REGIONAL GEOLOGICAL SETTING OF THE ADIRONDACK MOUNTAINS, NEW YORK

JAMES M. MCLELLAND

Department of Geology, Colgate University, Hamilton, NY 13346, jmclelland@citlink.net

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INTRODUCTION

The ~180 x 150 kilometer (km) (115 x 95 mi), slightly elliptical Adirondack dome (Figure 1) is underlain by Mesoproterozoic (1600-1000 Ma) metamorphic and igneous rocks that range in age from ca. 1350 to 1040 Ma and is surrounded by flat-lying ca. 500 Ma Lower Paleozoic sedimentary rocks. As shown in Figure 1, it is divided into the Adirondack Highlands Terrane (HL) and the Adirondack Lowlands Terrane (LL) separated by a steep, northwest dipping, oblique normal fault zone known as the Carthage-Colton shear zone (CCZ). The underlying Mesoproterozoic units have undergone pronounced high temperature ductile deformation that resulted in large, upright to flat-lying folds formed during two major orogenic events: the 1210-1140 Ma Shawinigan Orogeny and the 1090-980 Ma Grenville Orogeny. Orogenesis was accompanied by high grade regional metamorphism ranging from upper amphibolite (pressure of ~6-7 kbar, temperature of ~600-750 °C) to granulite facies (pressure of ~7-8 kbar, temperature of ~800-830 °C) conditions. During each orogeny, strong, widespread penetrative deformation resulted in mylonite and ribbon gneiss. Both orogenies were followed by post-orogenic igneous activity, i.e.,
a voluminous ca. 1155 Ma anorthosite-mangerite-charnockite-granite (AMCG) suite and the distinctive ca. 1050 Ma Lyon Mt. Granite that rims much of the Adirondack Highlands (shown in red on Figure 1). By ca. 550 Ma the mountain range had been eroded to sea level, deposition began, and marine sediments blanketed the area. During the Mesozoic Era (ca. 250-60 Ma), the area was vertically uplifted and exhumed by erosion to form the current topographic dome. Faulting, erosion, and glaciation further modified the present-day second generation mountain range. In this paper, I seek to relate these characteristics to the regional geology of Canada and the Appalachian Mountains.

The interested reader will find a more comprehensive and in-depth presentation for material in this article as well as an extensive bibliography in McLelland, Selleck, and Bickford (2010, 2013) and references given therein. These references are provided at the end of this article.

Figure 1. Generalized geological and rock type age distribution map of the Adirondack Regions. Units designated by patterns and initials consist of igneous rocks dated by U-Pb zircon geochronology with ages indicated in the legend. Units present only in the Adirondack Highlands terrane (AHT) are Royal Mountain Tonalite and Granodiorite (RMTG; southern HL only), Hawkeye Granite (HWK), Lyon Mountain Granite (LMG) and anorthosite (ANT). Units present in the Lowlands (LL) only are: Hyde School Granite Gneiss and Rockport Granite (HSRG; Hyde School also contains tonalite), Rossie Diorite and Antwerp Granodiorite (RDAG), Hermon Granite (HERM). Granitoid members of the AMCG suite (MCG) are present in both the Highlands and Lowlands terranes. Unpatterned areas consist primarily of metasedimentary rocks, glacial cover, or undivided units. Key: Antwerp (A), Ausable Falls (AF), Black Lake Shear Zone (BLSZ), Canton (CA), Canada Lake isocline (CLJ), Carthage-Colton Shear Zone (CCSZ), Gouverneur (GO), Gore Mt. (GM), Lyon Mountain (LM), Lake Placid (LP), Oregon Dome (OD), Piseco antiform (P), Rossie (R), Schroon Lake (ScL), Snowy Mountain dome (SM), Ophiolite (X). This figure is modified after McLelland et al. (2010).
RELATIONSHIP OF THE ADIRONDACKS TO THE CANADIAN GRENVILLE PROVINCE

Figure 2 shows an expanded view of eastern North America, including the large Grenville Province of Canada, its Adirondack extension, and related rocks occurring in inliers in the Appalachian Mountains. The area designated by an upper-left to lower-right diagonal ruling locates basement rocks of the 1600-980 Ma Grenville Orogen buried beneath Paleozoic cover. This region is divided by a northeast-trending magnetic anomaly referred to as the New York-Alabama lineament that was interpreted by King and Dietz (1978) as a suture marking the ca. 1250-1200 Ma collision (i.e., the Shawinigan Orogeny) of the ancestral Southern Appalachian basement with the Eastern Granite Rhyolite Province (EGR) to the northwest of the lineament.

