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Depositional Setting and Deformation History of Central-Western Maine: Silurian Stratigraphic Revisions for the Newry-Gilead Region

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Depositional Setting and Deformation History of Central-Western Maine: Silurian Stratigraphic Revisions for the Newry-Gilead Region

Bates College Geology Departmental Thesis

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by

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Abstract

The Newry-Gilead region of western Maine is comprised of migmatized Silurian (?) metasedimentary rocks intruded by members of a Devonian (?) quartz diorite suite, Devonian to Permian (?) two mica granite, and widespread migmatites and pegmatites. The bedrock was remapped in 2013, with the goal of reevaluating the region's stratigraphy and intrusive rocks, and to ultimately gain a more complete understanding of the region's tectonic history largely influenced by the Salinic and Acadian orogenies. Eight metasedimentary units and two igneous units were mapped for this project. This study focused on the metasedimentary units, and a complimentary study on the petrography of the igneous units was conducted by Saebyul Choe (2014).

The metasedimentary rocks from youngest to oldest (?) include the following units: Sgf, a biotite and/or calc-silicate granofels (Madrid Formation?); Ssqr, a rusty schist and quartzite (Smalls Formation?); Sqsc, quartzite and schist with calc-silicate pods (Perry Mountain Formation?); Ssq, a greyschist and quartzite with calc-silicate pods; Ssg, a greyschist; Ssr, a rusty weathering schist with calc-silicate pods; Ssqg, a biotite granofels; and Ssqm, grey schist and quartzite with calc-silicate pods. The five oldest units are interpreted to be correlative with the Rangeley Fm. The abundant calc-silicate pods may represent olisotromal features deposited in an active tectonic setting during the Salinic Orogeny. The mapped units here differ greatly from the current Bedrock Geologic Map of Maine, due to the reconnaissance nature of the previous mapping in the region. All of what was previously mapped as Devonian Littleton Formation in the study area has been redesignated as Silurian Rangeley Formation. Perry Mountain Formation was identified in the study area for the first time.

Two periods of ductile deformation and two periods of metamorphism occurred during and after the Acadian Orogeny. D1 is the establishment of schistosity and rare early folding. Four D2 folds were mapped in the field, and map and thin-section folds were also present. The area is heavily migmatized, which is correlated with Acadian subduction. Mineral alterations and late stage growth are associated with the intrusion of the Sebago Pluton. Fractures in the region are associated with the northwest-southeast tensile stress of Mesozoic rifting.

The findings from this thesis place the deposition of the majority of the rocks as in the Salinic Silurian Orogeney. The next three units were deposited after the Salinic, but before the deposition of the Littleton Formation at the onset of the Acadian Orogeney. This model has regional implications for Appalachian tectonics and suggests that further mapping is needed in surrounding areas.

Acknowledgments

I would like to thank the Bates College Geology Department for four great years of exploring the rocks in Maine and the constant support throughout the entire thesis process. The Geo community is by far one of the best at Bates, and I am so glad to be a part of it.

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I cannot thank my advisor, J. Dykstra Eusden, nearly enough for the enthusiasm and support he's had for this thesis. His guidance and dedication to helping make this project great have really kept me motivated.

The production of the map would have been much harder without Mat Duvall of the Bates College Imaging Center. Thanks for all of your help troubleshooting!

Thank you to all my fellow geo seniors for the feedback in thesis seminar and the late nights in Coram. Special acknowledgement goes to my field partner, Saebyul Choe, for a wonderful summer of mapping in the field, long afternoons in the rock-cutting room, and her loyal friendship.

My family has supported me through my entire time at Bates, and I am particularly thankful for their constant love and encouragement as I approach the end of my final year.

Finally, I would like to thank my seventh grade math and science teacher, Matt O'Connell. He fostered my budding passion for science, and prompted me to go home one day and say, "when I grow up, I want to study plate tectonics."

Team Blue Bandana. Thanks John for all of your help and congratulations on your retirement!

Me, Saebyul, and Dyk on our first day of mapping!

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Introduction

The Sunday River area in Newry, Maine is a popular destination for skiers in the winter and hikers in the summer. It is known for its natural beauty, which many visitors enjoy from their vacation homes. The area is rapidly developing to accommodate more tourists, and for this reason and others it is an important place to study the geologic history of. Travelers who come to the region to enjoy its natural aspects might be interested to learn about its geologic history, and knowing the bedrock types can be helpful with the development of the new condominiums and other attractions. Geologists are interested to know about the stratigraphy of the region, and the information that can give about the rocks' depositional setting and deformation history.

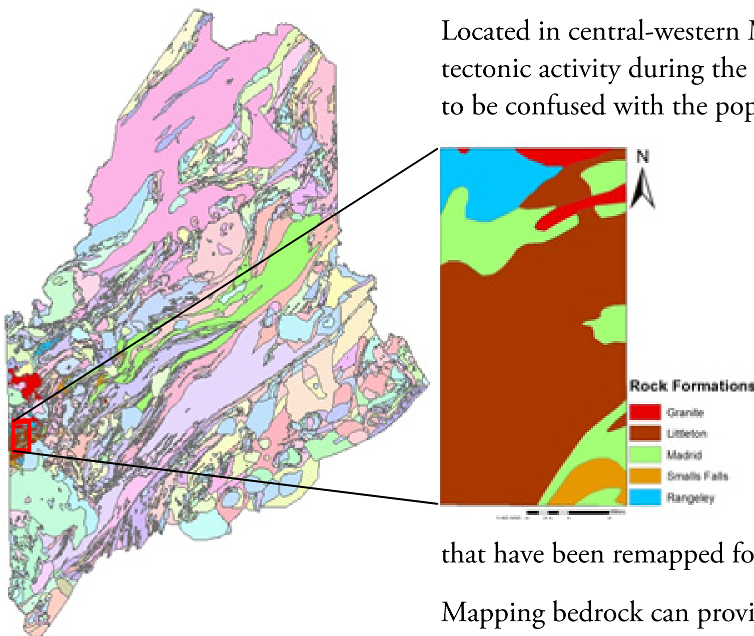

Figure 1: Study area location map of currently published bedrock types. Map from Maine Office of GIS Data (2011).

Located in central-western Maine, Newry experienced frequent tectonic activity during the orogenies that created Pangea. Not to be confused with the popular ski area, the actual Sunday River itself has carved out a path through the region's bedrock, which allows greater access for mapping the geologic units that would have developed as the region underwent these mountain building events. Additionally, recent logging in the area has uncovered outcrops which were previously inaccessible. Figure 1 shows the current state bedrock map from the Maine Office of GIS Data, and the inset displays the rock types in the study area that have been remapped for this project.

Mapping bedrock can provide information for analysis of the tectonic history of the region and the setting in which the rocks were deposited. The mineralogy and petrography of the rock types in addition to the spatial relationship of the units can help create a reliable story for the region's bedrock deposition. Previous studies have found that New England has undergone many mountain building events. During the assembling of Pangea, there were multiple periods of docking landmasses, which also created new land and therefore new rocks. The deformation that the region has experienced is also quite extensive, both during these orogenies and during the breakup of Pangea as the Atlantic Ocean was formed. Low pressure and high temperature conditions during mountain building caused much of the metamorphism in Maine (Guidotti 1989), and both large-scale and small scale folds have previously been mapped (Eusden 2013). Partial melting expressed as migmatism occurred along margins of granite plutons. Many of the joints in the region were caused by extension during the rifting of the Atlantic, giving the entire region a dominantly northeast-southwest joint strike. These are similarly oriented with the bedrock strike that was aligned during the collisional tectonism that formed the region.

In Newry, Maine, both the deposition of new rocks and their subsequent deformation are interesting and useful to study, and the results will have benefits for geologists and lay people alike. Vacationers may be interested to learn about the processes that shaped the region. The map can be useful for identifying where resources might be, such as granite which is often used in construction. Fracture orientations could help with groundwater assessments, along with the rock types within an aquifer. For example, one rock type found in the quad, a two-mica granite, can release uranium and radon which can be a health hazard. Understanding the depositional and deformational setting of the study area is useful in figuring out the tectonic history of a much broader region, for example all of New England. This thesis aims to create a map and provide the background of the area's tectonic history that will be useful to those with any level of interest in the geology of the region.

Mapping Project

The study region for this report covers the western half of the Gilead 7.5' Quad and the southern boundary of the Old Speck 7.5' Quad in Western Maine, incorporating the Bull Branch of the Sunday River and Goose Eye Mountain. Figure 2 outlines the parts of the quads where data was collected. From mid-July to mid-August 2013, mapping was done for the Maine Geological Survey in this thesis' study area and the westernmost portion of the Shelburne 7.5' Quad with my field partner, Saebyul Choe. Data was collected on the lithology, mineralogy, metamorphic grade, and structural features of each outcrop, and recorded in a Juno Trimble GPS unit. It was used to create a map detailing contacts between rock types and metamorphic grade. Rock samples collected from the field were turned into thin-sections, which were then analyzed using transmitted light microscopy to help define the different rock units based on slight differences in petrography.

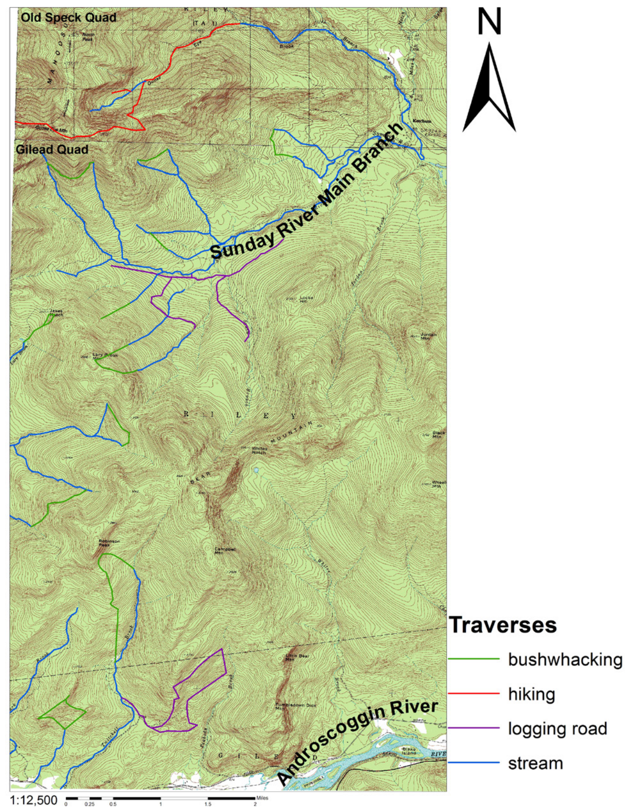

Figure 2: Topographic map of study area with color-coded lines indicating the traverses covered for this thesis. Gridded area in the North is the Old Speck Quad.

The units that were mapped are all formations that have been previously discovered, but may not have the same spatial and stratigraphic relationships as is reported on the current published bedrock maps of the area. The study area was very close to the New Hampshire border, so the rock types mapped could be extended and may require an additional mapping project to look for similar stratigraphy in the surrounding areas.

General Purpose

Significant information can be learned about the geologic history of Newry from the collected bedding and joint strike and dip information, and the recorded and sampled bedrock types. The findings from the collected data will not only have meaning for this specific study area, but for regional stratigraphy and deformation history as well, extending into New Hampshire and eastward into Maine. The remapping of rock units could offer a new perspective on regional geologic history and may end up altering other currently held beliefs about the region's stratigraphy. Observations from the field of the bedrock types and characteristics offer insight on the potential setting during the deposition of the rocks. Mineralogical differences and microstructures in thin-section can help further separate rock units, and contribute to the analysis of deformation history. The main questions this thesis aims to explore are: “What was the depositional setting of the region’s stratified rocks?” and “What is the history of regional deformation?” Together the answers to these two questions will tell a story about the complete tectonic history of the region, with a focus on events during and since the Silurian period. There are already existing interpretations of this story; however they were based on older maps and data for the area. Remapping the rock types in the region may present a revised model for the region’s tectonic history. This thesis connects with and updates previous studies conducted in this and surrounding study areas to both discover the tectonic history of the region, and produce a new bedrock map of the Sunday River area in Newry which may have greater implications for current theories on the region’s geologic past.

Previous Studies

The area was last mapped about 30 years ago in a reconnaissance study by Moench, Hatch, and Lyons, based off of findings presented in their 1983 paper. Both they and Billings and Billings (1975) mapped much of the region as Devonian Carrabasset Formation, although the Billings’ mapping was done just to the west in the Gorham 15’ Quad in New Hampshire. The Gorham 15’ Quad includes the Shelburne 7.5’ Quad which shares a border with the Gilead 7.5’ Quad. The findings from Moench, Hatch, and Lyons (1983) were incorporated into the statewide Bedrock Geological Map of Maine published in 1985 and is shown in Figure 1. From last summer’s mapping, however, it appears that at least some of what was previously mapped as Carrabasset Formation is actually Silurian Rangeley Formation. The researchers from last summer, Professor J. Dykstra Eusden and Riley Eusden (Bowdoin 2014), mapped an adjacent region and found Rangeley Formation similar to that outlined by Tim Allen (1996) in the Carter-Moriah Range of New Hampshire. The Littleton Formation is described as a well-bedded grey schist and quartzite, whereas recent field observations found schists of varying degrees of rustiness and partial melting, with abundant calc-silicate pods. In Billings and Billings’ 1975 report, the Littleton Formation includes some of what they call lime-silicate rocks, but they make up a very small percentage of rocks in the formation.

