5

METAMORPHIC CONDITIONS OF ADIRONDACK ROCKS

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KEYWORDS:

Adirondacks, Metamorphism, Pressure-Temperature-Path, Fluid Composition, New York

ABSTRACT

The Adirondack Highlands were metamorphosed to granulite facies conditions during the Ottawan phase (1090 to 1020 Ma) of the Grenville Orogenic Cycle, whereas the Adirondack Lowlands were metamorphosed to mid to upper amphibolite facies conditions during the Shawinigan phase (1190 to 1140) of the Grenville Orogenic Cycle. Metamorphic temperatures ranged from 750 °C to 850 °C in the Highlands and 650 °C to 750 °C in the Lowlands. Metamorphic pressures were between 6.0 and 8.6 kilobars in the Highlands and 6.5 to 7.5 kilobars in the Lowlands. Following the peak of metamorphism, Adirondack rocks took a counter-clockwise path in pressure-temperature space. The activity of water is generally low in Adirondack metamorphic rocks, and many rocks did not contain a free fluid phase during metamorphism.

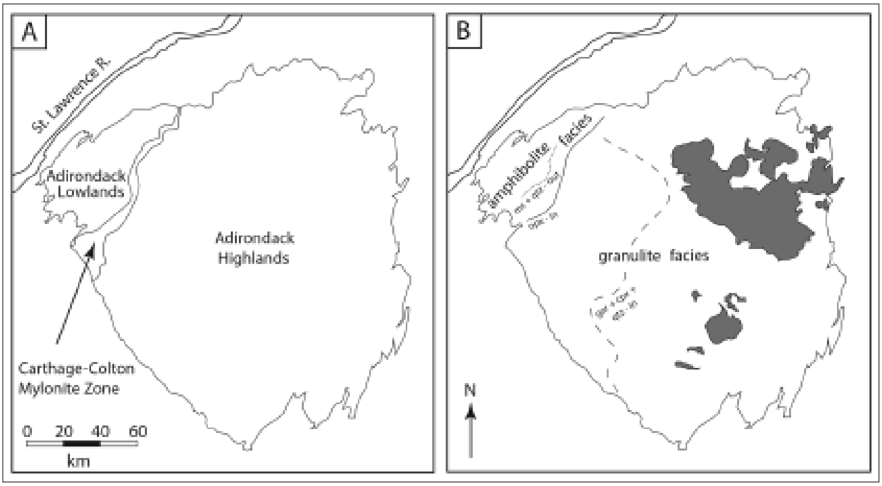
INTRODUCTION

Ever since Emmons (1842) first reported geological descriptions of the Adirondack region, scores of geologists have travelled to northern New York to study the Mesoproterozoic basement rocks the make up the Adirondack Mountains. Early studies tended to focus on mining and economic resources of the region, but a number of researchers attempted to better understand the rocks types and their interrelationships (see Peck, this issue). An emphasis on bedrock mapping occurred in the early part of the 20th century, and a number of 15-minute quadrangle maps were published by the New York State Museum. Later, in his monumental treatise on the Adirondacks, Buddington (1939) summarized descriptions of a wide variety of igneous rock types, compositions, intrusive relationships, and textures but also described and interpreted the structural, textural, mineralogical, and facies changes that occurred in the metamorphic rocks. However, it was not until the late 1950s that metamorphic studies of the Adirondack began to proliferate. Thus, a great deal of effort has been expended on trying to understand the complete history of Adirondack metamorphic rocks and what they can tell us about the Grenville Orogenic Cycle in eastern North America (McLelland, Daly, and McLelland 1996; Tollo, Corriveau, McLelland, and Bartholomew 2004; Rivers 2008). Most attention has been focused on: 1) determining the temperature and pressure conditions of metamorphism, 2) what role fluids play during metamorphism and partial melting, 3) the pressure-temperature path the rocks took while in the crust, and 4) the timing of igneous and metamorphic events in the Adirondacks. This effort has contributed much to our understanding of the Grenville Orogenic Cycle as well as geologic processes in deep parts of the continental crust, but many unanswered questions remain. In this paper, we hope to summarize the current state of knowledge of metamorphism in the Adirondacks but also hope to point out areas where additional work needs to be focused.