The Grenville Province has been divided into a number of subunits (Rivers 1989). The largest of these are the Allochthonous Polycyclic Belt (APB, Figure 2), the Allochthonous Monocyclic Belt (AMB, Figure 2), and the Parautochthonous Belt (PB, Figure 2). The term Allochthonous refers to the fact that these belts have been tectonically transported from the site(s) where the belt originally formed. Alternatively, autochthonous refers to belts that have remained in place at the site(s) where they originally formed. A polycyclic belt has experienced multiple major orogenies associated with the opening and closing of ocean basins over a long time interval. A monocyclic belt is one that has experienced a single major orogenic cycle. Parautochthonous belts have been tectonically displaced by relatively small distances from where they formed.

**Figure 2.** Generalized map depicting major tectonic and geochronological subdivisions in the eastern USA. The Grenville Province is shown in medium gray and its exposed portions are indicated by heavy outlines. Dark areas along the spine of the Appalachians are inliers of Grenville Rocks affected by Appalachian orogenesis. See legend on figure for details and other symbols. The diagonally ruled area along New York-Alabama Lineament is covered portion of the Grenville Province in the eastern United States. The diagonally ruled northeast corner of the diagram is parts of the orogenic lid (i.e., rocks relative high in the crust during Grenville deformation). Abbreviations: AD = Adirondack Mountains, EGR = Eastern Granite-Rhyolite Province, LE= Lake Erie, LO= Lake Ontario, SLR= St. Lawrence River. This figure is modified after McLelland et al. (2010).
The APB evolved from ca. 2000 Ma to 1000 Ma as a series of successive accretive continental margin arcs and orogenies. Remnants of several of these arcs extend through the EGR. The AMB, to which the Adirondacks belong, contains only rocks in the age range 1350-1000 Ma. The AMB experienced two major orogenies and associated high temperature metamorphic events, i.e., the Shawinigan (ca. 1200-1150 Ma) and the Ottawan (1090-1020 Ma) orogenies. The latter resulted from the collision of Amazonia with eastern North America, i.e., Laurentia (Figure 3). The Rigolet Orogeny (ca. 1010-980 Ma) was the final pulse of this collision and caused thrusting of the northwestern margin of the Grenville Province over the ancient > 2500 Ma basement rocks of the Superior Province forming the Grenville Front Thrust (black teeth on Figure 2) and the Paraautochthonous Belt. The Rigolet Orogeny was a relatively mild tectonothermal event and, in the Adirondacks, has few manifestations other than some narrow overgrowths on zircons.

Both the Shawinigan and Ottawan orogenies resulted in pronounced crustal thickening caused by compression and thrust stacking during the collision of large blocks of continental crust. A simplified history of these orogenic events is summarized in map view in Figure 3 and in cross-section in Figure 4. Beginning at ca. 1350-1250 Ma the continental margin arc of Laurentia was rifted apart by southeastward extension producing several ca. 1350 Ma fragments that were situated in a widening seaway similar in size to the Sea of Japan. Sediments accumulated in the growing basin (Figure 3A) that would eventually evolve into the Central Metasedimentary Belt that is a major constituent of the AMB and is bordered on the west by the Central Metasedimentary Belt Tectonic Zone (CMBTZ, Figure 2). The 1350 Ma fragments were distributed throughout the basin and today are found along the western margin of the CMB near the town of Dysart, as well as, the Adirondacks, and Mt. Holly region of the Green Mts. in western Vermont. Taken together, these ca. 1350 Ma fragments are referred to as the Dysart-Mt. Holly suite. To the east of this basin lay a large block of continental crust referred to as Adirondis that had been rifted from the margin of what is now Quebec. The future locations of Vermont, New York, and New Jersey are indicated on Figure 3A.

