0.5	2	0.6	6.4	
Tm	0.2	<0.1	0.1	0.1	0.2	0.3	0.2	0.1	0.7	0.8	<0.1	0.3	<0.1	0.9	
Yb	1.4	0.5	0.7	0.6	0.8	1.9	1.2	0.6	3.8	4.8	0.4	1.8	0.6	5.7	
Lu	0.2	<0.1	0.1	<0.1	0.1	0.3	0.2	<0.1	0.6	0.7	<0.1	0.3	<0.1	0.9	
Rock type	QMD	GR	GR	GR	GR	GD	MD	MD	GR	GD	QMD	MD	GR	GR	MD
Location	NAD 27														
Easting 18T	444632	447995	451193	451187	463731	478316	473487	472718	472504	467357	466924	444413	444776	448975	453262
Northing 18T	4917102	4914533	4896445	4894445	4906638	4910700	4918055	4917993	4915433	4909635	4907226	4915609	4917989	4910362	4924803

Note: International Union of Geological Sciences rock type abbreviations: GD—granodiorite; GR—granite; MD—monzodiorite; QMD—quartz monzodiorite. LOI—loss on ignition. Location: Universal Transverse Mercator system.

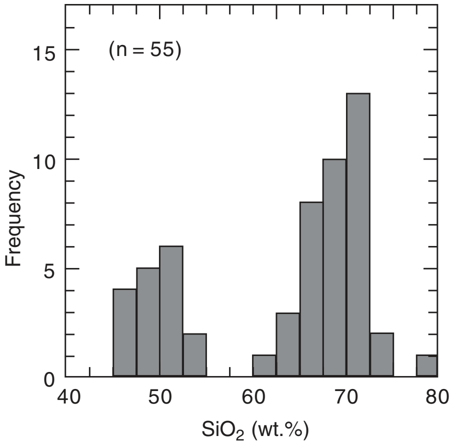


Figure 5. Histogram of SiO_2 wt% of samples of the Antwerp-Rossie suite.

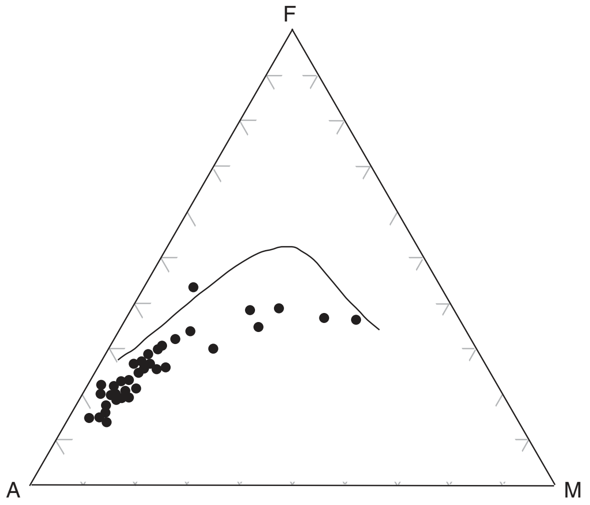


Figure 7. Alkali-iron-magnesium (AFM) diagram showing samples of the Antwerp-Rossie suite.

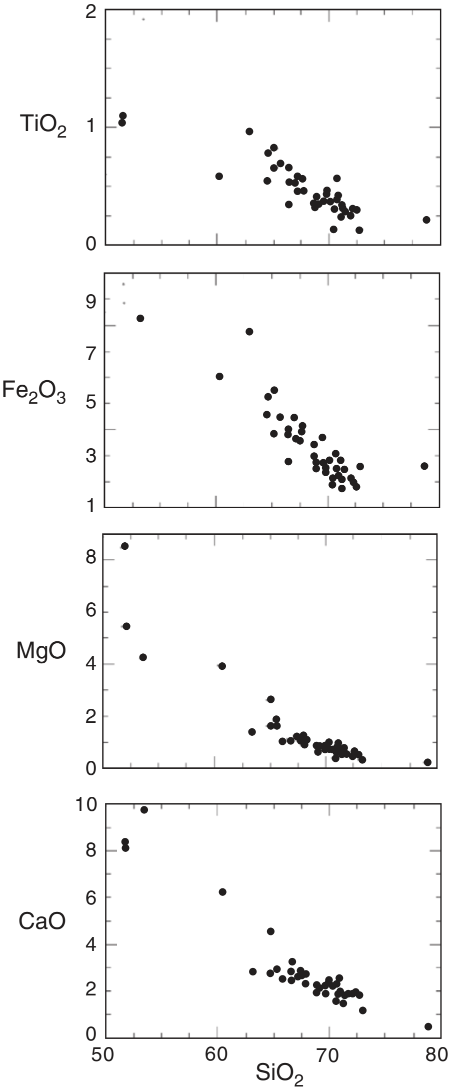


Figure 6. Select Harker diagrams of samples of the Antwerp-Rossie suite.

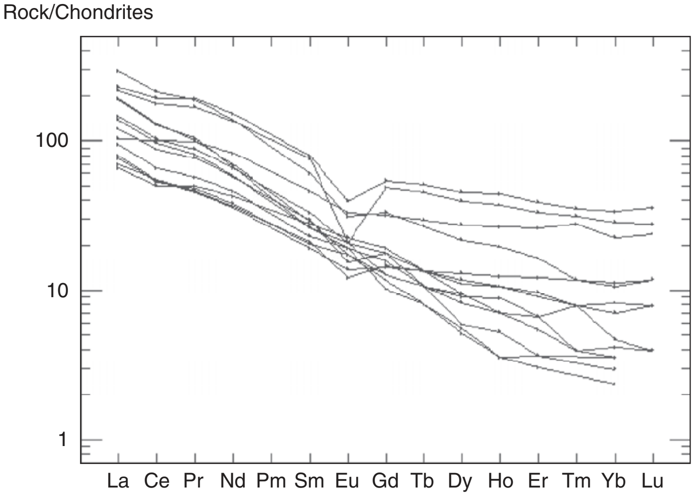


Figure 8. Rare earth element diagram normalized to chondritic values showing samples of the Antwerp-Rossie suite (after Sun and McDonough, 1989).

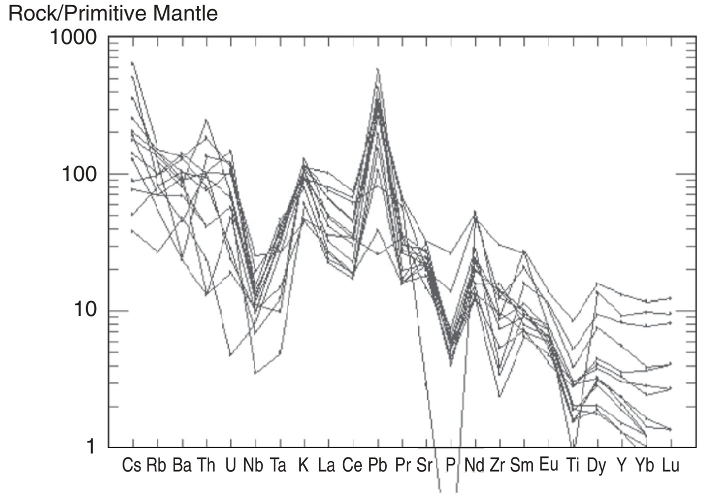


Figure 9. Incompatible element diagram normalized to primitive mantle values showing samples of the Antwerp-Rossie suite (after Sun and McDonough, 1989).

