Structural analysis of the Gonic Formation in Berwick, Maine

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STRUCTURAL ANALYSIS OF THE GONIC FORMATION
IN BERWICK, MAINE

Abstract of
A thesis presented to the Faculty
Of the University at Albany, State University of New York
In partial fulfilment of the requirements
For the degree of

Master of Sciences
College of Arts and Sciences
Department of Earth and Atmospheric Sciences

Joseph F. Renda
2004
ABSTRACT

RELATIONSHIP OF THE GONIC FORMATION AND NONSUCH RIVER FAULT TO THE NORUMBEGA FAULT ZONE IN BERWICK, MAINE

Located in southwestern Maine the Gonic Formation abuts the Nonesuch River Fault of the Norumbega Fault System. The rock types of the Gonic Fm. consist predominantly of micaceous schist and lesser amounts of quartzite. Fieldwork suggests that the units have undergone transposition and thus appear to be interlayered and pinch-out along strike. Granitoid rocks have also been observed and are interpreted as related to either the Lyman Pluton or White Mountain Complex and serve as the backbone to the line of low-lying hills within the Gonic Formation.

The unit is entirely within the amphibolite zone of metamorphism. Hand specimens show reaction rims of staurolite and muscovite around andalusite crystals suggesting a localized secondary metamorphism, most likely due to the intrusion of the Lyman Pluton during the Carboniferous period.

Large scale F_1 recumbent folding is evident from stereonet plots of the primary schistosity (\(S_1\)). F_2 folding is observable at the outcrop scale as a folding of \(S_1\). F_2 related folding and structures show dominantly southwest trending plunges. Evidence of F_3 folding is observable at the map scale as a variation of \(S_1\) strike and F_2 trend directions.

Kinematic indicators such as: asymmetric and rotated porphyroclasts and S-C fabric throughout the field area indicate sinistral deformation occurred within the Gonic Fm. This is contrary to regional deformation displacement along the Norumbega Fault System and may support evidence for off shore deflection of the Norumbega Fault System as a dextral transpression system.
Acknowledgements

This thesis really began in 1988 when I first moved to the state of Maine. As a kid out in the woods looking for a discovery, I peeled back a carpet of moss and realized that rocks are everywhere. My studies at the University of Southern Maine began my understanding of what I have seen.

I would like to thank all of the landowners who graciously allowed me to wander their property: Win on Diamond Hill, Peter Gamble, Mr. Grover and Joe Putnam. Joe Bean for coffee breaks and Paul Lucia for directions around the mountain. Obviously, this would not have been possible without the support of my family and friends, thanks for waiting.

I am dedicating this thesis and my hard work to Louis Renda and Ed Jarmulowicz.
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CHAPTER 1

INTRODUCTION

The Norumbega Fault system (NFS) is located in the northern Appalachian Orogen of the northeast United States (Figure 1). In only the past 25 years has the complexity and scale of the NFS been recognized and given equal attention as its modern analogue, the San Andreas Fault system in California and sister system, the Brevard zone of the southern Appalachians. The extent of the Norumbega fault system is documented as extending approximately 450 km from Casco Bay in southwestern Maine to central New Brunswick (Hussey, 1988; Hussey et al., 1986; Newberg, 1985; Swanson 1992, 1994; Swanson et al., 1986; West 1993, Pankiwskyj, 1996; Ludman, 1991, 1998; Hubbard et al., 1995). Geophysical evidence from seismic reflection surveys (Durling and Marillier, 1990) and more recent mapping by Bothner and Hussey (1999) suggests that the NFS extends from the Gulf of St. Lawrence, Canada to southern Connecticut, increasing the length of the NFS to 1200 km. Geophysical data gathered by the U.S. Geological Survey and the Geophysical Survey of Canada between Quebec and the Gulf of Maine (Stewart et al. 1986), and a marine reflection profile, (Durling and Marillier, 1990; after Ludman and West, 1999) found that faults of the NFS penetrate steeply to the middle and lower crust before becoming listric and flattening to the northwest and southeast respectively.

Timing of deformation along the NFS has been difficult to determine. Thermochronological dating and crosscutting relationships have constrained the onset of activity to the Middle Devonian (ca. 380 m.y.), after the accretion of a
composite peri-Gondwanan terrane to North America in Late Silurian to Early Devonian time. The earliest Norumbega related dextral shear deformation occurred at this time (West, 1999; Ludman et al. 1999). In south-central Maine $^{40}$Ar/$^{39}$Ar age dating of hornblende has constrained the latest amphibolite facies metamorphism to ca. 380 Ma (West et al. 1993). The upright folding and related schistosity in this region has been overprinted by dextral shear deformation. The deformation is consequently younger than ca. 380 Ma (West et al. 1993), so the relationship between the dextral shear fabrics and metamorphic events indicate a maximum age of 380 Ma for the development of the shear zone in south-central and south coastal Maine. At least two periods of reactivation have been identified (late Paleozone and Mesozoic; West et al., 1993; West and Lux, 1993; Doll et al., 1996).

Post-Acadian tectonic activity (later than ~360Ma) in the Casco Bay region produced brittle faults (Hussey, 1985). The Nonesuch River fault (NRF) splays off of the main segment of the NFS, extending from the Casco Bay area into southeastern New Hampshire. The NRF is interpreted to separate the Merrimack Group sequences of metasediments, which includes the Gonic Formation, from the Kearsarge-Central Maine Synclinorium (KCMS) metasediments (Figure 1) (Lyons, Boudette, and Aleinikoff, 1982; Bothner et al. 1984; Gaudette et al. 1984).

The trace of the NRF, as depicted on the Bedrock Geologic Map of Maine (Osberg et al. 1985) extends southeast from the Biddeford/Saco area into southeastern New Hampshire. Amid the Maine-New Hampshire border and the Lyman Pluton, Gonic Formation metasediments of the Merrimack Trough
compose the inferred southern side of this segment of the NRF. The Rindgemere Formation, of the Kearsarge-Central Maine Synclinorium, composes the northern side (Figure 2).

This work focuses on structural and metamorphic evidence within the Gonic Formation to support a detailed analysis in an area where potentially significant contributions to understanding regional deformation and metamorphic history can be made.
Figure 1: Geographical Map of North America. State of Maine enlargement shows major structural features
and field area. Modified from Osberg et al. 1985
Purpose

Extensive prior work in southwestern Maine and southeast New Hampshire has been completed for a majority of the land in these areas. Even the focus of this study, the Gonic Formation, has been studied in the past. However, those investigations were mainly rock identification, correlation and first order structural analysis (folding sequences and foliation directions). There were four primary goals of this investigation. The first was to document evidence for the Nonesuch River Fault in the Somersworth USGS quadrangle as inferred from Hussey (1985) and depicted on the Geological Bedrock Map of Maine (Osberg et al. 1985). The second goals, if the fault was directly observed, is to verify that the Nonesuch River Fault is a post-Acadian brittle fault, as concluded by Hussey (1985), and determine the relationship of the Nonesuch River Fault to the Norumbega Fault System.