By ca. 1250-1220 Ma eastward subduction of oceanic crust had begun beneath the rifted fragments as well as Adirondis and gave rise to igneous activity and deformation referred to as the Elzevirian Orogeny (Figure 3B). By 1220-1200 Ma the western seaway closed out against Laurentia and subduction switched to a westward polarity beneath the CMB resulting in intrusions of granodiorites, diorites, and granites of the Antwerp-Rossie (RDAG) and Hermon (HERM) suites located on Figure 1 in the Adirondack Lowlands. In addition, an ophiolite complex including oceanic crust and upper mantle peridotite was emplaced in what is now the Adirondack Lowlands (Figure 3C). Similar ophiolites occur in the Central Metasedimentary Belt in Ontario.
Figure 3. Schematic panel diagram summarizing the distribution and interaction of various segments of northeastern Laurentia during the interval 1300-1050 Ma encompassing the rifting, opening and closing of the Central Metasedimentary Belt back-arc basin (CMBB), Trans-Adirondack back-arc basin (TAB), and the Ottawan collision with Amazonia. Note that prior to ca. 1300 Ma subduction had been to the northwest beneath the Laurentian margin. Blocky black arrows indicate polarity of subduction. Different shades of gray identify important terranes and arcs. Blocky white arrows represent extension. The crustal block labeled Adirondis is a large E–W crustal fragment rifted from Laurentia at ca. 1400-1300 Ma and by collision at ca. 1200-1000 Ma. Vermont (VT), New York (NY), and New Jersey (NJ). Amazonia is inferred to remain south of the Adirondis region until ca. 1090 Ma. The Pyrites Ophiolite Complex is represented by the small black region in the CMB. Abbreviations: AM = Amazonia, AMCG = anorthosite-mangerite-charnockite-granite suite, AT = Atikonak River Anorthosite, FGF = future Grenville Front, LSJ = Lac St. Jean Anorthosite, MA = Marcy anorthosite. This figure is modified after McLelland et al. (2010).

By ca. 1200-1160 Ma subduction beneath the eastern margin of the AMB closed out the eastern seaway and resulted in the powerful Shawinigan Orogeny, including the intrusion of the Hyde School and Rockport synorogenic granites (HSRG on Figure 1). During this collision rocks of the Lowlands were thrust eastward over the Adirondack Highlands for a large but unknown distance, and Adirondis became welded to Laurentia (Figure 3D). The Shawinigan collisions greatly increased the thickness of the crust and lithosphere and by ca. 1155 Ma delamination set in, and the crustal and lithospheric mantle root foundered, then sank, into the hot, ductile mantle. The foundered material was replaced by juvenile asthenosphere that underwent melting to produce gabbroic magma. The gabbroic melts crystallized plagioclase that floated in the dense, high pressure gabbroic magma and formed rafts of plagioclase-rich anorthosite with individual grains of andesine reaching 0.25 m or more in size. Simultaneously, magmatic and mantle heat caused melting of the granitoid
material of the lower crust to produce compositions ranging from mafic syenite, monzonite, and granite and further weakened the crust. Ultimately, the gabbros and their anorthositic cumulates ascended along zones of weakness and were emplaced in the mid- to upper-crust to form the ca. 1155 Ma AMCG suites, e.g., Marcy and Oregon Dome (OD) massifs, Morin (M) massif, Lac St. Jean (LS] complex, and perhaps the Atikonak (AT) massif (Figure 3E).

During all of the preceding orogenic activity, oceanic crust between North America and Amazonia had been closing out via subduction beneath the latter. Closure came at ca. 1090-1050 Ma when the collision between the two finally took place and resulted in the powerful Ottawan Orogeny that produced the Allochthon Boundary Thrust (open teeth on Figure 2), great crustal thickening, widespread ductile deformation, etc. Within the Adirondack Highlands granulite facies temperatures of 750-810 °C and pressures of 6-8 kbar were attained and titanite cooling ages of ca. 1030 Ma are common. By contrast, the Adirondack Lowlands record titanite and hornblende cooling ages greater than ca 1060 Ma reflecting temperatures that the Lowlands did not exceed experience temperatures exceeding ~500 °C during the Ottawan Orogeny.