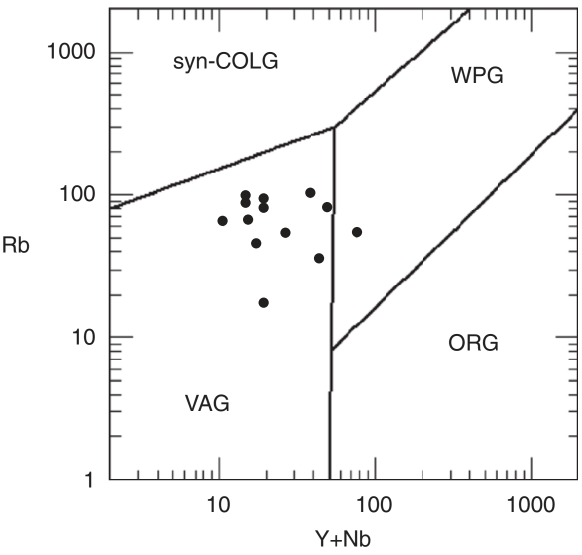


Figure 10. Rb versus Y + Nb tectonic discrimination diagram showing samples of the Antwerp-Rossie suite (after Pearce et al., 1984). Abbreviations: ORG—orogenic granites; syn-COLG—syncollisional granites; VAG—volcanic arc granites; WPG—within-plate granites.

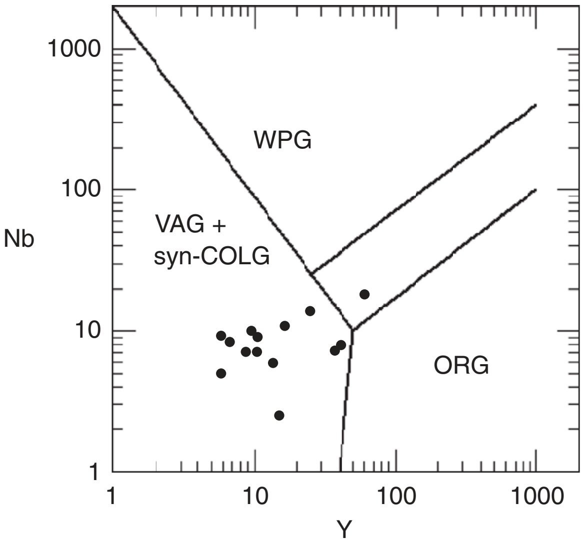


Figure 11. Nb versus Y tectonic discrimination diagram showing samples of the Antwerp-Rossie suite (after Pearce et al. 1984). Abbreviations: ORG—orogenic granites; syn-COLG—syncollisional granites; VAG—volcanic arc granites; WPG—within-plate granites.

On an Nd evolution diagram (Fig. 14) the suite has similar Sm/Nd ratios and slopes. Samples of amphibolite, metagabbro, and metadiorite from the Balmat area and the Hermon gneiss from Trout Lake (ε_{Nd} = 3.31, T_{DM} = 1424 Ma), some of which intrude the upper marble, are within the same range.

Neodymium T_{DM} model ages for the ARS range from 1288 to 1634 Ma and average 1504 Ma. Taken together, the Nd and geochemical evidence and nearly 300 m.y. difference between the crystallization age and Nd model ages suggest the variable influence of a mantle source with enriched characteristics similar to those imparted by subduction and/or evolved crust. The incompatible element pattern and Nd isotopic systematics of the ARS are also similar to those of ultramafic rocks recently discovered at Pyrites, New York (Chiarenzelli et al., 2010). The rocks at Pyrites and the Adirondack Lowlands amphibolite belts represent a tectonically emplaced sliver of the enriched upper mantle and corresponding ocean crust within the Adirondack Lowlands likely emplaced during the Shawinigan orogeny, which strongly influenced subsequent magmatic events (Chiarenzelli et al., 2010), perhaps including the $\delta^{18}O$ values of igneous zircon from the AMCG suite in the Frontenac terrane (Peck et al., 2004).

TOWARD A REFINED TECTONIC MODEL FOR THE LOWLANDS

Dickin and McNutt (2007) identified a 150-km-wide belt of juvenile crust with Nd model ages younger than 1.35 Ga in the Central Metasedimentary Belt. This area is interpreted as the remnants of a failed backarc rift zone. This backarc basin is believed to have formed in response to westward-directed subduction and rifting along the Andean-type margin of Laurentia (Hanmer et al., 2000; McLelland et al., 2010). The boundary of the proposed rift extends eastward to the western boundary of the Frontenac terrane (Maberly shear zone) and to the south under Phanerozoic cover. However, the recent recognition of dismembered oceanic crust (amphibolite belts) and mantle rocks in the Adirondack Lowlands (Chiarenzelli et al., 2007, 2010) and the lack of older basement rocks suggest that supracrustal rocks in the Adirondack Lowlands, and perhaps the Highlands, may have once been deposited in a similar backarc basin floored by oceanic crust. The widespread occurrence of marbles across the region, interpreted as shallow-water carbonates (Hanmer et al., 2000; Whalen et al., 1984), and evaporate units in the upper marble is consistent with deposition in a backarc basin that closed during the Shawinigan orogeny. In addition, others have noted the similarity of the supracrustal rocks in the Adirondack Highlands and Adirondack Lowlands, and have attempted to make, or infer, stratigraphic correlations across the Carthage-Colton mylonite zone (Wiener et al., 1984; Heumann et al., 2006).

Peck et al. (2004) found some of the highest magmatic $\delta^{18}O$ values ever measured in zircons separated from 1155–1180 Ma AMCG granitoids in the Frontenac terrane. Despite this, the plutons have typical igneous whole-rock chemistry and radiogenic isotope values. In order to account for the anomalous $\delta^{18}O$ values, Peck et al. (2004) suggested that hydrothermally altered basalts and/or oceanic sediments were subducted or underthrust beneath the Frontenac terrane during closure of an ocean basin between the Frontenac terrane and the Adirondack Highlands at or prior to 1.2 Ga. Our work supports this contention, and Chiarenzelli et al. (2010) identified potential fragments of the underplated basalt and enriched upper mantle shown schematically in Figure 9 of Peck et al. (2004).

