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BEDROCK GEOLOGY OF THE ADIRONDACK REGION

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ABSTRACT

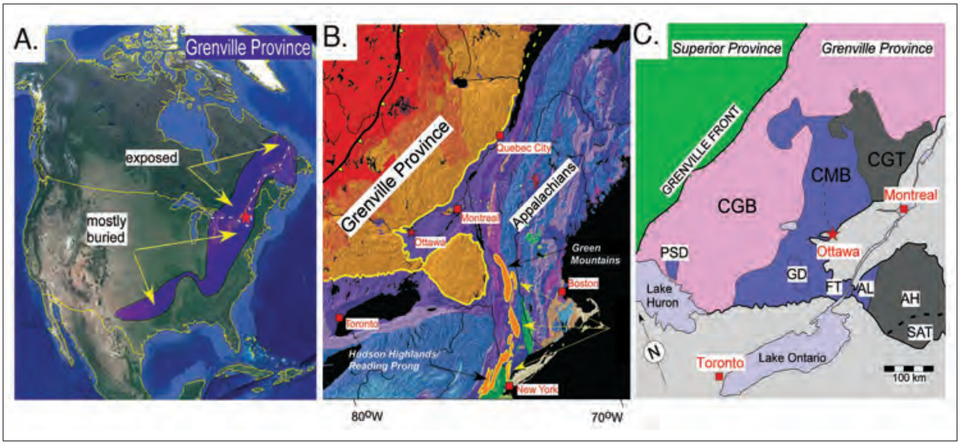
Precambrian rocks of Adirondack Region were part of a global system of mountains whose formation approximately one billion years ago led to the assembly of a supercontinent called Rodinia. In New York State, the eroded remnants of these enormous mountains extend beneath the Paleozoic cover rocks on the edge of the Adirondack topographic dome to form the basement rocks of New York State and connect, through exposures in the Thousand Islands Region, to the bulk of the contiguous Grenville Province of the Canadian Shield. Similar rocks are exposed in basement windows along the spine of the much younger Appalachian Mountains and can be traced into Mexico and beyond. Like other areas in the Grenville Province, the High Peaks region of New York is underlain by a large intrusive body of massif anorthosite, a rock composed of exceptionally large crystals of plagioclase feldspar. Rocks in the Adirondacks range in age from approximately 1350 to 1000 million years old and record as many as three or four tectonic events which were part of the Grenville Orogenic Cycle. The net results of these events were high-grade metamorphism, strong deformation, and the widespread overprinting of original relationships and primary textural features. Younger Paleozoic rocks include Cambrian and Ordovician sandstones, limestones, and shales deposited on the eroded metamorphic and igneous basement. These sedimentary rocks are found in fault-bounded outliers within the Adirondack massif and around the Adirondack margins.

The current topography of the Adirondacks is related to doming which began about 180 million years ago, when the Atlantic Ocean opened; although the reason(s) for this doming remain to be fully elucidated. Doming has stripped away the younger Paleozoic rocks and exposed the roots of the mountains, which at one time were deformed and metamorphosed deep in the crust.

INTRODUCTION

The Precambrian rocks exposed in the Adirondack Mountains range in age between ca. 1350-1000 million years old. They are a small part of a vast area on the southeastern edge of the Canadian Shield which is known as the Grenville Structural Province (Figures 1 and 2). Rocks in the Grenville Province share a SW-NE structural grain and a complicated tectonic history which ultimately led to the assembly of supercontinent Rodinia (Figure 3). Similar in many respects to the much younger Pangea, Rodinia included all the Earth's continents which were joined together by a global system of broadly synchronous mountain belts marking areas of continental convergence and eventual collision (Hoffman 1991).

Figure 1: *A.) Satellite photographs showing the location of the Grenville Province (purple shading). White dashed line separates exposed from covered areas. Red star lies on the Adirondack Region. B.) Terrane map of the southern Grenville Province (GP). The GP is divided into the Central Gneiss Belt (pink), the Central Granulite Terrane (grey), and the Central Metasedimentary Belt (blue). Subdivisions include the Adirondack Highlands (AH), Adirondack Lowlands (AL), Frontenac Terrane (FT), Grimsthorpe Domain (GD), Parry Sound Domain (PSD), the Southern Adirondack Terrane (SAT), and others not shown. The Appalachian Orogen and lower Paleozoic cratonic cover is stippled. C.) Location of the southern GP in the context of eastern North America. Grenville inliers in the Appalachian Mountains are shown in orange. The Grenville Front Tectonic Zone (GFTZ) separates the Archean Superior Province from rocks deformed by the Grenville Orogeny. The colored base, corresponds to rock age (Barton et al. 2003). Major population centers are shown for geographic context.*



The hallmarks of the Grenville Province include widespread deformation and metamorphic overprint that occurred during a series of events between ca. 1250-1000 million years ago, known as the Grenville Orogenic Cycle (McLelland et al. 1996; Moore and Thompson 1980). This deformation occurred deep within the crust and resulted in the addition of large amounts of new crust onto the margin of ancestral North America (i.e., Laurentia) more than a billion years ago. These crustal elements included tectonic features such as those observed today: island arcs, back-arc basins, continental arcs, continental and oceanic fragments, and intervening sedimentary basins. Deformation associated with the Grenville Province extended into the eastern margin of Laurentia where older crust of the adjacent provinces extends into, and is strongly reworked within, the Grenville Province. The Grenville Front separates rocks of the Superior Province last deformed in the Neoarchean from those affected by the Grenville event to the southeast.

The tectonic history and evolution of the Grenville Province is similar to that of the Appalachian Mountains in many respects, but Grenville mountain building represents a much older and distinct series of events (Figure 4). Similar to the timespan of the Appalachian Orogeny, Grenville orogenic or mountain building events occurred over a 250 million year period. In addition, four distinct events have been recognized in the Grenville Orogenic Cycle including the Elzevirian (1245-1220 Ma), Shawinigan (1200-1150 Ma), and Grenvillian (Ottawan Phase – 1090-1020 and Rigolet Phase – 1000-980 Ma) orogenies (Rivers 2008). This is comparable to the series of events (Taconic, Acadian, and Alleghanian orogenies) that shaped the Appalachians. Note that rocks of the Grenville Province, which form the basement in southeastern New York in the Hudson Highlands portion of the Reading Prong and are located on the edge of North America, have been affected by both Grenville and Appalachian tectonic events.

Because of the great age of the Grenville mountains, they have long since been worn down to sea level, been covered with Paleozoic sedimentary rocks, and the sediment derived from them transported to sedimentary basins in distant locations (Rainbird et al. 1997). The Adirondack Region is unique among much of the Grenville Province displaying uplift, seismic activity, and neotectonism that continues to this day (Isachsen 1981). The end result is that rocks once buried as much as 30 km in the crust are now exposed in a topographic dome elevated 1.6 km above sea level. An important part of the geologic history, which will not be fully addressed here, is how this enormous mountain range was eventually worn down to sea level. Recent studies have documented some of the major structures (normal faults) that operated when tectonic convergence ceased and the entire mountain range began to collapse under its own weight (Selleck et al. 2005).

