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EPISODES IN GEOLOGICAL INVESTIGATIONS OF THE ADIRONDACKS

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INTRODUCTION

The crystalline rocks of the Adirondacks are now recognized to preserve a record of magmatism and metamorphism formed during Proterozoic tectonic episodes, but to early workers their origin was not obvious. After reconnaissance in the early 19th century, it became clear that rocks of the Adirondacks sit below the Potsdam Sandstone and other Paleozoic strata and contain a variety of igneous and metamorphic rocks that record a complicated, multi-stage history. Subsequent work focused on untangling these relationships, but basic questions about how particular Adirondack rocks formed persisted well into the 20th century, which saw the incorporation of Adirondack Geology into plate-tectonic theory. This contribution broadly summarizes the history of geological investigations of the Adirondacks, with a focus on the 19th and early 20th century, and provides a somewhat brief summary of more recent developments.

EARLY INVESTIGATIONS

The first geological map of the United States does not include the Adirondack Mountains (Figure 1). This map covering the eastern states was published in 1809 by William Maclure [1763-1840], a wealthy Scottish émigré. Maclure, the "father of American Geology," was well-traveled, conversant with the geology of Europe, and surveyed the geology of the eastern seaboard during 1808 and 1809 (Doskey 1988).

This early geological map represents one of the first attempts anywhere to synthesize the geology over a large area by use of color to represent rock units. In 1817, Maclure's updated *Observations on the Geology of the United States of America* and map (Figure 2) were published, incorporating new geological data and an expanded discussion including "the boundaries of the great primitive formation, north of the Mohawk" (Maclure 1817), referring to the then-unnamed Adirondack Mountains. Maclure's maps used the nomenclature of the influential Prussian geologist Abraham Gottlob Werner [1749-1817], subdividing American geology into Primitive (oldest), Transition, Secondary, and Alluvial (youngest) rocks. In this system, Primitive rocks such as those in the Adirondacks represent the oldest kind of rocks and are devoid of fossils, with fossil-bearing sedimentary rocks being younger and sitting at stratigraphically higher levels. Maclure (1817) colored Primitive rocks "sienna brown" on his map and recognized the classification as including most igneous and metamorphic rocks: "Granite, Gneiss, Mica Slate, Clay Slate, Primitive Limestone, Primitive Trap, Serpentine, Porphyry, Sienite [syenite], Topaz-rock, Quartz-rock, Primitive Flinty-slate, Primitive Gypsum, and White-stone."

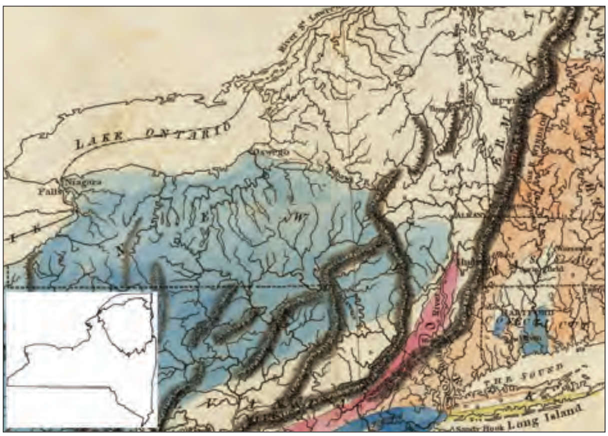


Figure 1 (top): *Section of Maclure's 1809 geological map of the United States of America (Maclure 1809). Orange= Primitive rocks, Red= Transition rocks, Blue= Secondary rocks, Yellow= Alluvial rocks. Inset shows the outline of New York and Precambrian exposure of the Adirondacks. From davidrumsey.com.*

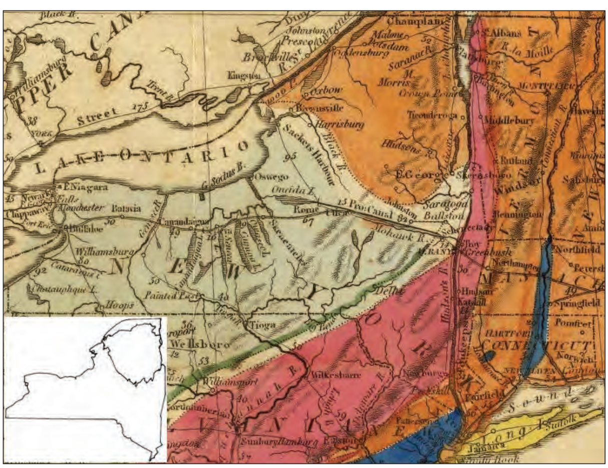


Figure 2 (bottom): *Section of Maclure's 1818 geological map of the United States of America (Maclure 1818). Orange= Primitive rocks, Red= Transition rocks, Blue= Secondary rocks, Green= Rock Salt, Yellow= Alluvial rocks. Inset shows the outline of New York and Precambrian exposure of the Adirondacks. From davidrumsey.com.*

