A REVIEW OF THE METAMORPHIC PETEROLOGY OF THE APPALACHIAN MOUNTAINS

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Introduction:

The Appalachian mountains run along the entirety of the North American east coast (see Figure 1) (Murphy, n.d.). The most northern part of the mountain belt is the oldest, with age decreasing to the southwest (Murphy, n.d.). It also exhibits strong variation in metamorphic petrology throughout the range due to it being made from multiple mountain-building events (USGS: Geology of the Southern Appalachian Mountains, n.d.; Marshal University, 2010). Three main orogenies occurred in order to make this polyorgenic belt: the Taconic orogeny, Acadian orogeny, and Alleghanian orogeny ("USGS Geology and Geophysics," n.d.; USGS: Geology of the Southern Appalachian Mountains, n.d.; Marshal University, 2010; Rast, 1989) These orogenies represent the collision of island arcs, the destruction of Paleozoic oceans, and the collision of

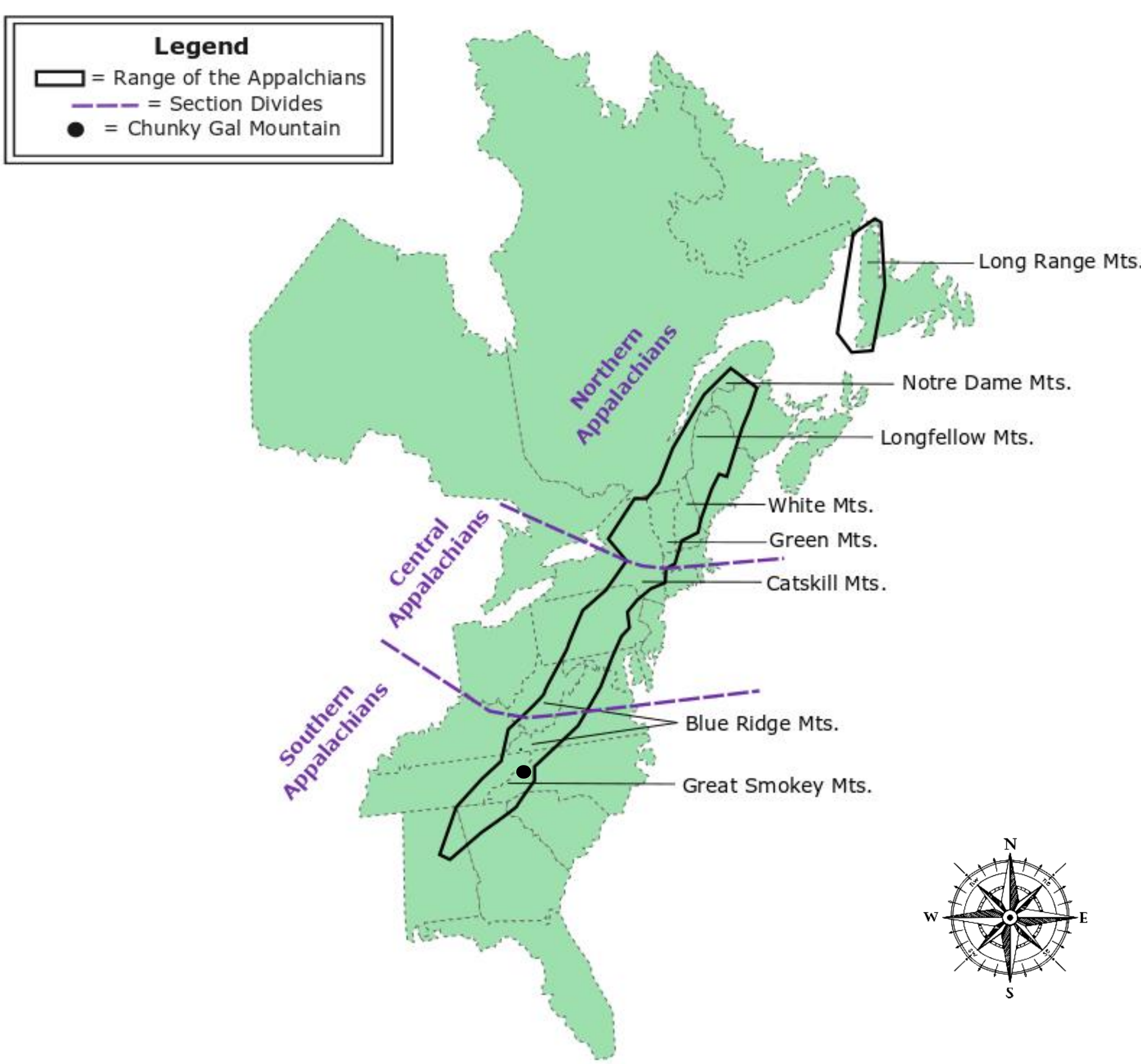

Figure 1: A map of North America showing the location of mountain ranges and sectional divides of the Appalachian Mountains.

Africa with North America during the formation of Pangaea (USGS: Geology of the Southern Appalachian Mountains, n.d.; Marshal University, 2010; Hatcher, 2002). The basement of these orogenies is comprised of plutonic and metasedimentary rocks that metamorphosed into gneisses (Rast, 1989). The majority of the northern Appalachians contains charnockites and paragneisses, with the southern Appalachians being mainly orthogneisses (Rast, 1989).

Northern Appalachians and the Taconic Orogeny:

The Taconic orogeny formed the northern Appalachians in the Ordovician and Silurian (Murphy, n.d.; Marshal University, 2010; Rast, 1989). It involved an extensive amount of thrusting and the convergence of volcanic island arcs (Murphy, n.d.; Marshal University, 2010; Rast, 1989; Hatcher, 2002). The area that is most widely considered Taconian by researchers is the western margin of the northern Appalachians, likely because it is the area least impacted by the other orogenic events (Rast, 1989). As designated by Rast (1989), the Northern Appalachians are comprised of the Long Range Mountains (Newfoundland), the Notre Dame Range (Quebec), the Longfellow Mountains (Maine), the White Mountains (New Hampshire), and the Green Mountains (Vermont) (See Figure 1) (Slattery, Cobban, Mckinney, Harries & Sandness, 2013). In the northern Appalachians, the age of the deformation decreases to the north, placing the youngest deformation in the Long Range Mountains (Murphy, n.d.). It can be seen that higher temperatures and pressures quickly follow the regional metamorphism of the Taconic orogeny in this section of the Appalachians (Dorfler, Tracy, & Caddick, 2014).

The Catskill Mountains of New York, USA are the most publicized of the ranges in the Northern Appalachians and show high-grade metamorphism succeeded by rapid uplift (Murphy, n.d.; Dorfler, Tracy, & Caddick, 2014). Dorfler, Tracy, & Caddick (2014) described the contact metamorphism in New York as pelitic schists which underwent the regional metamorphism of the Taconian orogeny. This regional metamorphism was immediately followed by contact metamorphism produced by mafic intrusions from the same orogenic event (Dorfler, Tracy, & Caddick, 2014).

The first evidence of metamorphism in the samples is the staurolite-garnet-plagioclase Taconic regional metamorphism. Calcium enrichment in plagioclase and garnet crystals is representative of an intermittent cooling period between the stages of high-pressure crystal growth (Dorfler, Tracy, & Caddick, 2014). While the regional metamorphism produced porphyritic and schistose textures, contact metamorphism generated reaction textures. Samples that had undergone both forms of metamorphism also possessed overprinting textures. In these textures, marks of earlier processes were still visible but overlain by the new contact metamorphism (Dorfler, Tracy, & Caddick, 2014). Evidence of overprinting in samples from the northern Appalachians included:

1. Garnet porphyroblasts with chemically modified rims (see Figure 2),
2. A difference in composition between the matrix and inclusion plagioclase/biotite,
3. And the presence of spinel within the matrix.