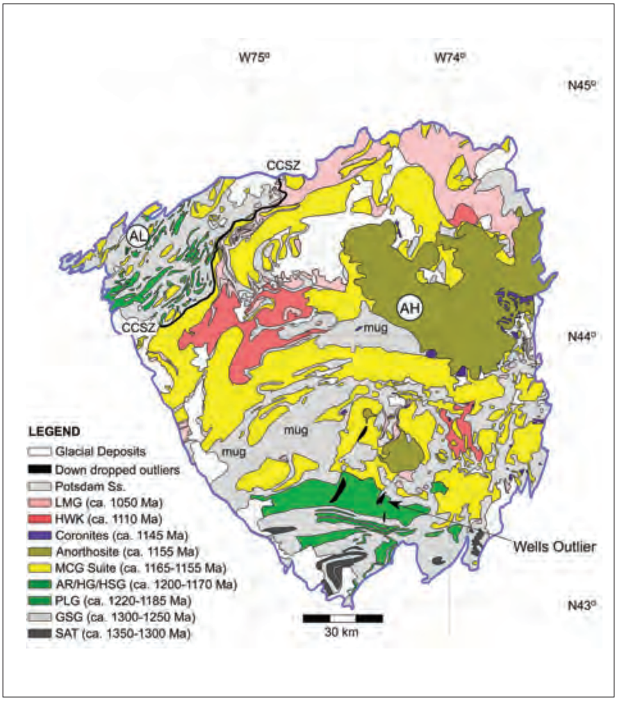


Figure 2: *Major rock types of Adirondack Region. Major rock types and their respective ages are shown by colors indicated in the legend. Abbreviations:*
AH - Adirondack Highlands;
AL - Adirondack Lowlands;
AR - Antwerp Rossie Suite;
CCSZ - Carthage-Colton Shear Zone;
GSG - Grenville Supergroup;
HG - Hermon Granitic Gneiss;
HSG - Hyde School Gneiss;
HWK - Hawkeye Granite;
LMG - Lyon Mountain Granite;
PLG - Piseco Lake Gneisses;
and SAT - Southern Adirondack Tonalite Suite.

A TIMELINE OF OROGENIC EVOLUTION

In this contribution, we will focus on the geologic events that resulted in the rocks we see exposed at the surface in the Adirondack Region today. Adirondack rocks share many similarities to those exposed in the Grenville Province of adjacent parts of Ontario and Quebec, and studies of these regions have provided us with the context for our own area. Here we will step through time from the oldest to youngest events using an approximate 50 million year interval to explain the evolution of adjacent parts of the Grenville Province and Adirondack Region (see Figure 5). The 50 million year interval is convenient as it allows discrete events to be discussed in their proper sequence and approximate duration. Note that this discussion would not be possible without the application of modern geological tools to the rocks in question. The extensive development and use of mineral geochronometers, primarily zircon and monazite, provide the critical temporal dimension to our understanding of the region's history (McLelland et al. 1988). Also note that the Adirondacks are a small portion of the Grenville Province in the approximate center of the orogenic belt that developed over a billion years ago. The scale of plate tectonics is often global, and events vary from place to place. Hence, we often have to rely on what we know about other areas and analogy to younger orogenic belts to provide the context for our discussion here.

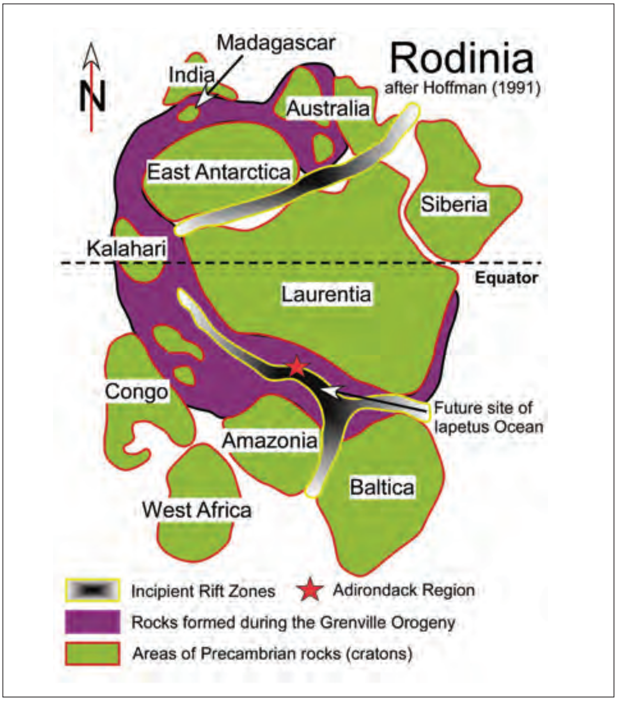


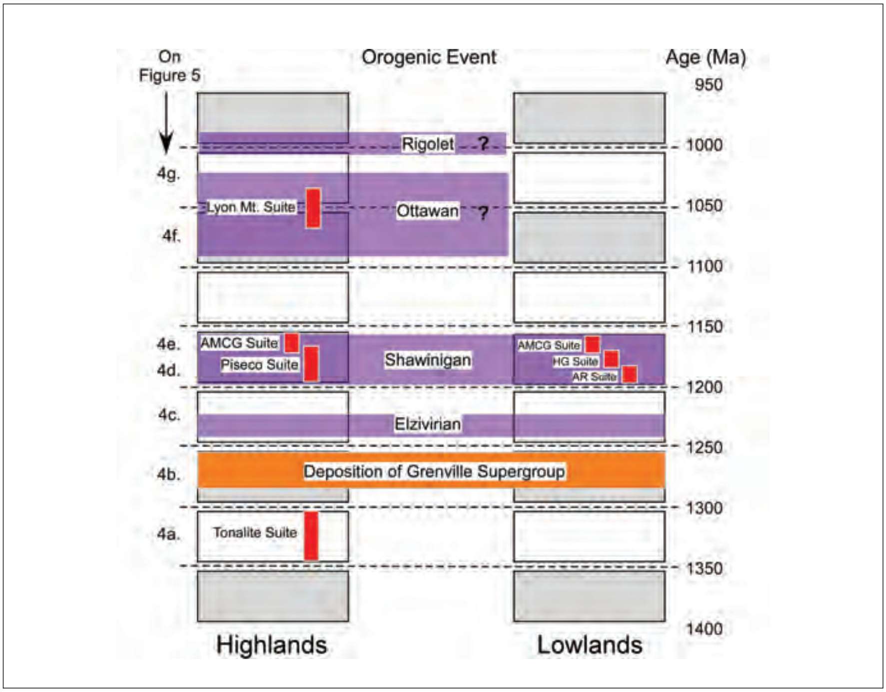
Figure 3: *Paleoreconstruction of Rodinia at about 900 million years ago after Hoffman (1991). Precambrian cratons are shown in green, while the rocks affected by the Grenville Orogenic Cycle are shown in purple. The red star shows location of the Adirondack Region in the center of one segment of the orogen.*

1350-1300 MILLION YEARS AGO—SUBDUCTION ALONG THE SE MARGIN OF LAURENTIA AND DEVELOPMENT OF A CONTINENTAL ARC(S)

The oldest rocks exposed in the Adirondacks occur in the southern and eastern portions of the Adirondack dome (Figure 2). They consist of several strongly deformed belts of tonalitic gneisses, interlayered with younger rocks, which have yielded crystallization ages between 1350-1300 million years ago (McLelland and Chiarenzelli 1990). Their chemical composition, petrography, and other characteristics suggest they formed as part of a continental arc that rimmed the southeast margin of Laurentia (present coordinates). Continental arcs, such as the modern day Andes and the Mesozoic Sierra Nevada batholith, form incrementally as magma related to subduction beneath a continental margin emplaced in the overlying continental crust. Over time, individual batches of magma (i.e., plutons) derived from the subducting slab can amalgamate and form a batholith of truly immense proportions.