The third goal focused on the structural and metamorphic features observed in the Gonic formation, and using that information, with conclusions from other studies in the general southwestern Maine-southeast New Hampshire area, attempted to determine the relationship of the Gonic Formation to the deformation and metamorphic history of the Norumbega Fault System. The final goal was to create a detailed geologic map of the Gonic Formation within the USGS 15 minute Somersworth Quadrangle.
Geologic Setting of Study Area

In southwestern Maine, near Casco Bay, a probable fault strand of the Norumbega Fault Zone (NFZ) branches off as the Nonesuch River Fault (NRF) and extends into New Hampshire, possibly re-connecting with the Campbell Hill-Hall Mountain Fault (Bothner and Hussey, 1999). The Nonesuch River Fault (NRF) is interpreted to separate the Kearsarge-Central Maine Synclinorium (KCMS) from the Merrimack Group (Figure 1).

This study has concentrated on the Gonic Formation, which is the northeastern most lithologic unit within the Merrimack Group of southwestern Maine (Figure 2). The Carboniferous age Lyman Pluton and the NRFKCMS provide structural boundaries to the northeast and northwest. The Berwick Fm. of the Merrimack Group and the political border between Maine and New Hampshire were chosen as the southeast and southwest limits of the field area.

Outcrop exposure in the field area is limited to less than 1% due to heavy vegetation and large amounts of glacially deposited sediments. This thesis presents the foliation, lineation, petrographic, and mineralogical data collected primarily within the USGS 7.5 minute Somersworth topographic quadrangle. Additional geologic data were obtained within the adjacent Alfred, North Berwick and Sanford 7.5 minute USGS quadrangles.
Figure 2: Area Map showing Nonesuch River Fault (NRF); Lyman Pluton, Webhannet Pluton, Agamenticus Pluton, Kearsarge-Central Maine Sequence, Merrimack Trough and Gonic Formation. Map modified from Osberg, 1985.
Early Models of the Norumbega Fault System

Fieldwork in central and eastern Maine during the 1940’s through the 1970’s revealed a significant metamorphic and structural discontinuity between low-grade and simply deformed rocks of central Maine and high grade, intensely polydeformed strata of the mid-coast region (Doyle and Hussey, 1967; Bickel, 1976). This discontinuity was not interpreted as a fault until 1974 when Stewart and Wones first used the name ‘Norumbega’ to describe a fault zone 300-400 meters wide in mid-coast Maine. Through detailed mapping, the NFS became recognized in the middle to late 1970’s as a structure of regional significance (e.g. Hussey and Newberg, 1977; and Wones and Thompson, 1979).

Complex coastal Maine geology records the multiply deformed and multiply metamorphosed history that has been linked primarily to the Acadian orogeny during the Devonian period. However present knowledge recognizes several superimposed events ranging from the Permian (286 to 245 Ma; West et al. 1988) to Silurian (440 to 410 Ma; West et al. 1995). The major structural feature that developed during these events was the Norumbega Fault Zone (NFZ). Synchronous and post-tectonic plutonism further complicated multiply deformed terranes in the Devonian and Carboniferous periods (Ludman and West, 1999).

The NFZ roughly follows the coast of North America along its ~450 km length from New Brunswick to New Hampshire. Previous studies (Swanson, 1999) have shown the NFZ has a dominantly dextral shear sense. In addition to being one of the most extensive and longest-lived structural features of the Appalachian Mountains, the NFZ has been interpreted to separate medial New England from composite Avalon (Ludman and West, 1999).
**Tectonic Models**

There have been several interpretations describing the tectonic activity along the eastern seaboard. They typically include closure an ocean from convergence of the Laurentian, Baltica and Gondwana land masses and accreted terranes. In the scope of this thesis, discussion of plate tectonic models and origins of the Appalachian mountain chain begins during the Early Paleozoic.

An interpretation by Rast and Skehan 1993, based on a system proposed by Soper and Hutton (1984), describe Post-Taconian movements of continental plates as originating from a triple junction, where Laurentia, Baltica, and Gondwana represent the interacting landmasses.

In their reconstruction the Iapetus Ocean has two branches, one separating Greenland and the Scandinavian part of Baltica; the other branch separating Laurentia from Gondwana. Plate motion across the triple junction led to the approach of Greenland and Baltica toward Laurentia. They propose several small oceans and intervening islands, as volcanic and continental blocks or terranes, comprised the southwest portion of the Iapetus Ocean. Some of these island blocks in the northern Appalachians adhered to, or approached, the Laurentian craton. The largest are the Merrimack trough and the Avalon block.
An interpretation by Bradley (1983) and Bradley et al. (2000) more narrowly depicted an interpretation of the Acadian Orogeny. Bradley discusses the two volcanic arc belts and deep-water stratigraphy that extend across the northeastern United States from Connecticut to the Gulf of St. Lawrence and reasons their development (Figure 3).
The lithology, in which the two arcs formed, are divided in two four basins; the Connecticut Valley-Gaspé Basin, Aroostook-Matapedia Basin, Fredericton Basin and the Central Maine Basin (Merrimack Trough in Figure 4). These deep-water Silurian age lithological units are believed to represent the sedimentary deposits of the ocean that closed during the Acadian Orogeny.

The two volcanic arcs are designated the Piscataquis Volcanic Arc (PVA) and the Coastal Volcanic Arc (CVA) (Figure 4). The PVA is a northeast-southwest trending belt with four distinctive volcanic centers, stretching from central Connecticut to the Gaspé Peninsula. Rankin (1968) traced just a 160 km volcanic belt, but is credited as first recognizing the Devonian volcanic belt. Andesitic volcanoes dotted the shallow marine sedimentation within this belt. Bradley refers to McKerrow and Ziegler, 1971; Rodgers 1981 and Hon and Roy 1981 as attributing this to an arc over a west or northwest dipping subduction zone beneath North America. Volcanic activity in within the Arc was sporadic until the Devonian, when a distinct increase in activity occurred during the Devonian.
Bradley then characterizes the Coastal Volcanic Arc as a Silurian to early Devonian belt of shallow marine volcanism built on Precambrian to early Paleozoic basement. This belt has been traced discontinuously from southern New Brunswick to eastern Massachusetts, approximately 600 km. The area is referred to as Avalonia by most. These volcanics, composed of basalts, andesites, rhyolites and interbedded sedimentary rocks were deposited in deep marine to non-marine environments.

These volcanic arcs are thought to have formed as the result of the Avalonian crustal block converging with Laurentia (North America). Whereby, northwest-dipping subduction occurred beneath Laurentia and southeast-dipping subduction occurred beneath Avalon. As Avalonia converged, the ocean closed,
the lithology was deformed and metamorphosed and the volcanic arcs developed (Figure 4).
Previous Work in the Area

Katz originally mapped the lithology of southern Maine in 1917. He proposed the name Berwick Gneiss for what is now the Berwick formation. Katz assigned a possible Precambrian age based on his determination that the Berwick is more metamorphosed and deformed than the Eliot or Kittery Formations (Hussey, 1962).

The assignment of the Gonic Fm. to one of the two adjacent groups has, in the past, been debated. Hussey (1962) originally assigned the Gonic Fm. to the ‘Shapleigh Group’ of the KCMS, based on its pelitic compositional similarity to the nearby Rindgemere and Towow Formations. However, it is now believed that the Gonic Fm. belongs to the rocks of the Merrimack Group, based on the observance of the Gove Member within the Berwick Fm., which are lithically very similar (Hussey, 1985).