Samples that experienced both types of metamorphism contained quartz, biotite, plagioclase, garnet, sillimanite, spinel, ilmenite, and graphite and lacked muscovite and alkali feldspar. Biotite, plagioclase, quartz, and sillimanite are abundant inclusions within the garnet porphyroblasts. Some minor inclusions of ilmenite can also be seen. Garnet, plagioclase, and biotite are often the minerals used in thermobarometric calculations, as they best record the changes in metamorphic conditions (Williams, 2011; Dorfler, Tracy, & Caddick, 2014).

A large fluctuation in heat generated high enough temperatures to produce melting, allowing the overprinting thermal metamorphism to remove the matrix muscovite and staurolite. This left only the inclusion muscovite and staurolite and explains the depletion of these minerals within the matrix. The gabbroic melts formed by the high temperatures also depleted the melt of water and felsic components through the recrystallization of plagioclase and removal of muscovite (Dorfler, Tracy, & Caddick, 2014). The heating initiated the breakdown of available micas, staurolite, and garnet, releasing the necessary elements to produce sillimanite. This mineral assemblage could only be produced by the heat from intruding magmas (Dorfler, Tracy, & Caddick, 2014). Since there was no exchange of iron or magnesium between garnet and biotite crystals, it can be inferred that there was rapid cooling from the high temperatures made by the gabbroic melts (Dorfler, Tracy, & Caddick, 2014). In comparison to a collision of two continental edges, the mafic intrusions and hydrous minerals within the samples are further indicative of a collision of island arcs due to the amount of water present during formation (Dorfler, Tracy, & Caddick, 2014).

Garnet poikiloblasts in the northern Appalachians showed distinct zoning patterns that indicated multiple thermal events. There are biotite, sillimanite, quartz, and ilmenite inclusions in the inner crystal; however, the outer rim only has the rare inclusion of spinel. Electron probe analysis by Dorfler, Tracy, & Caddick (2014) revealed the outermost rim of garnet poikiloblasts to be enriched with calcium and the opposite to be true with magnesium, as seen in Figure 2. This chemically modified rim is the result of a change the composition of surrounding material and minerals produced, indicating high temperatures.