The tonalitic rocks of the southern and eastern Adirondacks are similar in age and chemistry to tonalitic rocks exposed in the Green Mountains of Vermont, the Reading Prong, and in parts of Ontario and Quebec. This has led numerous workers to suggest that a large continental arc or arcs were built on the margin of Laurentia during the period between 1350-1300 million years (Rivers and Corrigan 2000). This was likely the direct result of the northward subduction of ocean crust beneath Laurentia. However, these tonalitic arc fragments are now widely dispersed and separated by intervening rocks of younger age (Moretton and Dickin 2013). Thus, it appears likely that some of these rocks have traveled far from their place of origin on the margin of Laurentia and have been fully incorporated into the tectonism that followed.

Figure 4: *A timeline showing the metamorphic and intrusive events in the Adirondack Highlands and Lowlands. The events noted by labels on the left between dashed lines are shown schematically in Figure 5.*



1300-1250 MILLION YEARS AGO – RIFTING, DEVELOPMENT OF BACK-ARC BASINS, AND DEPOSITION OF THE GRENVILLE SUPERGROUP

In order for rocks originally developed on the margin of Laurentia to be widely dispersed and now occur far outboard from where they developed, they must have moved laterally over great distances. One way to facilitate such movement is by the opening of a rift. Much of eastern Africa is currently splitting apart; the edge of Laurentia is believed to have begun splitting apart at ca. 1300 million years ago (Dickin and McNutt 2007). This rifting allowed the dismemberment and movement of tectonic elements from the margin of Laurentia, including the tonalitic arc rocks noted above. If rifting continues, a mature ocean can develop, much the same as the Atlantic did when North and South America split apart from Europe and Africa after the formation of Pangea. However, because much of the Grenville Province shares a very similar sequence of metamorphosed sedimentary rocks, known as the Grenville Supergroup, it is unlikely that a full-scale ocean developed and rifting and spreading eventually slowed and stopped.

A more likely possibility, which would allow the limited transportation of dismembered fragments of the tonalitic continental arc once located on the margin of Laurentia, is the opening of a back arc basin. This would allow once continuous pieces of older crust to be widely dispersed and separated by younger rocks that formed in the intervening basins. Back arc basins, like the Sea of Japan, develop when high heat flow and magma beneath an arc leads to the development of a spreading center. As happened along the coast of Asia, spreading can split apart a portion of the former continental margin (i.e., Japan), and the subduction zone "steps" outward away from the newly created continental margin. Although back-arc basins are not as large, or long-lived, as true oceans, they can be as much as 1000 km or more across and serve as a depocenter from thick accumulations of volcanic rocks and sediment. Eventually, they flood with sea water and develop an active volcanic spreading center, which begins to create oceanic crust. In addition, as they open, pre-existing continuous tectonic elements drift slowly away from each other and occupy locations on both sides of an opening sea or ocean.

It should be emphasized that the Adirondack Region is a small piece of the greater Grenville Province (McLelland et al. 1996), and much variation can be expected along its length; however, workers have suggested that much of the southeastern coast of Laurentia was rimmed by back-arc basins at this time (Rivers and Corrigan 2000). Evidence for the development of one or more back arc basins in the Grenville Province includes volcanic and sedimentary rocks of the appropriate type and, more importantly as indicators of this environment, slivers of oceanic crust produced during their life span. Rocks called ophiolites are tectonic fragments of oceanic crust, often including thin slivers of the underlying mantle, that get thrust up (i.e., obducted) into rising mountain ranges. Such rocks are found up and down the spine of the Appalachian Mountains and in many mountain belts around the world. Recently, such rocks have been identified in the Adirondacks (Chiarenzelli et al. 2011) and in the Grenville Province of Ontario (Smith and Harris 1996). Because these two basins are separated by an intervening older fragment of crust known as the Frontenac Terrane, it has been suggested that a series of back-arc basins were operative at this time off the coast of Laurentia (Chiarenzelli et al. 2015). They provide indisputable proof that small basins with spreading centers produced oceanic crust between 1300-1250 million years ago. It was in these basins that sedimentary rocks of the Grenville Supergroup were deposited.

The hallmark of the Grenville Supergroup (GSG) is a thick sequence(s) of metamorphosed carbonate rocks, such as marble and calc-silicate gneisses. These rocks generally form in warm climatic regions where the production of carbonate detritus greatly exceeds that of clastic sediment delivered to the depositional basin. Even more telling, in terms of the paleoclimate conditions during its deposition, is the occurrence of thick evaporitic deposits found in some portions of the GSG (de Lorraine 2001). Rocks containing evaporitic minerals like gypsum, anhydrite, or halite require evaporation rates well in excess of precipitation amounts and, generally, restriction from the open ocean.

Sand-sized grains of the mineral zircon ($ZrSiO_4$), an important geochronometer, separated from clastic units with the Grenville Supergroup in the Adirondacks suggest it was deposited between 1300-1250 million years ago (Chiarenzelli et al. 2015) within a back-arc basin that extended from the margin of Laurentia to a rifted arc fragment off the coast. This time fits well with the known depositional age of similar GSG rocks in other areas of the Grenville Province. Furthermore, it suggests that in addition to providing valuable information on the conditions at the Earth's surface when these rocks were deposited, they have been affected by all of the subsequent orogenic events that comprise the Grenville Orogenic Cycle. From an economic standpoint, rocks of the GSG in New York, primarily near Balmat in the Adirondack Lowlands, serve as an exploitable resource of zinc, talc, marble, as well as, other resources (de Lorraine 2001).

1250-1200 MILLION YEARS AGO – INITIAL CONVERGENCE, DOCKING OF AN ARC, AND THE ELZEVIRIAN OROGENY

Plutonic rocks, deformation, and metamorphism associated with an orogenic event thought to be of relatively small areal extent occurred between 1245-1220 Ma in the Grenville Province in Ontario. At this point in time, the back-arc basin in Ontario, the Central Metasedimentary Belt (Figure 2), began to collapse and rocks on the margin of Laurentia were thrust northwestward towards the Superior Province. The cause of this tectonic activity, known as the Elzevirian Orogeny, is believed to be the docking of an arc fragment, previously rifted away, back on to the margin of Laurentia (Carr et al. 2000).