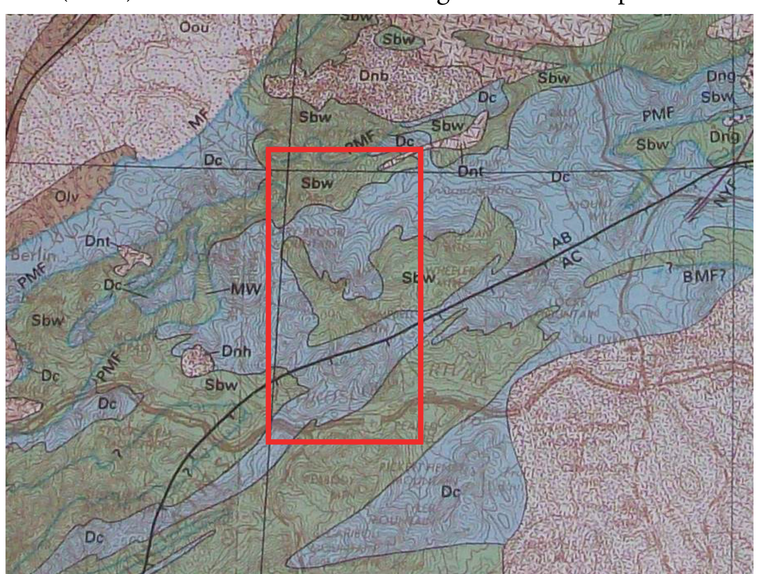

Figure 3: Moench, Boudette, and Bothner 1999 map of Sunday River region. Dc=Carrabasset (blue), Sbw=Rangeley (green). Tan colors are igneous. Red box outlines this project’s study area.

Since then, more studies have been done which began to revise some of what was identified as the Littleton Formation and changed it to the Rangeley Formation. Moench, Boudette, and Bothner mapped the area in another reconnaissance study in 1999. The portion of their map that includes this project’s study area is shown in Figure 3. It shows nearly equal amounts Carrabasset Formation and Rangeley Formation, which is much more than in previous versions of the map. The Rangeley Formation is described as “gray and rusty orange weathering coarse-grained pelitic schists and migmatite gneisses, with minor interlayered quartzites, and abundant, distinctive calc-silicate pods” (Allen 1996). This is very similar to Moench’s description of the unit he called Rangeley C (1970), though updated and more specific. Though Moench, Boudette, and Bothner actually did remap some of Billings' Littleton Formation as Rangeley Formation (1999), recent mapping in the region suggests that a greater amount of what was Littleton Formation in central western Maine should be redesignated. The mapping done by Eusden (2013) in the eastern Gilead Quad and western Bethel Quad found eight units that correlate with the Silurian Rangeley Formation (Figure 4). If a significant amount of the rock in the unmapped portion of the quads is indeed Rangeley Formation, it could have implications for the stratigraphy of the entire region.

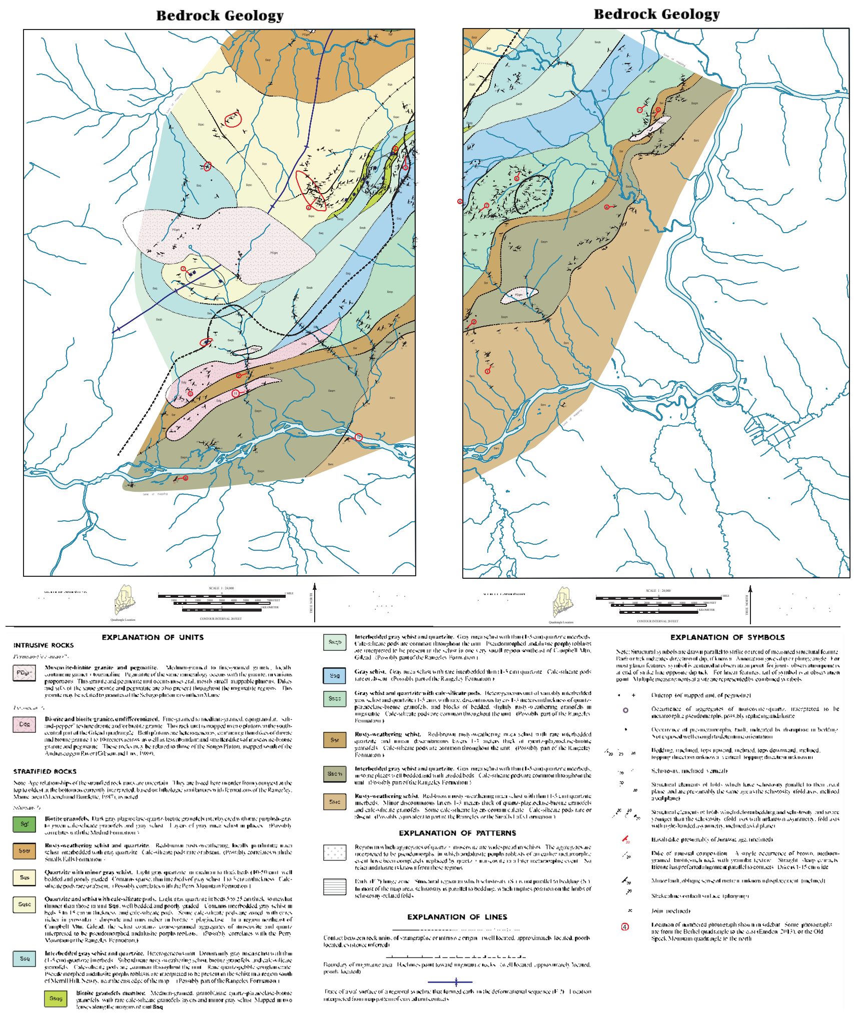

Figure 4: Maps of bedrock units in the Gilead and Bethel Quads based on data collected by J. Dykstra Eusden during the 2012 field season.

Depositional Setting Models

A modern interpretation of New England's depositional setting is that it contains units deposited during the Late Ordivician and Silurian Taconic and Salinic Orogenies and deformed by the Devonian Acadian, Devonian-Carboniferous Neoacadian, and Permian Alleghenian Orogenies. For this thesis, the focus was on the rocks from the Salinic Orogeny and younger. The Salinic Orogeny was in the Early Silurian period, and featured the deposition of the Rangeley Formation (Figure 4). During the Salinic Orogeny, Ganderia was accreting to Laurentia. This active tectonic zone exhibited rock formation from the sub-marine sedimentary basins. Moench (1970) illustrates the units being deposited along a sub-marine slope, flowing down towards the basin due to increased fluid pressure in some of the layers (Figure 5). The bottommost layers, Ordovician Dixville Formation and older, were stable and unpenetrated by the excess fluid, and so were not deformed during the Silurian period, or with the rocks deposited then. He also describes the Rangeley Formation as being "deposited on an active southeast-dipping slope" (Moench 1970). This is most likely a description of terrigenous sediments being deposited as either turbidites or sub-marine fans. In some accounts, the slope is tectonically active, which may indicate that the slope is on the overriding plate at a convergence zone. The Rangeley and Perry Mountain formations were deposited on top of the Ordovician units later during the Silurian period and then deformed with them in the early Acadian Orogeny, beginning during the early Devonain at around 408 Ma (Bradley and Tucker 2002). The Smalls Falls and Madrid units were then deposited and deformed synchronously during two different Acadian events (Moench 1970), as the subcontinent Avalonia began to collide with the northeastern margin of North America. An update to the model was proposed more recently by Moench, Boudette, and Bothner (1999), claiming that during the Silurian period in Maine, there was actually an extensional environment due to two opposite-facing subduction zones. The extensional region was closed by the early Devonian in this model, and then deposition continued as described above. This is similar to what is presented by van Staal et al. (2009) in Figure 6, and helps to more specifically place the slope on which the deposition and then deformation of sediment would occur. This model for depositional setting is consistent with the present theory on the region's tectonic history during the Silurian and Devonian periods, which exhibited an active boundary between docking terranes and what there was so far of New England.

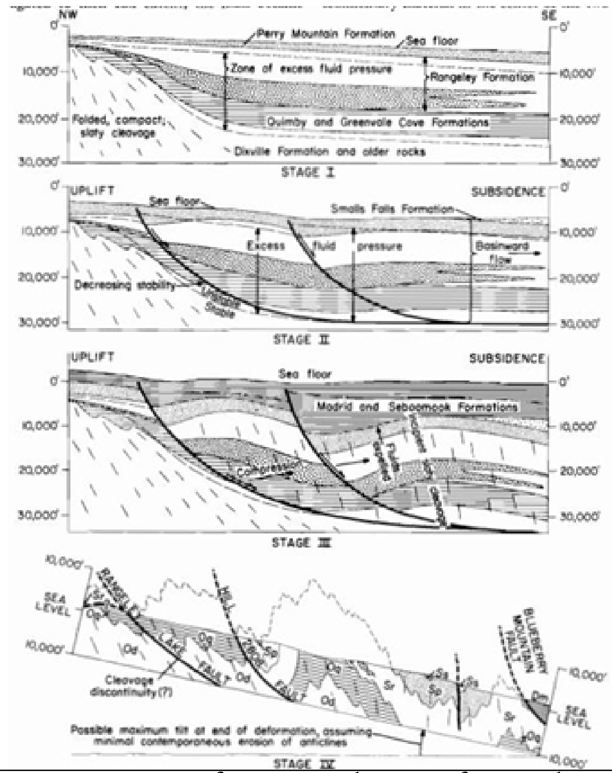

Figure 5: Diagram from Moench 1970 of regional stratagraphic sequences being deposited and deformed along a SE dipping slope. Perry Mountain deposited above undeformed Rangeley, with Smalls Falls and Madrid being deposited during deformation.

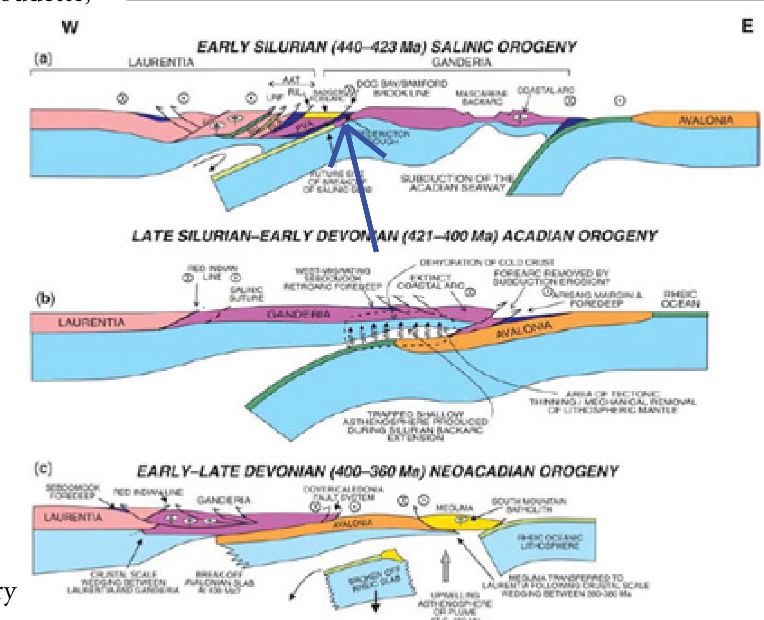

Figure 6: Tectonic setting of New England during the Salinic and Acadian Orogenies. Blue arrow points to deposition location for rocks found in central-western Maine and surrounding areas. Figure from van Staal et al. 2009.

Macrostructures as Clues

In the above description of the Rangeley Formation from Tim Allen, he mentions that one of the identifying factors of the unit is the presence of calc-silicate pods. These could end up being good indicators of depositional setting, because they are formed in unique environments. A present theory on their formation is that in a marine basin, sediments get deposited along a continental slope in layers. Within the sediment there are layers containing calcium, from limestone, and silica, from sand or other siliceous rock types. In the pods these minerals are expressed as calcite and clay minerals, which are then metamorphosed into diopside and grossular garnet. During earthquake events the calc-silicate layers are broken up into clasts, and during deformation they were stronger than the surrounding sediment and held their shape, becoming clastic pods in the finer-grained matrix. This is illustrated in Figure 7 from Eusden (1996). If this is the case, the produced rock unit might be what is called a melange. A melange is a rock unit that does not have continuous internal strata and contains inclusions of all sizes, according to Raymond (1984). Units containing calc-silicate pods might be olisostromal mélanges, which are often formed in sub-marine active subduction margin settings (Allen 1996). Layers containing these minerals are deposited among layers of schist on a continental slope above an acretionary wedge. When seismic activity occurs, the layer is fractured and the chunks are incorporated into the surrounding matrix. In the field, they appear in both grey and rusty schists. If an olisostromal mélange is indeed what was observed in the field at the study sites, it would be very good evidence for narrowing the tectonic setting down to a forearc basin in an active subduction zone. This is an example of how macrostructures in bedrock mapping can provide valuable information on the geologic history of the region.