Examination of the distribution of Nd model ages from the ARS yields an intriguing pattern (Fig. 12). Three samples collected from the southeastern side of the Black Lake fault (Wallach, 2002) yield the oldest Nd model ages of 1613–1634 Ma. In addition, these three samples have the lowest ε_{Nd} values, ranging from 1.52 to 1.80. This may provide credence to the suggestion that the Black Lake fault (also known as the Black Creek fault or Black Lake lineament) and nearby ductiley deformed rocks of the Black Lake shear zone define an

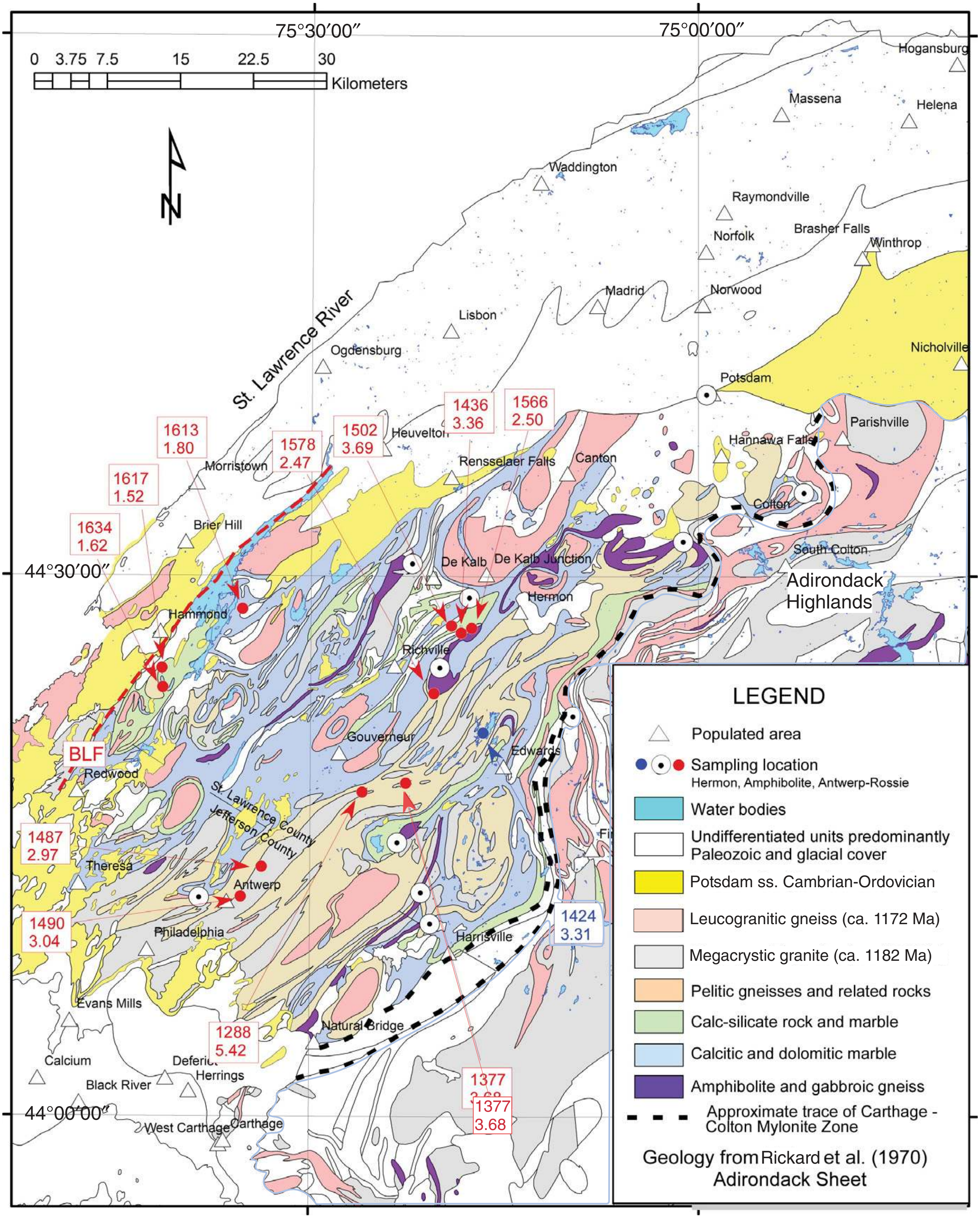


Figure 12. Locations of samples of the Antwerp-Rossie suite analyzed for Sm-Nd isotopes in this study. Depleted mantle model ages and ε_{Nd} values are shown (red numbers in boxes) and calculated at 1200 Ma. Ss.—sandstone; BLF—Black Lake fault.

TABLE 2. SM-ND ISOTOPIC COMPOSITIONS OF THE ANTWERP-ROSSIE GRANITOIDS (ADIRONDACK LOWLANDS)

Sample number	Sm (ppm)	Nd (ppm)	^{147}Sm/^{144}Nd	^{143}Nd*/^{144}Nd	ε_{Nd} (0)	ε_{Nd} (T)	T_{DM} (Ma)
SPR-1	4.05	20.67	0.1186	0.512100	–10.49	1.52	1617
SPR-8	5.38	28.47	0.1142	0.512140	–9.71	2.97	1487
SPR-9	4.26	22.00	0.1171	0.512166	–9.20	3.04	1490
SPR-11	3.40	19.50	0.1049	0.512192	–8.71	5.42	1288
SPR-17	11.80	72.82	0.0980	0.512029	–11.87	3.31	1424
SPR-21	4.74	20.79	0.1378	0.512363	–5.37	3.69	1502
SPR-22	5.34	30.58	0.1055	0.512092	–10.66	3.36	1436
SPR-24	7.91	37.33	0.1280	0.512223	–8.09	2.47	1578
SPR-25	13.37	64.30	0.1257	0.512206	–8.42	2.5	1566
SPR-27	5.09	37.03	0.0831	0.511931	–13.79	3.68	1377
SPR-28	4.83	23.54	0.1241	0.512149	–9.54	1.62	1634
SPR-31	14.91	73.43	0.1227	0.512147	–9.57	1.80	1613

Note: T—1200 Ma. T_{DM}—depleted mantle model age. SPR-17 is a sample Hermon granite from Trout Lake.
*Measured ratio, corrected for spike and normalized to ^{146}Nd/^{144}Nd = 0.7219.

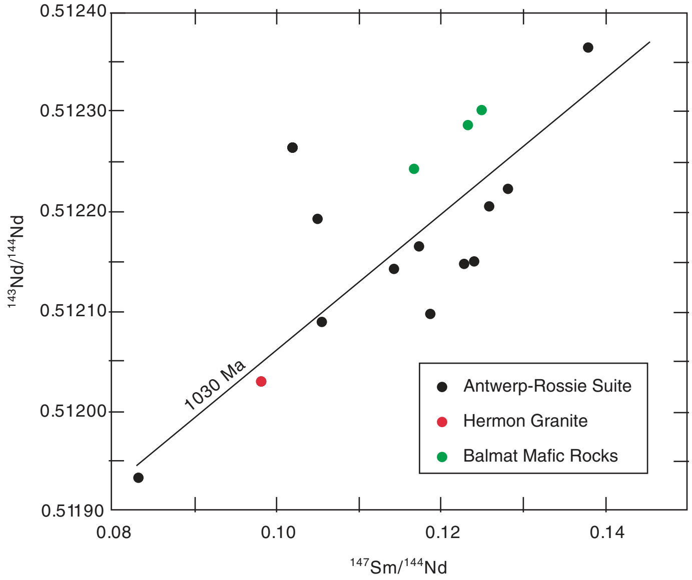


Figure 13. Sm-Nd isochron for whole-rock samples of the Antwerp-Rossie suite.

important boundary in the Adirondack Lowlands (Davidson, 1995; Peck et al., 2004). The kinematics and significance of the boundary are currently being investigated (Baird and Shrady, 2009; Peck et al., 2009); similar shear zones to the west at Wellesley Island show contrasting right-lateral motion (Reitz and Valentino, 2006).