Our knowledge of the Elzevirian Orogeny, including its ultimate spatial extent, is incomplete. This is largely because the rocks affected by it have been profoundly impacted by later orogenic events, which may have partially or completely obliterated or overprinted features related to the Elzevirian Orogeny. Essentially, it becomes an issue of trying to "see" through younger events which strongly affected the rocks in the area. Whether or not the Elzevirian Orogeny impacted the Adirondack Region is not known for sure. However, some field evidence suggests that the rocks of the Grenville Supergroup deposited within a back-arc basin between 1300-1250 Ma underwent deformation and isoclinal folding prior to 1200 million years ago. This would make this deformation older than the recognized initiation of the Shawinigan Orogeny at 1200 million years ago. This evidence is best seen in the Adirondack Lowlands, which were spared some of the later stages of orogenesis due to their eventual location higher in the crust.

1200-1150 MILLION YEARS AGO – CONTINENTAL COLLISION, THE SHAWINIGAN OROGENY, AND AMCG SUITE

The Shawinigan Orogeny was first recognized by Corrigan (1995) and may be the most important in terms of regional metamorphism and structure in the southern Grenville Province. It is also associated with a magmatic event of immense proportions, which included the intrusion of the Marcy anorthosite massif of the High Peaks and several other even larger massifs elsewhere in the Grenville Province. Massif anorthosites are enigmatic igneous rocks and the details of their origins are still under debate. We know that they are largely restricted to the Grenville Province, are mostly restricted to the Proterozoic Era (mostly Mesoproterozoic), and are associated a distinct suite of high temperature “felsic or granitic” igneous rocks collectively known as the AMCG suite (anorthosite-mangerite-charnockite-granite suite). Until the recognition of the Shawinigan Orogeny, the AMCG suite was largely thought to be unassociated with orogenic activity (i.e., anorogenic) but are now known to have been intruded just prior (1165-1155 Ma) to the cessation of Shawinigan tectonic activity. At least in the Adirondacks, and perhaps elsewhere in the Grenville Province, the Shawinigan Orogeny set the stage for the intrusion of massif anorthosite.

The Shawinigan Orogeny is thought to represent the initial collision of a large continent with Laurentia. Based on a variety of lines of evidence (Stein et al. 2014), the most likely candidate is the Precambrian core of South America, Amazonia. All the tectonic elements in between the two continents underwent extreme deformation and shortening, and accompanying metamorphism. In the Adirondack Lowlands, the Shawinigan Orogeny was the last event to affect the region, so we can get a sense of its structural style and metamorphic conditions. In general, the Lowlands show thrusting and folding towards the southeast imparting a strong SW-NE structural grain during the period 1180-1160 million years ago (Heumann et al 2006). The metamorphic grade was upper amphibolite facies and corresponded to temperatures in excess of ~660 ^{o}C, which enabled partial melting of some metasedimentary rocks of the Grenville Supergroup.

Prior to, and during, deformation a number of igneous rock suites were intruded into the deformed metasedimentary rocks of the Lowlands (Peck et al. 2013). These include rocks that range in age from 1200 to 1155 million years ago. They represent renewed arc plutonism (Antwerp-Rossie Suite – ca. 1200 Ma), which gradually transitioned into the AMCG suite (Pope Mill mafic syenite – ca. 1155 Ma). In the Highlands, similarly-aged (ca. 1200-1170 Ma) rocks of arc chemistry are found within the Piseco Lake Shear Zone, which separates the central and southern Adirondacks (Gates et al. 2004). From 1165-1155 Ma enormous quantities of anorthosite and associated felsic or granitic members of the AMCG were intruded into the Adirondack Highlands (McLelland et al. 2010b). These rocks occur largely as strongly deformed, E-W arching belts of rock interleaved or interfolded with strongly deformed and attenuated metasedimentary keels.

The structural architecture of the Adirondack Highlands is dominated by these E-W trending belts of strongly deformed rock. In addition, they often contain a shallowly plunging mineral lineation, parallel to the overall trend of the lithologic units. Within the Piseco Lake Shear Zone, a broad region (>30 km) of strongly deformed, megacrystic granitic gneisses, this lineation often becomes the dominant fabric element in the rock. So called L-tectonites with shallow lineations are the hallmark of transpressional deformation (Valentino et al. 2008), where two crustal blocks converge but also have a component of strike-slip motion as they slide past one another. In this case, structures in the rock used to decipher the relative sense of movement indicate a left-lateral displacement (Valentino et al. 2008), much as if you viewed the side of a stack playing cards lying on a table while moving them to your left. However, in this case, the playing cards are embedded in the Earth vertically. U-Pb zircon ages indicate that the movement along this shear zone and across the Central Adirondacks, in general, occurred at high-grade metamorphic conditions near the end of the Shawinigan Orogeny (ca. 1160). Sporadic development of lower-grade minerals like chlorite and muscovite also aligned with the dominant fabric may indicate movement occurred later or continued at lower grade conditions as well (Valentino et al. 2008).

The proximal cause for Shawinigan deformation appears to be collision of the Southern Adirondack tonalitic arc fragment and collapse of the back-arc basin to the north. However, outboard of the Adirondacks, to the south, Amazonia may have already been converging towards, or sliding along, Laurentia (Stein et al. 2014), much the same as India is impinged on southern Asia trapping, deforming, and uplifting everything in between for the last 60 million years. Examination of the geological map of the Adirondacks presents a paradox in that the large Marcy Anorthosite appears to punch through the E-W belts of strongly deformed rock and thus post-date deformation. However, this may be more apparent than real, as the large block of relatively homogeneous anorthosite crystallizes at very high temperatures (near 1100 ^{o}C) and thus is very strong and rigid even at high-grade metamorphic conditions experienced in the Highlands, whose peak temperature was about 800 ^{o}C. Thus, the anorthosite is considered to have been intruded late in the Shawinigan deformational sequence (McLelland et al. 2010a), but probably not afterwards, and its general lack of a deformational fabric is related to its strength as more ductile rocks deformed around it. Recent work on landslide exposures in the High Peaks indicates that although original igneous textures are well preserved in the interior of the Marcy anorthosite massif, some areas show thin, zones of highly deformed rock along lithologic contacts (Chiarenzelli et al. 2015). This implies the transfer of strain from tectonism into the interior of the massif in favorable locations.

The reason for AMCG plutonism, including the Marcy anorthosite massif, which underlies the Adirondack High Peaks region, is less clear. Models suggesting the inevitable detachment of a down going slab of oceanic crust or delamination of the crust and mantle during collision have been proposed (McLelland et al. 2010a). Regardless of the reason, the production of large quantities of anorthosite involves the fractional crystallization of large amounts of plagioclase from a basaltic magma derived from the mantle. Basalt is readily produced in copious quantities beneath mid-ocean ridges where the Earth's asthenosphere bulges upward and undergoes a small amount of partial melting due to decompression. A similar origin has been proposed for the Adirondack Suite where the ponding of basalt at the base of the crust would lead to massive melting of the lower crust and the production of felsic or granitic igneous rocks that rose upwards along with the anorthosite. This provides an explanation of coeval nature of the suite but still accounts for their different source regions (felsic or granitic rocks – lower crust; anorthosite – upper mantle).

1150-1100 MILLION YEARS AGO – QUIESCENCE (?)