This otherwise enigmatic result can be explained by the fact that, during the Ottawan Orogeny, the Lowlands was situated on top of the Highlands as an orogenic lid; an area higher in the crust above the main zone of ductile deformation. At the end of the Ottawan, during orogenic collapse, the Lowlands (LL) was dropped down along the CCZ (Figure 1) into juxtaposition with the Highlands (HL). Here we note that much of the AMB was situated within the orogenic lid during the Ottawan Orogeny. It is due to this insulation that sedimentary units are so well preserved in the AMB and led to its title of the Central Metasedimentary Belt (CMB, Figure 2) within which greenschist facies assemblages are common. Another orogenic lid is present in the far northeastern reaches of the Grenville Province (diagonal ruling in the top right corner of Figure 2). Due to the inaccessibility of the region its contents and boundaries are not well known, but its existence is certain.

By 1090 Ma southeastward subduction beneath the northwestern margin of Laurentia (Figure 3F) eventuated in the closure of the ocean basin and a powerful head-on collision between Amazonia and southeastern Laurentia that resulted in the Ottawan and Rigolet orogenies. It was at this time that the Allochthon Boundary Thrust (ABT) drove great wedges of southeast-dipping metamorphic rocks to the northwest producing the APB. The thrusting was accompanied by very high temperatures in the deep crust, which became very ductile and flowed to produce large, tight folds with overall sub-horizontal attitudes. These structures are referred to as nappes and are characteristic of hot, long-lived orogens. One of these structures is shown in Figure 1 where its western portion in the southern Adirondacks is represented by a “bent index finger” outcrop pattern. This nappe structure extends ~100 km east to Saratoga Springs where it disappears beneath young cover rocks. Other folds in the Adirondacks are of similar dimensions and rival structures in the Himalayas and Alps. In terms of its extent (i.e., world-wide) and the metamorphic conditions attained, the Ottawan Orogeny was a world-class mountain building event.
Figure 4 presents a cross-sectional summary of the events discussed above. The rifted fragments of the Dysart-Mt. Holly suite are shown just after ca. 1300 Ma together with the Elzevirian (E) arc and southeastern Adirondis marginal arc separated by the CMB and Trans-Adirondack Basin (TAB). The AHT and Green Mountains are shown along the eastern margin of Adirondis. By ca. 1200 Ma (Figure 4B) the CMB basin closed out against the Central Gneiss Belt (CGB) producing the Central Metasedimentary Belt Boundary Zone Thrust (CMBBBZ) and constituting an early phase of the Shawinigan Orogeny. To the east, ophiolites were obducted onto the Adirondack Lowlands Terrane (ALT) and subduction driven magmatism ceased in the Adirondack Highlands Terrane and Green Mountains Terrane (AHT-GMT). By ca. 1120 Ma the Shawinigan Orogeny was fully developed, and the TAB closed out resulting in the collision of the CMB-ALT terrane with the AHT. Importantly, the CMB-ALT terrane was thrust eastward over the AHT for an unspecified and unknown distance. Strong high temperature deformation resulted in large, flat-lying ductile nappes. The nappes are labelled F1 in order to differentiate them from later Ottawan nappes labelled F2 (Figure 4F). Figure 4D depicts the delamination of the over thickened Shawinigan crust and lithosphere and consequent orogen collapse together with ascent of hot asthenosphere and the formation of AMCG magmatism.

Figure 4. Plate tectonic models showing proposed tectonic evolution along a line from the Adirondack Mountains to the Central Metasedimentary Belt Boundary Zone (CMB-BZ). The green areas schematically represent the Dysart-Mt. Holly suite (DAMH). Abbreviations: AHT = Adirondack Highlands terrane, AHT-GMT = Adirondack Highlands-Green Mountains terrane, ALT = Adirondack Lowlands terrane, AMCG = anorthosite-monzonite-charnockite-granite suite, BSZ = Bancroft shear zone, CCZ = Carthage-Colton shear zone, CGB = Central gneiss belt, CMB = Central metasedimentary belt, E = Elzevir Terrane, EASZ = Eastern Adirondack shear zone, F = Frontenac shear zone, HSG = Hyde School, MSZ = Maberly Shear Zone, OPH = Pyrite Ophiolite Complex, RLSZ = Robertson Lake Shear Zone, TAB = Trans-Adirondack basin. The eastern Adirondack extensional shear zone is shown by the heavy fault line and arrow in the bottom (1050 Ma) panel. This figure is modified after McElllland et al. (2010).
Figure 4E is hypothetical and represents an attempt to account for a group of intrusive rocks referred to as the Hawkeye Granite suite that yield ages between ca. 1100 Ma and 1090 Ma. However, these ages were determined in the mid-1980’s when geochronological techniques allowed for less precision. The ages may well be hybrid and result from the incorporation of both igneous cores and metamorphic overgrowths. Zircon, the mineral used for dating, has been shown to retain its isotopic systematics throughout high-grade metamorphism but often also can grow new metamorphic rims on igneous cores. The age of the Hawkeye Granite suite is regarded as conjectural until additional data is collected.