The Black Lake fault appears to form the northwestern limit of ARS and Hermon gneiss magmatism. Rocks of the Hyde School Gneiss are also found exclusively southeast of the Black Lake fault, but are the same age and presumed equivalent to those of the Rockport Granite to the northwest (Carl and deLorraine, 1997; Marcantonio et al., 1990; however, see Carl and deLorraine, 1997, for differences between the two suites). The timing of assembly can therefore be relatively well constrained by the age of the HGG (1182 ± 7 Ma; Heumann et al., 2006) of limited spatial distribution, and widespread A-type 1155–1180 granitoid magmatism (Hyde School Gneiss and Rockport Granite) that spans the boundary. The timing of this plutonism is in excellent agreement with the 1160–1180 Ma age of widespread leucosome production in the Adirondack Lowlands and part of the Highlands (Heumann et al., 2006), presumably the result of metamorphic effects of Shawinigan convergence.

One plausible interpretation is that the Black Lake fault represents the approximate location of the rifted margin of Laurentia prior to the Shawinigan orogeny (Chiarenzelli et al., 2009; McLelland et al., 2010). In such an interpretation, the gross correlation of supracrustal units from the Frontenac terrane eastward into the Adirondack Highlands is likely; however, facies changes from predominantly shallow-water shelf sediments (carbonate and quartz-rich sandstones) to deeper water basinal rocks (shales and muds) would be expected. Implicit in this scenario is the interpretation of the Popple Hill Gneiss as, in part, a fine-grained clastic sequence, consistent with its major and trace element composition and grain size (Engel and Engel, 1953). In such a scenario the edge of the craton and bounding faults or stress fields may have served to channel and/or deflect subduction-related melts into structurally active areas, thereby limiting the geographic distribution of the ARS and Hermon gneiss. The mechanism for the localization of melts was removed by 1180 Ma, when widespread granitic members of the AMCG suite were intruded across the entire region.

The location of the original subduction zone responsible for the arc plutonic rocks of the ARS is unknown; however, one potential candidate is the Piseco Lake shear zone in the southern Adirondacks. Recent study of the associated granitoids shows an arc-like geochemistry (Chiarenzelli and Valentino, 2008; Valentino et al., 2008) and older (ca. 1180–1190) zircon and monazite populations (Chiarenzelli and Valentino, 2008; M. Williams, 2008, personal commun.). The Piseco Lake shear zone also separates the remainder of the Adirondack Highlands from the Southern Adirondacks, where 1300–1350 Ma tonalitic gneisses of the Dysart–Mount Holly Suite are exposed (McLelland and Chiarenzelli, 1990). However, it is also possible that the Carthage-Colton mylonite zone, with its long and complex history, may have originated as a subduction zone and/or cryptic suture (Mezger et al., 1992). If so, it separates metamorphosed sedimentary sequences that were deposited on opposite flanks of the Trans-Adirondack back-arc basin. Rocks correlative to the upper marble, with its attendant Zn-Pb mineralization, have yet to be identified in the Adirondack Highlands and may well represent a unique depositional event or conditions only recorded or preserved in the Adirondack Lowlands, whereas marbles and pelitic gneisses are widespread throughout.

The Adirondack Lowlands have a strong southwest-northeast structural grain and have been divided into parallel structural panels across which the gross stratigraphic relationships are preserved (deLorraine and Sangster, 1997; Carl, 2000). However, as might be expected in areas of complex structure, the internal stratigraphy of each fault slice is unique (Brown, 1988, 1989), and probably cannot be traced for large distances (tens of kilometers). Conceivably these panels are bounded by subsidiary faults to the main Carthage-Colton mylonite zone detachment (Selleck et al., 2005). Some (Baird, 2006; Colony et al., 2010; Reitz and Valentino, 2006)

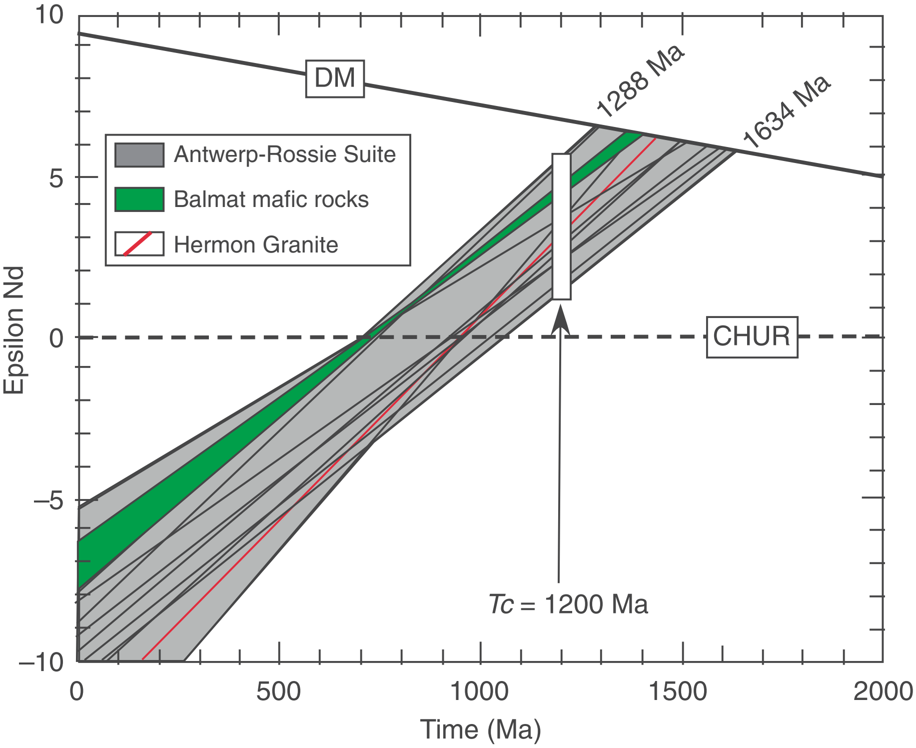


Figure 14. Nd evolution diagram for samples of the Antwerp-Rossie suite. DM—depleted mantle; CHUR—chondrite uniform reservoir; T_c—age of crystallization.

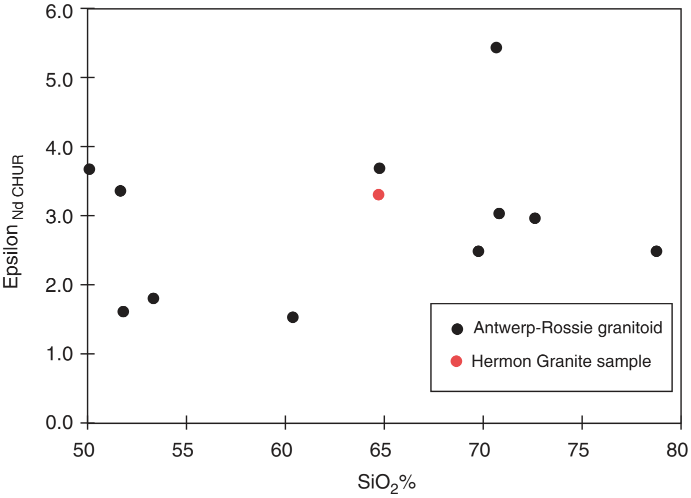


Figure 15. ε_{Nd} values versus SiO_2 wt% for samples of the Antwerp-Rossie suite. CHUR—chondrite uniform reservoir.

suggest that there are components of strike-parallel shearing in the Adirondack Lowlands. This shearing, likely of late Shawinigan age, focused strain along the margin of elliptical Hyde School Gneiss bodies (Brown, 1988; Hudson and Dahl, 1998; Rickard et al., 1970) and within intervening supracrustal belts. If so, the Black Lake fault and other parallel shear zones and faults in the Adirondack Lowlands may have developed along, and served to modify, the original geometry of the Laurentian margin.