Relatively little is known for sure about the period between 1150-1100 million years ago in the Adirondack Region. It may have been a period of time during which tectonic processes slowed or halted temporarily. Some igneous rocks are thought to have been intruded during this time (Chiarenzelli and McLelland 1991), but they are generally similar in their chemical composition to the earlier AMCG suite. Further, reinvestigation has revealed that they may be older than originally thought. On the other hand, rocks in the Grenville Province in Quebec fall within this time window and late plutonism associated with the AMCG suite or a younger suite of similar origin cannot be ruled out. There is relatively little evidence for voluminous magmatism, deformation, or rapid uplift in this time interval. This may, however, be an artifact of our incomplete knowledge, and we may have to look further afield to understanding what was going on in the context of a tectonic scale.

By 1100 million years ago, voluminous volcanic and plutonic rocks associated with the enormous Mid-Continent Rift centered in the Lake Superior Region marked the initiation of extension of the crust (Stein et al. 2014). The Mid-Continent Rift eventually failed, but not before its largest arm propagated all the way south to Oklahoma and produced thick accumulations of rhyolite and basalt now exposed in the Upper Peninsula of Michigan and adjoining areas of Wisconsin, Minnesota, and Ontario. Given the relative proximity, on a plate tectonic-scale, to the Adirondack Region (one arm of the rift extends underneath Michigan to the western end of Lake Erie and possibly all the way to Alabama), far-field plutonic rocks or other effects associated with mid-continent extension are a distinct possibility. Further research will likely explore this possibility.

1100-1050 MILLION YEARS AGO – PLUTONISM, HIGH-GRADE METAMORPHISM, AND EXTENSION, AND THE OTTAWAN OROGENY

Granites, pyroxene syenites, fayalite-bearing granites, and leucogranitic rocks ranging in age from 1100-1050 Ma are well known in the Adirondack Highlands (McLelland et al. 1988) but are lacking in the Lowlands (Peck et al. 2013). This has led many workers to surmise that the rocks of the Lowlands were located higher in the crust and escaped deformation and metamorphism (and accompanying plutonism) and/or were located at a distance from their current location in a lateral sense. One consequence of continental collision is the shortening and thickening of the crust and rock units may be moved many hundreds, if not thousands, of kilometers. Some workers have proposed that parts of the Grenville Province are part of an extensive orogenic "lid" (Rivers 2008). Orogenic lids are regions high in the crust during deformation, like the current Tibetan Plateau, which is not currently deforming due to its previous tectonic uplift despite the intensive tectonism beneath it deep in the crust. Essentially, these areas were "along for the ride" but not deformed during it.

A logical question, then, is how did the Lowlands come to be juxtaposed against the higher grade Adirondack Highlands and avoid intrusion by these late plutonic rocks? The answer lies along the boundary between the Highlands and Lowlands, known as the Carthage-Colton Mylonite (or Shear) Zone (CCSZ) for the two North Country towns that mark its end points where it is covered by younger Paleozoic rocks. Workers have confirmed the intrusion of late, syntectonic, 1040 Ma leucogranites along this structure (Selleck et al. 2005). Their syntectonic nature confirms that they were intruded during active deformation. Thus we know, regardless of the earlier, high-temperature history of the CCSZ, the two terranes were brought together at the same crustal level by ca. 1040 Ma. Extensional normal faults like these are common in the late stages of an orogeny and mark the beginning of its long collapse and eventual return to normal crustal thickness via erosion and associated isostatic uplift.

In contrast, rocks of the Adirondack Highlands were profoundly affected by the Ottawan Orogeny (ca. 1090-1020 Ma), particularly in the eastern portion of the Adirondacks (McLelland et al. 2001). Our understanding of the deformation that occurred at this time is hampered by high-grade metamorphism; with some workers suggesting the entire crustal architecture of the Adirondacks was produced by this event and others suggesting its effects were more localized. In any event, a profound metamorphic pulse was felt throughout much of the Highlands during this time. It resulted in melting in some rock types, the growth of new metamorphic zircon, and partial to complete resetting of zircon ages in other lithologies.

Perhaps the most profound event that occurred between ca. 1100-1040 Ma was the intrusion of a vast amount of leucogranite and related rocks named the Lyon Mountain Granite for the host rock of the large iron deposits on Lyon Mountain in northern New York (Lupulescu et al. 2015). Rocks of this type are found in a large arcing belt extending from the eastern to western Adirondacks Highlands along the northern margin of the topographic dome. They also can be found in various locations within the central portion of the Highlands around the High Peaks. Associated with these rocks are numerous iron deposits that were discovered near the western shore of Lake Champlain and elsewhere and exploited from the late 1700's until relatively recently. These iron deposits are relatively unique in that they are mostly composed of magnetite and apatite (Lupulescu et al. 2015). In addition, the apatite can contain as much as 20 wt% rare earth elements, which are in high demand because of their essential role in many modern electrical devices.

Since the Lyon Mountain Granite appears to have escaped much, or all, of the deformation associated with Ottawan Orogeny (ca. 1090-1020 Ma), it may well be post-orogenic and would thus place a lower limit on the deformation associated with the Ottawan Orogeny. Post-orogenic igneous suites throughout the world consist of voluminous, alkali-rich, leucogranitic rocks. They have a highly evolved chemistry and concentrate some of the less common elements including the lighter rare earth elements, indicating derivation from melting of the deep crust. In many areas, they intrude faults and shear zones and are often associated with hydrothermal fluids and retrograde metamorphism, which is highly dependent on the addition of water to rocks that were essentially dried out by prograde metamorphism.

The Lyon Mountain Granite has all the hallmarks of a post-orogenic suite, including the lack of a deformational fabric and high-grade metamorphic mineral assemblages, cross-cutting relationships with other older rock types, intrusion along extensional faults and shear zones, association with ores and hydrothermally altered rocks, and appropriate geochemical and petrologic trends. In addition, study of zircon from Lyon Mountain Granite bodies indicates that some samples have a large amount of inherited cores from the crustal rocks they were derived from (McLelland et al. 2001). Zircon is a very robust mineral and often survives melting. Many of the cores are about ca. 1150 million years in age and indicate partial melting of the voluminous AMCG suite in the Highlands deep in the crust. Thus, the Lyon Mountain Granite appears to an essential part of the orogenic cycle in the Adirondacks and formed as the typical product of the extensional phase of the region. Its vast volume may have supplied part of the heat required to drive the metamorphic growth of zircon and develop hydrothermal convection cells along faults.

1050-1000 MILLION YEARS AGO—CONTINUED COLLAPSE, THE TERMINAL RIGOLET PHASE

As noted above, much of the Lyon Mountain Granite intruded at ca. 1040 Ma. In some locations, it is itself intruded by iron ore and granitic pegmatites. Geochronology on zircon and monazite from various iron ores, late granite pegmatites, and other associated rocks yield ages that fall between 1040 Ma and 990 Ma (Lupulescu et al. 2011). These ages suggest that the intrusion of post-orogenic rocks continued on for several tens of millions of years, as might readily be expected. Some sections of the Grenville Province, mostly to the north and east of the Adirondacks, show renewed deformation and metamorphism at ca. 1000 Ma, and this event has been named the Rigolet pulse of the Grenville Orogenic Cycle (Rivers 2008). Aside from a few late intrusions, the growth of some metamorphic zircons and monazite, there is little direct evidence that the Rigolet was an important part of the history of the Adirondack Region. However, new data can always necessitate rethinking its role in the region.