Mapping in the area has most notably been carried out by Hussey in the 1960’s through the 1980’s. Lithological units documented by him are the same followed within this report. A few miles northwest of the field area, located within the Kearsarge-Central Maine synclinorium of Eusden et al. 1987, the Lebanon antiformal syncline has been documented. They reported that within this area three folding events are present, and their descriptions are addressed in “Folds” of Chapter 4. Although the descriptions of these folding events have been used for the Lebanon antiformal syncline and is located across the NRF, the proximity to the Gonic Formation makes the descriptions potentially useful for
comparison to Gonic Formation structures, particularly if the NRF is not a major structure.

Chapter 2

Lithology

Merrimack Group

Billings (1956) reported the name “Merrimack Group” had been first used by C.H. Hitchcock in 1870. Hitchcock defined the Merrimack Group as an undifferentiated sequence of quartzites and quartzose slates and phyllites as typically exposed along the Merrimack River Valley near Salisbury, Massachusetts. In 1917 Katz further defined the Merrimack as consisting of the Kittery, Eliot and Berwick Formations.

The nature and extent of the Merrimack Group sequences were better characterized by Bradley 1983, as “a belt of deep water metasedimentary rocks of mainly Silurian age, considered here to be preserved in an accretionary complex which marks the site of the Acadian Ocean.”

Currently, Merrimack Group sequences are considered to be located in southwestern Maine, southeast of the Nonesuch River Fault and extending as far north as the Biddeford and Saco area, where it has been interpreted to terminate at a pair of northwest-southeast trending thrust faults, and southwest into New Hampshire and Massachusetts (Hussey 1985). The southeastern limit is
unconstrained due to the ocean (Figure 2). Deformation as a whole within the Merrimack Group shows effects of three principal fold sets (Hussey, 1985).

Hussey (1985) groups four formations in the Maine division of the Merrimack group: Kittery Fm., Eliot Fm., Berwick Fm., and Gonic Formation. The stratigraphic relations of the Vassalboro Fm (now Hutchins Corner Fm.; Osberg, 1988) and the Windham Formation are unclear and may also belong to the Merrimack. On a geographical basis these two Formations fall within the Kearsarge-Central Maine Synclinorium. However, on a temporal scale the Vassalboro Fm. is positioned as slightly older than the Merrimack Group and the Windham Fm. is positioned slightly younger than the Merrimack Group (Hussey, 1985).

**Kittery Formation**

The Kittery Formation extends in a belt 5 to 16 km wide along the Maine coast from Kennebunkport to Gerrish Island in Kittery, further extending into southeastern New Hampshire, to the Hampton area. Hussey identified three lithologies associated with the Kittery Fm.:

1. A buff-weathering very fine-grained thinly laminated calcareous and feldspathic quartzite;
2. A fine-grained to flinty textured hard chocolate-brown to medium gray feldspathic, micaceous (chlorite and/or biotite) and calcareous quartzite; and
3. A dark gray or brownish gray chlorite or biotite phyllite.
Eliot Formation

The Eliot Fm. extends in two belts from Epping, New Hampshire to North Berwick, Maine narrowing from 7 to 1km. A second belt extends from Eliot, Maine into New Hampshire where it divides into eastern and western synclinal sub-belts. The composition of the Eliot Fm. consists of:

1. thin-bedded alternations of medium buff-gray weathering,
2. medium bluish gray ankerite and
3. calcite-bearing quartz-mica phyllite, and dark gray finely-crenulated phyllite.

Vassalboro Formation

Two-lithologies are prevalent in the Vassalboro Formation. One, in the Gorham-Bonny Eagle-Hollis area, consists of thin to medium (2-30 cm) bedded, fine to medium grained, medium gray non-salt and pepper textured quartz-plagioclase-biotite-hornblende granofels and slightly schistose granofels, with thin interbeds of buff-weathering medium greenish gray calc-silicate granofels. Schist of staurolite to sillimanite grade is also included as rare, thin inter-beds.

The second lithologic type is found in the Brunswick to Portland area (Falmouth Formation) consisting of thin bedded to massive salt and pepper-textured fine to medium grained medium gray quartz-plagioclase-biotite-hornblende gneiss locally lit-par-lit injected by foliated pegmatite stringers commonly 15cm to 2m thick.

Windham Formation

Hussey’s (1985) distribution of the Windham Fm. is restricted to three northeast-southwest trending belts: a 2 km belt occupying a doubly plunging
synform between the north end of the Lyman Pluton and Windham Center; a synformal belt up to 3 km wide stretching 20 km southeast from the Sebago Pluton at west Gray; and a synformal belt 2 km wide and 20 km long between northern Hollis and North Windham. The lithology is comprised predominantly of thin bedded to massive rusty and non-rusty weathering muscovite-biotite-garnet-quartz schist with kyanite and staurolite, or sillimanite depending on metamorphic grade.

Berwick Formation

The Berwick Formation is located southeast of the Gonic Fm. and they are presumably in gradational contact. The contact has been narrowed down to a 3-meter location on the southeast side of Windy Hill. Here the schistosities of both formations are parallel and the rocks are unsheared, suggesting conformability according to Hussey (1985). The Berwick Fm. consists of a multitude of characteristic rock types. The rock descriptions used by Hussey, 1962 provide the guidelines used for rock identification in this thesis. The descriptions are:

(1) Fine-grained mottled green and purplish gray quartzite with abundant dark green actinolite porphyroblasts;

(2) dense, conchoidal fracturing greenish gray quartzite with abundant actinolite;

(3) mottled light green and purplish gray quartzofeldspathic actinolite-biotite granulite with a slight tendency toward gneissic structure, and containing abundant thin actinolite-feldspar veins;
medium purplish gray, rather granular quartz-biotite schist, locally containing elongate biotite porphyroblasts which give a gneissic structure and lineation to the fabric;

gray quartzo-feldspathic biotite-actinolite gneiss marked by conspicuous streaks and bands of biotite, and

greenish gray interbeds in association with the other types.

In the same publication Hussey also gives a description of the Berwick Fm. within proximity to the Lyman Pluton as: a medium gray, granular, medium grained quartz biotite schist with occasional thin interbeds of actinolite gneiss. In addition, hard brittle purplish gray quartzite, the dominant lithology of the Kittery Formation, is also common in the Berwick Formation.

Another lithology reported in the Berwick Formation is the Gove member. According to Hussey the Gove is lithically very similar to the Gonic Fm. Based on this similarity the Gonic has been included in the Merrimack Group of lithological units (Hussey, 1985).

### Gonic Formation

The focus of this thesis is the Gonic Formation. It is a northeast trending unit of multi-deformed rocks within the Merrimack Group. The extent of the formation within the Somersworth quadrangle is approximately 10 miles long and 1-mile wide trending northeast-southwest. According to the Metamorphic Reaction Zone Map by C. Guidotti, found on the Geologic Bedrock Map of Maine (Osberg, 1985) and reproduced in part below, the field area appears to be completely within the epidote-amphibolite facies (Figure 5).
Topographically, a line of low-lying hills distinguishes the Gonic Formation from the surrounding bedrock units (Figure 6). The hills from northeast to southwest are; (1) Windy Hill, (2) Beech Ridge, (3) Diamond Hill, (4) an unnamed hill; the name Buttonwood Hill will be used in this thesis, (5) a second unnamed hill north of Buttonwood Hill, referred here as Small Hill. Pine Hill (6) is the furthest southwest (Figure 6). The most outcrop exposure is located on the northeast side of Windy Hill.
The Gonic Formation is characterized as pelitic schist consisting of two dominant lithologies. They are:

(1) medium-gray silvery muscovite schist with prominent porphyroblasts of staurolite, garnet, biotite, andalusite, graphite, ilmenite? and retrograde chlorite.
(2) A fine-grained, medium gray, slightly muscovitic and biotitic quartzite and quartz mica schist with very minor feldspar (Hussey, 1985).