Maclure made pains to specify that his use of Werner's classification was not genetic ("Without entering into any investigation of the origin" of the rocks), and that the Wernerian classification seemed the most suitable to him, because it was the most comprehensive and seemed to correspond with the order of formations he had observed in the United States. To Maclure, using Werner's classification did not mean adopting the accompanying theory of Neptunism – that most rocks (including the Primitive) formed in a regressing world ocean. Maclure was, for the most part, an actualist, and, when theorizing on rock origins, he preferred to classify rocks that are formed by observable causes (such as sedimentary rocks and lavas) separately from rocks that were similar to these but whose origin was more uncertain, such as gneiss, slate, and granite (White 1979). More importantly, Maclure recognized that Primitive rocks probably had a variety of ultimate origins and that a lengthy timescale was required to form them (White 1979).

The second major American geological map that covers the Adirondacks is the first geological map of New York by Amos Eaton (1830; Figure 3). With Benjamin Silliman, Eaton [1776-1842] was one of the first American-born geoscientists. Originally trained in law, Eaton's geology was largely self-taught before beginning a career as a lecturer in Natural History at several institutions across New York and New England. During the 1820s, Eaton rose to prominence in scientific society through his work in geology and biology and by his influence as an educator under the patronage of Stephen Van Rensselaer (Spanagel 2014). Eaton and his assistants made the first systematic geological and agricultural surveys of the area around Albany followed by an extensive geological survey of the route of the Erie Canal. In 1824, he was instrumental in founding the Rensselaer School (later Rensselaer Institute), training many of the prominent American scientists and engineers of the next generation.

The late 1820s found Eaton embroiled in a dispute of stratigraphic nomenclature and priority with the English-American geologist George William Featherstonhaugh [1780-1866]. When Featherstonhaugh requested state money to produce a geological map of New York, Eaton quickly enlisted Van Rensselaer's support to fund a map of his own, first, and to block Featherstonhaugh's becoming the first state geologist (Aldrich 2000). The resulting map is reasonably close to the modern geological maps for the center of the state where Eaton's fieldwork had been concentrated, but, especially in the Adirondacks, it is very different (Figure 3). Eaton's notebooks show that he was perplexed by the geology of the Adirondacks and its connection with other mountain ranges, and he hypothesized that the edges of mountains and river valleys could control or be controlled by the boundaries between geological units (Spanagel 2014). This may have caused Eaton to extrapolate the geology, especially his mapped north-south sedimentary units, into a region for which he had little data. On this part of Eaton's map, Ebenezer Emmons editorialized later: "It is sufficiently evident that all this was imaginary; it is even difficult to conceive how imagination could have carried even a partial observer so far from the truth" (Emmons 1842).

When discussing specific occurrences of Primitive rocks Eaton's (1830) descriptions are almost entirely of localities from New England, and his description of Adirondack geology is for the most part a secondary account of the few early observers in this area. He recognized Primitive rocks as including granite, gneiss, talc-bearing slates, and marble but did not distinguish between these on his geological map. Eaton's map divided geology into eight units based on rock-type, and the Primary became part of the grey 'I' unit, rocks containing graphite (plumbago) and parts of the blue unit, which contains marble, calc-silicate rocks, and limestone (Figure 3). Eaton does not develop a geological history for the Primitive, except to hypothesize that they were deposited as a worldwide layer "before any plants or animals had been created," and provided the material from which subsequent geological units would be later made (Eaton 1830).

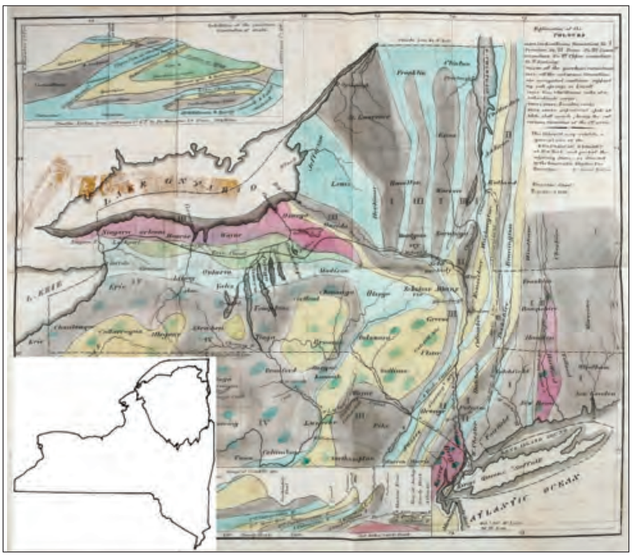


Figure 3 (top): *Eaton's Economical Geology of New York (Eaton 1830). Grey= Carboniferous formations (I: Primitive, II: Transition, III: Lower Secondary, IV: Upper Secondary, V: Tertiary), Yellow= Quartzose formations, Blue= Calcareous formations, Red= Variegated sandstone supporting salt springs or basalt, Green= Lias and ferriferous rocks of a subordinate series. Inset shows the outline of New York and Precambrian exposure of the Adirondacks. From library.si.edu/digital-library.*

