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Preliminary characterization of rock units to determine layer divisions in a high-pressure metamorphic rock package of the Goshen Dome, western Massachusetts, USA

by

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An undergraduate honors thesis submitted in partial fulfillment of the
requirements for the degree of

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2016

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ABSTRACT

In Western Massachusetts a package of rocks, known as the Damon Pond section, has been the focus of ongoing study due to characteristics signifying it may have formed under suspected ultra-high pressure (UHP) conditions. Currently there are no confirmed UHP terranes in North America causing research surrounding this package of rocks to be of particular significance. In order to better understand the Damon Pond section and a mechanism of emplacement for this potential UHP terrane, more must be known about its size and the surrounding strata. Prior to this study, relatively little was known about the units of rock surrounding this unique package despite it being previously mapped. Field observations, structural measurements, and samples were collected from in-situ outcrops surrounding the Damon Pond section where it is exposed at the edge of the Goshen Dome in order to determine the lithologic units present and if they show signs of disruption indicating the Damon Pond section is more extensive than currently mapped. Petrographic analyses were conducted on 11 representative samples from the surrounding area focusing on the metamorphic mineral assemblage, relative abundance of minerals, notable structural characteristics, distribution of mineral grains, size variance of mineral grain populations, and the spatial association of metamorphic minerals. The Damon Pond section was found to be distinctly different from the surrounding lithology due to abundant megacrystic garnet and kyanite, nesting boudinage features, and significant folding that disrupts the preexisting mineral foliation, which were not found to be present in the surrounding units. Three divisions based on rock type were made in the surrounding lithology from analysis of hand samples and thin sections, independent of their location in the field. When plotted on the map, spatial location of the samples showed these lithologic divisions to be consistent along strike with no repeating sections or disruptions that would indicate significant folding or faulting. The strike and dip measurements of foliation were consistent across the divisions

Figure 1: Regional map showing Goshen Dome relationship with the post-Taconian tectonic cover (Top after Karabinos et al., 1998). Geologic map (Middle) and cross section (Bottom) through the dome, Damon Pond section shown in red (modified from Hatch and Warren 1981).

Figure 2: Picture of megacrystic garnet present in the Damon Pond section taken during field work conducted in 2015, pen for scale (photo by E.A. Lahart). Garnet of this size was not observed in the surrounding lithology. Image is of an inclined rock face with North to the right.

microcontinents as they were grafted onto the North American craton as the result of subduction. The Appalachian Mountains of New England were formed this way through multiple orogenic events, including the Taconic, Salinic, Acadian, and Alleghenian, with many proposed hypotheses for the associated subduction and collisional settings (e.g. van Staal et al., 2009, Macdonald et al., 2014). The rocks affected by the Acadian Orogeny contain a well-preserved record of its extensional and collisional phases but little to no evidence for the early subduction-related phases. In Western Massachusetts, dome structures expose rock units dated to the Acadian orogeny, including a suspect metapelitic terrane, known as the Damon Pond section, that preserves geochronological evidence for this early Acadian deformation (Peterman et al., 2014). Structurally, the Damon Pond section is associated with the décollement of a thrust sheet exposed at the edge of the Goshen Dome (Figure 1).

Although the area had been mapped previously (Hatch and Warren, 1981), the Damon Pond package of rock is relatively unstudied. The package of metapelitic rocks is contained within what was mapped as a structural dome. New data by other researchers (e.g. Koziol and Snoeyenbos, 2008; Peterman and Snoeyenbos, 2015) as well as preliminary data and observations done for this project indicate that the Damon Pond section may preserve a tectonic history unrelated to the dome or the surrounding rock units. Fieldwork conducted in the summer of 2015 found that the mineral lineations and outcrop-scale structures (Figure 3) present in the package are not consistent with structures expected for rock units positioned on the edge of a dome, challenging the idea that these rocks preserve any evidence for the formation of the dome. Furthermore, a kyanite, garnet schist layer in the westernmost exposure of the Damon Pond Section includes within the mineral assemblage megacrystic

whereas the mineral lineation varied between the gneiss and schist, showing a top to the south sense of shear in the schist. The units present were determined to be Amphibole Gneiss, Amphibole Quartz Garnet Gneiss, and Garnet Schist as well as an un-sampled Pegmatitic body.

INTRODUCTION

The metamorphic rocks of the east coast of the United States preserve the history of a long-lived, active convergent margin. The coastal region was built through the collision and accretion of terranes and the accumulation of sediments shed from the uplifted mountains. Existing rocks and newly formed sedimentary rocks were metamorphosed during the collision of off-shore island arcs and

Figure 3: Photo of isoclinal fold present in the Damon Pond section taken during fieldwork conducted in 2015, pen for scale. The fold axis is shown in blue (photo by E.A. Lahart). Image is of an inclined rock face with North to the right.

garnet (Figure 2) and kyanite thought to have grown under high-pressure (HP) conditions and possibly ultra high-pressure conditions (UHP). These megacrystic minerals are unlike any other porphyroblasts present in the area and suggest that all or part of the Damon Pond section may represent an exhumed UHP terrane. There are currently no accepted UHP terranes in North America (Gilotti et al., 2013), making this package of well-preserved metapelites and the strata in which they are emplaced of particular interest for further study.