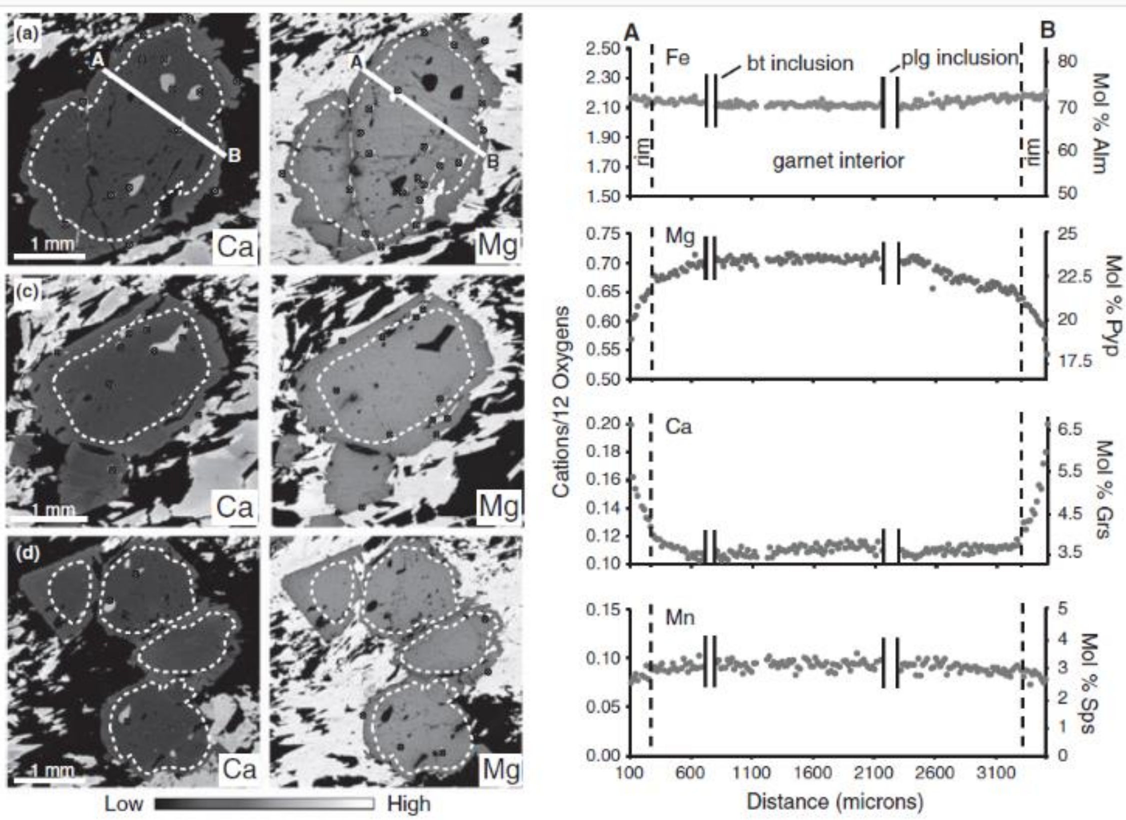

Figure 2: An x-ray map showing the geochemistry of a garnet porphyroblast from the Northern Appalachians. This zoning was the result of partial breakdown of garnet rims caused by contact metamorphism.

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Biotite is distributed throughout the matrix as anhedral crystals and also as inclusions within garnet poikiloblasts. Compared to the matrix plagioclase, which shows distinct calcium zoning, there is no evidence of iron or magnesium zoning of biotite regardless of its location. Spinel is only present within the matrix and not as inclusions within the core of garnet crystals (Dorfler, Tracy, & Caddick, 2014).

Multiple periods of metamorphism are also suggested by the lack of zoning in inclusions and absence of spinel in some samples (Dorfler, Tracy, & Caddick, 2014). This can also be used to extrapolate how some metamorphism only affected minerals in the matrix (Dorfler, Tracy, & Caddick, 2014). The presence of spinel is also and indicator of high-temperature metamorphism.

Central Appalachians and the Acadian Orogeny:

The central Appalachians contain the Taconic and Catskill Mountains, as well as the northernmost part of the Blue Ridge (see Figure 1) (Marshall University, 2010). Beginning in the Devonian, the Acadian orogeny formed part of the northern and central Appalachians, but petrologic and dating evidence has shown limited effects in the southern chains (Murphy, n.d.; Marshall University, 2010; Rast, 1989). The majority of the central Appalachian chain was made by mid-carboniferous greenschist to lower-amphibolite facies metamorphism (Murphy, n.d.; Rast, 1989).

The northern Blue Ridge basement is composed of granitic gneisses and weakly to strongly foliated granitoids. The gneisses are typically older than the surrounding granitoids, and the crystallization of most rocks indicates a Granulite facies (Tollo, Aleinikoff, Borduas, Hackley, & Fanning, 2004).

In order to determine the geographical extent to which the northernmost part of the Blue Ridge was affected by the Acadian Orogeny, Tollo, Aleinikoff, Borduas, Hackley, & Fanning (2004) examined samples from two separate massifs on opposite sides of a fault that runs parallel to the Appalachian chain. Rocks located on either side of the fault are coarse-grained with porphyroblasts. The eastern side of the fault shows a slightly lower grade of metamorphism than the western side. Biotite is the dominant mineral in eastern gneisses, and it shows varying degrees of recrystallization. Orthopyroxene and garnet are the major minerals in the western samples, which show a stronger gneissose texture when compared to their eastern companions. The oldest rocks, located on the eastern side of the fault, are strongly foliated granitic/monzonitic gneisses (Tollo, Aleinikoff, Borduas, Hackley, & Fanning, 2004).