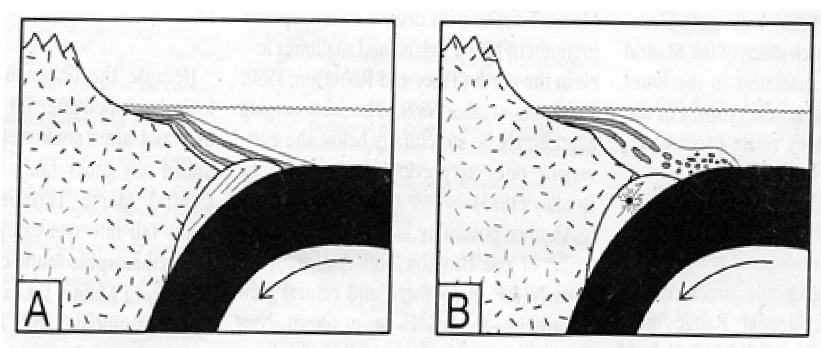

Figure 7: Model of how olisostromal mélanges form. A shows deposition of sedimentary layers over active subduction zone. B shows the breakup of layers into clasts during a seismic event. (Eusden et al.1996; Maconochie 1994).

Models of Stratigraphy

The Devonian Littleton Formation was deposited in front of the westward-advancing Acadian Orogeny (Bradley et al. 2000). It has been described as a well-bedded greyschist and quartzite. Though not a direct result of the tectonism, such as volcanic ash deposits or basalt flows, the metasedimentary rocks that were formed during the Acadian Orogeny were deposited in an active tectonic zone.

Besides the Rangeley and Littleton Formations, other rock types in the area are the Silurian Perry Mountain Formation, Silurian Smalls Falls formation, and the Silurian Madrid Formation (Moench 1970, Allen 1996, Eusden 2013). These were all deposited similarly but contain different rock types, with the Smalls Falls being a rusty schist and the Madrid being a granofels layer. These units were all deposited in between the Rangeley and Littleton Formations, in the order listed above (oldest to youngest). In Moench's 1970 paper, he discusses at length the stratigraphy of western Maine according to his field studies. In the Rangeley Quadrangle he found that Ordovician units such as the Quimbly and Dixville Formations unconformably exhibited less deformation than their overlying Silurian and Devonian aged units. Moench found two sequences in his study area, the Northern and Southern sequences. In the Southern sequence, the older layers are not exposed. Instead Moench describes two Devonian aged units which would overlie the Silurian units. They are both well-bedded sulfidic metashales with lesser metasandstones, calc-silicate rocks, and marble, although the lower unit also contained feldspathic metasandstone. He also acknowledges the presence of a Silurian aged unit that he believes may underlie the upper two units despite the lack of outcrop. In the Northern sequence, all of the units from the Ordovician Dixville Formation to the Silurian Madrid Formation, along with a unit called the Devonian Seboomook Formation were mapped. These units have been widely accepted and many models for the region's tectonic history have been built upon the faith that these and updated versions of mapped units are accurate. Moench conducted his study from 1970, but more recent studies on the regional stratigraphy cite his paper for the main parts of their work. Moench also continued to update his findings in a 1983 paper with Hatch and Lyons. As mentioned above, this remapping featured more Rangeley formation than earlier maps, indicating that the stratigraphy may be slightly different. This thesis will use Moench's framework of stratigraphy for central-western Maine, but will incorporate observed data from the 2012 and 2013 field seasons.

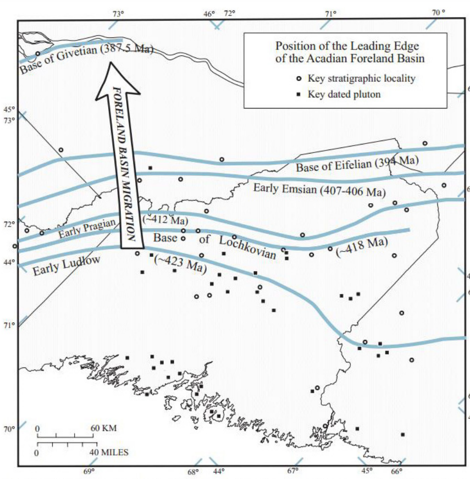

Figure 8: Migration of the Acadian foreland basin across the state of Maine. From Bradley et al. (2000).

Metamorphism

As a result of all the active tectonism during the assembly and separation of Pangea, the area has experienced a significant amount of metamorphism. The Acadian Orogeny, which encompasses the last five million years of the Silurian period and a large but debated amount of the Devonian period, is now interpreted as having affected and deformed the entire state of Maine (Bradley et al., 2000). Folding and other ductile deformation seen in the study area were products of the Acadian Orogeny and the following mountain-building events. The ductile deformation occurred in two phases: the establishment of schistosity and rare early folds at the onset of the Acadian Orogeny, and large scale folding during the inland advance of the active deformation front (Figure 8).

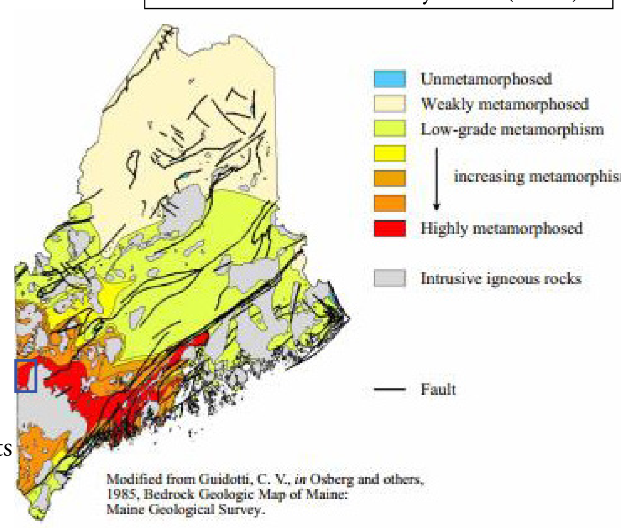

Figure 9: Grades of Acadian metamorphism in Maine (Osburg et al. 1985). The blue box outlines the study area for this thesis, which includes amphibolite and upper amphibolite grade metamorphism.

Maine was mostly affected by the Siluro-Devonian low pressure-high temperature metamorphism, according to Guidotti's three phases of metamorphism (1989). Igneous plutons intruded through the stratigraphy, which produced heat that caused additional metamorphism. Both granite and diorite plutons have been mapped in central-western Maine, and a few igneous dikes were also found. According to many authors (Moench, 1970; Guidotti 1989; Solar and Brown 1998; etc), the plutons are all Devonian age as they intrude through the metasedimentary layers, and therefore are a result of the Acadian Orogeny. The kind of metamorphism associated with these plutons often includes mineral recrystallization. In central-western Maine, rocks reached the amphibolite and upper amphibolite grades of Acadian metamorphism (Figure 9). This is indicative of a more syn-tectonic period of deformation as well.

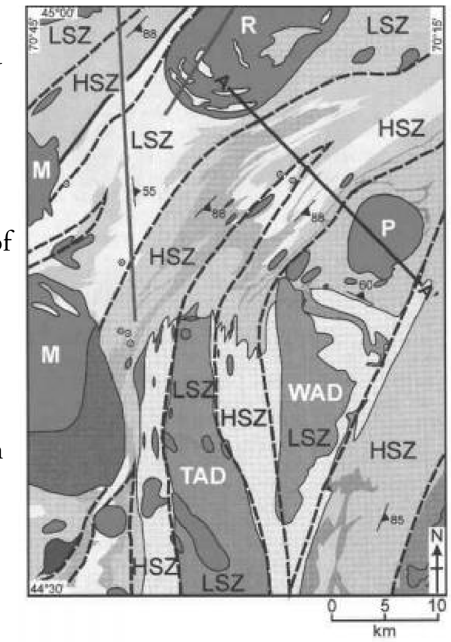

Figure 10: Tumbledown and Weld Anatectic Domains (TAD &WAD), representing the upper migmatite boundary in western Maine according to Solar and Brown (1999). Their study area is just northeast of the study area for this thesis.

The region also has abundant migmitites, which are often caused by the heating from igneous intrusions (Guidotti 1989). Solar and Brown (1999) determined that this study's general area is the northern migmatite boundary of the Central Maine Belt (Figure 10). Brittle deformation caused the ubiquitous fractures seen in the region, which are likely due to Mesozoic rifting (Faure et al. 2004). The different types of metamorphism and deformation that affected western Maine are common throughout much of New England, as during the Acadian, Neoacadian, and Alleghenian Orogenies, the dockings of Gander and Avalonia had similar effects on the region.

Research Questions

The Sunday River region in Newry, Maine has many interesting rocks to study because they can reveal so much about all aspects of the region's tectonic history. Several previous mapping projects have been completed in the region, but are out of date or inaccurate due to the limited number of bedrock outcrops in the area at the time they were conducted and their reconnaissance nature. The region is still mostly covered by forest, but logging and development projects in recent years help allow for more updated mapping, as new roads were built which created new bedrock exposures. Macro-scale features and generalized rock types can help define units and give clues about the depositional setting. Micro-scale deformation of the rocks can be analyzed using thin-sections of samples collected from the field, and strike and dip data of bedding and joints help to see big folds and regional deformation patterns. Using both field collection and information from past studies, this thesis has analyzed the tectonic setting of the region during and after the Silurian period; mainly the depositional setting of rock types as well as the deformational events the rocks have undergone. A broader region is studied because rock types were not deposited locally, but in massive regional events. Billings and Billings (1975) discuss the importance of being able to see the bigger picture and connect rock types across state lines to get a full understanding of the geologic events that took place. This thesis used field data collected from the Sunday River region in Newry, Maine, to model the tectonic history of central-western Maine and northeastern New Hampshire. In terms of the rock types observed in the field, a few specific questions are raised. Is what has previously been mapped as Devonian Littleton Formation actually the Silurian Rangeley Formation? To what extent? Is the Rangeley Formation an olisostromal mélange and formed at an active subduction margin? What implications does this mapping project have on currently mapped units for New Hampshire and Maine? The map produced will be published by the Maine Geological Survey, and together with this thesis, will provide important information to all people interested in the geologic history of Newry, Maine.

Methods

Field Mapping Methods

The mapping for this project was done over five weeks during the 2013 field season, with each week containing forty hours of fieldwork. The study area was about 5-10% outcrop, since most of the region is either wooded or developed. Additionally, many of the river drainages were mostly filled with boulders. Bedrock exposures were found by hiking up all of the Sunday River and a few of the Androscoggin River drainages, and exploring logging roads in the regions of Gilead and Newry. Bushwhacking was also a method of getting between drainages and finding occasional forest bedrock exposures that were present at steep changes in slope on heavily wooded mountainsides (Figure 11). Each outcrop was measured for any applicable strike and dip of bedding, which was parallel to foliation, and fractures. Fold axial plane and hinge line, as well as dike contact data, were also measured and recorded, along with rock type and any unique features. Strike and dip data was taken using Brunton compasses and following Right Hand Rule, then recorded in both a Trimble Juno handheld GPS unit and a Rite in the Rain 540F notebook. The Bethel State Map data dictionary was used in the Trimble to record data, and the GPS unit was also loaded with DRG images of the Gilead and Old Speck 7.5' Quads.

About 345 data points were collected during field mapping. When outcrop exposures were continuous, a point would be taken to mark its beginning and end. Otherwise data was collected about every 50 m when exposures were available, or earlier in the case of a change in rock type. At a location with multiple exposures, all present bedrock types were recorded. In this way it was hoped that the traverses were thoroughly covered and the contacts accurate. With migmatized exposures the bedding direction was difficult to determine, and occasionally joints required a remote method of taking strike and dip, aligning the compass with a clear expression of the fracture across a stream. Also sometimes it was necessary to peel moss off an outcrop to access the bedding information. Each traverse was carefully recorded on a paper ortho- and topo-map, created by Josh Sturtevant and Cam Held (Bates 2014). This helped visualize what had already been mapped and what was left to accomplish, and backed up the electronic data. Samples were taken at nearly every site using rock hammers, with an emphasis of getting a wide representation of rock types and unique characteristics. For this study, schist, granofels,

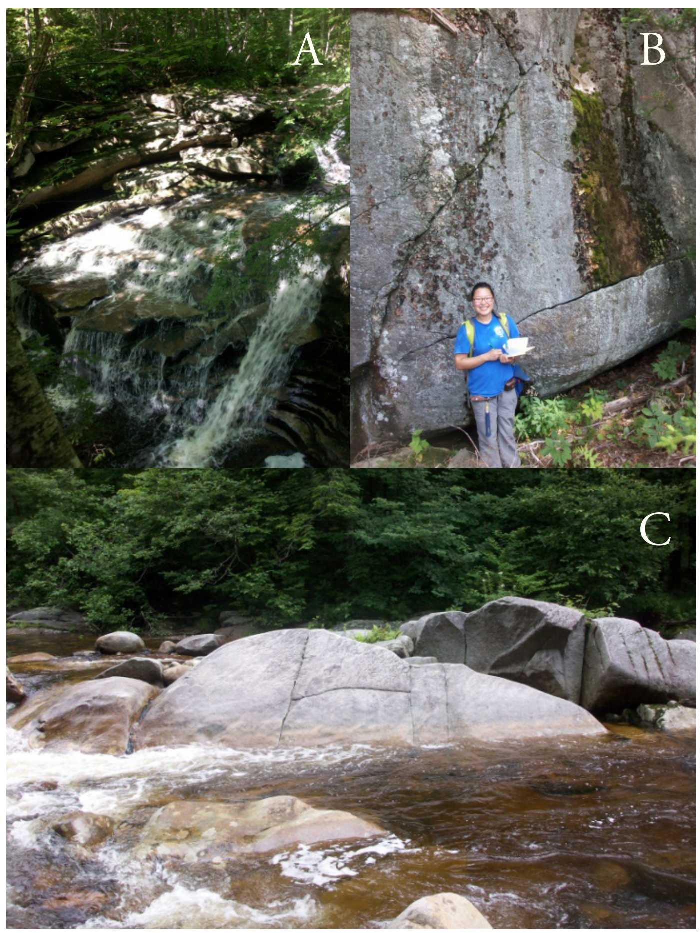

Figure 11: Three examples of field outcrops. A: waterfall exposure. B: logging roadside exposure. C: Stream bank exposure.

and calc-silicate samples were the most important, though igneous plutons and dikes were also mapped and their samples were collected. The field data was collected mostly in the Gilead 7.5’ minute quad, which was done for the purposes of adding to the Eusden’s mapping from the previous summer to add to the map for the Maine Geological Survey. The data collected in the Bull Branch of the Sunday River and the Goose Eye Mountain region of the Old Speck Quad was for the purposes of this thesis.