The bulk composition (predominantly granitic) and older Nd model ages (300 m.y. older than their crystallization age) of the ARS argue against an island arc origin; however, they may represent remnants of a continental arc developed along the leading edge of a microcontinent that included the Adirondack Highlands. In such a scenario subduction would have been toward the southeast and generated melts would have intruded supracrustal rocks unaffiliated with Laurentia. However, as discussed here, the ARS primarily intrudes marbles correlated across the Central Metasedimentary Belt (Hanmer et al., 2000) that were deposited in shallow water after rifting at 1.3 Ga (Dickin and McNutt, 2007). In addition, work by others, including Wasteneys et al. (1999) and Peck et al. (2004), based on a variety of tectonic and isotopic arguments, strongly suggests northwest-directed subduction prior to Shawinigan orogenesis. Thus we tentatively suggest that the ARS represents melt generated and emplaced during, or just prior to, Shawinigan orogenesis within the attenuated Laurentian margin during northwest-directed subduction, perhaps along the present location of the Piseco Lake shear zone, which was modified by later reactivation during Ottawan orogeny (Gates et al., 2004; Valentino et al., 2008).

The failed backarc rift zone model of Dickin and McNutt (2007) for the Central Metasedimentary Belt provides context for understanding the events leading to Shawinigan orogenesis in the Adirondack Lowlands. We propose that a parallel but physically separate and outboard rift zone to the east of the Frontenac terrane developed into a backarc basin that once separated the Southern Adirondacks and the Frontenac terrane (Fig. 17). This basin was

TABLE 3. U-PB SHRIMP RG ANALYTICAL DATA FOR THE SPLIT ROCK DIORITE BODY OF THE ANTWERP-ROSSIE SUITE

Spot location	U (ppm)	Th (ppm)	Th/U	$^{206}Pb^*$ (ppm)	$^{207*}Pb/^{235}U$	$^{207*}Pb/^{235}U$ error (%)	$^{207*}Pb/^{205*}Pb$	$^{207*}Pb/^{205*}Pb$ error (%)	$^{207}Pb/^{205}Pb$ age (Ma)	Discordance (%)
29-2.1 c	104	40	0.38	18.7	2.28	1.4	0.0792	1.2	1177 ± 23	–4
29-2.2 e	201	108	0.54	36.2	2.29	1.1	0.0792	0.9	1178 ± 18	–4
29-3.1 c	169	86	0.51	29.9	2.27	1.2	0.0799	1.0	1193 ± 19	–1
29-1.1 e	292	132	0.45	50.8	2.24	1.0	0.0802	0.8	1202 ± 16	1
29-3.2 e	434	282	0.65	80.7	2.41	0.7	0.0808	0.6	1217 ± 11	–4
29-1.2 c	134	53	0.40	23.5	2.29	2.0	0.0811	1.1	1224 ± 21	2

Note: All errors on ratios and ages reported at 1σ level of uncertainty. SHRIMP—sensitive high-resolution ion microprobe; c—center; e—edge.
*Radiogenic lead.

formed by splitting of the Elzevirian arc along an Andean-type margin ca. 1350 Ma (Hanmer et al., 2000; McLelland et al., 2010). Remnants of this arc are currently exposed in the southern and eastern Highlands Adirondacks and Green Mountains (McLelland and Chiarenzelli, 1990) and regionally as the Dysart–Mount Holly arc. This assemblage, and its likely extension to the east (McLelland et al., 2010), was named Adirondis by Gower (1996). Elzevirian arc rocks were also left behind within the composite arc belt to the northwest of the Frontenac terrane (Carr et al., 2000).

In our model, sedimentation accompanying rift and drift led to the development of trailing sedimentary wedges, represented by the Popple Hill Gneiss in the Adirondack Lowlands and similar pelitic gneisses in the Highlands (Heumann et al., 2006). The Popple Hill Gneiss was extensively intruded by sill-like bodies of basalt and gabbro, now amphibolite, with enriched mid-ocean ridge basalt (MORB) or island arc tholeiite composition (Carl, 2000) prior to the initiation of Shawinigan compression or during development of a foredeep basin. The upper marble, with extensive siliceous carbonates