ADIRONDACK HIGHLANDS COMPARED TO THE ADIRONDACK LOWLANDS

Figure 1A shows the location of Mesoproterozoic rocks of the Adirondack Highlands and Adirondack Lowlands. The two areas are separated by the Carthage-Colton Mylonite Zone, a deep-crustal shear zone with complex kinematic indicators (see Streepey, Johnson, Mezger, and van der Pluijm 2001; Johnson, Goergen, and Fruchey 2004; Baird and MacDonald 2004; Selleck, McLelland, and Bickford 2005, for latest review). The Highlands differ from the Lowlands in two important respects. First, the Highlands were metamorphosed to higher temperature and pressure conditions than the Lowlands (see section on metamorphic facies). Secondly, ages from the collisional Ottawan phase of the Grenville Orogenic Cycle (1090-1020 Ma) dominate the Highlands, whereas ages from the earlier accretionary Shawinigan phase of the Grenville Orogenic Cycle (1160-1140 Ma) characterize the Lowlands (Mezger, Rawnsley, Bohlen, and Hanson 1991; Mezger, Essene, van der Pluijm, and Halliday 1993; Wasteneys, McLelland, and Lumbers 1999; Heumann, Bickford, Hill, McLelland, Selleck, and Jercinovic 2006).

__Figure 1:__ A) Map showing exposed Mesoproterozoic rocks of northern New York State. Adirondack Highlands and Lowlands are separated by the Carthage-Colton Myonite Zone; B) Metamorphic facies map of exposed Mesoproterozoic rocks in northern New York State. Anorthosite bodies shown in gray shade. Facies boundary is marked by the orthopyroxene (opx)-in isograd as mapped by Hoffman (1982). Note the proximity between the opx-in isograd and the Carthage-Colton Mylonite Zone. Short dashed line represents the maximum stability of muscovite (ms) and quartz (qtz) as mapped by deWaard (1969). Long dashed line is the garnet (gar) + clinopyroxene (cpx) + quartz (qtz)-in isograd as mapped by deWaard (1969).



METAMORPHIC ROCKS OF THE ADIRONDACKS

Most of the rocks exposed in the Adirondacks are metamorphic. A small percentage of non-metamorphic rocks occur locally, including: small-scale Mesozoic or late Proterozoic mafic igneous intrusions, undeformed granitic pegmatite dikes of late Ottawan-age, hydrothermal quartz, calcite, and/or fluorite mineralization, tectonic breccias, and fault-bounded, Early Paleozoic sedimentary rocks. Many of the metamorphic rocks clearly originated as igneous or sedimentary rocks, but all of them show, to various degrees, a metamorphic fabric and/or growth of new metamorphic minerals. In many cases, bulk rock composition can be used to infer an igneous or sedimentary protolith, but the meta-igneous rocks are more likely to preserve primary textures, especially in coarse-grained mafic lithologies. Primary sedimentary structures or textures are all but destroyed in Adirondack meta-sedimentary rocks, with the only exceptions being inferred stromatolite fossils in marbles (Isachsen and Landing 1983) and rare relict cross-beds in quartzites (Engel and Engel 1953) in the Adirondack Lowlands. However, some meta-sedimentary rocks display compositional layering that may reflect original differences in sedimentary rock type (Engel and Engel 1953; Chiarenzelli, Kratzmann, Selleck, and deLorraine 2015).
The meta-igneous rocks typically originated as: granites, anorthosites, gabbros, syenites,

charnockites, tonalites, and mangerites. Meta-sedimentary rocks typically include: marbles, calc-silicate and metapelitic gneisses, and quartzites. Different amphibolites have been interpreted as both meta-igneous as well as meta-sedimentary (Buddington 1939; Engel and Engel 1953). Schists are more abundant in the Lowlands than the Highlands, but in the Adirondack Highlands, biotite is the phyllosilicate phase, as all primary muscovite (± quartz) has been converted to K-feldspar + sillimanite, melt, or more rarely, K-feldspar + corundum (Bohlen, Valley and Essene 1985).