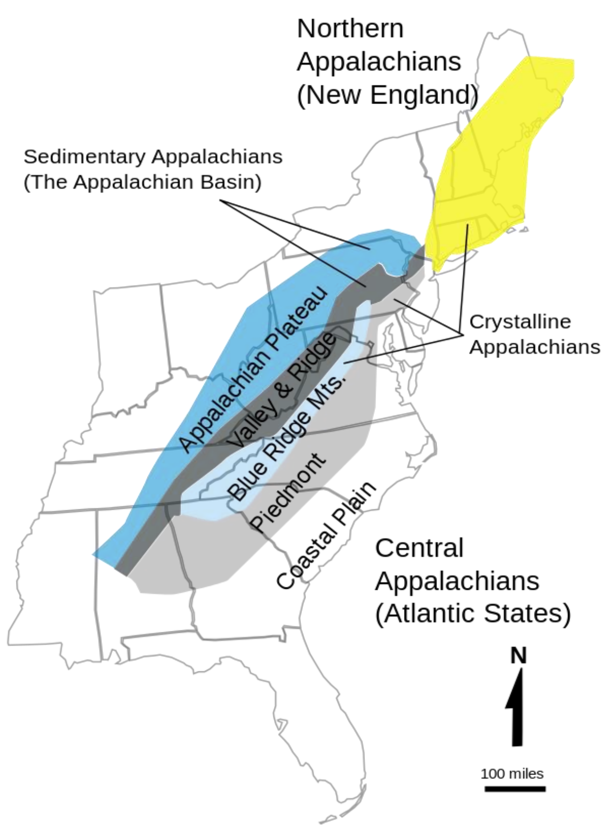

Figure 3: A map showing the Blue Ridge Mountains and Peidmont province in the Northern and Central Appalachians.

Two hypotheses were proposed to explain the varying degrees of metamorphism:

1. The basements of these two massifs are two different responses to amphibolitic metamorphism
2. The two sides of the fault experienced different degrees of metamorphism

Additional to having experienced a higher grade of metamorphism, the rocks on the western side of the fault are slightly younger and possess low amounts of dark minerals when compared to the eastern side. This makes the second hypothesis more likely to explain the variations (Tollo, Aleinikoff, Borduas, Hackley, & Fanning, 2004).

Southern Appalachians and the Alleghenian Orogeny:

The third orogeny, which formed most of the southern Appalachians is the Alleghenian orogeny of the Late Carboniferous and Permian, also known as the Appalachian Orogeny (Murphy, n.d.; Marshal University, 2010; Hatcher, 2002). The entirety of the Appalachian chain shows the regional metamorphism of this event as it was caused by the rotational collision of the African continent with the eastern coast of North America (Murphy, n.d.; Rast, 1989; Hatcher, 2002). Figures 3 and 4 were adapted from PerryGeo (2006) and Merrigum (n.d.), and they show that North America and Africa were part of larger continents called Laurentia and Gondwana during this orogeny (Hatcher, 2002). This tectonic event can be classified This tectonic event can be classified as what is known as "Zipper Tectonics," where the Northern edge of Africa collided with Eastern North America (Murphy, n.d.; Rast, 1989; Hatcher, 2002). In the process of this collision, the Theic Ocean between these two continents was closed from North to South in a zipper-like pattern, causing subduction-setting metamorphism (Hatcher, 2002). This model explains why similar metamorphism is seen throughout the Appalachian Mountains but with different age ranges (Hatcher, 2002). Several I-Type and S-Type intrusions were also created in this collision and caused additional contact metamorphism (Rast, 1989; Hatcher, 2002). While there was a large amount of time between the first two orogenies that created the northern and central Appalachians, the Alleghanian orogeny almost immediately followed the preceding Acadian orogeny. (Rast, 1989). This causes difficulty when attempting to differentiate between the regional metamorphism caused by each event, especially near

Figure 4: A map of Laurentia with an outline of modern North America. The red zone represents the Appalachian Mountains.

Figure 5: A map of Gondwana with inner traces of the continents it was composed of. The red patch is where Africa contacted North America in the Appalachian Orogeny.

the boundary between the central and southern sectors.