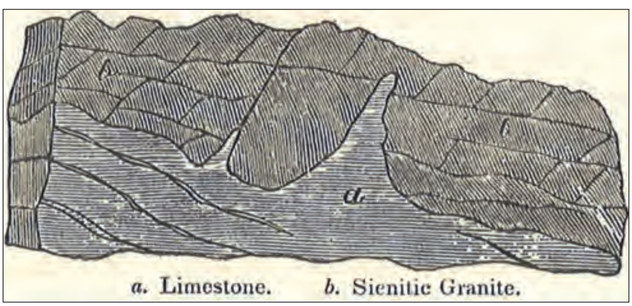


Figure 4 (bottom): *Adirondack marble (limestone) cross-cutting syenite (sienitic granite) (Emmons 1842).*

THE STATE GEOLOGICAL SURVEY

In 1836, the New York State Natural History Survey was finally approved by the state legislature, and Governor Marcy appointed four principle geologists for four districts of the state. The Adirondacks lie in the second of four geological districts, and the region was assigned to Ebenezer Emmons [1799-1863]. Emmons was one of three district geologists trained by Amos Eaton at the Rensselaer School and brought with him mineralogical expertise and field experience from work in the Berkshire Mountains and Nova Scotia (Aldrich 2000). Emmons was to spend five field seasons in preparation of the report of the Second District and is best known to later generations of geologists for his involvement in the ensuing *Taconic Controversy* – a contentious dispute about whether or not metamorphosed sediments in the Taconic Mountains were correlative to (or younger than) un-deformed Paleozoic sediments mapped by the survey elsewhere in New York (Schneer 1969). In the Adirondacks, Emmons was first assisted by James Hall (his later adversary in the Taconic Controversy) and thereafter by his son Ebenezer Emmons Jr. Field work in the Second District concentrated on establishing the lower Paleozoic stratigraphy around the Adirondack periphery, characterization of Precambrian bedrock in the Adirondacks, and was especially focused on topographic and cartographic work in areas of the High Peaks that had not yet been fully surveyed (Aldrich 2000). Emmons coined the term "Adirondacks" to describe the mountain range and led the first group to ascend Mt. Marcy, which he named for New York's eleventh Governor (Emmons 1837). Emmons's fieldwork in the second district was partially determined by economic interests, such as a focus on agriculture, surveying a proposed railroad route, and detailed study at working iron mines in the region (Aldrich 2000).

The report on the Second District (Emmons 1842) contains detailed descriptions of the Primary (or crystalline) rocks of the Adirondacks. Emmons subdivides Primary rocks into Unstratified (granite, hypersthene rock [anorthosite], primitive limestone [marble], serpentine, Rensselaerite [talc pseudomorphs after pyroxene]), Stratified (gneiss, hornblende, sienite [syenite], talc), and subordinate rocks (porphyry, trap, magnetite, specular hematite) that can occur in either, or younger, rocks. For their economic importance, the iron oxide ore deposits receive the most detailed descriptions, but, of Primary rocks, the Unstratified category is clearly the focus of the scientific interest in the report. A particular interest of Emmons's is the origin of Primitive limestone [marble], about which he concludes "…I propose to establish the igneous origin of this limestone; following out the train of reasoning by which Hutton has proved the igneous origin of granite, and the great mass of unstratified rocks." A.F. Buddington (1939) later commented that this was "not a strange conclusion, for [marble] forms dike-like bodies in the country rocks and appears to contain inclusions of them" (Figure 4). Emmons interpreted the Primary Unstratified rocks as igneous, and, of the Stratified category, the sienite, gneiss, and hornblende "at least in some circumstances… to be regarded as of igneous origin." Likewise, the cross-cutting and discordant nature of magnetite and hematite was also taken as evidence for igneous intrusion.

On cross-sections and on the state map synthesizing data from the four districts, the rocks of the Adirondacks are assigned to the Primary System but are not further differentiated, although some specific names of rock-types are noted on the cross sections themselves. It is interesting that although Emmons described the geographic distribution of a number of igneous and metamorphic rocks in his report, they do not appear on state geological maps until the last decade of that century (e.g., Figure 5). The second half of the 19th century saw little new geological work in the Adirondacks, and, from the perspective of many geologists, the state survey stood as the authoritative account of the region's geology:

> *"To read a report of results reached, as left by Professor Ebenezer Emmons, is easy; but when we visit the wilderness and test its difficulties, and reflect that Emmons wrote a description of the structure of the Adirondacks forty-five years ago, we become deeply impressed by the energy and skill brought into exercise by the older geologists. To a great extent, the difficult work has been accomplished."*
>
> Alexander Winchell
> **WALKS AND TALKS IN THE GEOLOGICAL FIELD**
> *1886*