Lab Mapping Methods

After each field day, the datafile was transferred to a Panasonic Toughbook using GPS Pathfinder Office and exported as an ESRI Shapefile. In this form it could be added as a layer in ArcGIS 10.1. Data from each day was appended to a master file, which was used to create feature classes divided by rock type. There were divisions between schists, igneous rocks, and granofels; as well as different degrees of rustiness and migmatism, and presence of calc-silicate pods or coarse-grained micas. Each outcrop is represented on the map with an inclined bedding symbol from the Geology 24K style references. The contacts which were drawn between rock type units used strikes and dips to guide the lines. The decision of where to draw the contacts was also aided by the contacts made last summer by J. Dykstra and Riley Eusden directly to the east of the study area. The units were determined as being mostly one rock type, with a differentiating characteristic such as a different level of rustiness, partial melting, or the presence of calc-silicate pods or coarse-grained micas. Units are represented on the map using different colored polygons. The map was sent to the Maine Geological Survey to be edited and published. The units on the map represent differences in rock type and not necessarily different formations, but the formations were determined for the Discussion section. The version of the map in this thesis focuses on the different features as well as strike and dip information that can be used for interpreting stratigraphy and deformation in the Newry-Gilead region of Maine.

Thin-section Production

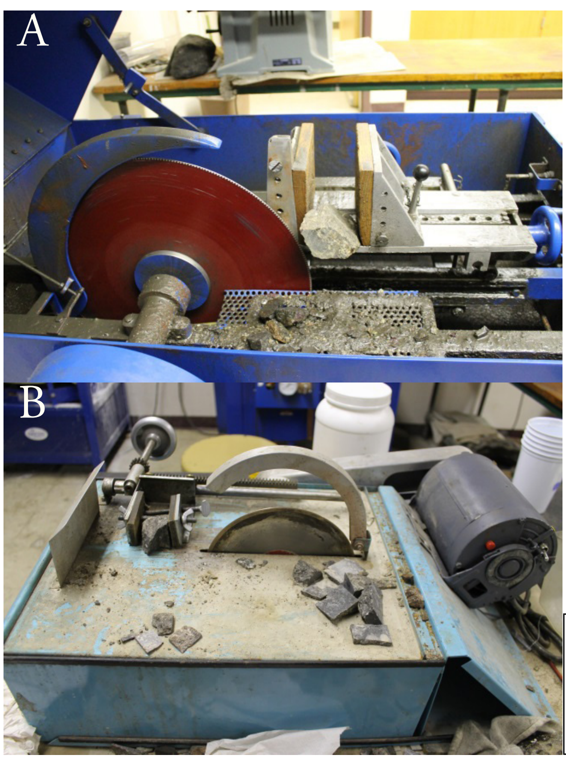

Figure 12: Rock saws used for thin-section production. A is the Diamond Pacific TR-18 Slab Saw, used to make the initial cuts of the sample. B is the Lortone, Inc. Lapidary Trim Saw FS8, used to trim the sample into a block.

To make thin-sections out of the samples from the field, two different rock saws were used. The big Diamond Cutter saw used rock oil to lubricate the blade and cut the field samples down to a smaller size. Then the sample would be trimmed using the manually controlled rock saw until it was a block, with the thin-section face fitting inside a 27 by 46 mm rectangle. The saws used are depicted in Figure 12. For the schist samples, the face that was turned into a thin-section was perpendicular to the bedding, whereas for calc-silicate and granofels samples it did not matter. The samples were labeled on the side opposite the thin section face. Twelve blocks were made and the samples were sent out to Spectrum Petrographics in Washington State to be mounted and polished. The samples were carefully picked to best represent the different rock types with each of the different characteristics, as well as from a wide range of locations from the field, in hopes of being to analyze all of the units. Seven schist, one granofels, and three calc-silicate pod samples were turned into thin-sections. The production of the slides took about a month, and the thin-section samples were received in mid-November to begin analysis.

Thin-section Analysis

The thin-sections were analyzed for petrography using transmitted light microscopy on Olympus BH-2, model BHSP polarizing microscopes, where the light passes through the thin-section to reach the eye. Photographs of the minerals were taken with the Olympus DP21 camera. The minerals and microstructures seen under the microscope helped to create a much more detailed deformation history for the rock types found. The types of minerals and mineral percentage can tell about conditions of formation or recrystallization during metamorphism. The minerals can help distinguish between types of schist, which helps differentiate between units. Different end members of a mineral such as feldspar suggest that different chemical conditions were present at the time of formation, which can give clues about the depositional or metamorphic setting. They can also reveal a difference between two rocks that appear to be exactly the same to the naked eye. Rocks like amphibolites indicate higher grade metamorphism, whereas greenschists suggest a lower grade. Special mineral properties can be observed under the microscope by using polarized and double-polarized light. The way the minerals relate to each other is also telling. For example according to Solar and Brown (1999), biotite in thin-sections can be very informative. If the crystals are bladed and subparallel to muscovite crystals, that means the sample was from a high strain zone. If they are pulled apart and separated by infilled quartz, that indicates a lower strain zone. The higher strain zones appear to represent extension, while the lower strain zones imply compression (Solar and Brown 1999). Microfolds and crenulations also are telling about the deformation history. Looking at the samples under the microscope can be very helpful in uncovering clues about both deposition and deformation that are invisible to the eye on a sample in the field.

Deformation History-Stereonet Production & Analysis

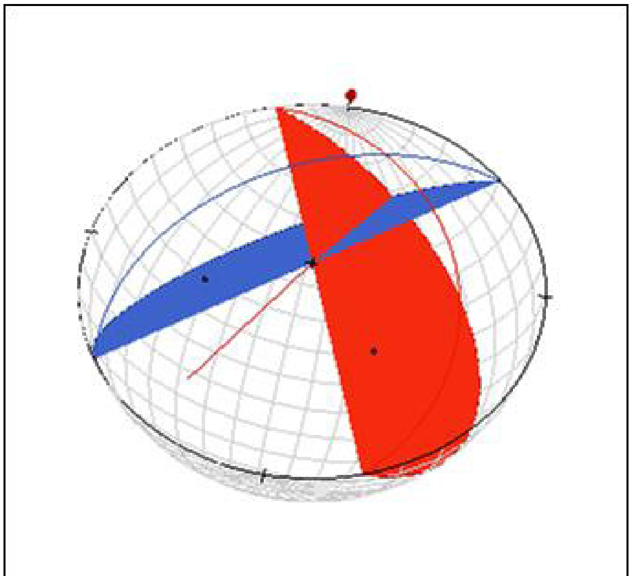

Figure 13: Model showing how the lines of a beta diagram represent the strike and dip of the bedding in the field and how the intersection of the lines would represent a fold axis. Visiblegeology.com

To learn about the deformation history of the region, the strikes and dips for both bedding and joints were used. From the attribute tables in ArcMap 10.1, the data was exported to a Microsoft Excel worksheet and saved as a text file with delimited tabs. In Rick Allmendinger's Stereonet 8 program, the bedding strikes and dips were plotted as beta and pi diagrams to reveal any regional folds and help construct the ductile deformation history. In the beta diagram, cylindrical lines representing the strikes and dips of the planes displayed the data, and where the planes intersected is a fold axis (Figure 13). In the pi diagram, the data was plotted as poles to the bedding planes, and a cylindrical best fit line of the poles was picked by the program using the Bingham Axial Distribution as outlined in Fisher (1987), which uses probability to find where the most poles are and draw a cylindrical line thorough them. The line is not a plane; instead, the pole to the cylindrical best fit line represents a fold axis. Contours were picked on the pi diagram using the Kamb method to show where the highest concentration of poles was. This helps separate out sets of bedding strike and dip directions. The joint strikes and dips were also analyzed using Stereonet 8 by plotting the data as a rose diagram to show fracture directions and brittle deformation. The data from smaller folds seen in the field during the last two field seasons was also analyzed using Stereonet 8. In addition to folds and fractures, the migmatites in the region played an important part in piecing together the deformation history. The partial melting of preexisting and formerly well-bedded schists indicates deformation of some type, and the introduction of a heat source. Together, the data shown in the beta, pi, and rose stereonet plots and the location of the migmatites proposed a picture of the region's deformation history that was interpreted in the context of previous work done on the region.

Literature Analysis

The map, thin-sections, and stereonets are all used cooperatively to piece together the tectonic history of the study area, but without context it is hard to truly get a full picture of the region's geologic past. Luckily many studies have already been done on the region, so this research is more of an addition to current theories. There are multiple papers that have been written on the region's depositional setting, deformation history, and stratigraphy; many of which are mentioned in the introduction. Since there is so much information on the current models of the formation of New England, it is good to see where the data from this research fits in. The reading of these papers was integral to understanding the general geologic history of New England, and gave a context in which it was possible to use the collected and analyzed data to form the new theories of deposition and deformation presented in this thesis.

Results

The products of this thesis are a bedrock map of the entire study region, thin-sections of collected rock samples, equal-area projections of the bedding strike and dips, and suggestions for revisions of stratigraphy in surrounding regions. The map shows the relationship of the different rock units. Thin-sections help define the mineralogy of those units and give clues to the conditions under which they formed. The minerals and their fabrics can be indicators of deformation. The stereonets delineate folds that were not visible in the field, as well as the most common bedding orientations. Together, these help define the rock units in the area and give clues as to how they were formed, and later deformed.

Description of Map and Rock Units

The bedrock map created for this thesis (Plate 1) shows the ten rock units found in the southern Old Speck 7.5' Quad and Gilead 7.5' Quad, that were interpreted to be younger in the northeast and older in the southwest (see Discussion section below). No graded beds or other topping indicators were found in the field area so this interpretation is based on the current stratigraphic positioning, correlation to other regions, and relationship of the layers. These ten units are further divided into two igneous units and eight metasedimentary units. The igneous intrusions include a quartz diorite suite in the south and a younger muscovite-biotite granite pluton in the area of the Sunday River. Just to the west of the large two-mica granite pluton is a region of the Ssg unit that has an overlay pattern symbolizing frequent igneous intrusions, as walking up the drainages to the south of the Sunday River, the rock type would switch between schist and granite every one to two meters. The older metasedimentary units were largely schists with varying levels of rusty weathering (Ssgm, Ssqr, Ssg, and Ssq). They were occasionally separated by marginal layers of quartzite-biotite granofels (Ssqg). Resting structurally and possibly stratigraphically above the older schist is a unit composed of quartzite with interbedded schists (Sqsc). Overlying that is another layer of rusty-weathered schist (Sqr), followed by a unit of biotite granofels (Sgf). Pegmatites and migmitites were prevalent throughout the entire study region and on the map (Plate 1) areas of migmatism are denoted with a lime green line. Calc-silicate pods were also found in many rock units, though their abundance varied. Coarse-grained muscovite was found mostly in the Old Speck Quad on the way up Goose Eye Mountain and along streams in the south of the Gilead Quad.

A cross-section was produced based on the contacts drawn on the map and plotting the dips of adjacent structural symbols. The line of cross-section is shown by the black line extending through Plate 1. Few folds were found in the field, and those are plotted on the map. Axial traces of more regional folds were drawn on the map based on strike orientations of the bedding. Equal area projections showing Pi diagrams were made to show dominant fold orientations on the local scale as well as for the entire study region. The results of this thesis will help to piece together the tectonic setting of the rocks' deposition and the history of their deformation.

Metasedimentary Rock Units

These metasedimentary units are described in interpreted age order from oldest to youngest, and appearing on the map from southwest to northeast. The abbreviations of the metasedimentary rocks were assigned by the Maine Geological Survey for the Eusden (2013) map from the 2012 field season. Thicknesses were estimated by measuring the perpendicular length of each unit on the cross-section. Calc-silicate pods are common in many of the metasedimentary units and are described in detail at the end of this section. Thin-section scale features are also discussed later in this chapter.

Ssgm

This is the southernmost unit within the study area, about 1,800 m thick, and is comprised dominantly of grey schist with very few calc-silicate pods (Figure 14). The schist includes muscovite, biotite, quartz, feldspar, chlorite, garnet, minor opaques, and some sillimanite. Few outcrops showed slightly rusty weathering. The schist is generally well foliated and includes migmatites. Small folds, about a millimeter wide, are present in a thin-section from the unit. Also in thin-section it is possible to see biotite alteration to chlorite.