ADIRONDACK METAMORPHIC FACIES

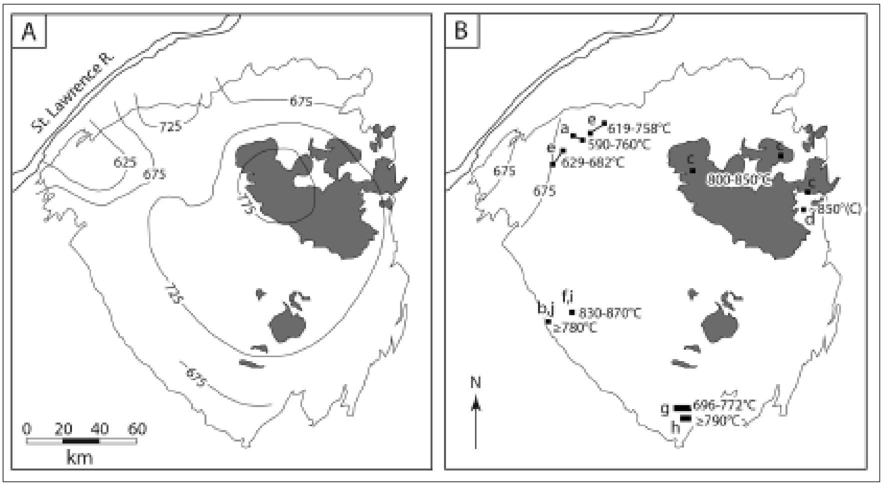
Metamorphic facies in the Adirondacks have been assigned based on specific metamorphic index minerals or mineral assemblages. In the Adirondack Highlands, for example, it is the presence of metamorphic orthopyroxene in mafic rocks that assign these rocks to the granulite-facies (Figure 1B). Throughout the Adirondack Highlands, metamorphic orthopyroxene has been described in meta-gabbros and anorthosites (Whitney and McLelland 1973; McLelland and Whitney 1977; Whitney 1978), amphibolites (Luther 1976), granitoids (McLelland, Hunt and Hansen 1988a), and even metapelites (Darling, Florence, Lester, and Whitney 2004). The first appearance of orthopyroxene (the opx-in isograd) in Adirondack rocks is proximal to the Carthage-Colton Mylonite Zone (see Figures 1A, B). Hence, the Adirondack Lowlands were metamorphosed to mid to upper amphibolite-facies, whereas the Adirondack Highlands were metamorphosed to granulite-facies (Figure 1B). The opx-in isograd shown in Figure 1A is from Hoffman (1982). Its location is proximal to opx-in isograds mapped earlier by Engel and Engel (1958) and Buddington (1963). Also shown is the maximum stability of muscovite + quartz in the Adirondack Lowlands. Southeast of this isograd, including all of the Adirondack Highlands, sillimanite + microcline are stable in metapelitic rocks. This is sometimes known as the second sillimanite isograd because a substantial modal volume of sillimanite is created by the breakdown of muscovite and quartz. Lastly, running through the central Adirondack Highlands is deWaard's (1965, 1969) garnet + clinopyroxene + quartz-in isograd. This isograd marks the first appearance of garnet in metabasic rocks (e.g., amphibolites, metagabbros) of the central and eastern Adirondack Highlands and accounts for the presence of the famous megacrystic garnet amphibolites at Gore Mountain and elsewhere (McLelland and Selleck 2011). To the west of the isograd, metabasic rocks are characterized by orthopyroxene + plagioclase rather than clinopyroxene + garnet + quartz. DeWaard felt this was such an important isograd that he proposed a subdivision of granulite facies based partially on these mineral assemblages (1965), and inferred that the garnet-free rocks formed under lower pressure conditions. Thus far, no evidence has been found that any part of the Adirondacks experienced eclogite-facies metamorphism, ultra-high temperature (UHT), or ultra-high pressure (UHP) metamorphism.

TEMPERATURE AND PRESSURE OF METAMORPHISM

The temperature and pressure conditions of Adirondack metamorphism have played a significant role in the development of plate tectonic models for the Grenville Orogeny. This is because the temperature and pressure of metamorphism can give useful information on the geothermal gradient as well as the depth of burial, which can be used to infer crustal thickness at the time of metamorphism.