The southern Appalachians encompass the Blue Ridge and Great Smokey Mountains (see Figure 1) ("USGS: Geology Of The Southern Appalachian Mountains," n.d.). The Blue Ridge and Peidmont province on the eastern side of the Appalachians were the main areas affected by this orogeny (see Figure 3). The Peidmont province, in contrast to the greenschist facies of the Blue Ridge, shows higher-degree amphibolite facies (Williams, 2011; Hatcher, 2002). Hatcher (2002) found the upper-amphibolite facies to have reached sillimanite conditions. There are also differences in basement composition throughout the Blue Ridge, with the north being comprised of gneisses and the south of charnockites (Rast, 1989).

Chunky Gal Mountain is a highly-publicized massif within the Blue Ridge whose basement experienced amphibolite facies metamorphism (Marshal University, 2010). Williams (2011) described the minerals and textures from opposite sides of the Chunky Gal Mountain fault to characterize the metamorphism of the central Blue Ridge. The study discovered that the more southernly located samples displayed lower degrees of metamorphism (amphibolitic) than those more northern (granulite) (Williams, 2011). This may infer that the Alleghanian orogeny had more limited effects near the southernmost part of the Appalachian chain, as the grade of metamorphism decreases towards the furthest edges of the Southern section (Hatcher, 2002; Williams, 2011).

Garnet and plagioclase crystals contained the most geochemical evidence for peak pressure and temperature values, as they would preserve the most evidence of changing conditions. Iron and magnesium oxide data in garnet and biotite were used for thermobarometry, while aluminum and silicate oxide data from garnet and plagioclase was used to calculate barometry values. These values were determined to range from 5.5-8kbar depending on the area examined, showing the differences in metamorphic grade with southern movement along the Blue Ridge. (Williams, 2011).

Garnet crystals in the examined thin sections have cores abundant in inclusions, but rims only contain trace amounts of sillimanite. Garnets examined showed zoning, poikiloblastic textures, and fractionation, which were evidence of three separate growth stages followed by a period of cooling (Williams, 2011; Hatcher, 2002):

1. Growth of garnet porphyroblasts that encompasses some of the surrounding mineral grains
2. Outward expansion of the garnet during a period where there was no remaining material to form inclusions
3. A period where sillimanite inclusions were incorporated into the garnet rim and tail
4. A rapid cooling period that caused the garnet crystals to fracture

Trace amounts of sillimanite inclusions within the rims and tails of the poikiloblasts differ from those in the matrix. A more fibrous shape is seen in the inclusions while matrix sillimanites have a more prismatic appearance. Since sillimanite inclusions are parallel to the crystals in the matrix, it is likely that they were formed in the same deformation event (Williams, 2011).

A green mica, along with fine crystals of potassium feldspar, was identified within the fractures of garnet poikiloblasts. As it is within the fractures and not the garnet grains themselves, it can be inferred that they formed after the porphyroblasts and during the final period of metamorphism in which the grains were cooling. The green mica, although not named in the study, is likely chlorite based on its birefringence and green color in plane polarised light (PPL) (Williams, 2011).

Potassium feldspar is also contained within the fractures and rim of garnet poikiloblasts. It lines the rim of the poikiloblast with a myrmeketic texture, potentially indicating an interaction with hydrothermal fluids at some point during the metamorphism (Williams, 2011).

Summary and Conclusions:

The Taconic orogeny was the first mountain-building event to occur, forming the northern Appalachians (Murphy, n.d.; Marshall University, 2010; Hatcher, 2002). Because of this it was also repeatedly impacted by mountain-building events, making it difficult to distinguish between the metamorphic results of each orogeny in some areas of the northern ranges. In this sector, regional metamorphism was later overlain by contact metamorphism. This causes a discrepancy in the mineralogy of samples that experienced one or both types of metamorphism. Multiple periods of metamorphism can also be seen in alignment and recrystallization of matrix minerals (Dorfler, Tracy, & Caddick, 2014). The main evidence of this is seen in the inclusions of garnet poikiloblasts and presence of matrix spinel and sillimanite.