Geodynamic models are used to investigate how subduction-related materials can be returned and emplaced closer to the Earth's surface (e.g. Hacker et al., 2013). Understanding the mechanisms and conditions that lead to the exhumation and preservation of a package of rock metamorphosed at UHP conditions is a major focus of study. Studying the layers that host the UHP minerals is just as important as studying the UHP minerals because such details are needed for the reconstruction of the history of emplacement. Features of the host layers; such as the metamorphic mineral assemblage, locality of deformation, and the presence and locality of melt; are used to answer questions connected to specific emplacement mechanisms, including whether or not the internal layering of the terrane is internally consistent or significantly disrupted. Therefore, a major first step in investigating the potential emplacement history of this package from HP or UHP depths is to characterize the layering in the Damon Pond section and surrounding rock. This study considered the rock type, sense of deformation present, and the metamorphic mineral assemblage of collected samples to determine the divisions in layering in order to ultimately gain a better understanding of what their stratigraphic relationships may be, whether or not the package is internally coherent or deformed, and, in future work, if the layers present share similar PTD histories.

BACKGROUND

Characteristics of Ultra High Pressure Terranes

The term ultra high-pressure (UHP) terrane refers to dominantly quartzofeldspathic continental material that was brought to depth at a convergent plate margin and metamorphosed relatively deep below the Earth's crust experiencing great pressure before being rapidly exhumed back to shallower crustal levels. These terranes experienced mantle pressures at 3GPa and greater (e.g. Gilotti et al., 2013), conditions at which coesite, a polymorph of quartz that forms under greater pressure, and diamond grow; these are the index minerals for UHP conditions. Typical characteristics of UHP terranes include the presence of coesite and/or diamond with other minerals that reflect high pressure (depths >150km) and moderate temperature (<800 °C).

Investigation of UHP terranes is hindered by the fact that few terranes survive exhumation to the surface and that, once exposed, are difficult to identify. It's uncommon for terranes to be exhumed at a rate in which the peak metamorphic reactions and mineral assemblages are preserved. There are few confirmed locations of UHP terranes exposed at the Earth's surface; this is due to retrograde reactions that change the UHP rocks so that they are unrecognizable by the time they are exposed. The index minerals are not always present or preserved. Coesite is not present in many UHP terranes due to the fact that the silica content is too low to form a free phase or it has already transitioned back to quartz during exhumation (Massonne and O'Brien, 2003). Also, diamond can only grow in rocks that have carbon precursor phases. Finally, because coesite and diamond are difficult or impossible to identify in hand sample, they are a poor way to identify the presence of UHP terranes in the field (Schertl and O'Brien, 2013). This may also explain why there aren't more confirmed outcrops.

There are over 20 recognized UHP terranes, the majority of which come from continental crust. These confirmed existing UHP terranes have been used to help shape the six current proposed models for the mechanisms of exhumation and emplacement of UHP terranes: crustal stacking, ductile return flow, exhumation, diapirism, microplate rotation, and slab roll back.

- *Crustal stacking (also known as the Chemenda model)*: A continental crustal sheet package that is fault bounded and that rises via shear deformation at its boundaries (Chemenda et al., 1995).
- *Ductile return flow*: Continental crust buoyantly rises in a subduction zone channel via internal flow triggered by an instability (Warren et al., 2008; Beaumont et al., 2009).
- *Eduction (also known as the Anderson model)*: Crustal material rebounds following slab break off (Anderson et al., 1991)
- *Diapirism*: Crustal material returns via the rise of diapirs through the overlying mantle leading to continental relamination (Stöckert and Gerya, 2005; Gerya and Stöckert, 2006; Currie et al., 2007; Gerya et al., 2008).
- *Microplate rotation*: Continental material is brought back up with plate motion caused by three-dimensional rotation of a smaller-sized plate (Hacker et al., 2000).
- *Slab roll back*: Continental material buoyantly rises in place of the mafic lithosphere that has rolled back (Brun and Faccenna, 2008).

Several trends have emerged from these models in the characteristics of the rock units of UHP terranes and the mechanism proposed for their emplacement. Larger terranes tend to have limited internal deformation, with shear/fault bounded structures, and mineral assemblages that represent pressure and temperature conditions consistent with coherent package emplacement through crustal stacking or eduction. Smaller terranes, on the other hand, tend to have complex internal structures containing a mixture of units that do not share pressure temperature histories, making them consistent with emplacement mechanisms such as channel flow and diapirism that both disrupt the package during emplacement. Smaller terranes that are also associated with significant volumes of melt are consistent with mantle crossing diapir emplacement.