Our understanding of metamorphic temperature and pressure in the Adirondacks began to advance in the late 1950s and through the 1960s after important experimental studies were performed on common rock-forming minerals. Thus, Engel and Engel (1958, 1962) and Buddington and Lindsley (1964), began providing the first-ever, quantitative estimates of metamorphic temperature for Adirondack rocks. Their estimates ranged from temperatures of 500 °C to 650 °C. A little later, deWaard (1967, 1969) increased those temperature estimates from 650 °C to 800 °C and for the first time provided quantitative metamorphic pressure estimates of 6 to 8.5 kilobars. More progress was made with additional discoveries of low variance mineral assemblages and the further refinement of geothermometers and geobarometers in the 1970's. Thus, temperature and pressure estimates made by Bohlen and Essene (1977, 1979), Boone (1978), Bohlen, Essene, and Hoffman (1980), and Bohlen, Essene, and Boettcher (1980) corroborated the estimates of deWaard (1967, 1969). In their summative work, Bohlen and his collaborators used feldspar, carbonate, and Fe-Ti oxide solvus geothermometers to document metamorphic temperatures of 650 °C to 700 °C in the Adirondack Lowlands and 750 °C to 800 °C in the Adirondack Highlands (Bohlen et al. 1985). They also document, using a wide variety of geobarometers and pressure-sensitive mineral assemblages, metamorphic pressures of 6.5 to 7.0 kilobars, in the Adirondack Lowlands, to 7.5 to 8.0 kilobars, in the Adirondack Highlands. Slightly higher pressures (up to 8.6 kilobars) were determined by Newton and Perkins (1982) and Newton (1983). Bohlen et al. (1985) also described a concentric ring-like pattern to metamorphic temperature estimates, with the highest temperatures recorded in the Adirondack high peaks region. This pattern, shown in Figure 2A, is widely known among the metamorphic geology community as "Bohlen's bull's-eye." The significance of Bohlen's bull's-eye is unclear. First, the southeast and southwest regions of the Adirondack Highlands have little or no data, and secondly, it is unclear whether much later domical uplift or heat from magmas (Bohlen et al. 1985) or some other processes resulted in higher apparent metamorphic temperatures in the northeast part of the Adirondack Highlands.

Figure 2: *Map showing exposed Mesoproterozoic rocks of northern New York State with: A) metamorphic isotherms (°C) from Bohlen et al. (1985); B) locations of post-1985 metamorphic studies: a) Edwards and Essene (1988), b) Florence et al. (1995), c) Spear and Markussen (1997), d) Alcock and Muller (1999) and Alcock et al. (1999), e) Liogys and Jenkins (2000), f) Darling et al. (2004), g) Peck and Valley (2004), h) Storm and Spear (2005), i) Storm and Spear (2009), and j) Darling (2013). Kitchen and Valley's (1995) thermometry data for the Highlands are not included, because they used temperatures from Bohlen et al. (1985) to calibrate their calcite-graphite thermometer. However, Kitchen and Valley's (1995) isotherms are shown in the Lowlands. See text for further discussion.*



Since the monumental work of Bohlen et al. (1985), studies of Adirondack metamorphic rocks have either corroborated, or in most cases increased, the metamorphic temperature estimates. Studies by Florence, Darling, and Orrell (1995) and Darling (2013) describe metamorphic temperatures of ≥ 780 °C on the westernmost edge of the Adirondack Highlands. Spear and Markussen (1997), Darling et al. (2004), and Storm and Spear (2009) document similar metamorphic temperatures of 830-870 °C on opposite sides of the Adirondack Highlands (Figure 2B). Pattison (2003a) and Pattison, Chacko, Farquhar, and McFarlane (2003b) argue that temperatures of 800-850 °C characterize all of the Adirondack Highlands. The studies of Peck and Valley (2004) and Storm and Spear (2005) show metamorphic temperatures of 696-772 °C and ≥ 790 °C, respectively, in the southernmost Adirondacks. The study of Kitchen and Valley (1995) shows marbles of the Adirondack Highlands experienced metamorphic temperatures from 670-780 °C. Lastly, Alcock and Muller (1999) and Alcock, Myer, and Muller (1999) report temperatures of 850-970 °C using Al abundance in hornblende and ternary feldspar compositions, but the high temperatures reported were contested by McLelland, Valley, and Essene (2001). There is little dispute with the temperatures on the lower end (~850°C) of their reported range and is shown as such in Figure 2B. All of these later studies demonstrate equivalent, or in many cases, higher metamorphic temperatures than those inferred by Bohlen et al. (1985), but, perhaps more importantly, are inconsistent with metamorphic isotherms mapped by many workers (see Bohlen et al. 1985). Consequently, it is difficult to assess whether the earlier mapped isotherms are meaningful. The post-1985 studies have the advantage of generally having newer and perhaps more refined geothermometers, but those geothermometers are restricted to specific mineral assemblages in a few locations, whereas the study of Bohlen et al. (1985) largely used only feldspar and oxide solvus geothermometers that are applicable in a variety of rock types over a wide area. Moreover, the inferred pressure-temperature conditions have been, until recently, assumed to reflect one episode of metamorphism, and this may not be the case in the Adirondack Highlands (see section on Geochronology).