Figure 4F depicts the collision of Laurentia with Amazonia and the onset of the Ottawan Orogeny with its very high grade metamorphism and ductile deformation. The figure emphasizes the northwest-directed thrusting and the large northwest directed F2 nappes with subhorizontal attitudes typical of major metamorphism in large, hot orogens associated with major continental collisions. The actual suture between Laurentia and Amazonia is not exposed and may lie buried beneath younger rocks in the Appalachians. In Figure 4G the Adirondack region has collapsed and the ALT down faulted to the west along the Carthage-Colton (CCZ) an oblique normal fault. A mirror image of the CCZ has been found in the easternmost Adirondacks where Highland rocks have been down faulted to the east. This major structure is referred to as the Eastern Adirondack Shear Zone (EASZ). Accompanying the down faulting was the emplacement of large volumes of the Lyon Mountain Granite.

RELATIONSHIP OF THE ADIRONDACKS TO APPALACHIAN GRENVILLE INLIERS

In Figure 2, the major occurrences of Proterozoic basement inliers in the Appalachians are shown in black. In most cases, these bodies, which are relatively resistant to erosion, form the upper elevations of the Appalachian mountain belt. There is remarkable continuity of Adirondack geology with that exposed within the Appalachian Proterozoic massifs. Thus, in the case of the Mt. Holly complex of Vermont Green Mountains, the ca. 1350 Ma tonalitic rocks of the Dysart-Mt. Holly complex are well represented and metasedimentary units are the same as those in the eastern Adirondack Highlands. However, the ca. 1050 Ma Lyon Mt. Granite and evidence of Ottawan metamorphism are sparse to absent in Vermont suggesting that the Mt. Holly rocks may have been part of the orogenic lid that sat on top of the Adirondack Highlands from ca. 1160-1050 Ma, similar to the Adirondack Lowlands. This possibility is under investigation. The ca. 1350 Ma Dysart-Mt. Holly suite is present in the northern Appalachian inliers and southward through the New Jersey Highlands and ca. 1250 Ma Elzevirian rocks occur as far south as the Baltimore Gneiss Domes.

Granitic rocks of ca. 1172 Ma Shawinigan age, common in the Adirondack Lowlands, are present within the Mt. Holly complex. In Massachusetts, 35% of the Berkshire massif is underlain by the ca. 1179 Ma Tyringham granitic gneiss that intrudes metasedimentary
gneisses similar to those in the AHT, Green Mountains, and Hudson Highlands. In the Hudson Highlands, the widespread Storm King granite has been dated at ca. 1174 Ma and was intruded by the ca. 1140-1130 Ma Canopus and Brewster plutons. Within the New Jersey Highlands, the Byram-Hopatcong pluton has been dated at ca. 1176 Ma. These ages indicate that Shawinigan magmatism extended well to the south of the Adirondacks and was followed by granitic magmatism of AMCG age. Some small occurrences of layers of anorthositic rock within the granitoids suggest that the full AMCG is present, and this possibility is reinforced by the presence of an Adirondack-type anorthosite in the Honeybrook Uplands of Pennsylvania. Consistent with this is clear evidence for the presence of strong Shawinigan deformation and metamorphism at ca. 1180 Ma throughout the northeastern Appalachian inliers including New Jersey. The deformation and metamorphism has been attributed to the closure of the Trans-Adirondack Basin against Laurentia followed by ca. 1176 Ma Shawinigan magmatism and later by ca. 1040 Ma AMCG magmatism.