Geologic Setting of the Damon Pond Section

The North Appalachians of New England USA, in Western Massachusetts, involve the folded Laurentian basement of the Grenville Orogen and the accreted Shelburne Falls arc of the Taconic Orogen (Karabinos et al., 1998). Metamorphism and isoclinal folding was caused by the west-directed emplacement of a thrust sheet over these basement rocks (Hatch 1968; Williams et al., 2001; Karabinos and Aleinikoff, 2011). Dome structures present in western Massachusetts act as tectonic windows exposing the underlying Taconic core gneiss (Hatch and Warren, 1981) and have been interpreted as structural domes formed by upright folding during the Acadian Orogeny (e.g. Robinson et al., 1998). The Damon Pond section is a rock package that is exposed at the western edge of one of these domes, the Goshen Dome, along what is thought to be a décollement (Hatch and Warren, 1981). Recent geochronological studies indicate that deformation and metamorphism occurred in these rocks during the Acadian Orogeny (Peterman et al., 2014). The lithologic units of the Goshen Dome were originally described in a geologic map published in 1981 by Hatch and Warren. The core gneiss at the center of the dome (Collinsville Fm., oco) is described as consisting of medium to fine grained, moderate- to well-foliated, plagioclase-quartz-biotite-(muscovite)-(garnet) gneiss and medium grained, well-foliated, hornblende-plagioclase amphibolite. The eastern, western, and southern edges of the dome (Cobble Mountain Fm., ocb) are described as quartz-muscovite-biotite-feldspar-garnet schist and quartz-feldspar-biotite gneiss. Also, present is a fine-grained muscovite- quartz schist with 10% tiny (<1mm) manganiferous garnet, 1-2 mm thick lenses of fine- grained quartz-garnet cotecule rock, and small layers of chlorite-quartz-plagioclase-biotite gneiss. Parts of the Damon Pond section were originally mapped on the western edge of the dome as two sub-members of the Cobble Mountain Formation (Hatch and Warren, 1981). The eastern-most layer is described as tan-brown, fine-grained feldspathic granulite with layers of medium- to coarse-grained gneiss, containing sprays of pale-brown amphibole. The western-most layer is described as black, medium-grained hornblende plagioclase amphibolite locally containing light-colored feldspathic gneiss bands. For the purposes of this project, the

Damon Pond Section (below the décollement to the east at the western edge of the dome) includes an outcrop of amphibolite gneiss with boudin structures (Figure 4) and a garnet-kyanite schist outcrop with isoclinal fold structures (Figure 3). The rock units structurally below the Damon Pond Section and to the west of Damon Pond are the focus of this study.

More recent work on the Damon Pond Section has described a peak metamorphic assemblage for the host rock and features present in megacrystic garnet consistent with growth at HP or UHP conditions. Megacrystic garnet (2-3 cm) present in this area of the dome display inclusion relationships that are consistent with growth at UHP conditions followed by decompression (Koziol and Snoeyenbos, 2008; Snoeyenbos and Peterman, 2015; Peterman and Snoeyenbos, 2015). These inclusion relationships are also observed in garnet from Rhodope terrane, Greece, a known UHP terrane (Snoeyenbos and Peterman, 2015). The peak assemblage of the rocks from elsewhere in the Damon Pond section were found (O'Brien, 2007; 2008) to contain:

*garnet + kyanite + plagioclase
+ biotite + rutile + quartz*

Geothermobarometric calculations indicate metamorphism at ~11kbars and ~720-740 degrees Celsius in the lower granulite facies (O'Brien, 2008). Previous work in the cover rocks that surround the Goshen Dome found a prograde metamorphic trend to the southeast indicating that the local rocks were only metamorphosed to as high as kyanite/staurolite grade (Abbott, Jr., 1979).

RESEARCH METHODS

Sample Collection & Preparation:

Samples were collected during preliminary fieldwork from outcrops that could be confidently identified as being in-situ. Care was taken to document the orientation of the samples and outcrop scale features, specifically the strike and dip of foliation as well as the trend and plunge of any mineral lineations, where available. At Portland State University, the strike and dip measurements were used to re-orient the samples. Each sample was cut perpendicular to the foliation and relative to the two dominant lineations

Figure 4: Boudin structures that are found in the Damon Pond package and are absent in the surrounding lithologic units. The features at outcrop scale are shown in A, with a close up on the nested boudin structures in B (adapted from Peterman et al., 2014; photos by D. Snoeyenbos). Image is of an inclined rock face with North to the right.

identified in the field: perpendicular to a fold intersection lineation or parallel to a stretching lineation. Thin sections billets were cut to view those kinematic reference frames. Billets were sent off campus for thin section preparation.

Data Collection:

One thin section was chosen from each sample for detailed analysis. Each thin section and hand sample pair were analyzed using a petrographic microscope. Thin sections were also scanned using a high-resolution slide scanner. The primary features that were characterized in each thin section are summarized below

- **Mineral assemblage (primary and secondary):** The minerals present were identified by the optical properties associated with each under the petrographic microscope and in consultation with the hand sample. Primary minerals of interest were quartz, feldspar, biotite, muscovite, chlorite, amphibole, kyanite, garnet, and staurolite. Zircon was a secondary mineral of interest.
- **Relative abundance of minerals:** Primary minerals were identified within thin section images by differences in color and brightness. First order estimates of abundant minerals were used to determine rock type. Minerals of interest included: biotite, amphibole, quartz, chlorite, kyanite, feldspar, staurolite, and garnet.
- **Distribution of mineral grains:** The distribution of mineral grains was noted for each thin section based on whether or not they were evenly distributed or clustered within the section. The manner in which they were grouped was noted with a focus on grains located along structural features, groupings consistent with pseudomorph relationships, grains located at the edges of porphyroblasts and along grain boundaries (e.g. rimmed garnet). The presence of gneissic banding defined by minerals was noted as well.
- **Size of mineral grain populations:** Relative grain size was noted for porphyroblast minerals with populations that were distinctly different, such as two different garnet size populations. Minerals of interest included amphibole, garnet, feldspar, kyanite, biotite, and chlorite.
- **Spatial association of metamorphic minerals:** The mineral assemblage of metamorphic rocks changes as minerals replace one another through reaction or a shift in abundance or chemical composition, reflecting the stability of the system. Minerals that have been broken down, created, or changed by metamorphic reaction will be spatially associated. Obvious relationships were noted, such as biotite and chlorite rimmed garnet, amphibole rimmed garnet, and quartz and feldspar inclusions in garnet.
- **Structural characteristics:** Key structural and microstructural features preserved in each thin section were noted. Structures considered: the presence of foliation, shear bands, microfolds, boudins, inclusion trails, and features created by the preferred alignment of mineral grains.