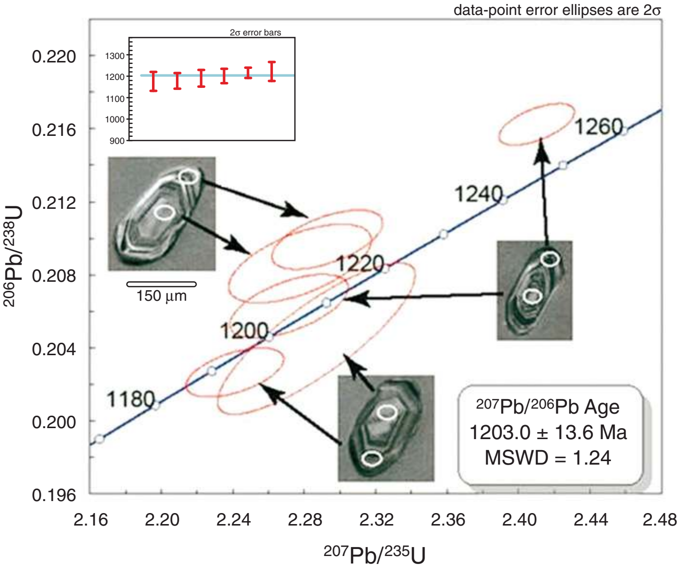


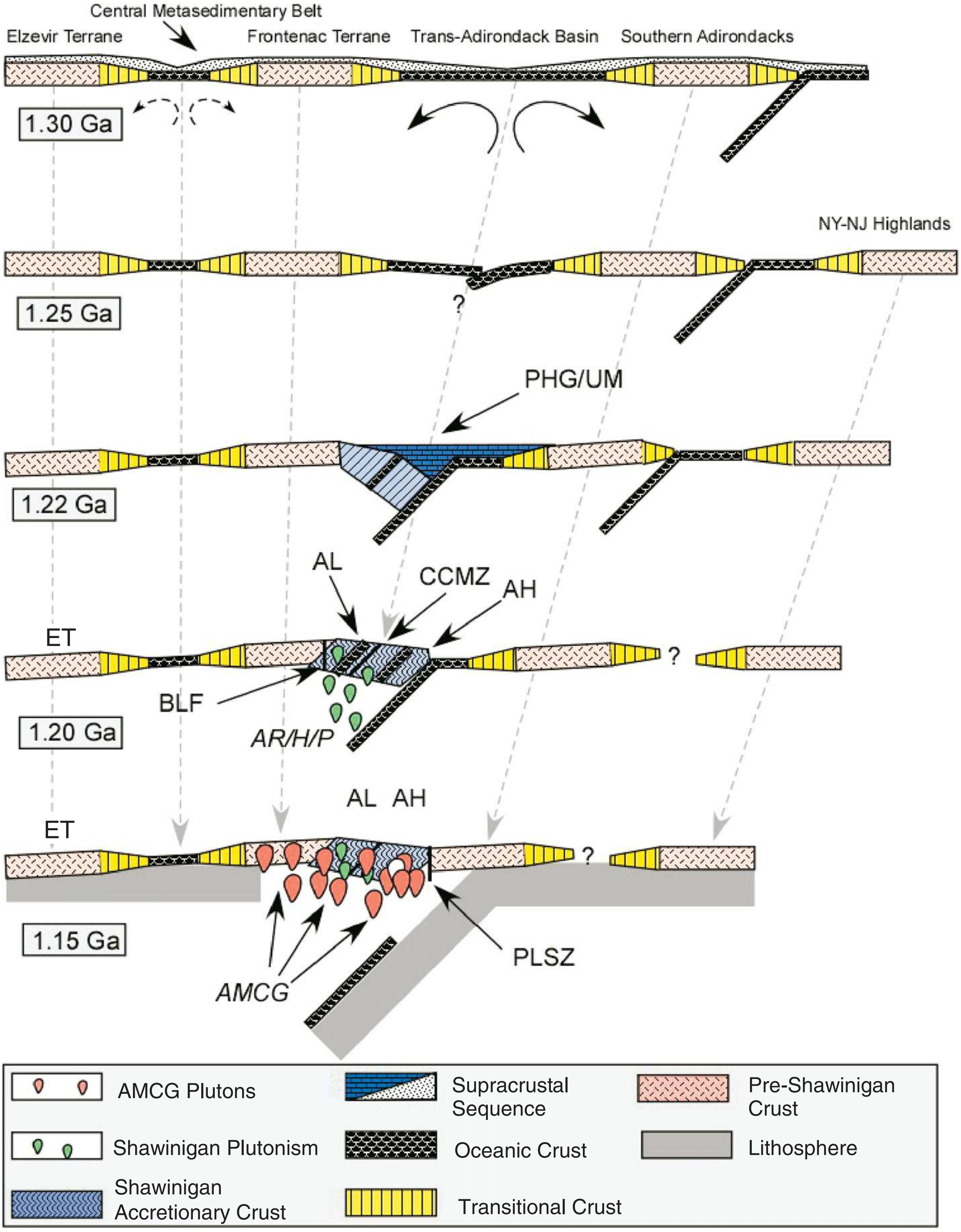
Figure 16. U-Pb SHRIMP RG (sensitive high-resolution ion microprobe reverse geometry) concordia diagram showing zircons from the Split Rock diorite (separated and analyzed by Graham B. Baird). Cathodoluminescence images connect spot locations with concordia ellipses; inset displays age-analysis chart. MSWD—mean square of weighted deviates.

TABLE 4. GEOCHRONOLOGICAL STUDIES OF THE ANTWERP-ROSSIE GRANITOIDS AND ASSOCIATED ROCKS

Age (Ma)	Technique	Sample	Location	Reference
1197 ± 53	Rb-Sr whole rock	Dioritic phase	various	Carl et al. (1990)
1160 ± 42	Rb-Sr whole rock	Granodioritic phase	various	Carl et al. (1990)
1183 ± 7	U-Pb zircon multigrain	Granodioritic phase	Rossie Village	McLelland et al. (1992)
1207+26/–11	U-Pb zircon SHRIMP I	Granodioritic phase	Rossie Village	Wasteneys et al. (1999)
1203 ± 1	U-Pb monazite	Tonalitic gneiss	Pierrepont	Selleck (2008)
1203 ± 13	U-Pb zircon SHRIMP RG	Dioritic phase	Split Rock Road	This study

Note: SHRIMP RG—sensitive high-resolution ion microprobe reverse geometry.

Figure 17. Time series cross sections showing the proposed tectonic evolution of the south-central Grenville Province from 1.30 to 1.15 Ga. At 1.30 Ga the backarc basin failed rift in the Central Metasedimentary Belt (CMB) has begun to open separating the Frontenac terrane (FT) from the Elzivirian Terrance (ET). Simultaneously, but outboard, the Trans-Adirondack backarc basin (TAB) developed and separated the 1.35 Ga arc rocks of the Southern Adirondacks (SA) from the Frontenac terrane. It is likely that this extension occurred as a consequence of northwest-directed subduction beneath the margin of Laurentia (subduction zone to the far right). Shallow-water supracrustal rocks drape the region and overlie transitional and oceanic crust in the TAB. At 1.25 Ga spreading in the CMB has stopped and the TAB has reached its maximum width. Orogenesis begins with the compression of the TAB and the initiation of deformation and subduction, perhaps along a transform or zone of weakness in the oceanic crust. The New York–New Jersey Highlands (NY-NJ) may be contiguous with the Southern Adirondacks or separated from them by another subduction zone, resulting in the intrusion of 1.25 Ga granitoids in the SA. By 1.22 Ga the TAB has undergone significant shortening and deformation. Tectonic slivers of oceanic crust and upper mantle are incorporated in the growing accretionary prism. Mud-rich protoliths of the Popple Hill Gneiss (PHG) are deposited in a foredeep trench, followed by deposition of the upper marble (UM) as a carbonate-evaporite sequence periodically restricted from the open ocean. At 1.20 Ga mafic and granitic melts generated by subduction beneath the collapsed TAB intrude the deformed metasedimentary sequence (*AR*—Antwerp-Rossie, *H*—Hermon, and *P*—Piseco suites). The edge of the FT, approximately located along the Black Lake fault (BLF), channels intrusive rocks into the deformational zone dominated by weak supracrustal lithologies (PHG/UM). The Adirondack Lowlands (AL) are thrust over the Highlands (AH) along the Carthage-Colton mylonite zone (CCMZ). Tectonic burial associated with the Shawinigan orogeny leads to upper amphibolites facies metamorphism, widespread metamorphic zircon growth, and anatexis in pelitic gneisses. By 1.15 Ga subduction has ended and delamination of the lithospheric mantle has occurred. The Piseco Lake shear zone (PLSZ) marks the location of the former subduction zone and forms the boundary between the TAB and SA. The rise of hot asthenosphere leads to ponding of mafic magmas and extensive melting of the lower crust, resulting in intrusion of the anorthosite-mangerite-charnockite-granite (AMCG) suite from the northwest to the southeast, from the FT to the SA and perhaps beyond.


Central Metasedimentary Belt
Elzevir Terrane
Frontenac Terrane
Trans-Adirondack Basin
Southern Adirondacks
1.30 Ga
NY-NJ Highlands
?
1.25 Ga
PHG/UM
1.22 Ga
AL
CCMZ
AH
ET
?
BLF
1.20 Ga
AR/H/P
AL AH
ET
?
1.15 Ga
PLSZ
AMCG
AMCG Plutons
Supracrustal Sequence
Pre-Shawinigan Crust
Shawinigan Plutonism
Oceanic Crust
Lithosphere
Shawinigan Accretionary Crust
Transitional Crust

and evaporitic units, represents the compression associated with Shawinigan orogenesis resulting in hypersaline conditions as the Trans-Adirondack backarc basin became isolated from the open ocean.