Bedrock exposure in the field area is limited to small areas on these low hills. The importance of this aluminous silvery muscovitic metapelite is potentially very significant in understanding the mechanisms of terrane accretion during the Acadian Orogeny and to understanding the development of the Nonesuch River Fault.
**Kearsarge-Central Maine Synclinorium**

The Kearsarge-Central Maine Synclinorium (KCMS) is adjacent to the Gonic Fm. on the northwest side of the NRF. The KCMS extends northeasterly from Connecticut to Maine and from the east flank of the Bronson Hill anticlinorium east to the Norumbega-Nonesuch River fault zone (Lyons, Boudette, and Aleinikoff, 1982). Silurian and Devonian cover rocks within the KCMS extend across the Norumbega fault toward the Atlantic Ocean in eastern Maine and New Brunswick (Ludman 1981). The Nonesuch River Fault, a.k.a. Campbell-Hill Fault in NH, has been inferred to form the contact between the Rindgemere Fm. of the Kearsarge-Central Maine Synclinorium and the Gonic Fm. of the Merrimack Group (Hussey 1985).

**Rindgemere Formation**

Katz (1917) performed the original mapping of the Rindgemere Fm. based on exposures in the Salmon Falls River in East Rochester. In 1985, Hussey divided the Rindgemere Fm. into an upper and lower unit. He reported that the lower unit was a sequence of variably bedded metamorphosed pelitic shale and argillaceous sandstone, with minor rusty-weathering and non-rusty calcareous sediments. The Rindgemere Formation is presumably in fault contact (NRF) with the Gonic Formation. A thin section from the Rindgemere Fm. (S1090) was analyzed and is discussed in *Petrography*.
CHAPTER 3
INTRUSIVE ROCKS

Sebago Batholith

New England’s largest plutonic body, located in southwestern Maine and east-central New Hampshire, is the Sebago batholith (~2,700 km²; Figure 8). Age constraints of the Sebago batholith have been identified on two varieties of granite, white and pink (Aleinikoff et al. 1985). Chemical analyses of eight samples from the pluton indicate very little difference in composition between the two varieties. U/Pb age dating shows that the ages of both varieties of the Sebago Pluton granite are synchronous at 325 m.y. ± 3 (Aleinikoff et al. 1985). The Pennsylvanian age of the Sebago pluton correlates with the age of the Lyman pluton (322 ± 12; Aleinikoff et al. 1985), suggesting that the intrusions occurred during the same event and possibly are from a common source. The Sebago batholith is elongated (~80km x ~35km) in a northwest southeast direction, which is contrary to other, smaller intrusive bodies in southern Maine. However, the outline of the southeastern portion of the batholith does seem to more closely approximate the regional structural trends. Metamorphic isograds approximately parallel its outline, as shown on the ‘Generalized Map of Regional Metamorphic Zones’ by Charles V. Guidotti of the ‘Bedrock Geologic Map of Maine’ (Figure 5; Osberg et al., 1985), in the vicinity of the batholith. According to Aleinkoff et al., (1985), gravity studies conducted by Hodge et al., (1982) indicate that the batholith is a sub-horizontal sheet-like body having a calculated thickness of <1km.
Lyman Pluton

The Lyman pluton is one of the major intrusive bodies of southwestern Maine. The two-mica granite pluton has an elongate shape in a northeast-southwest direction, parallel to regional structural trends, approximately 24 km x 8 km, spanning an area from the Great Works River to the Saco River. The Lyman Pluton, along with the Webhannet Pluton and Biddeford Pluton of southwestern Maine has been correlated with the New Hampshire magma series (Figure 2; Billings 1956; and Hussey 1962). Gaudette et al., (1982) performed rubidium/strontium (Rb/Sr) whole rock mineral dating on the Lyman Pluton. Their results yield an age of 322 ± 12 Ma, placing the timing of intrusion within the Carboniferous.

The southern terminus of the Lyman Pluton has been reported to be in contact with the Rindgemere Fm., Berwick Fm., and the Gonic Fm. (Gaudette et al., 1982). No direct contact between the Lyman pluton and the aforementioned formations was found during this study. However, at three locations within the pelitic schist of the Gonic Fm. granitoid intrusions were observed. Granitic outcrops were found on Diamond Hill, Small Hill and, approximately one-mile east-southeast of the summit of Bauneg Beg Mountain. A petrographic analysis of mineral abundances in these samples has been performed (Table 1).

Granites in the Gonic

Located at the primary outcrop on Diamond Hill lies a granitoid dike (Diamond Hill Dike, DHD). The undulating dike cuts the primary schistosity nearly perpendicular and does not show chill margins. Lack of chill margins
suggests the country rock and the intrusion were at similar temperatures during intrusion. An unoriented sample of the dike was obtained and a thin section was prepared. Point count analysis of the sample (DHD) revealed quartz comprised 53.7%, muscovite comprised 36.3%, and plagioclase comprised 5.57% of the rock. Undulose extinction is present in a small number of the individual quartz grains. Sutured grain boundaries are present in quartz-to-quartz interactions. The presence of plagioclase categorizes the rock type as tonalite. The overall texture of the tonalite exhibits a weak foliation defined by the alignment of muscovite.

Samples LR3.15 and LR3.5 were both obtained on Small Hill, approximately 50 feet apart. Sample LR3.15 is a medium to fine-grained granite with a uniform grain size. The characteristic of LR3.5, at the outcrop scale, that makes this sample distinctive is the presence of a strong foliation. At first glance the rock in outcrop appeared to possess a gneissic structure. Measurements of the foliation of LR3.5 and another nearby granite outcrop with a weak foliation, revealed a similar strike and dip. These measurements plot exceptionally close to that of a foliated granite sample found within the Gonic Fm. (at 803 Morrills Mill Road) approximately 3 miles north of Windy Hill (Figure 7).

![Figure 7: Stereonet Diagram. Foliated granite found with the Gonic Fm. Equal area projection. N= 4.](image)
Table 1: Point Count Results from Granitoid Samples in percentages.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Quartz (SiO$_2$)</th>
<th>Plagioclase (NaAlSi$_3$O$_8$ &amp; CaAl$_2$Si$_2$O$_8$)</th>
<th>Biotite (K$_2$(Mg, Fe)$_3$ AlSi$<em>3$O$</em>{10}$ (OH, O, F)$_2$)</th>
<th>Muscovite (KAl$_2$(Si$<em>3$O$</em>{10}$)(OH)$_2$)</th>
<th>Other *</th>
<th>Total %</th>
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<td>47.98</td>
<td>26.75</td>
<td>5.53</td>
<td>20.32</td>
<td>-</td>
<td>100.49</td>
</tr>
<tr>
<td>LR3.5</td>
<td>51.8</td>
<td>13.2</td>
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<td>-</td>
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<td>3.71</td>
<td>36.3</td>
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% Ratios

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<th>Bt./Muscov.</th>
<th>Muscov./ Qtz.</th>
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<td>0.102</td>
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* Other = opaque minerals

Based on point-count results of LR3.15 and LR3.5, two varieties of tonalite are present at the Small Hill locality. LR3.15 contains a higher percentage of plagioclase and biotite and a lower percentage of muscovite.