SUMMARY OF DATA AND OBSERVATIONS

Field Observations

Fieldwork conducted in the summer of 2015 was focused on collecting a suite of samples, describing outcrop-scale features of sampled units, and making structural measurements. The rocks that contain the megacrystic garnet and kyanite are foliated with a large amount of mica and are the eastern-most units of the Damon Pond section. The rocks hosting these units, exposed from the base of the Damon Pond Section in the west downhill to Damon Pond to the east, were observed in the field to contain three dominant rock types, referred to in the field as schist, gneiss, and pegmatite. The strike and dip of foliation measurements were found to be consistent across the units with a mean strike of 135° and mean dip of 35° (Figure 5). Strike and dip measurements were taken for the Goshen Formation outside of the Dome as well as the Damon Pond section but were not the focus of this study.

Figure 5: Strike and dip data from fieldwork conducted in 2015. The trend and plunge of mineral lineation for the Amphibole Gneiss and Amphibole Quartz Garnet Gneiss units are in agreement but are different from the measurements taken for the Garnet Schist unit. Data are plotted on equal area nets; foliation is plotted as poles to the strike and dip measurement.

The schist outcrops were characterized by large amounts of muscovite, feldspar and a uniformly-sized population of garnet, with a strong presence of schistose foliation. The schist layers contained asymmetrically off-set boudins (Figure 6) consistent with a higher shear strain component and local fold structures. The mineral and intersection lineation measurements were found to be at a different compass direction from dominant foliation and were in agreement with fold axis measurements observed. Elongate mineral shape was observed locally in garnet in an orientation parallel to the observed fold axis.

Figure 6: Example of Garnet Schist outcrop found in the area of study (photo by E.A. Lahart). Asymmetrically off-set boudins of quartz, consistent with a higher shear strain component are outlined in purple. Image is of a near vertical rock face with North to the right; the left-most boudin is approximately one meter in length.

Figure 7: Close up of Garnet Schist unit showing the foliation and abundant relatively uniform population of garnet, pen for scale (photo by E.A. Lahart). Image is of a near vertical rock face with North to the right.

The gneiss outcrops contained large amounts of quartz, amphibole, mica, garnet and the presence of weak to moderate gneissic foliation and banding. No boudins were observed in outcrop. Multiple populations of

Figure 8: Photo of Amphibole Quartz Garnet Gneiss outcrop with the author collecting strike and dip measurements of the outcrop (photo by N.A. Price). Image is of a near vertical rock face with North to the right.

garnet were present (including megacrystic in size) rimmed in amphibole; concentrated in the amphibole-, quartz-, and feldspar-rich areas; and appeared flattened in the foliation. The amphibole present had a weak mineral lineation with a dominantly NW trend and a shallow plunge.

Figure 8: Example of amphibole rimmed megacrystic garnet present in the Amphibole Quartz Garnet Gneiss (photo by E.A. Lahart). Image is of a near vertical rock face with North to the right.

Pegmatite outcrops observed were located on the edge of the field area but were not sampled. The outcrops were characterized by large amounts of quartz, feldspar, chlorite, and mica with weak to no foliation. The pegmatitic inclusions within the other units were observed for the outcrops in closest proximity to the larger observed pegmatitic body.

Sample Descriptions

Short descriptions for each sample investigated in this study are listed below and include observations of the dominant minerals present, their spatial association, population variance, and structural characteristics. These observations were made from hand samples and respective thin sections with the use of a hand lens and petrographic microscope. Due to their similar nature in thin section, all samples are assumed to have both quartz and plagioclase feldspar present. However, when signature characteristics of either mineral were observed it was noted.

DP-15-04-01: This sample is amphibole-rich with quartz and feldspar present in weak gneissic banding. Crystal size is fine to medium grained with a granular texture. Quartz, feldspar, and amphibole dominate this sample with additional biotite and a high relief mineral that lacks pleochroism (tentatively interpreted to be cummingtonite). The primary population of quartz and feldspar are mixed with amphibole and display granoblastic texture with no clear sense of an interconnected fabric, whereas some groupings of feldspar and quartz define bands in amphibole-dense areas, giving the sample weak gneissic structure observable at the thin section scale. The larger broken amphibole crystals present commonly contain calcite. A sparse population of small garnets is also present.

DP-15-05-01: The sample is composed of fine-grained biotite, feldspar, and quartz with some muscovite, chlorite, and garnet. Small tabular biotite crystals are aligned in the foliation. Chlorite, biotite, and oxides are present with garnet and in garnet-shaped clusters that are not aligned in the dominant fabric present.