Farther to the south, the Shenandoah massif of the Blue Ridge Mountains (Figure 2) extends through most of the State of Virginia. It contains a large volume of igneous rocks ranging in age from ca. 1185-1165 Ma that correspond to Shawinigan magmatism in the Adirondacks. They were followed by granitic magmatism at ca. 1153-1143 Ma including small volumes of anorthosite and are correlated with the Adirondack AMCG suite. Also present are granitic rocks dated at ca. 1050-1030 Ma that correspond to the Lyon Mt. Granite of the Adirondacks. The Shenandoah massif shows some evidence of metamorphism and deformation at ca. 1155-1144 Ma, but evidence of widespread, high grade metamorphism is not plentiful. However, within the Smoky Mountains of the French Broad Massif to the south in Tennessee (Figure 2), leucosomes in migmatites have been dated at ca. 1194 Ma and granitoid plutons yield ages of 1167 Ga, both of Shawinigan age. At Mt. Rogers near the north end of the French Broad Massif there are ca. 1174-1161 Ma plutons that were intruded into very hot (ca. 750 °C) upper amphibolite facies crust. These events reflect Shawinigan magmatism and high grade metamorphism. Given this, it is suggested here that it is just a matter of time before similar evidence for Shawinigan metamorphism is described from the Shenandoah massif.

Both the Shenandoah and French Broad massifs contain ample evidence for ca. 1050 Ma Ottawan magmatism and metamorphism similar to the Adirondack Highlands. The ca. 1050 Ma leucogranites in all these regions are generally only mildly deformed suggesting that they, like the Lyon Mt. Granite, were emplaced late in the Ottawan Orogeny and are interpreted as late-tectonic intrusions associated with the extensional collapse of the Ottawan orogen. Within the Pine Mountain window in Alabama and Georgia (Figure 2), intrusive rocks ranging in age from ca. 1060 to 1010 Ma and contain xenoliths ranging in age from ca. 1140 to 1020 Ma. Similarly, the 1050 Ma State Farm Gneiss and Montpelier anorthosite of the Goochland terrane in eastern Virginia (Figure 2) correspond to the Lyon Mt. Granite and the late- to post-Ottawan anorthosites of the CRUML-type (Chateau-Richer, St. Urbain, Matawa, Labrieville) AMCG suite in western Quebec and ca. 1045 Ma Roseland anorthosite of the northern Shenandoah massif. Like the post- to late-Shawinigan AMCG suite, the ca. 1050 Ma examples of AMCG magmatism are associated with the collapse of large orogens.
Notwithstanding the similarities between the Adirondacks and the Mesoproterozoic inliers of the Appalachians, there are some significant differences. The first of these is that the Adirondacks and the Canadian Grenville Province underwent orthogonal collision with Amazonia (Figure 4) and experienced maximum compressional strain. In contrast, the Appalachian region underwent a lower angle, oblique collision with Amazonia and contractual strain was less than farther north. In addition, lead isotope data indicates that the Canadian Grenville Province, including the Adirondacks, were derived from North American crust, whereas the southern and central Appalachian Mesoproterozoic massifs were derived from crust that was probably part of Amazonia until ca. 1200 Ma and was transferred to North America during continental collision.

SUMMARY AND CONCLUSIONS

The Adirondacks are clearly part of the Grenville Province of Canada equivalent to rocks in the CMB and the AMB (Figure 2). They experienced both the Shawinigan and Ottawan orogenies as well as intrusion of the ca. 1150 Ma AMCG suite that characterize the Grenville Province. The oldest rocks in the Adirondacks are the ca. 1350 Ma tonalites of the Dysart-Mt. Holly suite that was rifted from the Andean-type continental margin of Mesoproterozoic Canada. In addition to the above, lead isotope studies demonstrate that the Adirondacks as well as the Canadian Grenville Province evolved from North American basement rocks that extend to the southwest all the way to west Texas. In contrast to this, the Mesoproterozoic inliers of the Appalachians exhibit a non-North American lead isotope signature and are thought to have been transferred from Amazonia during its ca. 1250 collision with eastern North America. Aside from this fundamental difference, the Adirondacks and Appalachian inliers share a common history of Shawinigan and Ottawan tectonic events and igneous activity, although there is a paucity of ca. 1155 Ma anorthosite plutons. Perceiving the eastern USA in the foregoing manner provides a unifying framework for understanding the evolution of this large region and is critical to our understanding of the Adirondack portion of it.

LITERATURE CITED