A continental arc and backarc model was proposed by Volkert (2007) for the New Jersey Highlands. Stromatolitic marbles and associated metaplutonic and volcanic rocks are used to support development of a magmatic arc on the Laurentian margin. While it is intriguing to contemplate correlation of the zinc-bearing Franklin marble of New Jersey with similar, but not identical, mineralization in the upper marble in the Adirondack Lowlands, if our interpretations are correct, the Laurentian margin was well inboard to the north. In addition, the Franklin marble shows a much more restricted range of $\delta^{18}O$ values and is unlikely to be correlative to Adirondack marbles (Peck et al., 2006); in which case, the arc in the New Jersey Highlands was built within the remnants of the Elzevirian arc that rifted away from Laurentia at 1.3–1.35 Ga (Dickin and McNutt, 2007; Hanmer et al., 2000; McLelland et al., 2010).

The ARS has a calc-alkaline signature yet is bimodal with a near absence of compositions between 52 and 62 wt% SiO_2. In order to account for the bimodal nature of the ARS, a relatively rapid transition from backarc spreading or foredeep magmatism to arc magmatism is proposed. Furthermore, this was followed by widespread 1150–1180 Ma AMCG magmatism across the entire region, which lacks a bimodal character (Carl and deLorraine, 1997; McLelland et al., 1992). The mafic magmas associated with the ARS may be correlative with amphibolites of tholeiitic chemistry found as sill-like bodies within the Popple Hill Gneiss (Carl, 2000), and represent some of the last magmas related to backarc spreading or foredeep magmatism. Their composition and Nd systematics (Chiarenzelli et al., 2010) suggest derivation from an enriched lithospheric mantle source, similar to that currently exposed in Pyrites. Shortly thereafter, subduction-related granitic magma (ARS and perhaps Hermon gneiss; ca. 1180–1200 Ma), involving the melting of the descending slab and subducted sediments, was emplaced syntectonically into the deforming supracrustal sequence just outboard and along the Laurentian margin. A similar and contemporaneous scenario resulting in docking of the Morin terrane and associated plutonic suites in the Central Granulite terrane of Quebec was suggested by Corriveau and van Breemen (2000). The incompatible element composition and Nd isotopic systematics of the ARS and Hermon gneiss also suggest contributions from the enriched mantle underlying this portion of the Grenville orogen or rocks (MORB) derived from it (Peck et al., 2004; Chiarenzelli et al., 2010).

The restricted age range and limited geographic distribution of the ARS and Hermon gneiss are likely functions of a short-lived and geographically limited event compatible with the closure of a backarc basin of relatively small size in this area rather than the closure of a mature ocean. McLelland et al. (2010) equated it in size to the Sea of Japan. The presence of oceanic crust (dismembered amphibolites and overlying chemogenic sediments) and mantle rocks in the Adirondack Lowlands sequence is also compatible with the obduction of young oceanic crust. The known extent of the Shawinigan orogenic event is fairly limited, occurring in the Central Granulite terrane and adjacent parts of the Central Metasedimentary Belt (Fig. 1), but not currently recognized elsewhere with the exception of the Parry Sound domain (Fig. 7 of Rivers, 2008); however, its extension to covered areas to the southwest is unknown and overprinting may mask its effects elsewhere (McLelland et al., 2010).

Although associated with considerable deformation and high-grade metamorphism, the limited extent of the Shawinigan event suggests that it was not formed by continent-continent convergence, but is consistent with closure of the backarc basin formed during splitting of the Elzevirian arc (Hanmer et al., 2000). The recognition of a partial ensialic backarc and rift zone farther to the west in the Central Metasedimentary Belt (Dickin and McNutt, 2007) suggests that the margin of Laurentia underwent extension and consisted of a number of smaller rifts and attenuated crust prior to Shawinigan orogenesis during 1.4–1.2 Ga subduction events. However, evidence for considerable uplift and topographic relief during sedimentation is lacking because the area is covered by a veneer of marble and platformal metasedimentary rocks across most of its breadth (Carl et al., 1990; Easton, 1992). This is likely a function of the density of the crust and lithosphere, and generated the conditions that facilitated the catastrophic lithospheric delamination that followed the Shawinigan orogeny.

Shortly after collision of the outboard remnant of the Elzevirian arc (extending from the southern Adirondacks and/or Green Mountains into Quebec) and collapse of the intervening backarc basins, massive amounts of anorthosite-suite rocks 1150–1180 m.y. in age were intruded into the area affected by the Shawinigan orogenesis. These rocks include the massif anorthosites of the Central Granulite terrane and vast volumes of related granitic rocks across the region. The primary cause of this massive magmatic event has been suggested to represent the rise of hot asthenosphere after delamination of the upper mantle following Shawinigan terminal collision (see Fig. 7 of McLelland et al., 1996). Northwest-directed subduction beneath, rather than away from, the Laurentia margin has been indicated by a variety of workers (Hanmer et al., 2000; McLelland et al., 2010; Peck et al., 2004; Wasteneys et al., 1999; Rivers and Corrigan, 2000). Collision of an outboard arc remnant and collapse of a series of small backarc basins can explain the limited extent of Shawinigan orogenesis, and thus that of the ARS and HGG, and provide a mechanism and setting conducive for delamination. Models invoking docking of an outboard continental mass (e.g., Amazonia) are not necessarily required, and we suggest that the terminal collision with Amazonia occurred during the Ottawan phase of the Grenvillian orogeny (Gates et al., 2004; Hoffman, 1991; Rivers, 2008), rather than during the Shawinigan orogeny (cf. Hanmer et al., 2000).

CONCLUSIONS

1. The ARS intruded the Adirondack Lowlands supracrustal sequence ca. 1200 Ma, a time of active high-grade metamorphism, deformation, and zircon and monazite growth related to the Shawinigan orogenic event.

2. The ARS shares numerous characteristics with the HGG, including restricted geography, field relations, limited volume, enriched geochemical trends, and Nd isotopic systematics. Their similar age (ca. 1182 ± 7 versus 1203 ± 13.6 Ma) suggests that they were intruded in rapid succession, the alkaline HGG perhaps indicating a transition from arc-related to post-orogenic 1150–1180 Ma AMCG plutonism.

3. The ARS is bimodal, with an early mafic and later granitic phase, and lacks rocks of intermediate composition (52–62 wt% SiO_2). Nonetheless, the Antwerp-Rossie suite displays calc-alkaline trends and trace element compositions compatible with arc plutonic rocks. Mafic members of the suite may be correlative with numerous MORB-like amphibolitic sills in the Popple Hill Gneiss. These characteristics are best explained as the transition from backarc to arc or foredeep to arc magmatism during Shawinigan orogenesis. Numerous lines of evidence suggest that a component of enriched mantle like that exposed at Pyrites, New York, or rocks derived from it, were a substantial part of their source.

4. The ARS and HGG were intruded in rapid succession in a limited geographic area southeast of the Black Lake fault, followed by regional intrusion of the anorthosites and related granitoids that spans the area from the Adirondack Highlands across the Frontenac terrane.

These suites provide tight constraints on the timing of the assembly of Frontenac terrane and Adirondack Highlands (ca. 1172–1182 Ma).

5. Neodymium systematics of the ARS and HGG (oldest Nd model ages and smallest ε_{Nd} values along the Black Lake fault) indicate that the Black Lake fault may represent the approximate margin of Laurentia prior to Shawinigan orogenesis. If so, the ARS and HGG were intruded into a collapsing backarc basin (Trans-Adirondack backarc basin). The strong southwest-northeast structural grain of the Adirondack Lowlands including the Black Lake and parallel shear zones bounding structural panels may be related to the original geometry of convergence and late Shawinigan strike-parallel deformation.