DP-15-07-02: This sample is dominated by quartz, feldspar, amphibole, and chlorite with distinct disaggregation of megacrystic garnet, around which the surrounding mineral fabric deflects. It has fine grained, alternating gneissic bands of granular quartz/feldspar and amphibole. The garnet present is .5-1.5mm in size, possessing amphibole rims and often containing amphibole, quartz, and feldspar inclusions. The chlorite found in this sample has two variations in color; pale gray-blue and green. The larger, blue chlorite crystals are concentrated in close proximity to the garnet as well as in the matrix. Concentrations of chlorite in the matrix have gneissic foliation deflect about them, display a fan-like habit, and are comparable in size to the megacrystic garnet. A large vein that cuts across the thin section subhorizontal to the gneissic foliation and is composed of quartz and feldspar crystals. All the garnet present contain cracks that are oriented in the same direction at an angle to the foliation.

DP-15-08-01: Coarse crystals of quartz and feldspar dominate this sample in addition to mica (muscovite and biotite) and relatively uniform populations of garnet and staurolite. The garnet present are euhedral to subhedral ranging 1- 5mm in size. The staurolite present is disaggregated and found in close proximity to the garnet. Muscovite defines the schistose foliation, anastomosing about large quartz and feldspar lenses. Two populations of quartz and feldspar are present in the matrix and as inclusions throughout both populations of garnet. Muscovite is the dominant mica present with biotite and chlorite at the outer edges of the larger garnet porphyroblasts. The fabric of the micas deflects about the garnet as well as the quartz and feldspar clusters. Mica rims, consisting predominantly of biotite with some chlorite, are present around both populations of garnet and are more prevalent in the smaller sized group, with orientations that do not agree with the dominate orientation of the other micas present in the foliation.

DP-15-09-01: Garnet, mica, quartz, and feldspar are the predominate minerals in this sample. Biotite and muscovite define the foliation and deflect about the garnet. The garnet population is relatively uniform in size and includes small inclusions of quartz and feldspar. A sparse amount of kyanite is also observed, which distinguishes this sample from others of a similar makeup. Staurolite is present and is found in close proximity to the garnet.

DP-15-10-01: Quartz, feldspar, mica, and a relatively uniform size population of garnet dominate this sample. The feldspar present displays polysynthetic twinning. The garnet population contains inclusions of quartz and feldspar throughout, with rims composed predominantly of biotite and locally chlorite with several garnet crystals that have atoll style inclusions. The larger biotite crystals contain zircon halos.

DP-15-11-01: Coarse crystals of quartz and feldspar lenses dominate this sample with biotite and muscovite defining an anastomosing fabric about them. The more micaceous layers contain semi-uniformed size garnet and in some areas the mica shows a change in orientation consistent with a weak crenulation. The mica rich layers also contain micro folds. Garnet present is subhedral and display cracks that intersect the dominant mineral fabric at an angle. Many of the crystals have an atoll inclusion pattern, consisting of a garnet rim enclosing a core of quartz, feldspar, mica, and oxides. A second core of garnet is common within these inclusions. The atoll garnet commonly display radial cracks whereas others are orthogonal and perpendicular to the mineral.

DP-15-13-01: Gneissic banding of amphibole and quartz/feldspar layers dominate this sample. Megacrystic garnet is present in addition to amalgamated or broken up garnet. The euhedral megacrystic garnet is up to 20mm in size. The largest garnet porphyroblasts contain zones of quartz and feldspar inclusions that follow the overall crystal shape in a concentric pattern. The subhedral "broken" garnet are up to 15mm in diameter and have feldspar and quartz inclusions. Many garnet are rimmed with amphibole tails or pressure shadows that show no sense of asymmetry. The smaller population of garnet rimmed with

amphibole have a notable amount of chlorite in contact with them. The outermost amphibole rich layer contains clusters of chlorite, feldspar and quartz that do not agree with the dominant mineral foliation and appear to have the shape of a garnet crystal.

DP-15-15-01: Feldspar and quartz dominate this sample. There are two populations of fine grained garnet, the larger is up to 2.5mm and the smaller, more prominent group is relatively 1mm or smaller. Tabular chlorite is present throughout; a smaller grain orientation is aligned in the foliation whereas larger crystals have a fan-like growth pattern at an angle to the foliation and are a dull blue-gray. The larger chlorite crystals are up to 10mm in size. There is a black subhedral oxide that is sparsely present, with the largest oxide crystal measuring 2mm in size.

DP-15-16-01/02: Quartz, feldspar, mica, and garnet are the dominant minerals present in this sample. Quartz and feldspar populations differ in grain size. Biotite and muscovite define the schistose foliation anastomosing about large quartz and feldspar lenses. The garnet present are subhedral ranging from 1-10mm in size and are commonly elongated in the direction of the foliation. Garnet contain inclusions of quartz and feldspar with biotite rimming the edges. The biotite rims display zircon halos. Oxides are present throughout as well as tiny unidentified red crystals that are needle-like in shape accompanied by little pockets of anhedral shaped crystals that are clear in ppl and dark grey in xpl.

DP-15-17-01: This sample contains gneissic banding alternating between feldspar/quartz-rich and amphibole-rich layers. The more felsic layer is a fine grained and granular mix of feldspar and quartz with ~50% amphibole present. The coarser layers of amphibole and quartz possess elongate amphibole crystals that are aligned in the gneissic foliation. Feldspar crystals present display polysynthetic twinning. Small amounts of chlorite are present and display fan-like habit. Fractured amphibole crystals contain calcite and an oxide along the cracks.

Garnet Porphyroblasts

Garnet is a porphyroblast in many of the samples. Below, features of the garnet and associated minerals are described, including minerals in direct or close contact with the garnet present in each sample.