The textural differences between LR3.5 and LR3.15 also signify two distinct igneous intrusional events. Where LR3.5 intruded prior to the development of the S1 foliation, hence the foliation observed in LR3.5, and LR3.15 intruded later. Additionally, the lack of internal structure in LR3.15 suggests the later intrusion occurred after all plastic deformation had ceased. Therefore there was an event sequence:

Intrusion $\Rightarrow$ S1 $\Rightarrow$ Intrusion.

Hussey (1985) described the line of low-lying hills as a result of erosional resistance of the Gonic Fm. However, the alignment of the Lyman Pluton, and topographic features within the Gonic Fm. (ring shape at Small Hill) and the
presence of granitoid rocks found within outcrops on the hills hints at the presence of granites underlying the hills.

Figure 8: State of Maine Map showing location of Sebago Pluton relative to the Field Area. Norumbega Fault System shown in Red. (Osberg et. al. 1985)
CHAPTER 4

Structural Features of the Gonic Formation

Folds

Three phases of folding has been documented in the southwestern Maine and southeastern New Hampshire areas. Lyons, Boudette and Aleinkoff (1982) initially recognized these Acadia folding events within the Kearsarge-Central Maine Synclinorium (KCMS) as:

1) early recumbent folds (F1) that face westerly,
2) broad open folds (F2) with west or northwest trending axes and
3) isoclinal to open folds (F3) with northeast trending axes that refold earlier folds.

A few miles northwest of the Gonic Fm. field area, across the NRF and within the Kearsarge-Central Maine synclinorium, the Lebanon antiformal syncline has been documented (Eusden et al., 1987). They reported three folding events are present within that area. First, extensive areas of inverted strata that have been interpreted as overturned limbs of a large southeast-verging nappe (F1); second, southeast-verging dominantly downward facing antiforms and synforms (F2) control the map pattern. The third folding event (F3) is defined as a major deflection or regional bend along strike in the orogenic belt. At Bauneg Beg Mountain in the Berwick, Maine 15’ quadrangle, Eusden et. al (1987) also reported a southeast-facing, F1 fold, which has also been interpreted to verge southeast.

Eusden et al. (1987) divided their field area into structural domains to clarify F3 folding effects. They recognized four domains in their field area that
represent four areas of macroscopic, homogeneous structural fabric. Domain II, characterized as northeast striking S₀ surfaces and F₂ axes, is illustrated by them as roughly bordering the northwest side of the Gonic Formation. Their domains were made to represent rocks northwest of the NRF. However, the proximity and similarities of structures observed in the Gonic Fm. potentially make those descriptions a useful benchmark. Comparison of folding changes across the NRF into the Gonic Fm. could also lend evidence to verifying the location of the Nonesuch River Fault. 

Fargo and Bothner (1995) further expanded and fit the folding events into deformational events:

1) D₁, discontinuous bed parallel cleavage (S₁) and rare isoclinal folds (F₁);
2) D₂, upright to overturned east-directed Class 2 folds (F₂) with subhorizontal hinges and poorly developed axial plane cleavage (S₂);
3) D₃, map-scale anastomosing ductile shear zones with both dextral and sinistral kinematic indicators; interference of S₃ shear and F₂ folds produced steeply plunging sheath folds (F₃);
4) D₄, characterized by shallow east-dipping spaced cleavage (S₄) that cut both S₂ and S₃; west directed F₄ folds locally well developed in the Eliot Formation;
5) D₅, ductile to brittle shear zones within the Exeter Diorite and surrounding area;
6) $D_6$, formation of north-south trending, west dipping fractures within the central portions of the Exeter pluton and surrounding strata. The fractures host some sulfide mineralization.

Hussey (1985) also described several minor events that show development in the area as evidenced by slip cleavage, crenulations, kink bands, small scale folding and additional foliation development in the surrounding area. He further describes $F_2$ as the second major deformation that resulted in a macroscopic fold system that controls the map pattern. These folds are described as upright to slightly overturned with north to northeast trending fold axes, gentle to moderate angles of plunge and frequent reversals of plunge direction.

Within the Gonic Fm. the general descriptions used by Hussey (1985) best describe the folding observed by me. On the map accompanying this thesis, along the northeast side of Beech Ridge, Buttonwood Hill, Diamond Hill, and southwest side of Windy Hill, topographic contours suggest lineaments that reflect either $F_2$ folding or lithic layering. However, the trends of these lineaments are similar to directly observed and mapped $F_2$ folds within the field area. A USGS shaded relief map of the field area prominently shows these same northeast trending lineaments (Figure 9).

In the northeast of the Windy Hill area, mapping has revealed several smaller scale syncline and anticline $F_2$ folds, some only a few meters apart. Fold axis measurements show northeast and southwest trend directions with sub-horizontal plunges, predominately to the southwest.
Figure 9: Shaded Relief Map of the low-lying hills that define the Gonic Formation. Glacial transport direction is from the northwest to the southeast. Map depicts variations in elevation based on a specified position of the sun. Areas in the sun are bright, while areas in shadow are dark. Generated from the National Elevation DataSet. (USGS National Map Viewer, 2003)
F₃ folding is observed in the field by deflections in the primary foliation direction and variance in measured F₂ fold axis lineations. F₃ was recognized after mapping because of the dense vegetation and soil cover. The general trend of F₃ fold axis in the Gonic Formation (northwest) has a similar trend to those of Eusden and Lyons (west-northwest; 1993) across the NRF in the Central Maine Terrane. This similarity suggests F₃ deformation is related.
Transposition

Transposition develops during the progressive deformation of compositional layering in bedrock (Figure 10). Lithologic layering is folded or sheared and moves toward parallelism with the axial plane of isoclinal folding or shear planes. During the early stages of my fieldwork the contrasting lithologies between the schist and quartzite of the Gonic Fm. were mistaken for original stratigraphy (Figure 11a). However, Hussey (1985) reported transposition in the Berwick Fm. Fargo and Bothner (1995) hypothesised that the Berwick Fm. had attained a greater degree of transposed layering and higher grade of metamorphism prior to its juxtaposition along the western margin of the Merrimack Group. In light of this, macroscopic observation and interpretation of the interaction between these two differing lithologies supports transposition of the layer as an effect of deformation.

As previously described, the two dominant lithologies of the Gonic Fm. are the silvery grey muscovite schist (schist) and the muscovitic and biotitic quartzite and quartz mica schist (quartzite). The quartzite component typically occurs as narrow (3-25cm wide), non-continuous layers when observed normal to foliation. These layers have been
observed to terminate as both a ‘pinch out’ (Figure 10) and a feathered gradational pattern.