6. The continuity of shallow-water Grenville series metasedimentary rocks across much of the southern Grenville Province and the recent documentation of a failed backarc rift zone in the Central Metasedimentary Belt suggests large-scale extension across the region prior to Shawinigan orogenesis. This extension occurred behind the outboard fragment of the Elzevirian arc that rifted away from Laurentia after 1.35 Ga. The result of arc splitting, the Trans-Adirondack backarc basin included most of the Adirondack Lowlands and perhaps the Highlands, was floored by transitional to oceanic crust, and had opposing sedimentary prisms of similar lithologies. Deepening of the basin is represented by fine-grained sediments of the Popple Hill Gneiss, which was extensively intruded by basalts of MORB chemistry, perhaps in a developing foredeep. Eventual closure of this basin, due to the beginning of orogenic activity, is recorded in the sedimentary units of the upper marble in the Adirondack Lowlands composed of shallow-water siliceous carbonates and evaporates, with intervening pulses of sedimentary Zn-Pb exhalatives.

7. The restricted age range, volume, and geographic extent of the ARS and HGG and the restricted area of the Grenville Province affected by Shawinigan orogenesis are compatible with a tectonic origin that involved the subduction of a limited amount of oceanic crust such as that developed within a backarc basin rather than the open ocean. Closure of this basin set the stage and provided the mechanism for the obduction of oceanic crust and underlying mantle, underplating of the Frontenac terrane, and delamination of the underlying lithosphere and production of vast volumes of AMCG magmatic rocks.

8. Rocks of the 1150–1180 Ma AMCG suite formed as a consequence of closure of the Trans-Adirondack backarc basin and primarily intruded areas affected by Shawinigan orogenesis. The limited areal extent of the Shawinigan event and accompanying lithospheric delamination may explain the predominance of the 1150–1180 Ma AMCG suite primarily in the south-central portion of the Grenville Province.

APPENDIX: ANALYTICAL METHODS

Geochemistry

Samples for this study were collected from well-exposed and blasted roadcuts in August 2008 associated with the Keck Consortium project on the Adirondack Lowlands. The samples were cut using a rock saw and thin sections were prepared for petrographic analysis. Petrographic analysis was used to select samples for geochemistry and isotopic analysis. Samples for analysis were crushed using a rock hammer and small chips were pulverized in a ball mill. Major element chemistry was measured at Colgate University on a Phillips PW2404 X-ray fluorescence spectrometer using fused glass disks. AGV-2 was also analyzed 25 times during the September–November 2008 analytical period, and average precision averaged ±1.9% relative or better. Accuracy was assessed by comparison to long-term averages of AGV-2 from the X-ray fluorescence laboratory at Washington State University, and was within better than 2.7% relative for all oxides except Al_2O_3 (3.7%). Trace elements were measured by inductively coupled plasma–mass spectrometry at ACME Analytical Laboratories in Vancouver, British Columbia, Canada.

Sm/Nd Analyses

Sm/Nd isotopic analyses were performed at Carleton University in Ontario. Between 100 and 300 mg of sample powder were placed into a screw-cap Teflon vial, to which a mixed ^{148}Nd-^{149}Sm spike was added. The powder-spike mixture was dissolved in HNO_3-HF, then further dissolved in HNO_3 and HCl until no residue was visible. The bulk rare earth elements (REEs) were separated using cation chromatography (Dowex 50-X8). The REE-bearing residue was dissolved in 0.26N HCl and loaded into an Eichrom chromatographic column containing Teflon powder coated with HDEHP [di(2-ethylhexyl) orthophosphoric acid] (Richard et al., 1976). Nd was eluted using 0.26N HCl, followed by Sm in 0.5N HCl.

Total procedural blanks for Nd were < 200 pg. Concentrations are precise to ±1%, but $^{147}Sm/^{144}Nd$ ratios are reproducible to 0.5%. Samples are loaded with 0.3N H_3PO_4 on one side of an Re double-filament assembly, and run at temperatures of 1750–1800 °C in a 9 cup (~2160 mL) ThermoFinnigan TRITON T1 multicollector mass spectrometer. Isotope ratios are normalized to $^{146}Nd/^{144}Nd = 0.72190$. Analyses of the U.S. Geological Survey (USGS) standard BCR-1 yielded Nd = 29.02 ppm, Sm = 6.68 ppm, and $^{143}Nd/^{144}Nd = 0.512668 \pm 20$ (n = 4). More than 20 runs of the La Jolla standard averaged $^{143}Nd/^{144}Nd = 0.511848 \pm 10$ (April 2004–March 2006). Epsilon values at time T were calculated using the following relation:

$$\varepsilon^{T}_{Nd} = [(^{143}Nd/^{144}Nd_{sample}/^{143}Nd/^{144}Nd^{T}_{CHUR}) - 1] \times 10000,$$

where CHUR is the chondrite uniform reservoir and T is generally the time the rock was formed. Depleted mantle model ages are calculated assuming a modern upper mantle with $^{147}Sm/^{144}Nd = 0.214$ and $^{143}Nd/^{144}Nd = 0.513115$.

Zircon U-Pb Geochronology

A representative ~10 kg sample of the Antwerp-Rossie suite (ARS)–Split Rock road diorite body was collected on its northeastern margin for geochronologic analysis. Sample processing was conducted at the University of Minnesota Twin Cities mineral separation laboratory. Primary crushing was done with a jaw-crusher, followed by a disk mill. The crushed sample was then washed by a Gemini Gold table. The heavy mineral fraction recovered following the washing was magnetically separated by a hand magnet and a Frantz Isodynamic Magnetic Separator. The resulting least paramagnetic fraction was separated by density via methylene iodide (G = 3.32), which yielded a very pure zircon sample. Clear, 100–200 µm long, subhedral, elongate to stubby zircons were common and hand-picked for dating with a binocular microscope.

Grain mounting and SHRIMP RG (sensitive high-resolution ion microprobe reverse geometry) analysis closely followed the protocols of the Stanford USGS Micro Analysis Center (SUMAC). A broad overview of the procedure is provided here and additional details can be found elsewhere (e.g., Premo et al., 2008, and references therein). Zircon grains selected for SHRIMP RG analysis were mounted in epoxy with the 1200 Ma VP-10 standard. The mount was polished to reveal zircon grain interiors and imaged with reflected light microscope and cathodoluminescence on SUMAC's JEOL JSM 5600 scanning electron microscope. Zircon shape (subhedral dipyramidal terminated grains) in conjunction with the oscillatory zoning, with no signs of inherited cores, is consistent with the sample's zircon grains having grown from magma during crystallization of the Split Rock road diorite body of the ARS. Following imaging, the sample mount was washed and coated with Au. Dating of the zircon was done on SUMAC's SHRIMP RG. The instrument accomplishes sample isotopic analysis by ablating an ~20 µm area to a 1–2 µm depth on a sample grain with an O_2^- primary beam. The ablated sample (secondary ions) is then sent through the mass spectrometer portion of the instrument for isotopic analysis. Each analysis consists of ~6 scans through numerous masses of interest. Data reduction was accomplished by SQUID (Ludwig, 2001), and data analysis and concordia plots were generated with Isoplot (Ludwig, 2003). Following SHRIMP RG analysis, the sample mount was imaged via backscatter electrons on a JEOL 6360LV scanning electron microscope at Colgate University to confirm analysis spot locations.

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