Figure 14: Well bedded Ssgm grey schist with Trimble for scale.

Ssqg

The next is an 125 m thick unit of quartz and biotite granofels, consisting of biotite, quartz, plagioclase, sphene, opaques, and zircon inclusions with radioactive damage halos. The dark color and grainy, salt-and-pepper texture makes these rocks easily identifiable (Figure 12). This unit was deposited marginally between layers of schist and is infrequently dispersed throughout the region. In thin-section, the rock appears to be mostly quartz and plagioclase grains with the other minerals sprinkled throughout. There is no foliation, and the grains appear in a random orientation, much like sand on a beach.

Figure 15: Ssqg biotite granofels with magnet for scale.

Ssqr

This unit, 1,500 m thick, contains slightly to extremely rusty-orange weathered and often migmatized schists (Figure 13). Calc-silicate pods are present, but not abundant. The schist includes darker brown biotite, muscovite, plagioclase, leucosomes of partially melted quartz and feldspar, and fractured garnets. In addition to the rusty schist there are some greyschist outcrops and quartz diorite sills that are 60 and 150 m across. Rusty quartzite was a rare but present rock type as well. In the non-migmatized areas, a foliation is visible in thin-section that has also been gently folded. Again, biotite altering to chlorite was observed.

Figure 16: Logging road outcrop of rusty-weathered schist, hand for scale.

Ssg

This unit is of similar composition to Ssgm, but was deposited at a different time. By far the largest unit, it is at least 2,600 m thick. It is mostly grey schist without calc-silicate pods (Figure 14). The schist is made up of biotite, muscovite, quartz, plagioclase, sillimanite, grossular garnets, amphibole, an opaque mineral, and zircons with radioactive halos. There are both areas of strong foliation and areas of frequent migmatism. While mainly grey, some of the schists have a slightly rusty weathering appearance. Also present in the unit are two-mica granite sills, 80 and 120 m across.When walking up streams in this area, where the overlay pattern is in the Ssg, the rock type would alternate between schist and granite every one to two meters.

Figure 17: Ssg grey schist with Brunton for scale.

Ssq

Next is a Silurian (?) grey schist and quartzite with some rusty weathering and abundant calc-silicate pods (Figure 18) that is 950 m thick. The schist contains abundant biotite, large (3 millimeters) muscovite formed after and across the foliation defined by the sillimanite, quartz, feldspar, ilmenite, and garnet. In thin-section, the schist showcased a strong foliation in most areas, but also some areas with nearly no foliation. It was also possible to see D2 microfolds along the S1 axial planes of D1 folds.

Figure 18: Grey schist Ssq sample with strong foliation and penny for scale.

Sqsc

This layer, about 1,000 m thick, is mostly quartzite interbedded with slightly rusty weathered schist (Figure 16). Calc-silicate pods are common throughout the unit. Only four outcrops of this unit were mapped in the study area and it is interpreted as continuing from the same unit mapped by Eusden (2013) further southeast during the 2012 field season. The beds range from 1-10 cm in thickness (Figure 19).

Figure 19: Thinly bedded Sqsc quartzite and schist with handlens for scale.

Ssr

This schist layer, also 1000 m thick, dominantly exhibited rusty weathering throughout the unit, and calc-silicate pods are common (Figure 20). The composition includes small (half mm) biotite, large (2 mm) muscovite, quartz, and both plagioclase and potassium feldspar. Besides the pods, there are no other rock types in this unit aside from some of the schists being slightly less weathered than the majority.


Figure 20: Rusty-weathered and migmatized Ssr with two calc-silicate pods and handlens for scale.

Sgf

This northeastern most unit, about 1,300 m thick within the study area, is largely granofels and has a similar composition to those of the Ssqg unit below (Figure 21). They are interbedded with schists of varying degrees of rustiness, and calc-silicate pods are common throughout the unit. There is no foliation in the pods, but the grains have equant boundaries, when three grains meet at a point where each has a 120° angle. Approximately half of the outcrops in the unit have a strong foliation (eastern), while the other half are migmatized (western).


Figure 21: Fold in Sgf granofels, seen through a puddle in bedrock on the Sunday River. Handlens for scale.

Calc-Silicate Pods

These pods, abundant through many of the metasedimentary units, are often characterized by coarse grains of pinkish and greenish grossular garnet and diopside respectively. They also contain quartz, plagioclase feldspar, amphibole (possibly actinolite), and sphene. The pods resist migmatization, though they are susceptible to weathering. They often have a three-dimensional expression on the outcrop with recessed edges/rims and resistant cores that have more positive relief, and differ in shape, size, and composition. For example some are more elongate than others, though the most common size was between 10 and 14cm across (Figure 22 a-c). The grossular garnet in the pods can vary between well-formed, fractured, and those with a sieve texture (Figure 22 d-e). Rare, non calc-silicate lenses were also mapped in the field. Basalt Pods (Figure 23) were not common but a few were found. A couple of granofels pods were mapped as well.

Figure 22: Various types of calc-silicate pods. A-c: pods found in the field, outlined in red. Typical sized pod with handlens for scale (a), extra large pod with Dyk and Saebyul for scale (b), and medium sized pod with hammer for scale (c). D-e: pods under thin-section, showcasing intact and grossular garnets, respectively. mm bar for scale.

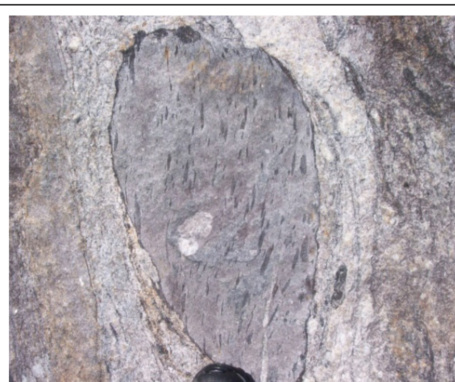

Figure 23: Basalt Pod found on the Bull Branch of the Sunday River. Foot for scale.

Intrusive Rocks

The region's intrusive units were mapped by this study, and a more in depth petrographic study was done on these plutonic rocks by the complimentary thesis of Saebyul Choe (2014). They were not studied extensively for this project, and igneous mineralogy descriptions and interpretations are courtesy of Choe (2014). There were two main types of igneous rocks in the region: a quartz diorite suite and two-mica granites. The quartz diorite suite tends to form sills that intruded parallel to the bedding of the sedimentary units, while the two mica granites often occur in plutons that intrude against the bedding. In the Sunday River drainages going up to Larry Brook Mountain, there was an area in the Ssg unit that featured frequent igneous injections, both of two mica granite and members of the quartz diorite suite. In addition to the main intrusive rock unit, basalt and granofel dikes were uncommon but present within the region.

Quartz Diorite Suite

The quartz diorite suite members in the study area were mostly found intruding the Ssr and Ssgm units (Figure 24). Though they appeared similar in the field, not all of the samples collected had the same composition, and they fell in different regions of a QAP diagram (Choe, 2014). Mostly they include plagioclase feldspar, some potassium feldspar, quartz, biotite, muscovite, amphibole (hornblende), sphene, and other accessory minerals. The types of quartz diorite vary depending on the percent composition of plagioclase versus potassium feldspar, the amount of quartz, and the presence of minerals like sphene and hornblende. The types found in the region are granodiorite, quartz monzodiorite, quartz monzonite, and quartz diorite (Choe 2014). The largest of these plutons mapped during the 2013 field season is about 900m at its widest point. Another pluton that was mapped by Eusden (2013) runs parallel to it and is about 450m at its thickest. Two diorite sills, about 60m and 150m, are present to the west of the major plutons, and another small pluton makes up the top of Robinson Mountain (Plate 1).

Figure 24: A member of the diorite suite being cut by the lighter granite on a stream up to Larry Brook Mountain. Dyk's hand for scale.

Two Mica Granites

These are a series of plutons found in the northern portion of the study area; the two mica granites intruded the Ssqr, Sqsc, Ssq, and Ssg units (Figure 25). They mainly consist of quartz, muscovite, biotite, potassium feldspar, and plagioclase feldspar. Samples from the field vary in grain size and percent composition of the different micas, but are all considered two-mica granites which are also known as muscovite-biotite granites. One major pluton was mapped that includes the main branch of the Sunday River, and is about 1,350m at its thickest point. Another pluton mapped by Eusden (2013) is also shown on the map, about 1,950m at its widest. Sills ranging from 90-110m across are present in the west and south of the study area.

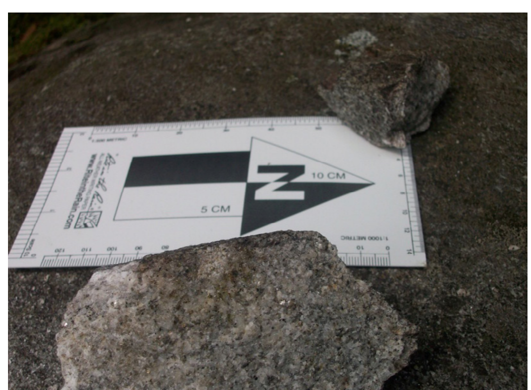

Figure 25: Two-mica granite from near Ketchum on the Sunday River. North arrow for scale.

Basalt Dikes and Other Intrusives

In addition to the igneous units there were two basalt dikes mapped in the field. One is located on the Sunday River going up to Goose Eye Mountain. It has a strike of 52 and dip of 64, and it intrudes the rusty migmatite of Ssqr. The other is further south on the main branch of the river and has a strike of 259 with a dip of 78. The Sunday River drainages from Larry Brook Mountain contained a few dikes of sulfide granofels that were parallel to the stratigraphy (Figure 26). Pegmatites were present at nearly every site in the region, running through all rock types.

Figure 26: A: Basalt dike with trimble for scale. B: Sulfide Granofel dike with Henry Berry's foot for scale.

Structural Geology

The sedimentary map units described above have undergone metamorphism and deformation since their deposition. Strong foliations, folding, migmatism, mineralogical alterations, and late stage mineral growth are some signs of this tectonometamorphism. Examples of this can be found on all scales; there are folds and migmatite boundaries visible on the map, folds and porphyroblasts visible in the field, and microfolds, crenulations, and metamorphic mineral assemblages in thin-section. There is evidence for two periods of ductile deformation that occurred simultaneously with complex metamorphism, one period of contact metamorphism, and one period of brittle deformation characterized by joints, possibly faults, and scattered late stage mineral alteration in the study region.

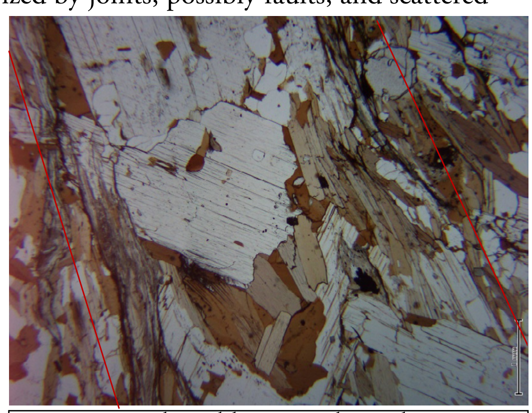

Figure 27: Foliated biotite, plagioclase feldspar, quartz, and ilmenite. Large muscovite grew later, and has a different orientation. Red lines show S1. Mm bar for scale.

First Deformation and Early Metamorphism

The first period of deformation formed a strong foliation, S1, in many of the rocks in the region. It is similar to what Guidotti (1989) calls M1. Isoclinal recumbent folds are inferred to be present, which is supported by a large fold found by Eusden (2013) on the map scale that was interpreted as a D1 fold. This fold is about 5000m across. Thin-sections from the region show areas with two generations of micas; an early finer-grained well-foliated fabric (S1, red line on Fig 27) that is overprinted by coarser, randomly oriented, late stage muscovite and biotite (large grains in center of Fig 27). This supports the idea that an earlier deformation foliated the finer minerals and early metamorphism was syn-kinematic. Then subsequent post-kinematic metamorphism resulted in the later growth of the coarse micas.

Second Deformation Folding

The structural data collected for this thesis primarily shows the strong effects of a second syntectonic period of deformation. Close, similar folds formed by flexural flow are observed on all three levels; micro, meso, and macro scale.

Macrofolds

The strikes and dips of bedding collected in the field were used to find map-scale folds in the study area. The clearest folds are in the northeast section of the map along the Bull Branch of the Sunday River. The contact between the Sgf and Ssr layers showcases a series of folds with axial planes running northeast-southwest (Figure 28). The synclines (purple) and anticlines (turquoise) are traced on all the folds that were found on the map but were not visible in the field. In the southern part of the quad, the axial planes have more of a north-south orientation (Plate 1). These map-scale folds are represented on pi-diagrams showing bedding strikes and dips throughout the region (Figure 29). D2 folds trend in a northerly direction (NNW-NNE) and are gently plunging (~35°).