When observed perpendicular to the foliation, the quartzite layers have been observed to be tightly folded (Figure 11b). Large-scale transposition may also explain the presence of the Gove member within the Berwick Formation as mentioned in the lithology section.
Transposition development within the field area would most likely have occurred during the F1 phase of deformation synchronous with foliation (schistosity) development.
Mylonites

Fault rock deformation is not homogeneously distributed in the crust. Commonly patterns of heterogeneous deformation are concentrated in planar zones that accommodate movement. The volume of rock within which lateral displacement of wall rock occurs is known as a shear zone.

Shear zone development can affect the characteristic fabric and mineral assemblages, reflecting the pressure and temperature conditions, flow type, movement sense and deformation history in the rocks. Shear zones are comprised of two sub-divisions: brittle and ductile. Brittle deformation will typically produce cataclastic fault rocks. Ductile deformation can stretch and deform rocks producing mylonitic rocks. Figure 14 is a graphical representation of the distribution of the main types of fault rocks with respect to depth (Passchier and Trouw, 1998).

Lapworth (1885) first used the term mylonite to describe rocks of the Moine thrust in NW Scotland. His description of mylonites concentrated on brittle deformation, although crystal plastic processes were also recognized. Since that time the definition has been debated and refined. According to a survey conducted by Mawer (1986) “mylonites occur in shear zones, that is, zones across which one block of rock is displaced with respect to another, and which show no evidence of major loss of material continuity. They develop primarily by ductile deformation processes. They are well foliated and commonly well lineated, and show an overall reduction in grain size when compared to their hosts. Mylonite zones can be developed at any scale, in rocks of any original composition and fabric.” Due to the nature of their formation, mylonites have a wide range of
textural characteristics. A useful classification scheme developed by Sibson (1977), and modified by Scholz (1990), is shown in Table 2.

Figure 14. Distribution of the main types of fault rocks with depth in the crust. **Left and Center** Schematic cross section through a transcurrent shear zone. The zone may widen, and changes in geometry and dominant type of fault rock occur with increasing depth and metamorphic grade. **Right** Schematic representation of four typical fault rocks (not to scale) and the local geometry of the shear zone in a 1m wide block, such as would develop from a phenocryst granite; gs generation surface. Inclined (normal or reverse) shear zones show a similar distribution of fault rocks and shear zone geometry with depth. No vertical scale is given since the depth of the transition between dominant ductile deformation and brittle fracturing depends on rock composition, geothermal gradient, bulk strain and other factors. Diagram from Passchier and Trouw, 1998.
At one location at outcrop scale a pair of structures was observed where the term mylonite can be applied. Situated on the northern side of Buttonwood Hill is a pair of shear bands with tapering widths from 0 to 30 cm. It is within the shear bands the rock can be classified as mylonite. This is based on several of the previously mentioned textural classifications. First, the mineral grains within the shear bands are much finer than the mineral grains outside of the shear band (grain size reduction). Second, a quartz vein which passes from the host rock through both shear bands appears to have been more extensively folded and flattened within the confines of the shear band. Third, alignment of biotite shows two
distinct alignment directions exhibiting a C-S structure. The most evident, and parallel to the shear band wall, possess a variable trend between N63 to 83E. This is the C-plane. The second alignment of biotite trends N82W and is positioned between the C planes. This is the S-plane. Additionally, the S-planes were observed to ‘sweep’ into the C-plane where they intersect. C-S structure is a common occurrence in mylonites. Based on the arrangement of C-S planes within these shear bands at Buttonwood Hill, a sinistral sense of shear is apparent.
**Foliations**

In metamorphic rocks, a foliation is described as a planar or laminar feature due to an alignment of minerals into layers that may or may not occur penetratively in a body of rock. Several fabric elements can define a foliation. These are described in Figure 15.

![Diagram of fabric elements](image)

*Figure 15: Diagrammatic representation of the various types of fabric elements that may define a foliation. A: Compositional layering. B: Preferred orientation of platy minerals (e.g. mica). C: Preferred orientation of grain boundaries and shape of deformed grains (e.g. quartz, carbonate). D: Grain size variation. E: Preferred orientation of platy minerals in a matrix without preferred orientation (e.g. mica in micaceous quartzite or gneiss). F: Preferred orientation of fractures of lenticular mineral aggregates. G: Preferred orientation of fractures or microfaults (e.g. in low-grade quartzites). H: Combination of fabric elements a, b, and c; such combinations are common in metamorphic rocks. Diagram modified from Passchier and Trouw 1998.*

In a shear zone composed of mylonites, it is common to have composite foliations. C-S fabric consists of two planes of preferentially aligned minerals. From the French ‘cisaillement’, meaning shear, the C planes are sub-parallel to the walls of the shear zone boundary, remaining relatively straight and continuous (Passchier and Trouw, 1998). The S planes, from French ‘schistosité’, in a mylonite are interpreted to form between, at an angle to, and simultaneously with the C planes (Berthé et al., 1979). As the proximity of the S planes to C planes...
decreases, the S planes bend into the C planes. This asymmetric geometry has been shown to be useful as a kinematic indicator (Passchier and Trouw, 1998). C’ shear bands show a crosscutting relationship to previous C or C-S fabric, are at a low angle to C and synthetic in offset. This is also a good kinematic indicator. The C’ shear bands are usually anastomosing, short and wavy (Figure 16). C’ planes are shear bands and are typically only formed after extended periods of high deformation, thus they tend to form in the latest stages of mylonite formation, but only after a strong mineral preferred orientation, crystal shape or crystallographic axes have been established (Passchier and Trouw, 1998). A stretching lineation also develops with C-S development. The stretching lineation is assumed to represent the direction of offset forming perpendicular to the S-C plane.

Figure 16: The three types of foliation pairs that are common in ductile shear zones. The shear zone is shown with typical foliation curvature. The main differences in geometry between the foliation pairs are shown in the center. Elements used to determine sense of shear are shown below. Figure modified from Passchier and Trouw 1998.
C-S fabrics have been observed in meso- and micro scales in the Gonic Fm. Mesoscale C-S fabric development at Buttonwood Hill developed within two sub-meter scale, apparently tapered, shear zones. The C planes are defined by a biotite matrix as thin (≤ 1cm) parallel bands. These bands are spaced 2 to 6 cm apart and strike between N63 to 83E, parallel to the local shear zone boundaries. The S planes ‘sweep’ into the C-planes (Figure 16) suggesting a sinistral shear sense. The general strike of the S-planes is N82W. Assuming the direction of stress responsible for the formation of the C-S-planes was more-or-less perpendicular to the S plane, the shortening for this local shear zone was N8E.
**Cleavage**

In broad terms, cleavage is the splitting or tendency to split, along parallel, closely positioned planes in rock. Cleavage in sedimentary and metamorphic rock tends to be associated with folds and oriented parallel to subparallel to the axial surfaces of the folds (Davis, 1984). In the vicinity of folds the axial-plane foliations often deviate from the simple planar geometry seen in homogeneously deformed rocks. Commonly the foliations appear to have been affected by the fold and are fanned or refracted. This is well known for axial-plane schistosity, crenulation cleavage, slaty cleavage and fracture cleavage.

Cleavage has been classified into two sub-divisions based on observable scale: continuous and discontinuous (Davis, 1985 after Dennis, 1972 and Powell, 1979). Continuous cleavage can be described where a distinction between cleavage domains and microlithons can be seen with the unaided eye. The main types of continuous cleavage are: slaty cleavage, phyllitic structure and schistosity.