1000-540 MILLION YEARS AGO—UPLIFT, EROSION, AND RIFTING

Our understanding of the long history between the end phases of the Grenville Orogenic Cycle and the deposition of Paleozoic sedimentary rocks in the Adirondack Region is limited by an absence of evidence. The assembly of Rodinia was followed by its eventual rifting (Figure 2), and plate tectonic reconstructions show that by 750 million years ago, the margins of Laurentia were beginning to appear. Rifting is associated with uplift of continental crust along fault systems that eventually form the new plate boundaries. This uplift and associated faulting likely enhanced the erosion and exposure of the once deeply buried Proterozoic basement. Some of the major north-northeast trending faults within the Adirondacks may have been activated during this rifting. The new ocean basin that opened to the east of the Adirondacks has been named the Iapetus, and the later Cambrian and Ordovician sedimentary rocks were deposited along the shore of that ocean.

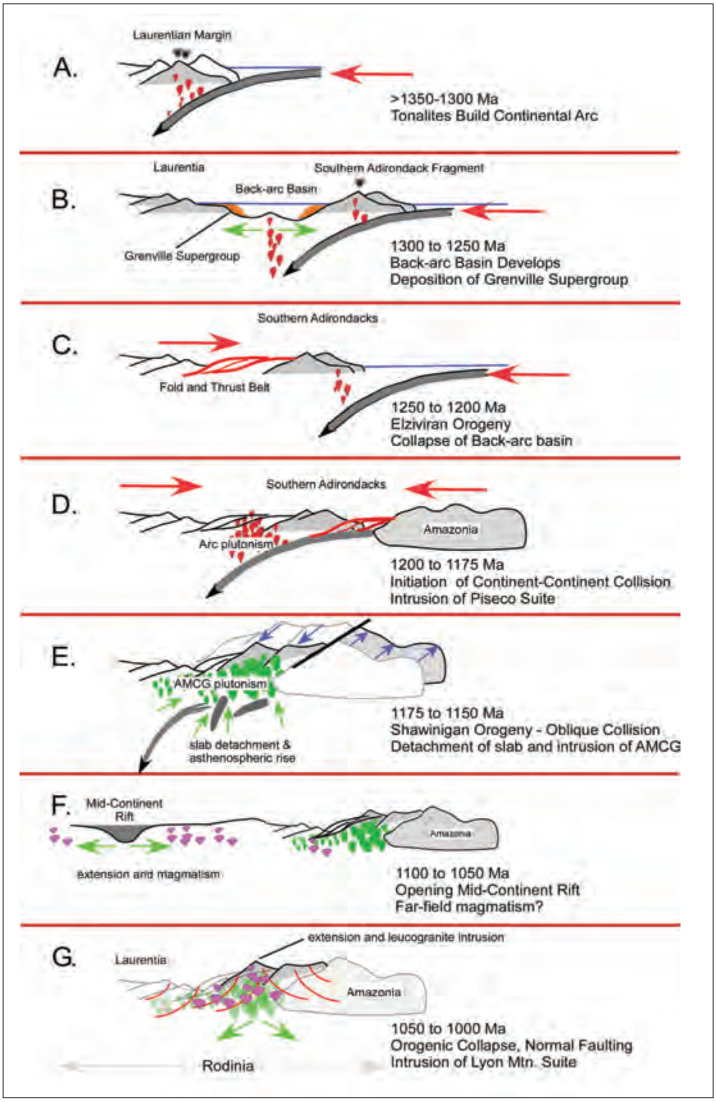


Figure 5: *A series of schematic cross-sections showing the evolution of Adirondack and surrounding regions from NW to SE. Arrows show direction of asthenospheric flow, tectonic movement or stress (green – extension; red – convergence; blue – strike-slip motion). Plutonic suites shown as inverted teardrops (red - calc-alkaline arc plutonism; green – AMCG suite; pink – late post-tectonic granites and leucogranites. Sedimentary rocks of the Grenville Supergroup are shown in orange.*

540-440 MILLION YEARS AGO: THE PALEOZOIC ROCKS

The Paleozoic, or 'Secondary' sedimentary rocks of the Adirondack region, are part of a sequence of layered strata that extend over much of North America. These strata were deposited on the continental interior during periods of global sea level high stand and tectonic events that caused submergence of the continental crust. Mapping of the geology of the Adirondack region in the 19th century focused on these sedimentary rocks for economic reasons. The limestone and dolostone strata provided material for agricultural lime-making, mortar and cement manufacture, and flux for iron smelting. The sandstones provided quartz sand for glass-making and solid but workable rock for building; the shales were worked for road fill and, when weathered, provided clay for brick and ceramic manufacture. While the older 'Primary' rocks, now called the Proterozoic basement, held economic value in metal ores and building stone, it is not surprising that Ebenezer Emmons (1838, 1841), in his reports on the second geological district of New York, paid special attention to the Paleozoic sedimentary rocks and their distribution in and around the Adirondack Massif. In this section, we briefly describe these sedimentary rocks, their distribution, and the geological history they record. While the Adirondacks are most well-known to geologists for its 'crystallines' (e.g., coarse grained gneiss, marble, and anorthosite), the Paleozoic strata provide insights into the landscape and evolution of the region over later periods of earth history.

THE LATER RECORD

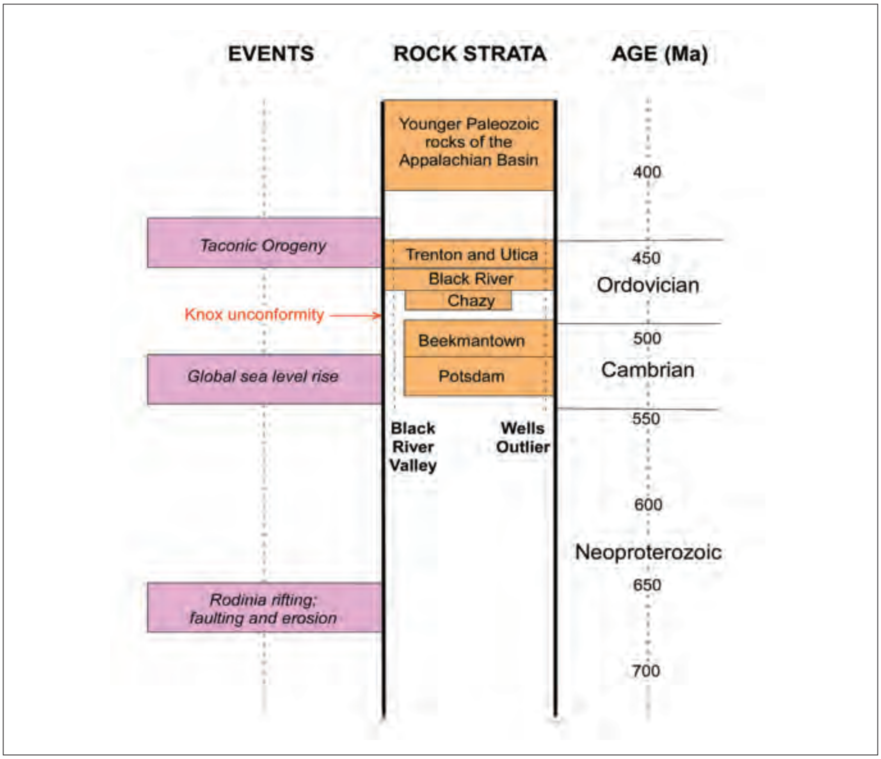
The sedimentary rocks of interest in the Adirondack Region are confined to the early part of the Paleozoic era, the Cambrian (~540-490 million years ago), and Ordovician (~490-445 million years ago) (Figure 6). The Paleozoic strata were laid down on top of eroded Adirondack basement, made up of the igneous and metamorphic rocks described earlier in this paper. The metamorphic conditions experienced by these basement rocks require burial to depths of 25 km or more, during the interval 1300 to 1000 million years ago. Yet, by early Cambrian time, the current surface of Adirondack basement was exposed, as the basement directly underlies sediment deposited at the earth's surface. The mass of material eroded away from the ancient Adirondacks was immense, but so was the interval of time available—nearly 500 million years.