DP-15-07-02- Garnet are fragmented with no euhedral crystals present. The mineral fabric deflects about lenses of the broken garnet. Close proximity mineral assemblage: quartz, feldspar, chlorite, amphibole, muscovite (or cummingtonite), and opaque oxides.

DP-15-08-01- Garnet are near euhedral to subhedral with the presence of many small inclusions that are evenly distributed throughout. The crystals are predominantly rimmed in biotite, muscovite, and chlorite with tails forming off the edges into the mica-defined fabric. Close proximity mineral assemblage: biotite, chlorite, muscovite, staurolite, quartz, and feldspar.

DP-15-09-01- Garnet are subhedral and contain numerous small inclusions of quartz and feldspar. They are predominately rimmed with an assemblage of mica minerals, including biotite, muscovite, and chlorite.

DP-15-10-01- The garnet population is relatively uniform in size, subhedral to anhedral, with a plethora of small quartz and feldspar inclusions present throughout. Cracks running orthogonal and parallel to the dominant mineral fabric decussate the sample. Biotite and (to a lesser extent) chlorite rims are common around garnet crystals with atoll style inclusions. Biotite occurs at the edges of all garnet observed; however, its extent is often insufficient to warrant the classification as a rim around the crystal.

DP-15-11-01- Garnet present are subhedral and display fractures but appear relatively intact. Many of the crystals have an atoll inclusion pattern consisting of a garnet rim enclosing a core of quartz, feldspar, mica, and oxides as well as in some cases a second core of garnet within these inclusions. The atoll garnet commonly display radial cracks whereas others are orthogonal and perpendicular to the mineral fabric. Many of the crystals present are elongate in the foliation wrapped by aligned micas. Close proximity mineral assemblage: muscovite, biotite, chlorite, quartz, and feldspar.

DP-15-13-01- Garnet present are sub to anhedral and are noticeably larger than the populations in other samples with varying degrees of fracture and disaggregation. Cracks present in the crystal are primarily orthogonal to the foliation present. The more intact crystals contain inclusions of quartz, feldspar, amphibole and oxides that follow a euhedral crystal shape alternating between concentric zones of inclusions and garnet. Aligned amphiboles deflect about disaggregated lenses of garnet. Close proximity mineral assemblage: amphibole, quartz, feldspar, and both blue and green variations of chlorite.

DP-15-15-01- Garnet present are subhedral and contain a high concentration of cross-cutting cracks that run parallel and orthogonal to the sparse aligned population of chlorite. Close proximity mineral assemblage: quartz, feldspar, and chlorite.

DP-15-16-01/02- Garnets present are sub to anhedral, display fractures, and contain many small inclusions of quartz, feldspar, and oxides throughout. The mineral fabric anastomoses about them with concentrated populations of quartz and feldspar found at the elongate edges causing a lenticular shape. Cracks present within the crystals are at a high angle to the foliation. Close proximity mineral assemblage: quartz, feldspar, biotite, chlorite, and muscovite.

DISCUSSION & INTERPRETATION OF DATA & OBSERVATIONS

The primary unit divisions are based on rock type from sample descriptions. When rock type divisions were plotted relative to sample location, their location and the strike and dip of foliation agreed with the divisions showing the samples within each rock type to line up along strike. Next spatial association of metamorphic minerals and structural characteristics were noted for

Figure 10: Map of sample location with corresponding rock type divisions showing how their division along strike agrees with the determined units. Satellite image from Google Maps (2016)..

potential metamorphic or structural subdivisions within each unit.

Primary Division by Rock Type

The primary unit division by rock type was based on primary mineral assemblage, relative abundance of minerals, the distribution of mineral grains, and the relative grain size populations and their structures. Amphibole, quartz, feldspar, mica (i.e. muscovite, biotite, and chlorite), and garnet were the minerals of focus for these divisions.

Amphibole Gneiss

Samples: DP-15-04-01, DP-15-05-01, DP-15-17-01, (DP-15-15-01*)

This amphibole quartz feldspar gneiss will be referred to as the *Amphibole Gneiss* for the remainder of this paper. This group is dominated by granoblastic amphibole (60%+), feldspar, and quartz crystals that are all close in size (<1mm) with an additional population of grouped amphibole crystals that are elongate in appearance. These clusters range from 1-3mm perpendicular to the foliation and range from millimeter to centimeter scale in length in the direction of the foliation. The elongate axes of both amphibole populations are aligned in the foliation. Samples display first order gneissic banding described by layers of predominantly amphibole with intermixed feldspar and quartz as well as layers rich in feldspar and quartz with significantly less amphibole. Second order gneissic banding is present in the form of mica-rich layers that are not as prominent in hand sample and are at the edge of the larger amphibole clusters. The lack of easily observable garnet is one of the strongest features that distinguish this group from the others. The samples contain garnet locally, that are easy to over look in thin section.

**Note about sample 15:* This sample has been grouped with the amphibole gneiss because of its location along strike, its strike and dip of mineral foliation, its uniform relative grain size of the quartz and feldspar populations, and because it does not share the defining characteristics of the other two rock type divisions. However, it does not share all of the defining characteristics of this group. It has easily observable garnet; which samples 04, 05, and 17 lack; there is only sparse presence of amphibole; and there are several populations of chlorite. Due to this, it remains an anomalous sample, and its close proximity to the unsampled pegmatitic body is worth noting for future investigation. Further sample collection in the outcrops close to sample 15's location would be needed to better determine its context within the three predominant units observed and to determine if it should be defined as its own rock type unit.