Schistosity is the dominant cleavage found in the pelitic rocks of this field area. Schistosity typically develops in rocks with a medium (1-10 mm) grain size. The distinctive outcrop scale characteristic is the parallel arrangement of micas.

Discontinuous cleavage can be described where the dominal character of a cleaved rock is too fine to be resolved without the aid of a petrographic or an electron microscope. There are two types of discontinuous cleavage: spaced cleavage and crenulation cleavage. Spaced cleavage, also known as fracture cleavage, is one that forms through brittle fracture. It can consist of an array of
parallel to anastomosing, stylolitic to smooth, fracture like partings (Davis, 1985 after Nickerson, 1972).

Crenulation cleavage is a discontinuous cleavage and is distinctive in that it overprints a pre-existing cleavage like schistosity. Two kinds of crenulation cleavage have been recognized: discrete and zonal. Discrete crenulation cleavage is one where very narrow cleavage domains sharply truncate the continuous cleavage of the microlithons, similar to faults. This type of cleavage tends to form in slate. Zonal crenulation cleavage is one where wider cleavage domains coincide with tight, flattened limbs of microfolds in the pre-existing cleavage (Davis, 1985 after Gray, 1977a).

Zonal crenulation cleavage within the Gonic Formation was observed throughout the field area. At Diamond Hill the crenulation cleavage is gradational between domains, folding and deflecting the foliation. The crenulation lineation at Diamond Hill trends 34° N86E. Crenulation lineation at Small Hill had a plunge of 0° and a trend of N50E. The transitions between cleavage domains are more discrete than those at Diamond Hill. However, grain size may have an effect on the development of the crenulation cleavage. A stereonet diagram of crenulation lineations has been constructed and a dominant southwest-directed plunge is evident (Figure 23). This is consistent with F2 fold axis plunge directions.
**Lineations**

A lineation is any linear feature that occurs penetratively in a body of rock. This is a broad definition that can describe a number of features (Figure 19). The most important types are the following (Passchier&Trouw, 1998):

- intersection lineations, formed by intersecting foliations or other planes, such as bedding and cleavage (Fig. 19a)
- crenulation lineations, defined by hinge lines of microfolds in a foliation plane (Fig. 19b)
- stretching lineations, defined by deformed mineral grains or other relict strain markers (sands, pebbles or fossils) that were originally equidimensional (Fig. 19c,d)
- mineral lineations, defined by the preferred orientation of euhedral or subhedral mineral grains with an elongate shape (i.e. staurolite, tourmaline) (Fig. 19e,f)

The direction of displacement, or shear direction, in mylonites is interpreted to be parallel to the stretching lineation (Garnett & Brown, 1973; Choukroune et al. 1986; Lin & Williams, 1990). The relationship between the stretching lineation for composite foliations, as discussed in the previous section, is that stretching lineations develop perpendicular to the intersection lineation of C-S and C-C’. Thus in order to determine the shear direction in a thin section or rock sample, that sample must be oriented parallel to this lineation and perpendicular to the foliation.
Figure 19: Diagrammatic representation of various types of fabric elements that may define a lineation: A) Intersection lineation of two planar structures. B) Crenulation lineation. C) Stretching lineation defined by deformed (constricted) grains. D) Stretching lineation defined by euhedral or subhedral grains with an elongate crystal shape (such as sillimanite or tourmaline). F) Mineral lineation defined by euhedral or subhedral planar grains (such as micas) which share a common axis. Diagram modified from Passchier and Trouw 1998.

The lineations most observed in the field area include: crenulation lineations, fold hinges (both lithic layers and quartz veins), quartz vein striation lineations and mineral lineations. The parallel arrangement of a mineral or group of minerals defined by euhedral or subhedral grains that share a common axis is a mineral lineation. Striations from brittle deformation, though not penetrative, are caused by layers moving across, and in contact with, a softer layer produce striae lineations. Crenulation lineations, quartz vein and bedrock fold hinges all generate an imaginary lineation parallel to their fold axis. Lineations are useful
in determining shear direction, fault slip direction, and distinguishing fold
developments. The lineation data collected from this project is discussed in the
Stereographic Projection section and the raw data is listed in Appendix B.
Porphyroclasts and Porphyroblasts

Porphyroclasts

Porphyroclasts are remnant grains that have a larger grain size than the surrounding matrix; they help define mylonite fault rock types. Asymmetric geometries of individual mineral grains (sigma ($\sigma$) and delta ($\delta$) porphyroclasts) have been shown to be particularly useful in determining shear sense in mylonites (Figure 20). In brittle regimes sense-of-shear can be inferred from the displacement across fractured grains (Figure 35 B). Grains fractured at a low angle to the bulk flow plane (0 to 20°) show a shear sense sympathetic to the flow plane. Grains fractured at a high angle (50° to 90°) show a shear sense antithetic to the flow plane. Initial orientation of the fracture/slip plane to the bulk flow plane is important to proper kinematic analysis.

Figure 20: Classification of mantled porphyroclasts. Sinistral sense of shear. Modified after Passchier and Trouw 1998.
Porphyroblasts

A porphyroblast is a relatively large crystal that formed by metamorphic growth in a more fine-grained rock. The nucleation of a porphyroblast can be a useful tool in determining a relative deformation or tectonic sequence. During growth inclusion patterns can mimic the structure in the rock at the time of growth (Passchier and Trouw, 1998).

Passchier and Trouw, (1998; after Zwart, 1960, 1962) developed a version with nine relationships based on relative crystal age (older, younger or the same) as specific deformation phases. They use the terms pre-, syn-, inter-, and post-tectonic, to describe the timing relation between porphyroblast growth and one or two specific phases of deformation, normally represented in the matrix surrounding the porphyroblast by a foliation or by folding (Figure 21).
Thin sections prepared from Gonic Formation rocks have revealed numerous inclusion patterns. Staurolite, garnet and chloritoid crystals were found to contain the most noticeable inclusions patterns. The discussion of porphyroblasts is found in the *Petrography* section.
Stereographic Projections

The stereographic projection (stereonet) is a method of displaying geometries and orientation of lines and planes without regard to spatial relations (Davis 1984). Geological data collected in the field area have been plotted on equal area Schmidt Net with lower hemisphere projections (Duyster, 2000).

Individual stereonet diagrams have been constructed for Windy Hill, Small Hill and Buttonwood Hill (Figure 6). Data collected at Diamond Hill and Pine Hill has been complied with the Buttonwood Hill data, because of limited available information at these areas. Data collected in the Beech Ridge Hill area is combined with the Windy Hill stereonet. Foliation planes, mineral lineations, fold hinge lines, crenulation lineations, mineral, and striae have been compiled onto individual stereonet diagrams corresponding to each hill as described above. The greatest outcrop exposure was in the Windy Hill area. Therefore, the most information has been collected in this area. All data can be found in Appendix B.
Figure 22: Equal area projection, lower hemisphere. Windy Hill area β diagrams. A. Measured foliations: poles to planes of predominant schist unit found within Gonic Fm. N=52. B. Measured foliations: poles to planes of secondary quartzite unit within Gonic Fm. N=15. In both figures the best-fit great circle is shown. The blue dot represents the pole to the great circle. The great circle pole is 2° S44W for the schist unit and 1.5° S42W for the quartzite unit.