During the late 19th century, there was no settled nomenclature for discussing rocks older than the Cambrian. Lacking fossils for correlation and having no way to determine the absolute age of rocks resulted in a situation where geologists had to rely on lithologic similarity to correlate rock units separated by distance. So often, when distinct Precambrian rocks were described, new sub-divisions of geological time were proposed. This issue came to a head as the US Geological Survey and state surveys tried to reconcile their geological investigations with the nomenclature erected by the Geological Survey of Canada in the 1850s (Eagan 1989). Most important to the Adirondacks is the description of the Laurentian Mountains of Quebec by William Logan [1798-1875], a British-trained geologist and first director of the Geological Survey of Canada (Logan 1863). Logan designated the most deformed and presumably oldest unit in southern Canada as the 'Fundamental Gneiss', which he interpreted to be the basement to all subsequent rocks; he also designated a regional metasedimentary package of marbles, quartzites, schists, and amphibolites as the "Grenville Series', named for its type locality at Grenville village on the Ottawa River. These two rock associations were together assigned to the 'Laurentian System'. Apparently younger Precambrian rocks elsewhere were designated the 'Huronian System' in this classification. This terminology was widely discussed in North American and abroad, and elements of it came to be used by the Geological Survey of Great Britain. James Hall, who at this point had engaged on-and-off with the work of the New York survey for almost

40 years, believed that marbles and other metasedimentary rocks of the Adirondacks were stratigraphically between the Laurentian and the Cambrian Potsdam Sandstone (Hall 1876), and thus not correlative with the Grenville Series. Late in the century, the similarities and links between the Grenville Series and metasedimentary rocks in the Adirondacks gained more traction with the new generation of American geologists in the Adirondacks (e.g., Smyth 1894). These geologists also took up the new term adopted by Canadian geologists *anorthosite* to describe the plagioclase-rich rocks of the Adirondack High Peaks (which Emmons had termed "hyperthene rock").

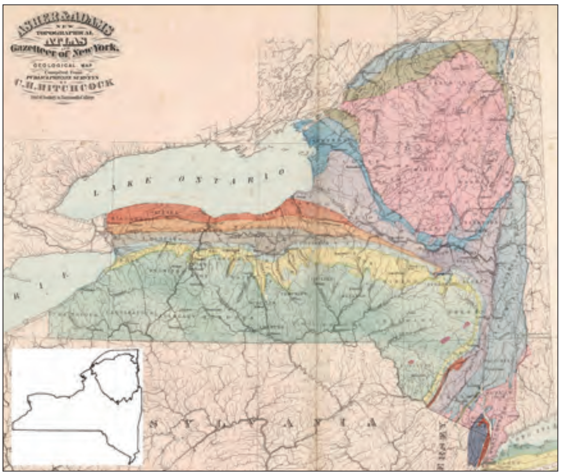


Figure 5 (top): *C. H. Hitchcock's Geological map of New York (Asher and Adams 1870). Pink= Eozoic, including the Laurentian, Red= Trap (or Dolerite?), Other colors= Paleozoic and Mesozoic units, drift or alluvium. Ultimately derived from the 1842 map produced by the state survey, this geological map is typical of those made during the second half of the nineteenth century where rocks of the Adirondacks are not differentiated, while Paleozoic and Mesozoic rocks are broken into more than a dozen geological units. Inset shows the outline of New York and Precambrian exposure of the Adirondacks. From davidrumsey.com.*

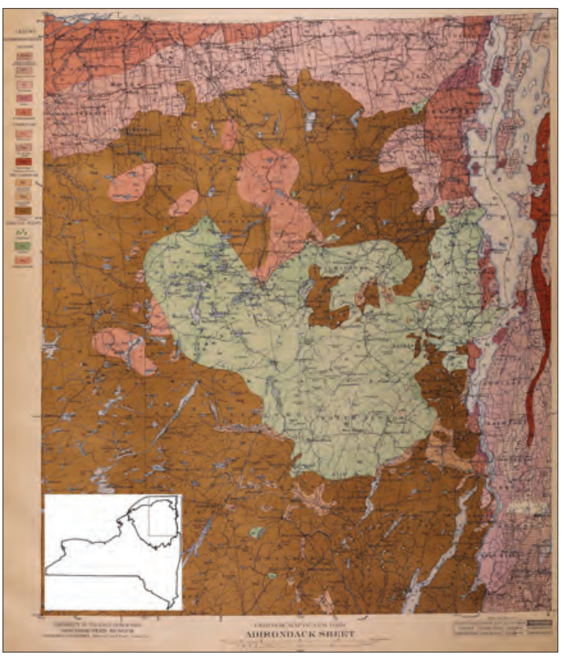


Figure 6 (bottom): *Adirondack sheet of the 1901 Geological map of New York (Merrill 1901). Precambrian rocks of the Adirondacks are shown as patterned light brown (Grenville limestone [marble] and gneiss), patterned dark brown (gneiss), gabbro [including anorthosite] (green), and augite syenite (diagonal patterned red). Inset shows the outline of New York and Precambrian exposure of the Adirondacks with the Adirondack Sheet shown as a rectangle.*