Possible reasons to subdivide: degree of gneissic banding (17-strong; 04, 05-weak), amphibole pseudomorphs in place of garnet (17-present), calcite (04, 05-present), oxides (17-present), heterogeneities in banding at the hand sample scale (17), and modal abundance of amphibole (e.g. 15).

Amphibole Quartz Garnet Gneiss

Samples: DP-15-07-01, DP-15-13-01

This group is dominated by quartz, feldspar, amphibole, and garnet. The samples possess strong gneissic banding of elongate layers that are rust tan, beige, gray, black, or white in appearance and predominantly monomineralic. Layers vary in size from the millimeter to centimeter scale and thin along strike, commonly tapering out at both ends. Banding present on the centimeter-scale alternates between coarser grained amphibole and quartz rich layers with feldspar and garnet intermixed. Banding present on the millimeter scale includes elongate lenses of amphibole, quartz, and feldspar crystals. Two populations of garnet are present that typically are concentrated in, but not limited to, the amphibole, quartz, and feldspar rich layers. The more prevalent garnet population varies in size from the millimeter to centimeter scale and contain amphibole, feldspar, and quartz as inclusions. The second population consists of megacrystic euhedral crystals that vary in size on the centimeter scale, with 2cm being the largest observed in hand sample. Both populations are rimmed in amphibole and feldspar. Two populations of amphibole are

present. The dominant smaller population is aligned defining a fabric that deflects about the garnets or form an amalgamation of minerals that are similar in shape and size to the garnet present (pseudomorphs). The second population of amphibole is found within these amalgamated clusters with feldspar, quartz, and chlorite.

Possible reasons to subdivide: megacrystic garnets (13-present), felsic or mafic mineral dominated (13-felsic, 07-mafic), strength of banding present (13-strong, 07- weak)

Garnet Schist

Samples: DP-15-08-01, DP-15-09-01, DP-15-10-01, DP-15-11-01, DP-15-16-01/02

This group contains predominantly mica, quartz, and feldspar with a uniformly sized population of garnet approximately 2-3mm in size. Muscovite and biotite are the dominant mica minerals present and define an anastomosing fabric around elongate quartz and feldspar lenses. A second population of large grained feldspar and quartz is present in bodies of pegmatite. These coarse crystals are not cut by the foliation, suggesting that they formed at a separate time from the foliation. The Schist group has coarsened grains of mica, quartz and feldspar, a uniform population size of garnet, as well as off-set boudins present in outcrop that distinguish it from the Amphibole Gneiss group and the Amphibole Quartz Gneiss Group.

Possible reasons to subdivide: staurolite (8 & 9-present), kyanite (9-present).

Figure 11: Representative hand samples for each rock type division with a sample location map for reference.

Interpretation of Metamorphic Mineral Relationships

The following observations in metamorphic mineral relationships were not used to define the divisions based on rock type but are worth further examination for possible subdivisions of the three units.

Garnet

Populations of garnet varied significantly from sample to sample. Below are groupings of garnet with similar features:

Figure 12: Photomicrograph of Sample 08 thin section in ppl showing garnet that is representative of those seen in the Garnet Schist unit. They contain inclusions of quartz and feldspar throughout and are rimmed by biotite. Staurolite was found locally in this sample, as well as sample 09 distinguishing it from the other samples within the unit. Standard-sized thin section; rock section is ~3.5cm in length.

- Samples 08, 09 (Figure 12), and 16 all contain garnet that is sub to euhedral with many small quartz and feldspar inclusions spread throughout the crystal. The mica-defined foliation anastomoses about the crystal with a concentration of biotite and chlorite around the rim that extends to create tails that lead into the foliation.

Figure 13: Photomicrograph of Sample 13 thin section in ppl showing amphibole-dominated rims on disaggregated garnet and garnet shaped pseudomorphs. Standard-sized thin section; rock section is ~3.5cm in length.

- Samples 07 (Figure 13) and Sample 13 contain garnet that is deformed and rimmed predominantly by amphibole with quartz and feldspar as inclusions. The amphibole-dominated rims continue as tails into the foliation. The samples contain garnet-shaped pseudomorphs made of the same predominant minerals as the rims.

Figure 14: Photomicrograph of Sample 11 thin section in ppl showing garnet with atoll inclusions. Nested atoll features present in the garnet to the top left. Standard-sized thin section; rock section is ~3.5cm in length.

- Sample 11 has garnet with an atoll inclusion pattern consisting of a garnet rim enclosing a core of quartz, feldspar, mica, and oxides (Figure 14). Some garnets possess a nested island of garnet with in the outer rim that contains a core of inclusions as well.

- Sample 15 (Figure 15) has sparse garnets that are subhedral and retain their crystal shape while cross cutting cracks run parallel and orthogonal to the foliation. It contains two populations, the smaller of which has an elongate mineral shape.

Figure 15: Photomicrograph of Sample 15 thin section in ppl showing garnet that is unlike the other samples within the Garnet Schist unit and could be grounds for the samples removal from this unit. Standard-sized thin section; rock section is ~3.5cm in length.

- Little to no garnet was observed in samples 04, 05, and 17. In those that did contain garnet, the garnet displayed similar characteristics to those observed in sample 15.