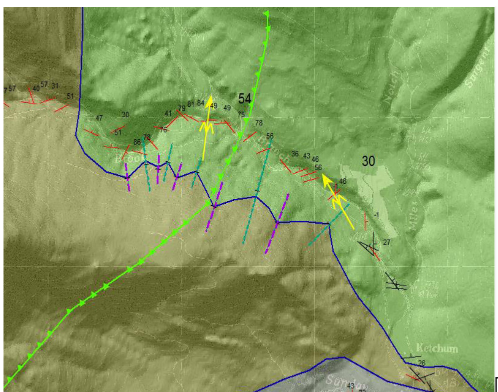

Figure 28: Map-scale folds near the Bull Branch of the Sunday River. Yellow arrows show folds mapped in the field.

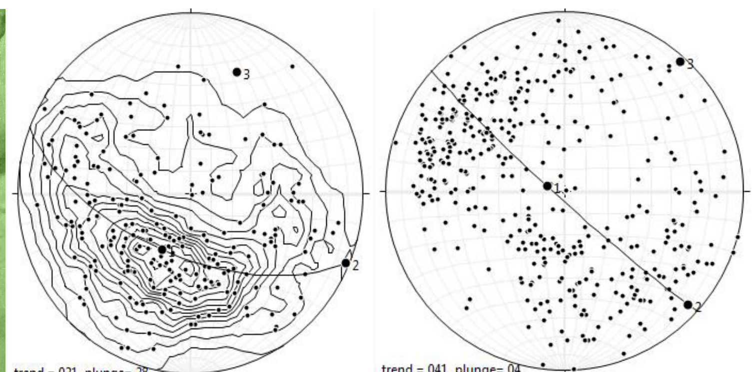

Figure 29: Pi-diagrams of the bedding strikes and dips with cylindrical best fit lines. Points labled 3 show D2 regional fold axes. A: 2013 field season in the Gilead & Old Speck Quads. B: 2012 field season in the Gilead and Bethel Quads.

Mesofolds

Four minor folds were mapped in the field, the biggest of which was in the granofels of Sgf. In the middle of the puddle shown in Figure 21, the fold is about 25 cm from limb to limb. A stereonet showing the axial plane strike and dips and hingeline trends and plunges of these folds is displayed in Figure 30. These are interpreted to be folding the previously formed schistosity. One of the folds mapped contained multiple syncline-anticline pairs. These had a wavelength of about 18 cm.

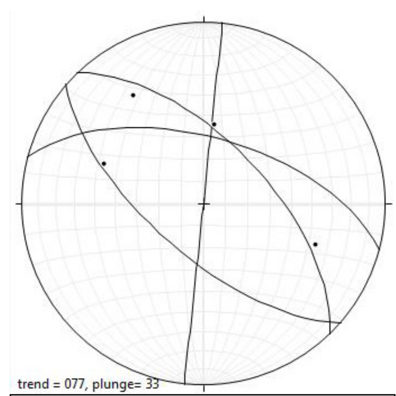

Figure 30: Planes represent the axial planes of the local folds; poles represent hinge lines.

Microfolds

The folds seen in thin-section are interpreted to be D2, since they appear to fold S1. They range in size from one to a few millimeters across. Ilmenite, a needle like opaque mineral, outlines the folds (Figure 31). They disturb the foliation and fold around garnets that grew at a lower temperature.

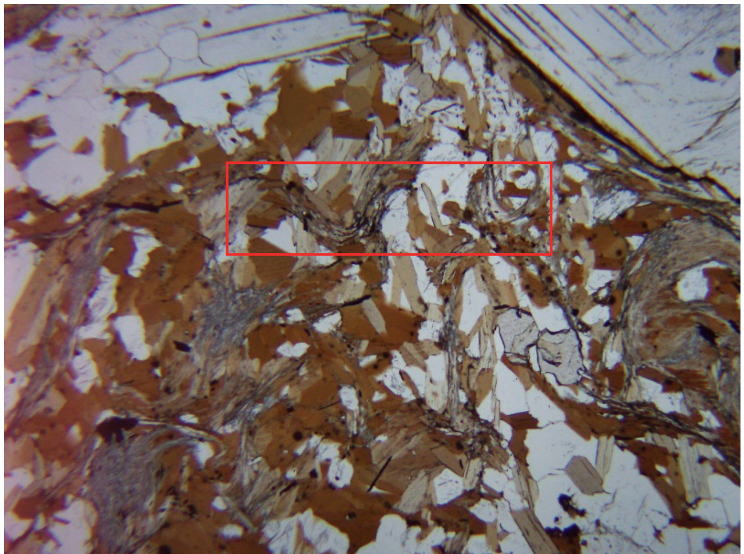

Figure 31: Folds in thin-section; D2 folding S1. Large and late muscovite is visible in the top right corner. This sample is from OSQ 63, in the Ssq unit. Red box outlines folds. mm bar for scale.

Contact Metamorphism: Migmatism and Mineral Alterations

Post-tectonic deformation created indicators like partially melted rock and mineral alterations that occur at very high temperatures.

Migmatism

Migmatites are abundant throughout most of the study area. For this project, migmatization was defined as any outcrop that exhibited more than 20% partial melting as evidenced by quartz+feldspar leucosomes. The neon green line to separate migmatized and non migmatized areas appears to cut the region in half, however the center of the non-migmatized area was mapped by Eusden (2013). These partially melted regions of rock represent a period of vey high heat during the peak of metamorphism. In the field, the migmatites appear as swirly, white areas of quartz (Figure 32). Under thin-section, the difference between the melted versus the well-foliated rocks becomes very visible (Figure 33). These features support a second tectonometamorphic period that provided enough heat to partially melt much of the region's rock.

Figure 32: Migmatized grey schist with field notebook for scale.

Mineral Alterations

Under the microscope, the minerals help tell a story about the region's deformation history through their

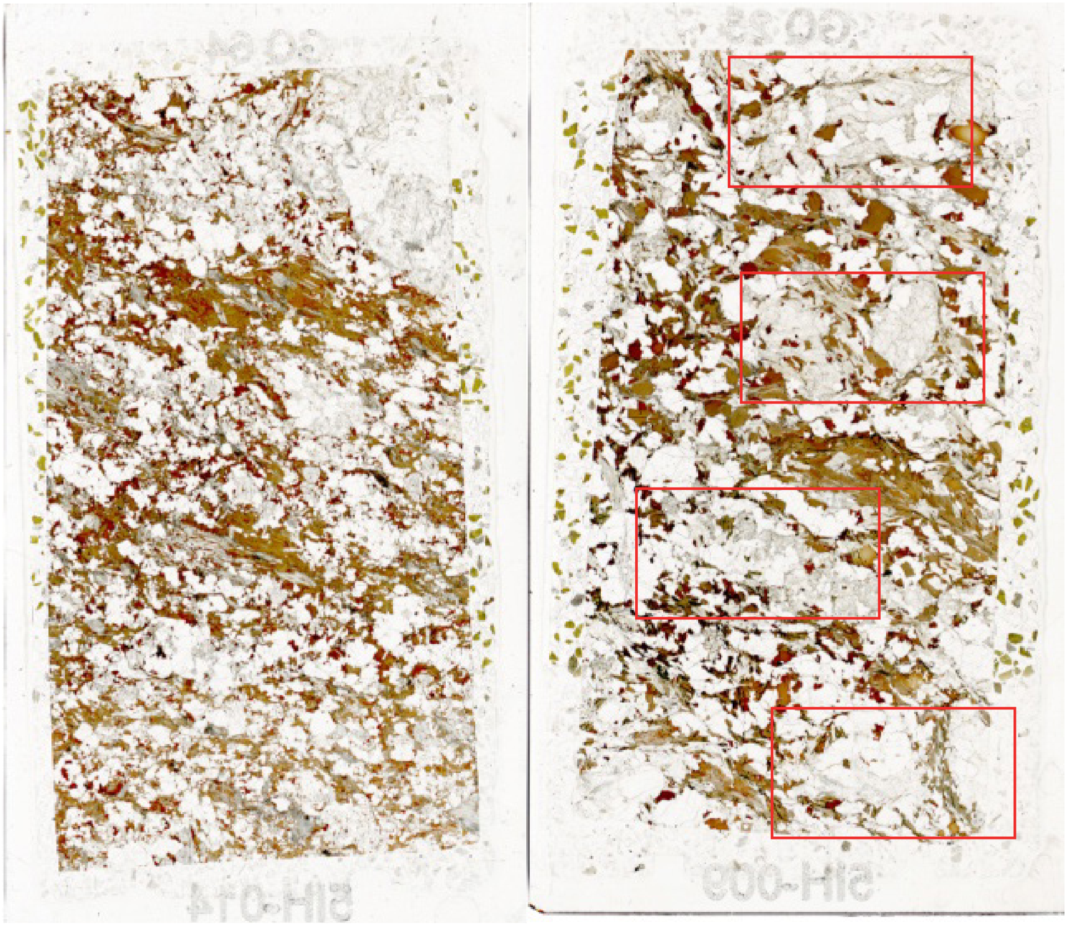

Figure 33: Comparison of a very well bedded, non-migmatized grey schist (GQ 64) and a partially melted grey schist (GQ 25). Red outlines show melted areas. Thin-sections are 27x46 mm.

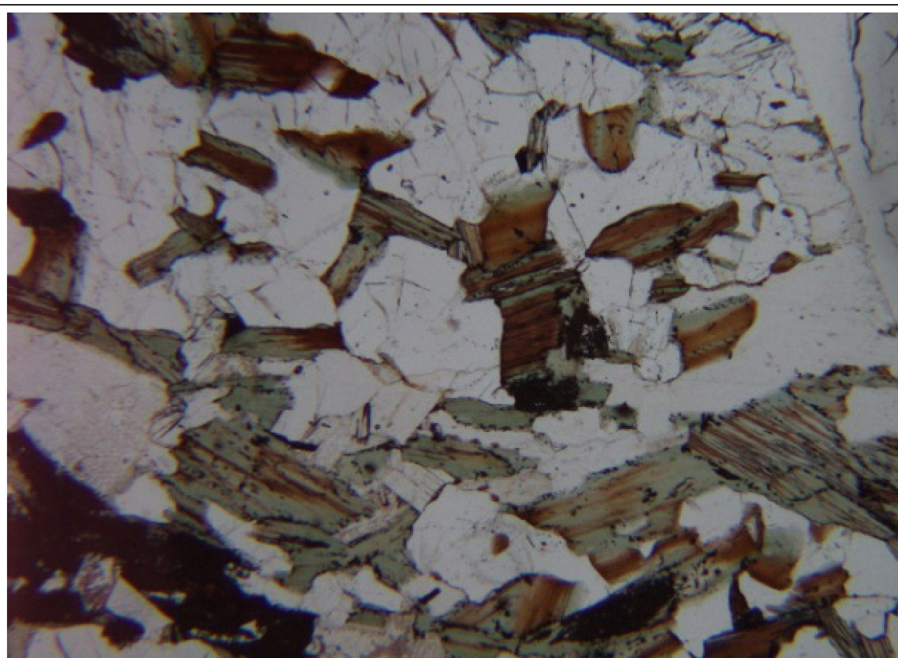

Figure 34: Biotite (brown) altering to chlorite (green). Mm bar for scale.

orientation, shape, size, and alterations. Alterations such as biotite to chlorite suggest lower P-T conditions (Figure 34), and minerals like sillimanite require very high temperature and pressure to form. Some samples exhibited grains with equant boundaries, which also indicate high temperature and pressure. These examples are good indicators that the region experienced a significant amount of complex metamorphism.

Brittle Deformation

The most recent deformation observed in the study area of this thesis was brittle fracturing. Fractures could be found at nearly every outcrop in the region. The dominant orientation was northeast to southwest, with a secondary east-west set (Figure 35). Most fractures were observed going into the outcrops and were one to a few centimeters in width, but in some cases the fracture plane was on the face of an outcrop (Figure 36). The dips had a wide range, but most were between 45-90. Many of these may be related to Mesozoic rifting during the break up of Pangea. These features cut the schistosity and the partially melted rock, which confirms they are the youngest period of deformation.

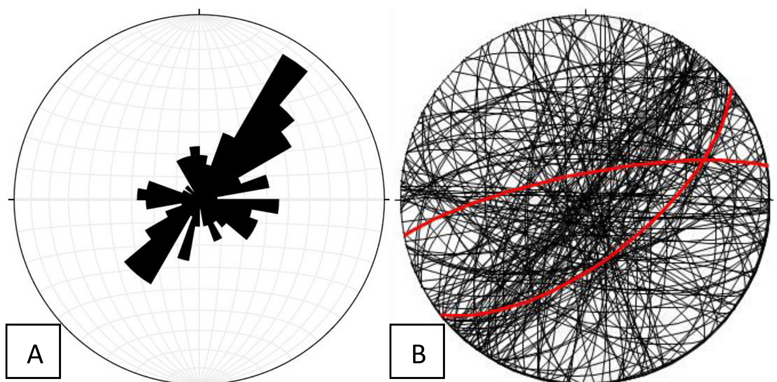

Figure 35: A: rose plot of joints measured in the field showing a strong northeast-southwest orientation. B: beta diagram of joints showing a similar trend and very steep dips. Red lines show strike and dip from the two dikes found.

Figure 36: Fractured outcrop showing fracture planes.