MORE DETAILS ON THE METAMORPHIC CONDITIONS OF THE ADIRONDACK LOWLANDS

Compared to the Adirondack Highlands, metamorphism in the Adirondack Lowlands has received less study, especially in the past few decades. Bohlen et al. (1985) and Edwards and Essene (1988) presented the state of knowledge in the mid-1980s for a variety of metamorphic thermometers and phase equilibria that constrain metamorphic pressures. Pressure estimates from these studies range from 5.4-8.0 kbar and are mainly determined from barometers in pelitic rocks. Most determinations tightly constrain pressures in the Lowland to 6.5-7.5 kbar. Metamorphic temperatures from these studies range from 600-780 °C, with most temperatures being in the range 650-750 °C. As in the Highlands, Lowlands thermometry were used to draw regional isotherms, and these are mostly controlled by the results of feldspar thermometry. Lowlands isotherms from these studies separate a low-temperature region in the central Lowlands from high temperatures closer to the periphery and from especially high temperatures in its northernmost part (Figure 2A). This temperature structure has not been confirmed by subsequent studies. Kitchen and Valley (1995) used the carbon isotope fractionation between calcite and graphite in a marbles to map the detailed temperature structure in the Lowlands. This approach yielded similar temperatures to earlier studies with most temperatures in the range 630 °C to 690 °C. A subsequent experimental recalibration of the calcite-graphite thermometer (Deines and Eggler 2009) applied to these data slightly lowers peak temperature estimates to ca. 590-650 °C. Isotherms drawn around these data parallel the structural grain of the Lowlands and mapped isograds and are different than those from earlier studies (Figure 2B); showing a symmetric low-temperature trough in the central Lowlands and higher temperature to the southeast (towards the CCMZ) and the northwest (towards the Black Lake Shear Zone). Supporting this, equivalent temperatures along strike crossing earlier isotherms were reported by Liogys and Jenkins (2000), who used the calibrated equilibrium between amphibole + clinopyroxene + quartz + plagioclase to calculate metamorphic temperatures ranging from 619-758 °C (Figure 2B). Northeast-southwest isotherms are also confirmed by the ^{39}Ar-^{40}Ar age structure of the Adirondack Lowlands, which suggests tilting of the terrane to the northwest (Dahl, Pomfrey, and Foland 2004). In detail, the higher metamorphic temperatures in the northwest Lowlands are not consistent with the Dahl et al. (2004) southeast-younging cooling ages, which may indicate that the higher peak temperatures in the northwest recorded by calcite-graphite isotopic equilibria (and other thermometers; Russell, Will, Peck, Perkins, and Dunn 2009) may not be synchronous with peak metamorphism in the rest of the Lowlands.

THE HIMALAYAN TECTONIC MODEL

The Himalayan tectonic model applied to the Ottawan phase of the Grenville Orogenic Cycle is based principally on metamorphic pressure measurements and the associated inferred crustal thickness estimate. Thus, the 8.6 kilobar maximum pressure (Newton 1983) means that present-day Adirondack rocks were buried to a depth of about 30 km (assuming 3.5 km of crustal rock per kilobar of pressure) during the peak of the Ottawan phase. If this 30 km depth is added to the 35 ± 2 kilometer (km) thick present-day continental crust under the Adirondacks (Klemperer 1987), the total thickness during the Ottawan phase was 65 ± 2 km. The only location on Earth today where the thickness of continental crust is about 70 km is under the Himalaya Mountains of southeast Asia (Nábělek 2009). Thus, the mountains formed during the Ottawan phase of the Grenville Orogeny were once as tall as the present-day Himalayas (Boone 1978; McLelland, Geraghty, and Boone 1978), and a continent-continent collision tectonic model is invoked for the Ottawan phase of the Grenville Orogenic Cycle (McLelland et al. 1996; Tollo et al. 2004; Rivers 2008).

