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

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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 ($T_{DM}$ depletated mantle model) range from 1288 to 1634 Ma; the oldest ages (1613–1634) are 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 ($T_{DM}$ depletated mantle model) range from 1288 to 1634 Ma; the oldest ages (1613–1634) and depleted mantle model) range from 1288 to 1634 Ma; the oldest ages (1613–1634) and smallest epsilon Nd ($\epsilon_{Nd}$) 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 orogeny. A more complete understanding of the Grenville orogeny 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 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 metabasaltic suite (ARS) in the context of our evolving understanding of the polyorogenic Grenville Province (Grenville orogenic cycle of McLelland et al., 1996; Elziviran, Shawinigan, and Grenvillian orogenies of Rivers, 2008). Foremost among these considerations is that the metamorphic rocks of the ARS are currently the oldest known intrusives 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 OROGENESIS IN THE ADIRONDACK LOWLANDS

The Adirondack Lowlands currently expose a wide variety of supracrustal rocks metamorphosed to mid-upper amphibolite facies and variably deformed during the Shawinigan orogeny (Fig. 1; Corrigan, 1995; Rivers, 2008). In descending stratigraphic and/or structural
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; Wasteney 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
Water bodies
Undifferentiated units predominantly Paleozoic and glacial cover
Potsdam Ss. (Cambrian-Ordovician)
Leucogranitic gneiss (ca. 1170 Ma)
Mega. granitic gneiss (ca. 1185 Ma)
Pelitic gneisses and related rocks
Calc-silicate rock and marble
Calcitic and dolomitic marble
Amphibolite and gabbroic gneiss

Approximate trace of Carthage-Colton zone (Lowlands/Highlands)

Geology from Rickard et al. (1970)

Adirondack Highands

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.

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, and magnetite, and...
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 SiO₂ content used in conjunction with the 15 major and trace element characteristics. Figures 5 and 6 show linear trends with increasing SiO₂, especially when plotted against CaO, MgO, Fe₂O₃, MnO, P₂O₅, and TiO₂. (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 depletions (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 granitic 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 (TDM) and epsilon Nd (εNd) 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 ¹⁴⁹Nd/¹⁴⁴Nd ratios range from 0.511931 to 0.512363 and ¹⁷⁴Sm/¹⁴⁴Nd ratios vary from 0.0831 to 0.1280 (Table 2). The εNd values range from 1.52 to 5.42, yielding a wide variance of model ages (TDM) 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 members 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 εNd values present in the suite. The whole-rock samples provide a poorly constrained Sm-Nd isochron model age of 1.03 Ga (Fig. 13). On an Nd evolution diagram, the slope of individual samples, including the Balmat tonalitic and gabbroic rocks of similar age to 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.

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. Three of the analyses show slight reverse discordance; however, the calculated age is in agreement with previous studies.
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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 SiO₂ wt% of samples of the Antwerp-Rossie suite.

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

Figure 7. Alkali-iron-magnesium (AFM) diagram showing 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).
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 ($e_{\text{Nd}} = 3.31, T_{DM} = 1424$ 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 Pyritess, New York (Chiarenzelli et al., 2010). The rocks at Pyritess 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 (Hammer 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 (Hammer 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 $e_{\text{Nd}}$ 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 ductilely 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 $\varepsilon_{Nd}$ values are shown (red numbers in boxes) and calculated at 1200 Ma. Ss.—sandstone; BLF—Black Lake fault.
Shawinigan Closure of the Trans-Adirondack Basin

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. 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 granitoid 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 backarc 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 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, 1992). If so, it separates metamorphosed sedimentary sequences that were deposited on opposite flanks of the Trans-Adirondack backarc 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 or conditions only recorded or preserved in the Adirondack Lowlands, whereas marbles and pelitic gneisses are widespread throughout.

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Table 2. SM-Nd isotopic compositions of the Antwerp-Rossie granitoids (Adirondack Lowlands)

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Sm (ppm)</th>
<th>Nd (ppm)</th>
<th>147Sm/144Nd</th>
<th>143Nd/144Nd</th>
<th>εNd (0)</th>
<th>εNd (7)</th>
<th>TDM (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPR-1</td>
<td>4.05</td>
<td>20.67</td>
<td>0.1186</td>
<td>0.512100</td>
<td>-10.49</td>
<td>1.52</td>
<td>1617</td>
</tr>
<tr>
<td>SPR-8</td>
<td>5.38</td>
<td>28.47</td>
<td>0.1142</td>
<td>0.512140</td>
<td>-9.71</td>
<td>2.97</td>
<td>1487</td>
</tr>
<tr>
<td>SPR-9</td>
<td>4.26</td>
<td>22.00</td>
<td>0.1171</td>
<td>0.512166</td>
<td>-9.20</td>
<td>3.04</td>
<td>1490</td>
</tr>
<tr>
<td>SPR-11</td>
<td>3.40</td>
<td>19.50</td>
<td>0.1049</td>
<td>0.512192</td>
<td>-8.71</td>
<td>5.42</td>
<td>1288</td>
</tr>
<tr>
<td>SPR-17</td>
<td>11.80</td>
<td>72.82</td>
<td>0.0980</td>
<td>0.512029</td>
<td>-11.87</td>
<td>3.31</td>
<td>1424</td>
</tr>
<tr>
<td>SPR-21</td>
<td>4.74</td>
<td>20.79</td>
<td>0.1378</td>
<td>0.512363</td>
<td>-5.37</td>
<td>3.69</td>
<td>1502</td>
</tr>
<tr>
<td>SPR-22</td>
<td>5.34</td>
<td>30.58</td>
<td>0.1055</td>
<td>0.512092</td>
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<td>3.36</td>
<td>1436</td>
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<tr>
<td>SPR-24</td>
<td>7.91</td>
<td>37.33</td>
<td>0.1280</td>
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<tr>
<td>SPR-25</td>
<td>13.37</td>
<td>64.30</td>
<td>0.1257</td>
<td>0.512206</td>
<td>-8.42</td>
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</tr>
<tr>
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<td>5.09</td>
<td>37.03</td>
<td>0.0831</td>
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<tr>
<td>SPR-28</td>
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<td>0.1241</td>
<td>0.512149</td>
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<tr>
<td>SPR-31</td>
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<td>73.43</td>
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<td>0.512147</td>
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Note: TDM = depleted mantle model age. SPR-17 is a sample Hermon granite from Trout Lake.