THE GREAT FLOODING OF THE CAMBRIAN

540 million years ago, as the ocean basins of the planet continued to open rapidly, global sea level rose and flooded the low lying edges of the continents. The edge of Laurentia was slowly subsiding as well, after the rifting apart of Rodinia. Along the hot, dry coast of Laurentia, in the Adirondack Region, beaches, shallow water tidal systems, coastal sand dunes, and braided streams deposited quartz-rich sand. These thin sand units were laid down on top of the deeply eroded basement rocks and, when buried and lithified, formed the oldest widespread Cambrian unit in the region – the Potsdam Sandstone, now known

as the Potsdam Group (Lowe et al. 2015). We use the term 'unconformity' to describe the contact between the Potsdam and the much older metamorphic and igneous basement. The Potsdam is thickest (nearly 300 m), in the northeastern Adirondack margin in Clinton County and is much thinner or absent from the stack of Paleozoic strata along the western Adirondack margin in the Black River Valley. There, the basal sandstone was never deposited or was eroded away before younger rocks were deposited on top of the basement. The Potsdam sandstones are mostly made of quartz sand grains along with other hard, resistant minerals such as zircon. Zircon can be dated using U-Pb techniques, and the ages we get from Potsdam zircons show that while much of the sand was derived from rocks of the same age as the local Adirondack basement crystallines, some sand must have come from much older basement to the north and west in central Canada. The Potsdam is known for its red-pink hues, colors that are caused by tiny iron and titanium oxide crystals that formed during burial and uplift episodes. The Potsdam is widely used as a building stone, particularly along the northern Adirondack margin (e.g., in Malone and Potsdam).

Figure 6: *Schematic illustration of events and sedimentary rock units in the Adirondack Region. The Little Falls and Galway Formations are part of the Beekmantown Group. The sequence at Wells, NY includes the Potsdam, Beekmantown, Black River, Trenton, and Utica (W on diagram); only Black River and Trenton Group strata are present in the Black River Valley (BRV), where Proterozoic basement directly underlies Paleozoic strata.*



LATE CAMBRIAN SEA LEVEL RISES AND FALLS, AND LIMEY SEDIMENTS ARE LAID DOWN

The Potsdam Group in the southern and eastern Adirondack Regions is followed by lime (calcium carbonate) sediment mixed with quartz sand (Galway Formation). The Galway is overlain by the Little Falls Formation, a dolomite rock (dolomite is an Mg-Ca carbonate mineral) that was laid down in very shallow tidal flats where algal heads (stromatolites) were common. The famous Little Falls or Herkimer 'diamonds' are very clear, well-formed quartz crystals that grew in open spaces within the rock during burial, when warm fluids circulated in the strata. The Galway, Little Falls, and overlying limestone and dolostones of uppermost Cambrian and lower Ordovician age (the Beekmantown Group) were deposited in shallow seas that episodically withdrew during short intervals of global sea level fall, only to re-flood the shallow continental area during modest sea level rise. This rising and falling and rising pattern makes for a complicated distribution of these shallow water strata, with some areas receiving little or no sediment at certain times, and areas subject to erosion of older sediment.

THE CRUST BUCKLES UP, AND SEDIMENTATION STOPS FOR A WHILE

During the latter part of early Ordovician time, and into early late Ordovician time, much of eastern North America stood above sea level as tectonic plate configuration began to change. The beginning of collisional tectonics of the Taconic Orogeny caused the continental crust to bulge up above sea level across most of the Adirondack region. During this period, the Cambrian and early Ordovician strata previously laid down were subject to erosion and weathering, and in some areas, completely stripped away. This period of uplift, and later deposition of late Ordovician sediments, produced the so-called Knox unconformity, representing a contact between older and younger marine sediments, separated by a period of erosion. This feature is much less grand than the unconformity separating the basal Potsdam sandstones from the underlying Proterozoic basement but is an important signature of the changing tectonic landscape of eastern North America.

COLLISION AND SUBSIDENCE IN THE LATE ORDOVICIAN

The Taconic Orogeny involved the successive collision of island arcs (think Japan) with the eastern margin of Laurentia. Those collisions telescoped rocks and sediment from the continental edge up onto the continent, resulting in loading of the continental crust with new material. This loading caused the interior of the continent, in the vicinity of the Adirondacks, to subside, allowing the seas to advance into the continental interior once again. The subsidence took place by bending of the crust, and locally, faults developed that accommodated the subsidence. Along the easternmost Adirondack margin, this subsidence allowed the seas to invade, and limestones of the Chazy Group were deposited. The Chazy is famous for its reefs, which are buildups of limestone sediment in areas where corals, algae, and other hard skeletal organisms were able to thrive. The reefs of the Chazy Group are best seen on the islands in northern Lake Champlain. More widespread limestone sediments were deposited following Chazy Group deposition as the Black River Group, which is made up of light to dark grey limestones found along the western, southern, and eastern Adirondack margins. These limestones are commonly used as building stone and for other purposes such as road metal and concrete aggregate.

The Black River Group is succeeded by the Trenton Group, which most commonly is made up of limestone beds interbedded with thin layers of dark shale. The Trenton was overall deposited in somewhat deeper water than the Chazy and Black River Groups as a consequence of the continued subsidence of the continental crust during the ongoing Taconic Orogeny. Trenton limestones are often very fossiliferous, with abundant brachiopods, bryozoans, and trilobites among the common fauna.

THE WATER DEEPENS AND THE SEDIMENTS DARKEN

The continued collisional tectonics of the Taconic Orogeny caused the Adirondack region to subside even more into the late Ordovician. In addition, mud derived from the uplifted land areas in the collisional zone to the east began to make its way across the region. The deeper, muddier water was less hospitable to organisms that make lime sediment, and the deposition of Trenton Group limestone was followed by accumulation of black mud rich in organic carbon that formed the shale of the Utica Formation. The Utica was first deposited in the eastern part of this shale basin, while limestone sediments were still accumulating in the western, shallower region. However, the foundering of the interior platform soon allowed dark mud to overtake the deposition of limestone, and the Utica spread across the basin. As the Ordovician drew to a close, coarser silt and sand made its way into the basin, and subsidence slowed, allowing shallower water sediments to build up, eventually filling the basin to near sea level. These sedimentary units that overlie the deep water Utica Formation include the Frankfort and Schenectady Formations, which are found to the south of the Adirondacks in the Mohawk Valley, and the Lorraine and Pulaski Formations, found in the Black River Valley and Tug Hill regions.