THE BEGININGS OF SYSTEMATIC GEOLOGICAL MAPPING

The next phase of geological fieldwork in the Adirondacks was inaugurated by James Furman Kemp [1859-1926], Charles Henry Smyth [1866-1937], and Henry Platt Cushing [1860-1921], who began detailed studies in different areas of Adirondacks in the early 1890s. Within a few years, they were joined in geologically mapping the Adirondacks by other workers, mainly other academic geologists. During the several-decade hiatus of geological work in the Adirondacks since Ebenezer Emmons's survey, much had changed in the landscape of science in the United States, with colleges providing the possibility for more specialized scientific education and the development of research universities and advanced degrees. Kemp, Smyth, and Cushing were all products of this new system: all had advanced degrees, all had studied geology in Europe, and all were professors themselves (at Columbia, Princeton, and Case Western, respectively). As a result, their studies and subsequent work grew more specialized, incorporating detailed outcrop descriptions, mapping, petrography, and chemical analysis of rocks and minerals to an extent not possible before. It is by this time that enough was known about Adirondack Geology that different Precambrian rock units were first portrayed in state geological maps (Figure 6).

The first decade of the 20th century saw the first availability of detailed topographic maps of the Adirondacks. These 1:62,500 scale 15-minute quadrangle maps, produced by the US Coast and Geodetic Survey, allowed for detailed systematic geological mapping in the Adirondacks and comparing the details of distribution of rock types and geological structures of separated areas. Mapped quadrangles and accompanying reports were mainly published by the Geological Survey in the Bulletin series of the State Museum, of which the Survey was now a part. The first quadrangle report published was *Geology of the Paradox Lake Quadrangle* (Ogilvie 1905), which was the dissertation of Ida Ogilvie [1874-1963], a student of Kemp's at Columbia. Ogilvie was a Bryn Mawr College alumna, and after her Ph.D. she founded the Geology department at Barnard College. Ogilvie was unusual as one of the few female geologists of her era but typical in that much of the work of mapping the Adirondacks was done by academics working during summers as 'temporary geologists' for the survey – many as part of their degree programs. Between 1905 and the beginning of World War II, 34 of the ca. 62 quadrangles making up Precambrian exposure of the Adirondacks were mapped, for the most part by Kemp, Smyth, Cushing, their students and colleagues, and William John Miller [1880-1965] of Hamilton College. Quadrangle mapping and the accompanying studies amassed a wealth of detail on the distribution of metasedimentary and igneous rocks, distinguishing different igneous suites and determining their relative ages, and trying to resolve the timing of geological structures. During this period, correlation with the Grenville Series of Canada was well-accepted, and it was observed that many igneous suites post-dated the metasediments and that regional deformation appeared to post-date or be synchronous with igneous intrusion (Buddington 1939). These relationships would prove to be important to the later controversy about the origin of granite.

It is useful to focus some attention on the career of Arthur Francis Buddington [1890-1980], who was a participant in the flurry of mapping early in the century and an important actor in later petrologic debates about the origin of Adirondack igneous rocks. Buddington finished his Ph.D. with Smyth at Princeton in 1916 and then became involved in Adirondack research when he began a mapping project in the Lake Bonaparte quadrangle. With the US preparing for the possibility of involvement in WWI, Buddington soon became involved in a project to assess Adirondack sulfur resources in Jefferson and St. Lawrence Counties for the New York State Defense Council (Buddington 1917). As for most academic geologists, after the US entered the war, Buddington became part of the war effort: for a time he taught aerial photograph interpretation at Princeton, and later he worked for the US Chemical Warfare Service. After the war, Buddington eventually joined the faculty at Princeton, where his early research focused on the Alaskan Coast Range, spending 16 months in the field there between 1921 and 1925 with the US Geological Survey. When this project ended he returned to Adirondacks, where he would eventually spend 76 months in the field between 1916 and 1960 (Buddington 1970). Buddington wrote or co-authored the Lake Bonaparte (1926), Hammond, Antwerp and Lowville (1934), Santa Cara (1937), Willsboro (1941) Saranac (1953) quadrangle reports, numerous conference abstracts and journal publications on the Adirondacks, and the Geological Society of America Memoir *Adirondack Igneous Rocks and their Metamorphism* (Buddington 1939). This major publication focused on the northwest Adirondacks, synthesizing his own and others' mapping with a focus on subdividing and grouping related intrusions. Beginning in 1944, Buddington took on the multi-year project to study iron deposits in the northeast for the U.S. Geological Survey's Strategic Minerals program, leading to field seasons and ore deposit reports for the Adirondacks, New Jersey, and Pennsylvania (Buddington 1970).

GEOLOGY IN THE ADIRONDACKS AFTER WORLD WAR II

Echoing Buddington's career, geological research in the Adirondacks after the end of WWII had a focus on Adirondack ore deposits: one third of the published research on the Adirondacks in the 1950s (indexed by GeoRef) was on economic geology or the new, related subfield of mineral magnetics. During the period 1900-1959, published scientific research in the Adirondacks was relatively constant, averaging two to three publications per year. Beginning in the 1960s, research in the Adirondacks grew exponentially, reaching a peak of ~70 publications per year in the 1980s. This acceleration in research mirrors the growth of academic science and science funding during the Cold War, and, in the Adirondacks, over half of this research activity was in the area of igneous and metamorphic petrology.