Figure 16: Photomicrograph of Sample 13 thin section in ppl showing zoned inclusions of quartz, feldspar, and amphibole present in the garnet population. Standard-sized thin section; rock section is ~3.5cm in length.

- The larger garnet porphyroblasts of sample 13 (Figure 16) contain zones of quartz and feldspar inclusions that follow the overall crystal shape and are nested within one another.

Samples 08, 09, 10, and 16 have similar garnet with similar inclusions to Samples 11 despite the atoll inclusion pattern, which is consistent with all of them belonging to the same Garnet Schist unit. All the garnet in this unit are rimmed with biotite as well. Samples 07 and 13 share similar amphibole rimmed garnet, which is in agreement with them both belonging to the Amphibole Quartz Garnet Gneiss unit.

Sample 15 contains two sparse populations of garnet, which disagrees with the Amphibole Gneiss grouping, whose other three samples (04, 05, and 17) contained no observable garnet.

Two predominate pseudomorphic or reaction relationships are present, both involving garnet. The Amphibole Quartz Garnet Gneiss unit contains garnet with rims of amphibole, feldspar, quartz, and opaque oxides as well as populations of these minerals that have growth patterns that are not aligned in the foliation and commonly are grouped in the shape of a garnet crystal despite garnet not being present (Figure 16). The Garnet Schist unit contains garnets rimmed in biotite with quartz and feldspar inclusions (Figure 12).

Other Minerals:

- Staurolite - Sample 08 & 09 contain a considerable amount of staurolite.
- Kyanite - Sample 09 contains a sparse amount of kyanite.
- Zircon - Samples 07, 11, and 16 contain zircon halos within the larger crystals of biotite that rim the garnet present.
- Chlorite: Samples 07, 13, and 15 all contain blue and green color variations of chlorite as well as fan and tabular growth patterns.

The presence of these minerals do not correlate with rock type divisions but could be used to make future subdivisions.

Interpretation of Structural Relationships

The Amphibole Gneiss and the Amphibole Quartz Garnet Gneiss units both had mineral lineations with similar trend and plunge measurements whereas the Garnet Schist unit differed from them.

Asymmetrically off-set boudins and local folds were observed in the Garnet Schist unit whereas no boudin or fold structures were observed in the Amphibole Gneiss or the Amphibole Quartz Garnet Gneiss units. All the units had similar strike and dip measurements of foliation.

Implications

Implications of Metamorphic Mineral Relationships

A small amount of Kyanite was observed only in Samples 09, whereas this mineral is abundant in the Damon Pond section, potentially indicating similar conditions of metamorphism at some point in their PTD history

The uniform size of the garnet population in the Garnet Schist could indicate that the crystals were all growing at the same time whereas the variation in the populations present in the Amphibole Quartz Garnet Gneiss could indicate different growth events among the garnet.

The garnet present in the Amphibole Quartz Garnet Gneiss were breaking down leaving garnet-shaped pseudomorphs, which could indicate this replacement reaction is taking place post deformation.

Garnet was found to be present in one of the four Amphibole Gneiss samples, which could indicate the unit does contain a significant population of garnet but that it was just not observed in the representative samples of the other three localities. If this were found to be the case, it would be necessary to rethink the

division among the gneissic units since the presence or absence of garnet was a key-determining characteristic.

The mineral assemblage and structural characteristics observed in the Amphibole Gneiss group are interpreted as pseudomorphs and could indicate that garnet was once present and reacted away.

The larger garnet porphyroblasts of Sample 13 contain zones of quartz, feldspar, and amphibole inclusions that follow the overall crystal shape and are nested within one another, which could indicate that there were multiple garnet growth events experienced by these porphyroblasts.

Implications of Structural Relationships

The gneissic layers showed a weak mineral lineation among the amphibole that had a dominantly NW trend accompanied by a shallow plunge which would be consistent with flattening-dominated strain. The Garnet Schist had mineral and intersection lineations that were found to be at a high angle in regard to the dominant foliation direction and contains asymmetrically off-set boudins, indicating back rotation and an overall top to the south sense of shear. The difference in mineral lineation between the rock types may indicate different deformation histories or behavior during deformation. The units all had similar strike and dip measurements of foliation, which indicates they are most likely internally coherent and do not show signs of significant folding or faulting. The Damon Pond section contains an isoclinal fold that suggests it preserves evidence for a part of the deformation history not seen or not preserved in the other rock units.

CONCLUSION

The lithologic units that were the focus of this study lacked the abundant megacrystic garnet and kyanite, significant folding, and nesting boudin structures that are defining characteristics of the Damon Pond section. This indicates that the units described in this study are distinctly different from the Damon Pond section, suggesting that the Damon Pond section is a relatively small terrane. The significant folding and boudinage in the Damon Pond section are more complex internal structures than in the surrounding units described in this study. The lack of large-scale deformation in the surrounding units, the internal disruption, and close proximity to a pegmatitic body are all consistent with small UHP terrane emplacement mechanisms, such as channel flow or diapirism. Sample collection of the areas surrounding the Damon Pond section that were not the focus of this study would need to be conducted in order to evaluate this hypothesis.

Due to the limited time in which the preliminary field work was conducted and the limited nature of outcrop accessibility from which in-situ samples could be obtained, a more comprehensive suite of samples will need to be gathered to determine the significance of the suggested divisions and sub-divisions. The implications of these divisions and suggested subdivisions are beyond the current scope of this thesis and could be investigated further in the upcoming year for graduate thesis focus.

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