PRESSURE-TEMPERATURE TIME PATH OF ADIRONDACK ROCKS

Equally important to understanding the tectonic history of Adirondack rocks is the relationship between pressure and temperature that the rocks experienced while in the crust (i.e., the PT-path). Mineralogical evidence formed during heating and burial (i.e., the prograde path) is commonly destroyed with progressive metamorphism (Bohlen 1987) and Adirondack rocks are no exception. Thus far, no evidence of the prograde metamorphic path has been reported. The retrograde path, however, has supporting evidence although it is incomplete. Bohlen et al. (1985) and Bohlen (1987) argue that a counter-clockwise retrograde path (i.e., early isobaric cooling followed by later isothermal decompression in a plot of pressure vs. temperature) is supported by: 1) chemical zoning of Fe in garnet rims from ilmenite + sillimanite + quartz + garnet + rutile assemblages and garnet + plagioclase + orthopyroxene + quartz assemblages, and 2) the presence of coarse primary sillimanite as the dominant Al_2SiO_5 phase. Similarly, Spear and Markussen (1997) show that metamorphic ortho- and clinopyroxene in meta-anorthosite from the northeastern Adirondack Highlands grew along a path where pressure decreased by 6 bars per 1 ºC from about 830 °C to 700 °C. Further cooling led to garnet growth between 575 °C and 675 °C at pressures of ~ 6 kilobars (Spear and Markussen 1997). A counter-clockwise PT path is further supported by Lamb, Brown, and Valley (1991) who studied $H_2O + CO_2$ fluid inclusions in Adirondack rocks and found steep isochores (lines of equal fluid density in PT space) in the latter part of the retrograde path. This study was further supported by Darling and Bassett (2002), who increased the minimum temperatures and pressures along the isochores. Both studies demonstrate that $H_2O + CO_2$ fluid inclusions, trapped during the retrograde path of Adirondack rocks, were *very dense* fluids, which is the opposite of what is expected and found in rocks taking a clockwise PT path to the surface (i.e., isothermal decompression followed by isobaric cooling). Well-documented clockwise retrograde metamorphic paths like those from the Himalayas (see Beaumont, Jamieson, Nguyen and Lee 2001) also contain *low density* $H_2O + CO_2$ fluid inclusions (Craw 1990; Craw, Koons, Zeitler, and Kidd 2005; Derry, Evans, Darling, and France-Lanord 2009).

The counter-clockwise retrograde metamorphic path preserved in the Adirondacks is unusual for a continent-continent collision. Typically, when continents collide, burial occurs at a faster rate than the rocks can warm resulting in a clockwise PT path (England and Thompson 1984). It appears an opposite process was operating in the Adirondacks, that is, the rocks were hot before they were buried deeply. This excess heat is thought to be left over from the widespread magma intrusion (anorthosite-mangerite-charnockite-granite) before deep burial during the Ottawan phase of the Grenville Orogeny (Bohlen 1987; Spear and Markussen 1997).

GEOCHRONOLOGY

Dating the age of metamorphism was an early goal of geochronology in the Adirondacks and was an essential part of determining its geodynamic significance, especially the relationship between intrusion of plutons and metamorphic heating. Early K-Ar dating led to the recognition that the Adirondacks and the Canadian Grenville Province were younger than other regions of the Precambrian Canadian Shield, yielding ages of ca. 1100-800 Ma (Doe 1962; Harper 1968), in most cases reflecting cooling of the rocks. Rubidium-strontium isochron geochronology proved to be difficult to apply in the Adirondacks, especially in meta-igneous rocks where dates could not unequivocally be assigned to igneous crystallization or subsequent metamorphism. Thus, ages of 1110-1030 Ma for intrusions and their country rocks (e.g., Hills and Gast 1964) could be taken as evidence for synmetamorphic intrusion or for isotopic resetting of the igneous rocks during later metamorphism.