Discussion

The current interpretation for the rocks in this region is that they were deposited in a sedimentary basin that was thought to be part of a passive margin (Moench 1970) and consisted of the Rangeley stratigraphy (Rangeley, Perry Mountain, Smalls Falls, and Littleton Formations) being dominated in outcrop pattern by the Littleton. However the mapping done this summer provides support for revising the model of regional stratigraphy and the current theories of tectonic setting. The presence of calc-silicate pods in what is interpreted as an olisostromal melange suggests that the rocks in the region were deposited in an active tectonic zone that experienced earthquake events, which correlates better with the Silurian Rangeley Formation. Work by van Staal (2009) first revealed the Salinic Orogeny as a time of active tectonism, and this is when the Rangeley was deposited.The majority of the area is heavily migmatized. This is inconsistent with most accounts of the Littleton Formation, which tends to be far less migmatized than the Rangeley Formation (Wall 1988 and Allen 1992). These findings could have implications for extending the revisions into the surrounding areas of central Maine and Eastern New Hampshire.

Correlations to the Silurian Rangeley Formation

There are several pieces of evidence to support the proposed theory that the region mapped for this thesis is mostly Silurian Rangeley Formation. The combination of the rusty weathering and migmatism that many of the rock types exhibit are contrary to descriptions of the strictly well-bedded grey schist and quartzite of the Littleton Formation. The calc-silicate pods, which are interpreted to be clasts in an olisostromal melange, are a sign of tectonic activity which is more commonly associated with the Salinic Orogeny. The evidence for this will be discussed below.

Weathering and Migmatism

More than a third of the mapped schist exhibited some degree of rusty weathering. This occurs when the buried schist contains iron sulfides, which rust when they come in contact with oxygen during exhumation. These rocks, along with the grey schist, were frequently migmatized. This requires a metamorphic event that would partiallly melt the pre-deposited rock. Both of these features are uncharacteristic of the Devonian Littleton Formation as described by Wall (1988) and Allen (1992).

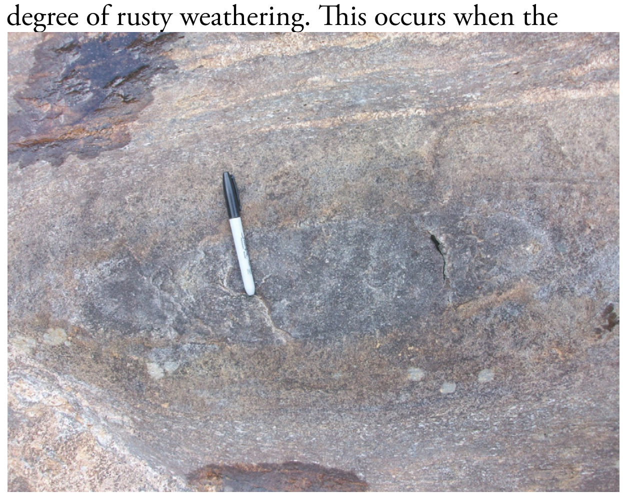

Figure 37: Calc-silicate pod in rusty, non migmatized matrix. Sharpie for scale.

Calc-silicate Pods

There are two theories about the formation of these features that are abundant through much of the study area. The first is that they are calcareous concretions, formed during rapid sedimentation of material flowing off the land down the continental slope due to some tectonic shift (Allen 1996). The other is that the pods are formed in diatexites from calcareous sediment layers (Solar and Brown, 2001). The majority of the pods in the region are within a migmatized matrix, however pods at four outcrops were embedded in non-migmatized rock, which implies that migmatization is not the cause of the pods' formation (Figure 37). The percentage of pods in migmatized rock is likely due to the fact that most of the rocks mapped in the region were migmatized. If the first theory is correct, it would also suggest that they were formed at a tectonically active time. The Acadian Orogeny also was a period of widespread tectonism, particularly evidenced by the Devonian-aged plutons in the study area (Choe 2014). However current models for the Salinic show much more activity than previously believed, with a subduction zone that could have produced these abundant olisostromal features during rupture events. The presence of these pods, combined with more evidence discussed below, supports the theory that the rocks that contain them were deposited as the Silurian Rangeley Formation.

Stratagraphic Position

The rocks in the northeast corner of the study area are interpreted to be Devonian-Silurian Madrid Formation, Silurian Smalls Falls Formation, and Silurian Perry Mountain Formation moving to the southwest. Stratigraphically, the Littleton Formation would lie above these units, which is outside the boundary of the map. Below the Perry Mountain Formation in most other areas in New England is the Rangeley Formation.

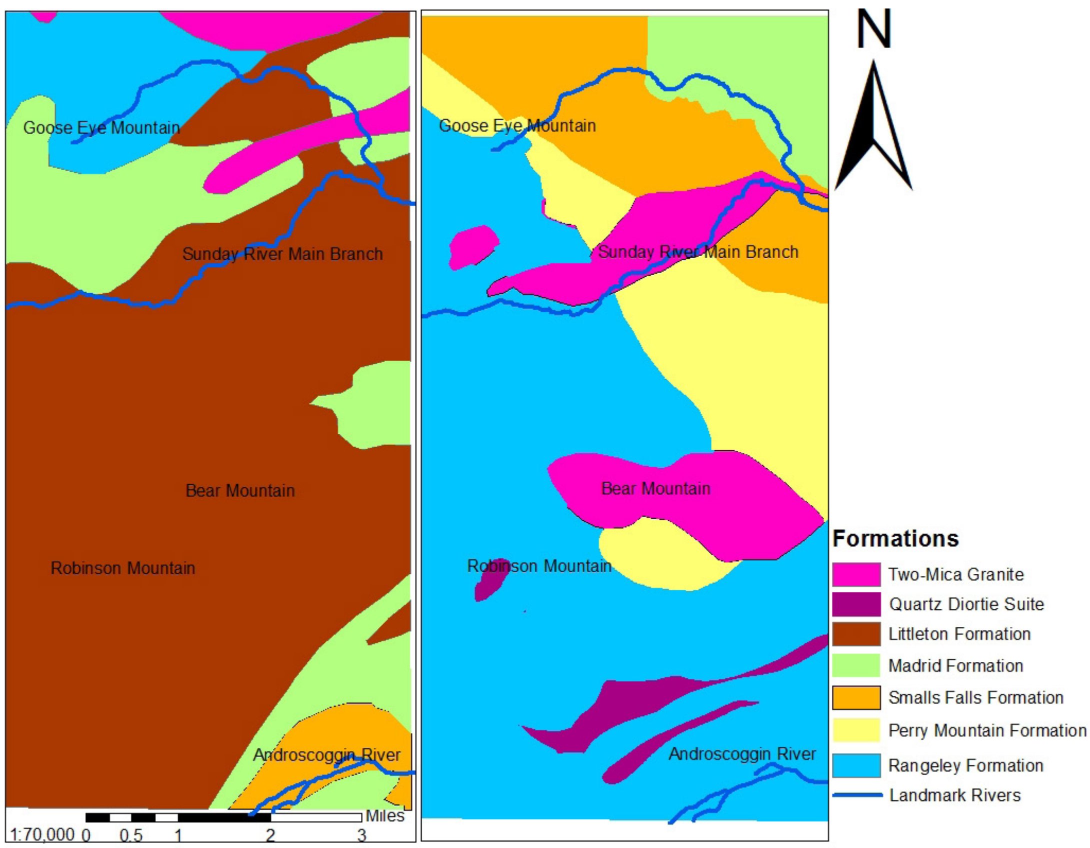

Figure 38: Formation revisions within the study area. Left: current state bedrock map showing mostly Littleton Formation (brown; Osberg et al. 1985). Right: formations based on mapping for this project showing a large shift to Rangeley Formation (blue) and the significatn addition of the Perry Mountain Formation (yellow).

Tops were absent in the field, so assuming that the units appear in the order they were deposited, everything southwest of the quartzite unit should be Rangeley Formation. That means that Ssq, Ssg, Ssqr, Ssqg, and Ssgm are all being redesignated for this project (Figure 38).

The major differences in the two maps are largely due to the fact that far fewer outcrops were accessible at the time of data collection for the state map, but there are some other explanations as well. It is likely that in the southeastern corner of the map, what the Osberg et al. (1985) map denotes as Smalls Falls Formation is actually rusty-weathered Rangeley Formation. Additionally, the Madrid Formation in the same area of the Osberg et al. (1985) map is close to areas of marginal granofels mapped for this study as well, however they are denoted differently. The Sgf of the Madrid mapped for this thesis is compositionally similar to the earlier-deposited granofels of Ssqg, however the marginal features are considered a part of the Rangeley for this study. This follows work by Allen (1996) and Eusden (1996, 2010) that redesignated Smalls Falls as rusty Rangeley and Madrid granofels as Silurian granofels during subdivision of the Rangeley Formation.

Until now, the Perry Mountain Formation has not been identified in this region. It was mapped to the east by Eusden (2013) and was extended here due to stratigraphic position and a few outcrops in Goose Eye Brook. The Madrid Formation in the top right corner and some of the Rangeley Formation in the top left corner are the only areas of the state map that were confirmed during field mapping for this updated version.

Proposed Sequence of Events

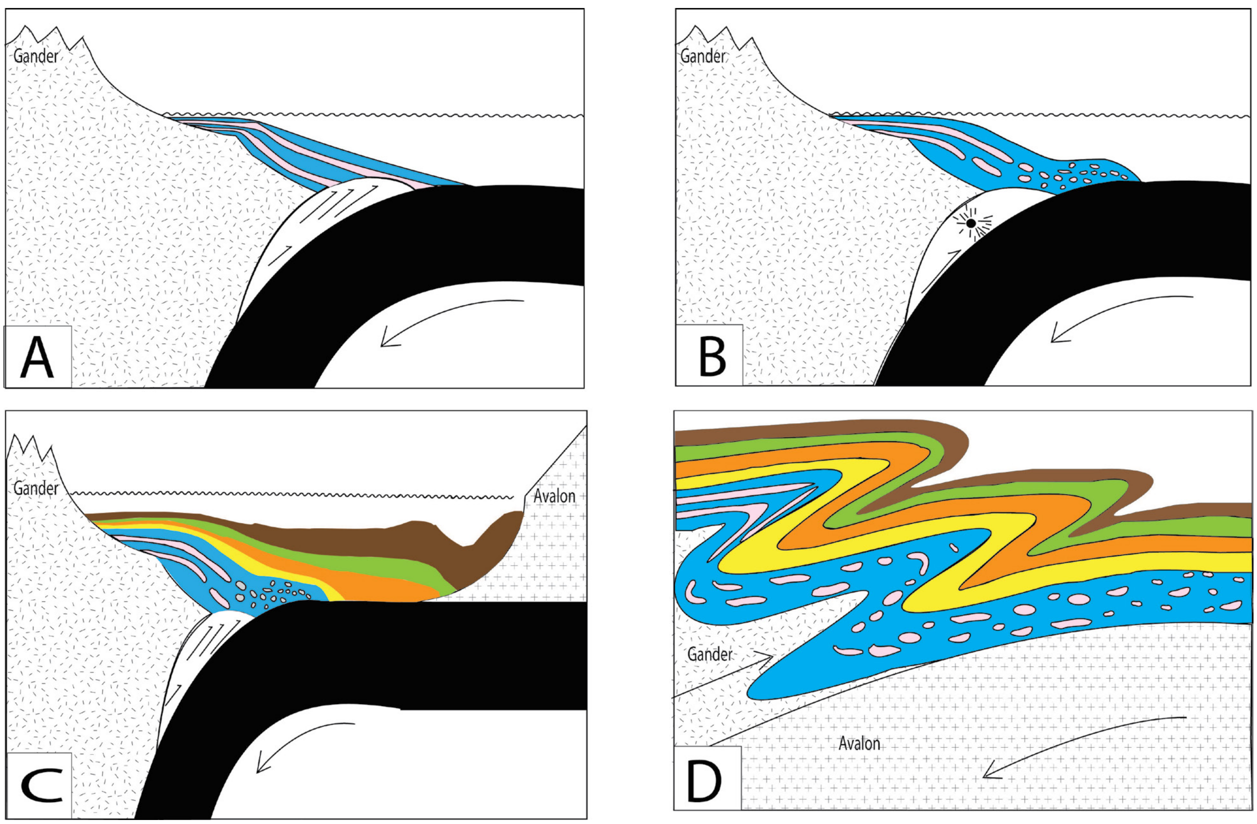

Figure 39: Sequence of events to form the rocks seen in the Gilead Quad and surrounding areas today. Rangeley Formation is blue and pink, Perry Mountain Fromation is yellow, Smalls Falls Formation is orange, Madrid Formation is green, and Littleton Fromation is brown. A: Deposition of Rangeley from west to east over a subduction zone during the Salinic Orogeny, including calc-silicate layers. B: rupture event causes the calc-silicate layers to fracture and an olisostromal melange forms. C: Deposition of Perry Mountain and Smalls Falls from west to east, and Madrid from northeast to southwest between the Salinic and Acadian; Littleton deposited from south to north at the onset of the Acadian. D: During deposition of Littleton, Acadian Orogenesis produces large-scale folding. Flow directions from Bradley & Hanson (2002). Figure adapted from Maconochie (1994).

Given the arguments above, it is likely that the sedimentary rocks of the Rangeley were deposited in an ocean basin overlying the accretionary wedge at a subduction zone (Figure 39 a). This was the tectonic setting of Salinic orogenesis during the Silurian period. Layers of calc-silicate were interbedded with greyschist during sedimentation, and then a rupture event broke the calc-silicate layers up in to pod-like clasts (Figure 39 b). Further Silurian sedimentation occurred with the deposition of the Perry Mountain, Smalls Falls, and Madrid Formations, before deposition of the Littleton at the onset of the Acadian Orogeny (Figure 39 c). Both the shape of the basin and the mineralogy of the input material changed between the deposition of these units.