The Acadian orogeny followed the Taconian orogeny and created the central and part of the northern Appalachians (Murphy, n.d.; Marshal University, 201 0; Rast, 1989). The more eastern central Appalachians were determined to be older but experienced less metamorphism, which may explain why biotite is the dominant mineral in the area. The western central Appalachians, although younger, are of a higher grade and contain high amounts of orthopyroxene and garnet. Differences between each side of the fault is most likely the result of experiencing different degrees of metamorphism followed by thrusting.

The Alleghanian orogeny quickly followed the Acadian event and affected the entirety of Appalachians (Rast, 1989; Hatcher, 2002). It caused extensive regional metamorphism and minor amounts of contact metamorphism from the mafic intrusions it created in some areas (Hatcher, 2002). It is also the only sector to show a potential for interaction with hydrothermal fluids.

The largest discrepancies in mineralogy and degree of metamorphism are between the northern and southern Appalachians. Cooling of northern garnet grains was intermittent between two types of metamorphism, but cooling in southern samples allowed for extensive mineral growth in fractures that did not occur in northern counterparts (Murphy, n.d.; Aleinikoff, Borduas, Hackley, & Fanning, 2004). Although similar in a lack of inclusions, the outer rims of garnet poikiloblasts in the north and south were not made by the same processes. Northern garnets have a rim that was made through the recrystallization of the outer crystal without any increase in size, while the rim of southern garnets represents growth with a lack of surrounding material for inclusions.

Further research could be improved with increased usage of an electron probe to give more accurate results than a scanning electron microscope, which focusses on a broader area of the thin section. This would better provide peak metamorphic temperature and pressures (Williams, 2011). Future studies may benefit from a research focus that distinguishes and defines the geographic boundaries of each orogeny, which would better explain the varying metamorphic facies throughout similar massifs.

References:

Dorfler, K. M., Tracy, R. J ., & Caddick, M. J. (2014) Late-Stage Orogenic Loading Revealed by Contact Metamorphism in the Northern Appalachians, New York (Vol. 32, p.p. 113–132). J. Metamorphic Geology.

Hatcher, R. D., (2002) Alleghanian (Appalachian) orogeny, a product of zipper tectonics: Rotational transpressive continent-continent collision and closing of ancient oceans along irregular margins. (p.p. 199-208). Geological Society of America.

Marshall University (2010) Petrology of the Blue Ridge

Merrigum (n.d.) Gondwana. Retrieved from http://www.merrigum.com/gondwana/

Murphy, J. B. (n.d.). The Acadian Orogeny in the Northern Appalachians, 26.

PerryGeo (2006) Animating Static Maps - The Geologic Evolution of North America. Retrieved from https://www.perrygeo.com/index20.html

Rast, N. (1989). The evolution of the Appalachian chain. In A. W. Bally & A. R. Palmer (Eds.), *The Geology of North America—An Overview* (pp. 323–348). Geological Society of America.

Slattery, J. S., Cobban, W. A., Mckinney, K. C., Harries, P. J., & Sandness, A. L. (2013). Early cretaceous to paleocene paleogeography of the western interior seaway: the interaction of eustasy and tectonism. *Unpublished*.

Tollo, R. P., Aleinikoff, J. N., Borduas, E. A., Hackley, P. C., & Fanning, C. M. (2004). Petrologic and geochronologic evolution of the Grenville orogen, northern Blue Ridge Province, Virginia. In *Memoir 197: Proterozoic Tectonic Evolution of the Grenville Orogen in North America* (Vol. 197, pp. 647–677). Geological Society of America.

USGS Geology and Geophysics. (n.d.). Retrieved February 20, 2019, from https://geomaps.wr.usgs.gov/parks/province/appalach.html

USGS SIM-2830: Geology Of The Southern Appalachian Mountains. (n.d.). Retrieved February 24, 2019, from https://pubs.usgs.gov/sim/2830/

Williams, C. A. (2011). An Analysis of an Appalachian Metamorphic Suite, *15*, 11.