It was not until broad application of the robust U-Pb isotope system to well-constrained samples that the multiple igneous suites of the Adirondacks could really be distinguished (McLelland and Chiarenzelli 1989) and that the diachronous thermal history of the Highlands and Lowlands was recognized. In the Adirondack Lowlands, U-Pb ages of refractory metamorphic minerals are 1168-1127 Ma, while those of the Highlands are ca. 100 m.y. younger: 1064-1033 Ma (Mezger et al. 1991). Both Highlands and Lowlands rocks cooled at an average rate of approximately 1.5 °C/m.y. following their respective thermal peaks (Mezger et al. 1991; Dahl et al. 2004). There is also evidence for earlier 1180-1160 Ma metamorphism and partial melting in the Highlands (Mezger et al. 1991; Heumann et al. 2006). Thus, metamorphism, as expressed in rocks of the Lowlands, was synchronous with voluminous 1155 Ma anorthosite-suite magmatism in the Highlands (McLelland et al. 2001), but the most recent metamorphism in the Highlands is later and overprints some anorthosite-suite rocks. As a result, in the Highlands metamorphism of the 1090-1020 Ma Ottawan phase are most clearly reflected by mineral assemblages and compositions of 1155 Ma anorthosite-suite rocks (Bohlen et al. 1985; Spear and Markussen 1997), while older metasedimentary rocks experienced both Ottawan and Shawinigan events (e.g., Florence et al. 1995, Kitchen and Valley 1995; Peck and Valley 2004; Darling et al. 2004; Storm and Spear 2005).

In the absence of direct dating of metamorphic minerals in these rocks, it is unclear if metamorphic assemblages that represent the Shawinigan orogeny were reset during Ottawan heating or if they reflect a combination of the two events. An example of this is the ≥790 °C, 7-9 kbar metamorphic determinations of migmatitic pelites of the southern Adirondacks (Storm and Spear 2005), where zircon associated with partial melting of these rocks has Shawinigan ages, but the majority of matrix monazite and monazite inclusions in garnets have Ottawan ages. These data are taken to indicate that the rocks melted during Shawinigan metamorphism but were not able to melt again during anhydrous Ottawan metamorphism (Heumann et al. 2006); phase equilibria and themobarometry of these rocks, however, reflect Ottawan conditions (Storm 2005). More work of this sort is required to unravel the polymetamorphic history of the Highlands. Only in a few localities of the Highlands are field relations amenable to isolating Shawinigan mineral assemblages, most notably foliated xenoliths included in anorthosite-suite rocks that preserve pre-1155 Ma metamorphism and deformation (McLelland, Lochhead, and Vyhnal 1988b; McLelland and Chiarenzelli 1989). Sillimanite + K-feldspar assemblages in pelitic xenoliths (McLelland et al. 1988b) indicate that Shawinigan metamorphism reached granulite or near-granulite conditions, broadly similar to Ottawan metamorphism.

CONTACT METAMORPHISM

Early work on the Proterozoic terrains noted the common association of massif anorthosite with high-grade metamorphism, and, lacking geochronological constraints, a causal relationship between magmatic heating and metamorphism was often assumed. This was the case in the Adirondack Highlands, where ca. 8 to 9 kbar (27 to 31 km) metamorphic pressures retrieved from anorthosite-suite pyroxenes were understood to indicate deep anorthosite intrusion during the metamorphic event (e.g., Jaffe, Robinson and Tracy 1975; Ollila, Jaffe and Jaffe 1988). The abundance of wollastonite at anorthosite contacts, as well as more uncommon contact-metamorphic minerals, such as akermanite and monticellite, are best explained by formation at low pressures during contact metamorphism and preservation during later fluid-absent granulite facies metamorphism (Valley, Bohlen, Essene and Lamb 1990). Most importantly, wollastonite + garnet + diopside skarns that formed in the northeastern contact zone of the anorthosite in the Willsboro-Lewis area have restrictively low oxygen isotope ratios. Low oxygen isotope ratios ($\delta^{18}O$ as low as -1.3‰ SMOW) in skarn minerals are indicative of interaction with heated meteoric water (Valley and O'Neil 1982; Clechenko and Valley 2003), a feature shared by anorthosites in the southern contact zone of the massif (Morrison and Valley 1988a). Most primary skarn minerals were recrystallized during Ottawan deformation, but zoned andradite-grossular skarn garnets formed during anorthosite emplacement are locally preserved in areas of low strain (Clechenko and Valley 2003). The presence of large volumes of surface fluids during intrusion constrains emplacement of the anorthosite to shallow depths (<10 km; Valley and O'Neil 1982). This recognition was an important line of evidence that contact metamorphism could not be the primary heat source for regional granulite-facies metamorphism, and this was confirmed by U-Pb geochronology in the 1980s and 1990s, which solidified the timing of anorthosite intrusion (1155 Ma) and Ottawan metamorphism (1090-1020 Ma). Decoupling these geologic events also allowed for the recognition that the thermal effects of anorthosite-suite magmatism could sometimes be distinguished from overprinting regional metamorphism. In the Highlands, carbon isotope ratios at the cores of graphites are consistent with ca. 860-890 °C contact metamorphic temperatures near the anorthosite massif, while graphite rims grew at regional Ottawan temperatures (Kitchen and Valley 1995).