Changing approaches to understanding high-grade gneiss terranes and a few full-blown petrologic controversies played out in the Adirondacks during the second half of the 20th century. The first of these was the debate over the origin of granite and granitic rocks, which emerged after WWII, reached its peak in the 1950s, and continued into the 1960s.

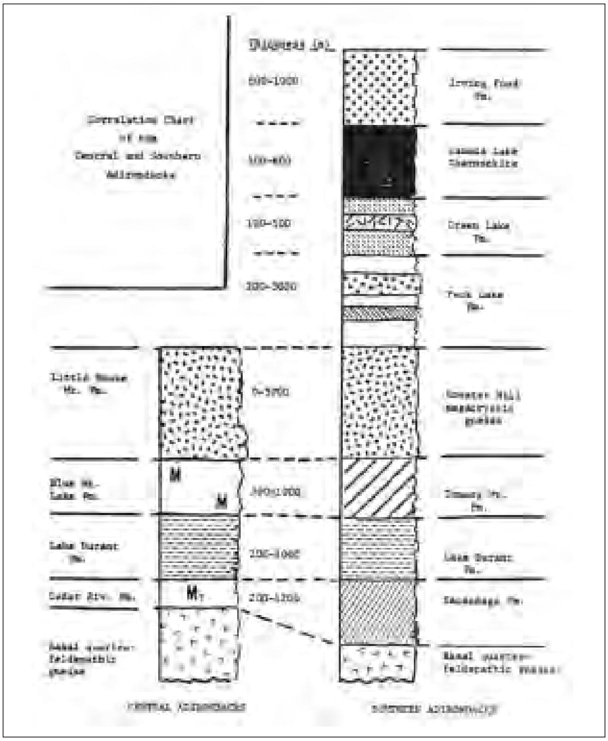
This controversy saw some petrologists dispute the model that granites are formed by crystallization from a silicate melt and instead called on high temperature fluids that transformed already-existing rocks into granitic compositions. This hypothesized process was called *granitization* and was invoked to explain gradational field relations at granitic pluton contacts and partial melting textures in high-grade gneiss terrains, in effect explaining away the 'space problem' associated with the mechanics of pluton intrusion (Davis 2003). Buddington weighed in on the debate as one of five principle speakers at the Geological Society of America's *Origin of Granite* conference in 1947. In his address, he laid out field evidence for magmatic intrusion of several Adirondack igneous suites, also describing some replacement of metasedimentary country rocks, which he thought could account for no more than 15% of igneous rocks in the northeastern Adirondacks (Buddington 1948).

Granitization as a large-scale process in the Adirondacks was proposed by Albert [1916-1995] and Celeste Engel [1923-2004], a husband and wife team at the US Geological Survey and later Caltech. Al Engel was first introduced to Adirondack geology by Buddington at Princeton, and after WWII the Engles conducted several petrologic and geochemical research projects rocks and minerals in the northwest Lowlands. Their first granitization study was of element migration and migmatite formation in the Major Paragneiss, an extensive package of metasedimentary rocks in the Lowlands (Engel and Engel 1958). Here metamorphic foliation and layering were taken as reflecting originally sedimentary features; a 'stratigraphic mindset' that was common to other Grenville workers of this era (Rivers 2015). The Engels later extended this mode of analysis to the 14 granitic domes now known as the Hyde School Gneiss bodies. Buddington (1929; 1939) had interpreted these domes as *phacoliths*, being the result of magma intrusion into the axes of actively folding metasedimentary rocks. Hyde School Gneiss geology was reinterpreted by Engel and Engel (1963) and Dietrich (1963), who took the structure of the bodies and their coherent internal layers to indicate a granitized sedimentary sequence. The Engels invited comment from Buddington, who wrote a one-page discussion that appeared in the *Geological Society of American Bulletin* after their article. In his discussion Buddington (1964) reiterated arguments for intrusion based on field relations, and cited experimental data that showed that the Hyde School Gneiss has the same composition as expected minimum melts in a granitic bulk composition.

THE 'STRATIGRAPHIC MINDSET' AND STRUCTURAL MAPPING

The origin of the Hyde School Gneiss bodies would continue to be a controversial aspect of Adirondack Lowlands Geology for the next 30 years. This particular dispute notwithstanding, there was broad acceptance of the basic premises that 1) a stratigraphic framework existed in the northwestern Adirondacks and that it could be used to trace structural features over large distances and 2) that this stratigraphy was especially useful for understanding the distribution of regional talc and sphalerite deposits (Brown and Engel 1956) to the extent that modified versions of this framework have continued to be used in the Lowlands to the present day. Sedimentary protoliths for some of these units were uncontroversial (e.g., marble and aluminous gneiss), but assigning protoliths to quartzofeldspathic units was generally problematic. The origin of the Hyde School Gneiss was especially unclear, given the concordant contacts and internal structure of the each body and their relatively consistent disposition relative to adjacent units. As a result, the initial interpretation as intrusive bodies (Buddington 1929) and subsequent reinterpretation as granitized sediments (Engel and Engel 1963) was followed by a model where Hyde School Gneiss was interpreted as having a zoned ash-flow tuff protolith that fit conformably into the regional stratigraphy (Foose and Carl 1977; Carl et al. 1990). This model was later disputed based on geochronology, and some of Buddington's original lines of argument for plutonic emplacement (McLelland et al. 1991).