Changes in the Sedimentary Basin

One rusty-weathered member of the Rangeley Formation indicates that at the time of its deposition, the basin was euxinic. This means that the iron sulfides in the schist were not taken up by bacteria. As the basin widened and became more oxygenated again, the iron-filled sediment quickly became buried by new turbidites. The iron-sulfides in the rocks rusted upon contact with oxygen during exhumation.

The Perry Mountain Formation is a quartzite and schist, which indicates the input of a more sandy material. This could be due to a shallower basin, either because of a drop in sea level or rapid sedimentation causing a rise in the sea floor.

The Smalls Falls Formation, another rusty unit, indicates that the basin became euxinic again, similar to how it was during the deposition of the rusty members of the Rangeley Formation.

The biotite granofels of the Madrid Formation also contained calc-silicate components and was formed from reworked carbonate and sand as it flowed down the continental slope. During this more oxygenated period of deposition, the input of sediment was coming from the northeast, instead of the west like the previous three units (Bradley & Hanson 2002).

The Littleton Formation was deposited in front of the advancing deformation front and sediment traveled

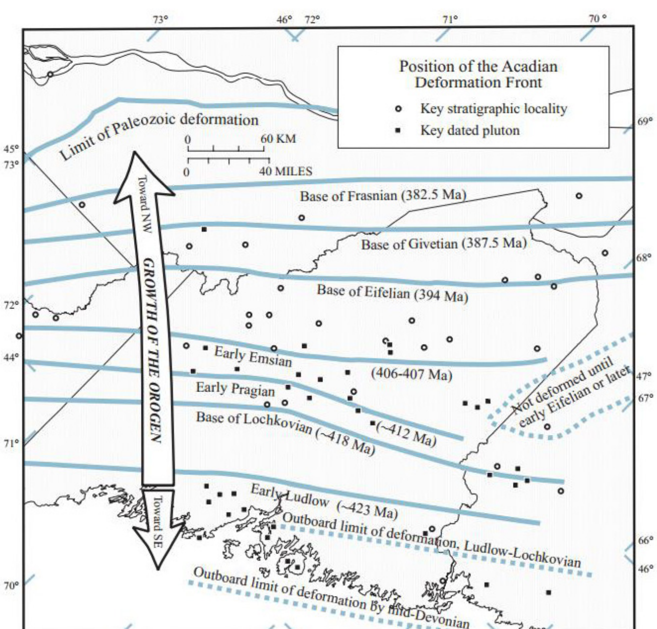

Figure 40: Migration inland of the Acadian deformation front. From Bradley et al. 2000.

mostly north, but later east and south as well. The active subduction margin was in the study area for this at this time, about 410 Ma (Figure 40, Bradley et al. 2000). These basin changes were all due to the migrating deformation front of the Acadian Orogeny subduction zone.

Deformation and Metamorphism

The timeline of the phases of deformation and metamorphism outlined in the Results section help place the deposition of the rocks in the Salinic Orogeny. Three deformation events and two metamorphic events occured after deposition. The first, establishment of schistosity and rare early folds, is a product of D1 and widely found throughout northern New England. Since it affects the Littleton Formtaion, it must have occured in the early Acadian Orogeny. The last, brittle fracturing, is almost certainly caused by Mesozoic rifting, as the fracture strike and dips match up with those in previous studies and are indicative of northwest-southeast tensile stress (Faure et al. 2006). The middle three events will be further expanded upon in this section.

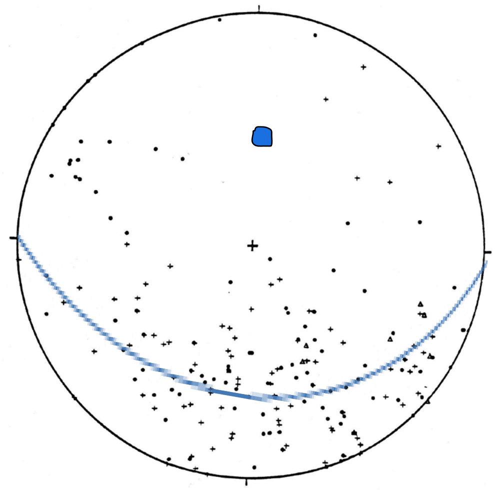

Figure 41: Pi diagram of F2 Planar features from Brady 1991. Estimated cylindrical best fit represented by blue line with corresponding fold axis shown by blue dot.

D2 Acadian Folding

Deposition of the Littleton Formation began in the early Devonian period, with the onset of Acadian orogonesis. During this time, the compressive forces from the active subduction zone folded the previously deposited rocks as the Littleton was continuing to be deposited ahead of the active margin (Figure 36 c). As the orogeny continued and Avalon advanced towards Gander, all of the sedimentary layers were deformed, producing the macrofolds shown in the results (Figures 28 and 39d). These have similar orientations to the majority of folds mapped by Eusden (2013) immediately to the east of the study area. A pi-diagram produced for John Brady's thesis (1991) shows similar bedding further east in the Bethel 7.5' Quad as well, which demonstrates the regional extent that D2 folding had (Figure 41).

Syn-tectonic Migmatism

A paper by Solar and Brown (1999) challenged Guidotti's previous designation of the metamorphic events in Western Maine as having been due to pure contact metamorphism. They suggested that the advance of a subduction zone is when migmatism occurs. This explains the migmatite line found in this study, and how it does not follow along the margins of the plutons, but continues up north out of the study area. They cite U-Pb age data from Smith and Barreiro (1990) that indicate two periods of metamorphism: 405–399 ± 2 Ma and 369–363 ± 2 Ma. The earlier Acadian-aged event likely could have caused the migmatism in this region. At the same time, the quartz-diorites in the region intruded in association with the Piscataquis Volcanic Arc (Choe 2014).

Intrusion of the Sebago Pluton

The second phase of metamorphism is associated with the intrusion of the Sebago Pluton during the Carboniferous period. The pluton created very high temperature conditions that caused mineral alterations and late stage mineral growth. These are metamorphic events that occur at high temperatures but do not require pressure or stress, as the folding does. The two-mica granite plutons

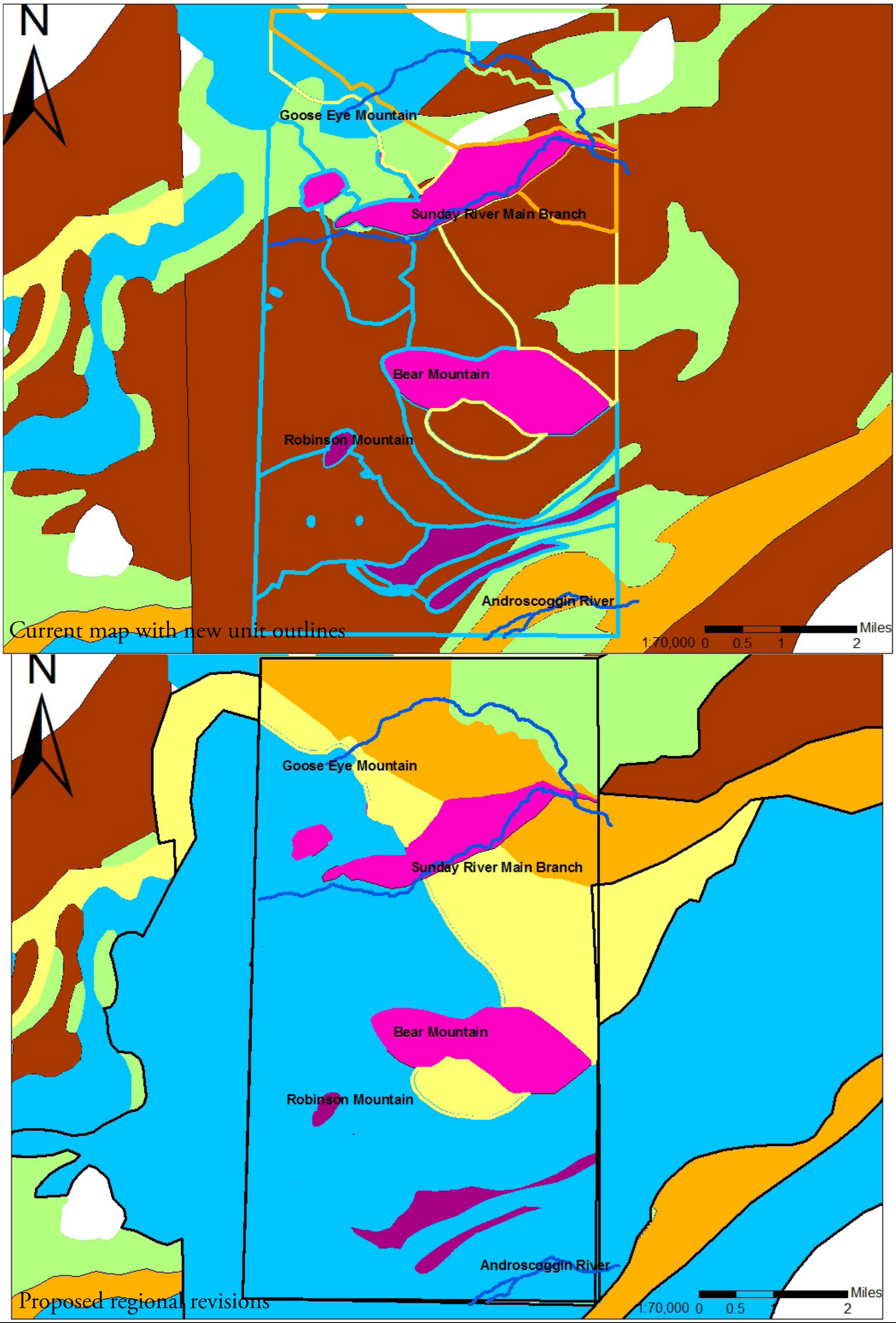

Figure 42: Suggestions for regional redesignation of Littleton (brown) as Rangeley (blue). The top map shows Osberg et al. (1985) and Lyons et al. (1997) formations overlain by this study's units. Yellow is Perry Mountain, orange is Smalls Falls, and green is Madrid. Pink plutons are two-mica granite, and purple are members of the quartz-diorite suite. Rivers shown in dark blue.

mapped in the north of this study area were found to be petrologically equivalent to the Sebago Pluton in the complimentary thesis by Choe (2014). They are surrounded by rocks containing features like post-kinematic coarse-grained muscovite and biotite to chlorite alteration.

Regional Stratigraphic Revisions

Rock units do not stop abruptly at the boundary of a map area, so to change one map often changes all of the surrounding ones. In this case, the study area is very close to the New Hampshire border, so stratigraphic revisions will cross state lines. The most recent bedrock map of New Hampshire was done by Lyons et al. in 1997, so they already have updated some of the Littleton Formation and changed it to Rangeley Formation. This project suggests that even more should be changed. Within Maine, the rocks surrounding the study area are also mostly mapped as Littleton. The new data collected during the 2013 field season was used to make potential revisions to the bedrock maps of both states (Figure 42).

Only the formations mapped in the field were used in the extension figures. They were drawn by connecting the units on the new map with nearby units of the same formation on the existing maps. Many more revisions may be necessary, particularly a large switch from Littleton Formation to Rangeley Formation in Maine and to a lesser scale New Hampshire. However this extension map demonstrates that there is further work to be done, and continued field mapping is required to make more progress on the mapping conducted by Moench et al. in 1983.

Conclusions

The bedrock in western Maine has a rich tectonic history with deposition in an active tectonic setting before being folded by compressive forces, partially melted and mineralogically altered by contact metamorphism, and fractured by tensile forces during the breakup of Pangea.

The 1985 Bedrock Geological Map of Maine, based on work done by Moench, Hatch, and Lyons (1983), is a useful map to see the general bedrock locations and relationships in the state. However since that time, logging and development have made many more outcrops in the state accesible. This is particularly true near the Sunday River, as rapid development takes place due to the region's popularity as a vacation spot. Mapping by Moench, Boudette, and Bothner at the 1:250,000 scale in 1999 began to revise some of what was mapped as Littleton Formation and redesignate it as Rangeley Formation. This project further redesignated all of the Littleton Formation in the Gilead 7.5' Quad as Rangeley Formation, based on the presence of olisostromal melanges, migmatism and rusty weathering, significant ductile deformation, and a revised stratigraphy that all support deposition during the Salinic Orogeny.

This change in the interpretation of the region's tectonic history not only redesignates the rock types, it also helps to support van Staal's (2009) model that the Silurian period experienced more tectonic activity than was previously believed. The calc-silicate pods form in a specific type of environment, which now relates to the Salinic Orogeny. Before, that time period was thought to be much more passive. Other pieces of evidence besides the calc-silicate pods suggest that the rocks were deposited at the time of the Salinic, so the pods help to confirm the type of environment that was present then.

There is more work to be done, as the correlations of rock types to formations are interpreted based on relative stratigraphy. Radiometric dates could be obtained to confirm this interpretation. Mapping in surrounding quads could be conducted to more confidently extend the stratigraphic revisions to other parts of Maine and into New Hampshire. This project continues to make progress on the current state map and contributes to a more complete understanding of the geologic history of bedrock in Maine.

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