LATER ON, BURIAL AND UPLIFT

Our record of Paleozoic sedimentary strata in the Adirondack region ends with the latest Ordovician. However, the sedimentary rocks now exposed at the surface show plenty of evidence of having been buried to greater depths during the later Paleozoic. Based on the 'thermal maturity' of organic compounds (oil and gas precursors in shale), the temperatures recorded by precipitation of minerals from hot water (e.g., Herkimer Diamonds), and the minerals present in volcanic ash beds (e.g., in the Black River and Trenton Groups), we estimate that the Paleozoic rocks currently at the surface were buried to depths of three or more kilometers across the Adirondack region. This means that additional younger sedimentary rocks of Silurian and Devonian age were present above the Adirondacks and were eroded away. To the south of the region, rocks of these ages occur as part of the thick sedimentary sequence of the northern Appalachian Basin. Uplift of the region likely began in early Mesozoic time, based on the ages recorded by fission tracks in minerals such as apatite (Roden-Tice et al. 2000).

A PRECIOUS PALEOZOIC RECORD IN THE WELLS OUTLIER

One might be tempted to ask at this point "If the Adirondacks have Proterozoic rocks at the surface, how do we know that this early Paleozoic history you just described is really true?" A very important record of the Paleozoic of the Adirondacks is found in the vicinity of Wells, New York. At Wells, normal faults have dropped down a block of Cambrian and Ordovician strata and preserved that record within the south-central Adirondacks (see Valentino et al. this volume). The Wells Outlier, a down-faulted area or graben, includes the Potsdam Group, Galway Formation, and Little Falls Formation, of Cambrian age, as well as the Black River and Trenton Groups and Utica Formation, of upper Ordovician age. Smaller outliers are found along similar normal fault valleys in the Adirondack region, but the Wells example is our most well-known. Exposures of the Paleozoic units are found within Wells Village and also in a rock quarry (permission required to visit).

SUMMARY

The Adirondack Mountains of New York form a small but significant portion of the Grenville Province, the bulk of which is exposed mostly in eastern Canada. Relatively recent vertical uplift has moved Adirondack rocks that were part of the roots of billion year old global system of mountain belts and exposed them at the surface. The rocks in the Adirondacks range in age from 1350-1000 million years old and record many of the events associated with the Grenville Orogenic Cycle, whose duration and complexity is similar to that of the Appalachian Orogeny, although they formed nearly a billion years earlier. Active tectonism and magmatism occurred, with some hiatuses, between ca. 1250 to 1000 million years ago in response to a series of tectonic events that affected the Grenville Province. Recent work has emphasized the importance of the Shawinigan Orogeny and its temporal links to intrusion of the Marcy anorthosite massif and associated granitic plutonic rocks. Metasedimentary rocks of the Grenville Supergroup can be used to decipher the region's pre-tectonic history. The region's location in the approximate center of a highly eroded and ancient mountain belt makes it ideal to study processes that occurred deep in the crust, and evaluate the tempo and architecture of mountain building in the distant past. The younger Paleozoic sedimentary rocks are a minor part of the Adirondack geological story but provide important records of the Cambrian and Ordovician history of the region and of later plate tectonic processes. The existence of fault-bounded, Paleozoic outliers, within the central part of the Adirondack dome, has much to tell us about the timing and nature of uplift of the region.

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MORE ABOUT PALEOZOIC ROCKS IN AND AROUND THE ADIRONDACKS

Apart from the examples mentioned here, and to get much more detailed information about rocks and where they are best found, seek out the website of the New York State Geological Association (http://www.nysga-online.net/). Guidebooks from the association's annual meetings are available for free download after three years, and more recent guidebooks can be purchased in hard copy using the website. Recent meetings of interest include 2002 (Lake George), 2004 (Potsdam), 2008 (Lake George, again), 2012 (Clinton), 2014 (Alexandria Bay), and 2015 (Plattsburgh). All but the last two years are currently available for free download.

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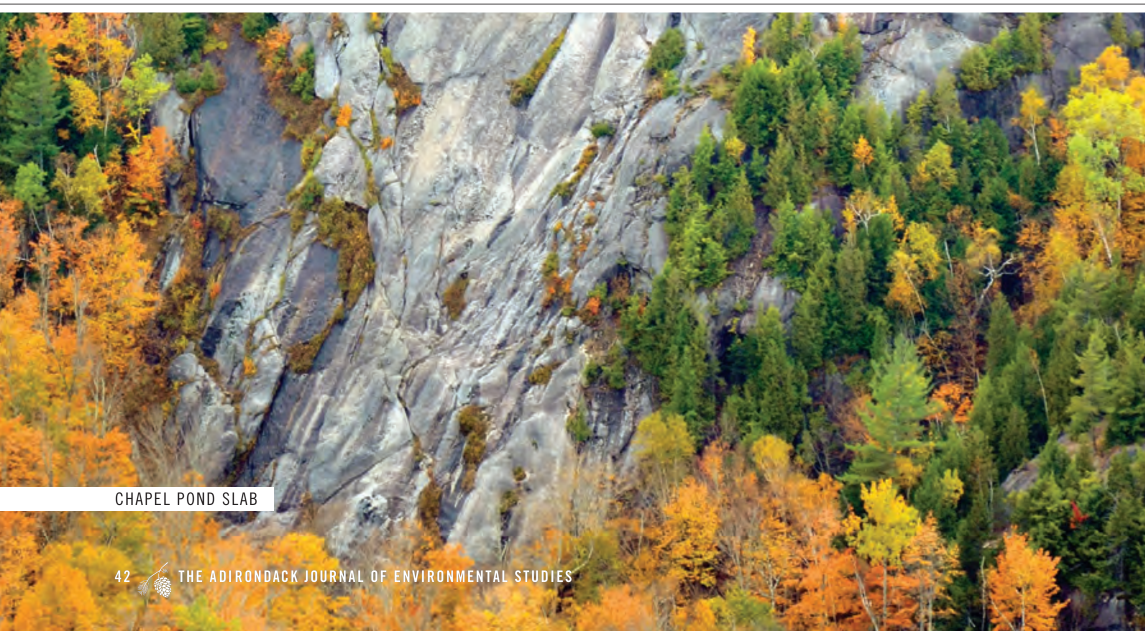
"The conical shape of the mountains formed of this rock [anorthosite], has led to the popular opinion that the region is volcanic; and accounts are often related, of lights being seen, explosions heard, and sulphur smelt. But in no part of the Adirondack group is there a trace of a crater, or any sign distinctly volcanic, either ancient of modern, except in the trap dykes which are so common throughout the whole territory."

Ebenezer Emmons
GEOLOGY OF NEW YORK: SURVEY OF THE SECOND GEOLOGICAL DISTRICT
1842



CHAPEL POND SLAB