Disagreement over the pre-deformation geometry and nature of high-grade rocks was not limited to the northwestern Adirondacks. In the 1950s and 1960s, Dirk deWaard and Matt Walton [1915-2004] undertook mapping programs in the central and eastern Adirondack Highlands, where apparently conformable contacts between anorthosite and surrounding metasedimentary rocks led them to interpret the anorthosite as basement to adjacent metasediments, as opposed to being intrusive into the metasedimentary sequence (deWaard and Walton 1967). This interpretation was in fundamental opposition to cross-cutting relations documented by early workers, but parallelism of unit contacts caused by structural attenuation of intrusive rocks and country rocks in part led to this interpretation. It was the parallelism of contacts and structural coherence over large distances that led subsequent mappers into the 1970s and 1980s to generalize the intercalated rocks of the Adirondacks in terms of a stratigraphy (although with the anorthosite and related rocks eventually confirmed to be intrusive), a manifestation of the 'stratigraphic mindset' common to workers in high-grade terrains in the middle 20th century. Commonly in these stratigraphies, quartzofeldspathic gneisses were interpreted as volcanic units in depositional contact with metasedimentary rocks, and along-strike transitions in rock types were interpreted as facies changes (Figure 7; e.g., Wiener et al. 1983), although the possibility that the apparent stratigraphic coherence was imposed by deformation was discussed by some (e.g., Mclelland and Isachsen 1980). The positive result of these trends in research was to encourage workers to try to interpret the structural geology of the Adirondacks over large areas, which allowed them to recognize a multi-stage history of folding and especially regional nappe structures (Figures 8 and 9), an important development in developing tectonic interpretations of the Adirondacks (Rivers 2015).



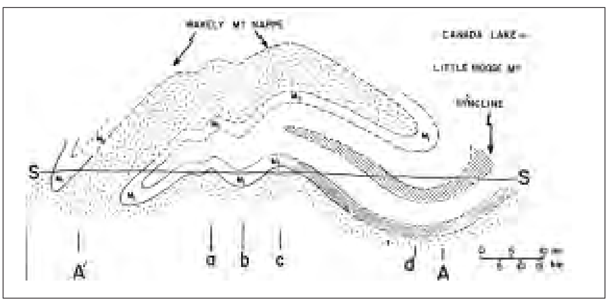


Figure 7 (top): *Interpreted stratigraphy of Adirondack metasedimentary and metaigneous rocks (Weiner et al. 1983).*

Figure 8 (bottom): *South-southeasterly oriented cross-section of the Adirondacks showing interpreted folding and nappe structure (McLelland and Isachsen 1980).*

THE ADIRONDACKS AS A NATURAL LABORATORY FOR PETROLOGY

As the field geology of Adirondack igneous and metamorphic rocks became better understood, the Adirondacks became a focus of geologists who were interested in using these constraints to explore fundamental petrologic problems. One example is investigation of the origin of anorthosite, an enigmatic igneous rock composed mostly of plagioclase feldspar that dominates the Adirondack High Peaks. One of the first general papers on anorthosites was the influential 1917 *The Problem of the Anorthosites* by the preeminent experimental petrologist Norman Levi Bowen [1887-1956]. His paper focused on field relations he was shown by Kemp and Cushing in the Adirondacks. It was in the framework of Adirondack field relations that Bowen articulated two questions that have preoccupied petrologists since: the nature of the anorthosite parent magma and the relationship between anorthosite and related granitic rocks (called the anorthosite–mangerite–charnockite–granite suite by later workers).

In the Adirondacks, somewhat equivocal field relations and major element geochemistry of these rocks kept these debates alive for decades. A 1966 symposium in honor of A.F. Buddington on the origin of anorthosites saw fourteen papers presented dealing primarily with Adirondack occurrences (Isachsen 1968). For the most part, authors agreed that anorthosite was an igneous cumulate of some kind with a mafic (or intermediate) parent magma, but there was no agreement on the relationship between anorthosite and surrounding granitic plutons. Buddington (1939; 1968) argued that these plutons post-date anorthosite emplacement and were not co-magmatic, while most authors at the anorthosite symposium interpreted gradational field relations and geochemistry as supporting a model where anorthosite and granitic rocks are consanguineous and related by filter pressing or some other mechanism of differentiation. It was not until isotopic investigations in the 1990s of other geological terrains where anorthosite was emplaced into significantly older crust that consanguinity was shown to be inconsistent with the geochemistry of many anorthosites and associated granitic rocks.