*Measured ratio, corrected for spike and normalized to 146Nd/144Nd = 0.7219.

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

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

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Note: TDM = depleted mantle model age. SPR-17 is a sample Hermon granite from Trout Lake.

*Measured ratio, corrected for spike and normalized to 146Nd/144Nd = 0.7219.
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
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 discordia ellipses; inset displays age-analysis chart. MSWD—mean square of weighted deviates.

### Table 4. Geochronological Studies of the Antwerp-Rossie Granitoids and Associated Rocks

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

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.

Geosphere, December 2010
and evaporitic units, represents the compres-
sion associated with Shawinigan orogenes-
s 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 associ-
ated metatuffic 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 interpreta-
tions are correct, the Laurentian margin was
well inboard to the north. In addition, the Frank-
lin marble shows a much more restricted range
of compositions compatible with arc plutonic rocks. Mafi
c magma 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 forearc magmatism. Their composition and Nd systematics (Chiarenz-
elli 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
typeconically into the deforming supracrustal
sequence just outboard and along the Laurent-
tian margin. A similar and contemporaneous
scenario resulting in docking of the Morin ter-
rane and associated plutonic suites in the Central
Granulite terrane of Quebec was suggested by
Corriveau and van Breenen (2000). The incom-
patible 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; Chiarrenzelli et al., 2010).

The restricted age range and limited geo-
graphic distribution of the ARS and Hermon
gneiss are likely functions of a short-lived and
geochemically 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 Shawa-
igin 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 defor-
mation 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 (Hamner et al., 2000). The recog-
nition of a partial ensialic backarc and rift zone
farther to the west in the Central Metasedimen-
tary Belt (Dickin and McNutt, 2007) suggests
that the margin of Laurentia underwent exten-
sion and consisted of a number of smaller rifts
and attenuated crust prior to Shawinigan oro-
genesis during 1.4–1.2 Ga subduction events.
However, evidence for considerable uplift and
topographic relief during sedimentation is lack-
ing 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 gen-
erated the conditions that facilitated the cata-
stronic lithospheric delamination that followed
the Shawinigan orogeny.

Shortly after collision of the outboard rem-
nant 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 orogen-
ensis. These rocks include the massif anorthosites
of the Central Granulite terrane and vast vol-
umes 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 (Hamner et al.,
2000; McLelland et al., 2010; Peck et al., 2004;
Wasteney 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 oro-
genesis, 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 dur-
ing the Ottawan phase of the Grenvillian oro-
geny (Gates et al., 2004; Hoffman, 1991; Rivers,
2008), rather than during the Shawinigan oro-
geny (cf. Hamner et al., 2000).

CONCLUSIONS

1. The ARS intruded the Adirondack Low-
lands supracrustal sequence ca. 1200 Ma, a time
of active high-grade metamorphism, deforma-
tion, 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 geo-
chemical 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% SiO₂).
Nonetheless, the Antwerp-Rossie suite displays
calc-alkaline trends and trace element composi-
tions 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 back-
arc to arc or forearc to arc magmatism dur-
ing Shawinigan orogenesis. Numerous lines of
evidence suggest that a component of enriched
mante 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 Adiron-
dack 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 εNd 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 closure of the Trans-Adirondack backarc basin (Trans-Adirondack backarc basin). The HGG were intruded into a collapsing backarc basin rather than the open ocean. Closure of this basin, due to the beginning of orogenic deformation in the Northwest Adirondack Lowlands, 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 basaltic 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 evaporites, 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 mechanical and thermal environment necessary for the development of the Frontenac terrane, and delamination of the underlying lithosphere and production of vast volumes of AMGC magmatic rocks.

8. Rocks of the 1150–1180 Ma AMGC 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 AMGC 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 Al₂O₃ (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 Ottawa. Between 100 and 300 mg of sample powder were placed into a screw-cap Teflon vial, to which a mixed 146Nd/144Sm spike was added. The powder-spike mixture was dissolved in HNO₃/HF, then further dissolved in HNO₃, and HCl until no residue was visible. The bulk rare earth elements (REEs) were separated using cation chromatography (Dowers 5–6000). The REE-bearing residue was dissolved in 0.26N HCl and loaded into an Eichrom Teflon vial, to which a mixed 148Nd-149Sm spike was added. The instrument accomplishes sample isotopic separation, doping on the zircon was done on SUMAC’s SHRIMP – primary beam. The instrument accomplishes sample isotopic separation, and data analysis and concordia plots were generated on a sample grain with an O₂ microprobe and cathodoluminescence microscope at ACM Analytical Laboratories in Vancouver, British Columbia, Canada. Zircon shape (subdipyramidal 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 instrument. The instrument accomplishes sample isotopic analysis by abating an ~20 µm area to a 1–2 µm depth on a sample grain with an O₂ 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 back-scatter electrons on a JEOL 6560LV scanning electron microscope at Colgate University to confirm analysis spot locations.

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