The other major igneous suite in the Adirondacks that shows evidence for contact metamorphism is the Hyde School Gneiss (HSG) of the Lowlands. The origin of the HSG bodies has historically been a source of controversy and has been interpreted at different times as plutons, granitized metasediments, and metamorphosed ash-flow tuffs (Peck, this issue). It is now recognized that this plutonic suite was emplaced at depth during the peak of Shawinigan metamorphism, at ~1172 Ma (Wasteneys et al. 1999) and that aluminous rocks found at the boundaries of the HSG preserve evidence of contact metamorphism. In these rocks, quartz + spinel assemblages yield metamorphic temperatures ≥875 °C (Powers and Bohlen 1985), corundum + spinel + sillimanite + garnet assemblages yield temperatures 780-810 °C (McLelland, Chiarenzelli, and Perham 1992), and garnet-biotite thermometry yields peak temperatures of 830-860 °C (Hudson 1994), all of which are to 200 °C above the regional Shawinigan temperature structure of the Lowlands.

METAMORPHIC FLUIDS

Investigations of metamorphic petrology coupled with better understanding of Adirondack geochronology in the 1970s-1990s allowed detailed petrologic and isotopic studies to constrain fluid composition and flow during metamorphism (see Valley et al. 1990). The lack of widespread melting in granitic rocks during granulite facies metamorphism indicates low water activity, and mineral equilibria that buffer $a(H_2O)$ yield low and variable water activities in a variety of Adirondacks rock types (≤0.2 in the Highlands and ≤0.5 in the Lowlands). Some assemblages that are very restrictive of fugacities of fluid components can be used to demonstrate that those rocks did not contain a free fluid during metamorphism, while other rocks appear to have been fluid-saturated. Outcrop-scale variability in $a(H_2O)$, $a(CO_2)$, $f(O_2)$, and other constraints on fluid composition demonstrate that metamorphic fluid flow, if present, was not pervasive and that in most cases fluid compositions were buffered by the local rocks. This conclusion is supported by steep isotopic gradients and minimal diffusion across lithologic contacts (Valley et al. 1990; Cartwright and Valley 1991).

The low $a(H_2O)$ in many Adirondack rocks is interpreted to have been mainly caused by a combination of metamorphism of already anhydrous igneous rocks and by desiccation of rocks by partitioning of water into partial melts (Valley et al. 1990).

RESOLVING THE TIMING OF METAMORPHIC CONDITIONS

Although geologists have made great progress in better understanding metamorphism throughout the Adirondacks, a number of unanswered or poorly answered questions remain. First, can strong evidence of pre-Ottawan metamorphism (i.e., Shawinigan-age) be found in the Adirondack Highlands, or is the evidence completely overprinted by Ottawan-age heating and burial? If so, it is reasonable to believe that evidence of the equally important *prograde* Ottawan metamorphic path could be preserved as well. Progress in this area will require coupled geochronologic and geothermobarometric studies with careful attention paid to interpreting textures of relevant minerals so that metamorphic temperature, pressure, and timing are robustly constrained. Second, more data are needed to help refine the pressure, temperature, and timing of the *retrograde* path of Adirondack metamorphic rocks. This requires new geothermobarometry and geochronologic studies on retrograde mineral assemblages. Part of the problem here is that new mineral growth on the retrograde metamorphic path is uncommon in the Adirondacks, but it is not absent. Chlorite mineralization along fractures in mafic minerals from Gore Mountain (Shaub 1949), healed fractures in Gore Mountain garnet (Ferguson and Darling 2013), secondary calcite mineralization in anorthosite rock fractures (Morrison and Valley 1988b), and chlorite + muscovite mineralization in mylonites from the south-central Adirondacks (Gates, Valentino, Chiarenzelli, Solar, and Hamilton 2004; Price et al. 2003; Valentino, Piaschyk, Price, Freyer, Solar, and Chiarenzelli 2005) all represent new mineral growth under lower temperature and pressure conditions, and, if not the result of Paleozoic burial, may yield important information on the post-Ottawan retrograde path.

ACKNOWLEDGEMENT

The authors are grateful to Dr. Jeff Chiarenzelli for a careful and constructive review of this manuscript.

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