The Adirondacks also played an important role in the development of metamorphic petrology. The mid-crustal rocks of the Adirondacks were an ideal testing ground for newly-developed metamorphic thermometers and barometers in the 1970s and 1980s, most notably by Eric Essene [1939-2010] and his students at the University of Michigan (Darling and Peck, this issue). The Adirondacks were also a key locality in debates about importance of CO_2-rich fluids in the production of high-temperature metamorphic rocks of the granulite facies. This debate (chiefly during the 1980s and 1990s) was called the 'granulite controversy' by some to purposely evoke the granite controversy of the 1950s and 1960s and questions as to the role of fluids in metamorphism. The point of contention was a model where the influx of CO_2-rich fluids were thought to have stabilized granulite facies minerals and suppressed melting by diluting the chemical activity of water during metamorphism (Newton et al. 1980). Numerous studies of fluid inclusions in minerals, isotope compositions, and estimates of past fluid composition from mineral equilibria in the Adirondacks all argued against pervasive flow of a CO_2-rich fluid (Valley et al. 1990). These studies were instrumental in the recognition that metamorphism of granulites often happens in the absence of introduced fluids.

Figure 9: *Adirondack sheet from the 1971 Geological map of New York (Fisher et al.1971; 1995 reprinting). Folded Precambrian rocks of the Adirondacks are subdivided into over two dozen distinct units. Inset shows the outline of New York and Precambrian exposure of the Adirondacks with the Adirondack Sheet shown as a rectangle. From nysm.nysed.gov.*

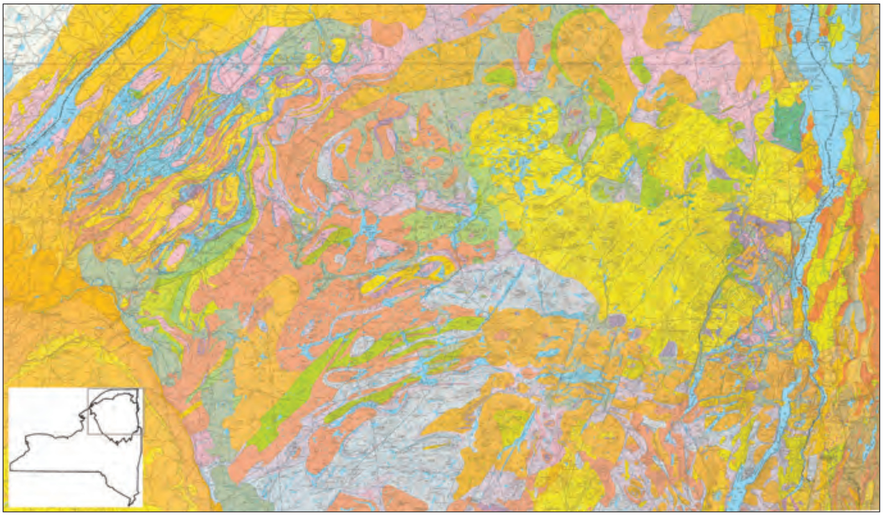


PLATE TECTONICS, ENVIRONMENTAL GEOLOGY, AND OTHER DEVELOPMENTS

Several radiogenic isotopic systems were applied to the Adirondacks in the 1960s and 1970s, but the overprinting effects of high-grade metamorphism made interpretations of these data problematic, and basic questions as to the timing of magmatism and metamorphism were still questioned. It was not until U-Pb geochronology studies of igneous suites (e.g., McLelland et al. 1988) and metamorphic minerals (e.g., Mezger et al. 1991) were made across the Adirondacks that the basic chronology was constrained (McLelland, this issue). These studies allowed the first direct correlation of Adirondack geology with the rest of the Canadian Grenville Province, and the development of the first well-constrained plate tectonic models in the 1990s (see Rivers 2015). Beginning in the 1970s, the Adirondacks also saw the rise in interest and focus on environmental geology, especially in the area of surface water chemistry and understanding the effects of acid precipitation (see April, this issue). These research trends have continued into the early 21st century. Currently, published geology research on the Adirondacks (indexed by Georef) ranges from environmental geology to geomorphology to geochronology, and is still dominated by igneous & metamorphic petrology and structural geology studies. New research leads to new questions, and the Adirondacks continues be a place where theories are tested and petrologic tools are developed. The importance of fieldwork to geology, and petrology in particular, is as A.F. Buddington aptly put it 60 years ago:

> *"… I believe it is also true that every advance in geochemistry requires ever greater knowledge and refinement of our knowledge based on field relationships and the two must go forward together, each reacting on the other. A specimen of rock can be treated in the laboratory as an entity in itself. But the significance for geology of the data obtained from it can only be as good as the thoroughness of the knowledge of the nature of the immediate surroundings of the specimen where in place and of its physical and chemical history as read by a field geologist with the appropriate background."*
>
> A.F. Buddington
> **ACCEPTANCE OF THE MINERALOGICAL SOCIETY OF AMERICA ROEBLING MEDAL**
> *1957*

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