Figure 22A shows poles to foliation of the predominant schist unit of the Gonic Formation. Figure 22B plots foliation poles to planes of the less abundant quartzite unit. In each figure the best-fit great circle (pi-circle) is shown with its pole (pi-axis). The pi-axis for the schist unit is 2° S44W and is 1.5° S42W for the quartzite unit. Both projections show northeast striking and mostly shallow to moderate dipping foliation planes. The overall similarity of poles to foliation between the two units implies foliation was folded about a similar axis during the same deformation event. Given that foliation in an area typically forms with a uniform orientation, the variation of foliation in Figure 22 indicates folding after development of the foliation.
Windy Hill Lineations

Orientations of crenulation lineations and fold hinges in quartz veins in the Windy Hill area show strong similarities (Figures 23a and 23b). Both stereonet diagrams show predominance of southwest-directed plunges with a lesser component of northeast-directed plunge suggesting that the formation of crenulation lineations and the quartz vein folding occurred during the same deformation/ folding phase (F2). Trend and plunge of the lineation direction of the crenulations and quartz folds correlate with the calculated trend and plunge of the F2 fold axis in Figure 22, suggesting these are small-scale folds associated with larger scale folds of foliation. The folding of foliation, small-scale crenulation development and quartz vein folding post-date foliation development.
Figure 24: β diagram. Equal area projection, lower hemisphere. Buttonwood Hill area. **A.** Measured quartz vein fold hinges (+). **B.** Measured foliations (+) and measured F2 fold hinges at Small Hill (X). Green circle represents calculated F2 fold hinge trend and plunge (~16° S61W). Great circle is best fit to foliation poles.

Figure 24A shows quartz vein fold hinge lineations measured at Buttonwood Hill. Three orientations of fold axis are evident. One orientation plunges to the west, one to the east and a third is sub-vertical. These three groupings of quartz vein fold hinge plunge are likely reflected in the ptymatic folding of quartz veins observed in this area (Figure 25).
Poles to foliation at Buttonwood Hill show that northeast-southwest trending strikes are dominant. The stereonet projection (Figure 24B) illustrates a folded foliation. The limbs of a fold are evident; a best-fit $\pi$-circle is shown. The two groups of foliation data represent separate limbs of a fold, one in the northwest quadrant of the stereonet, the second in the southeast quadrant of the stereonet. The average strike and dip were estimated for each group. The calculated fold axis trend and plunge of the bedrock fold in the Buttonwood Hill area is $\sim 16^\circ$ S61W (green circle). This fold axis orientation is consistent with other the fold axes that were directly measured (‘X’; Figure 24B, Small Hill) and calculated (Figure 22 A&B, Windy Hill) in the field area. Quartz vein fold limbs and crenulation lineations in the field area also correspond with the dominance for south-west directed plunge (Figure 22A).

Figure 26 is a stereonet of the measured and calculated $F_2$ fold hinges. A variation in trend of approximately 57 degrees of the $F_2$ fold axes directions suggests that the $F_2$ fold axis is folded, resulting in $F_3$ (Figure 26). At the outcrop
scale $F_3$ is observed as an undulation in the foliation along strike, producing a wide and scattered foliation girdle in stereographic projection (Figure 22 A&B). The trend and plunge of these $F_2$ axis are very similar to trend and plunges of crenulations and quartz vein fold hinges (Figure 23 A and B), which supports synchronous development of these structures.

Figure 26: Plot of measured and calculated $F_2$ fold axes showing predominance for south-west directed plunge.
Lineations

Figure 27: Stereographic projections. A. Striation lineations measured on quartz veins. “+” are poles to foliation planes with colour-coded great circles. Colour-coded dot is associated lineation. N=5  B. Mineral lineations. “+” are from Gonic Fm.; “∆” are from Rindgemere Fm. Colour-coded. N=9

Striation lineations were also observed on the surface of a few quartz veins in the Windy Hill area and are shown in Figure 27A with the associated foliation poles to plane and great circle. Observation of these angular groove channels and down-dip, stair-stepping, normal fault like features on the quartz veins indicate the striations have originated during a dip slip, brittle deformation event, which could perhaps have occurred during the Mesozoic rifting of Pangea. This is part of a regional brittle ‘fabric’ of small-scale normal fault surfaces.

Figure 27B shows the mineral lineations and associated foliation poles to planes and great circles observed in the Gonic Formation. It also includes the same observations in the adjacent Rindgemere Fm. The Gonic Formation mineral lineations are exhibiting oblique to dip slip sense. The Rindgemere Fm. mineral lineations observed are nearly horizontal and trend approximately north-south (~N10E), exhibiting strike slip. The orientation of the mineral lineations in
Figure 27B appears to have been folded. This is consistent with the calculated $F_3$ fold axis of Eusden et al. 1987. The mineral lineations in the Gonic are consistent with $F_2$ folding in the Windy Hill area. These mineral lineations formed during a recrystallization event prior to $F_2$ and could be synchronous with $S_1$ foliation development.
Pseudomorphs and Reaction Rims

Throughout the Windy Hill area elongate pseudomorphs and andalusite with reaction rims are present. These features were only observed in the Windy Hill area, closest to the Lyman Pluton (Figure 2). Based solely on spatial relationship an initial speculation was: does a metamorphic aureole exist as the result of Lyman Pluton intrusion?

Location 622LR1.4 in the Windy Hill area shows a relict core staurolite within a coarse-grained muscovite pseudomorph. Staurolite pseudomorphs to muscovite were found in ‘mats’ or clusters. These crystals are up to 10cm in length and 3-4 cm wide. The crystals were not observed to have been twinned and appear to have been single crystals. Where multiple individual pseudomorphs occur, the trend of the c-axis was measured with a compass to determine if a preferred direction of orientation was present during original crystal growth. These lineations are plotted on a rose diagram (Figure 28). A rose diagram has been chosen to graph this data because it best displays orientation distribution of two-dimensional data. The plunge of the c-axis could not be recorded because exposures of the pseudomorphs were limited to a 2-dimensional view only. The purpose of these measurements was to investigate the

Figure 28: Rose diagram of long axes direction of pseudomorphs found in the Windy Hill area. N=47
possibilities of crystal alignment with other lineations or foliations within the field area. The rose diagram demonstrates two preferred c-axis directions extending approximately N10E and N45E. The latter c-axis orientation coincides with the dominant strike of foliation measured in the Gonic Formation. The other c-axis orientation (~N10E) could be representing crystals that changed orientation during folding of the foliation. Interestingly the trends of these lineations are similar to the shallow plunging lineations shown in Figure 27B.

Signs of extension were also observed affecting these pseudomorphs. Evidence of this is that the porphyroblast are broken and segmented. The void space between the segments had been filled with quartz. A geologic timing sequence can relatively be inferred as:

Retro-metamorphic event $\rightarrow$ Extension event.

Figure 29: Comparison photograph of pseudomorph that has undergone re-crystallization followed by brittle extension. Yellow outlines represent crystal segments composed of muscovite. Red outlines represent quartz filled void spaces.
Field studies have also observed andalusite porphyroblasts with muscovite reaction rims (Figure 30). In the Petrology section, sample LR1, garnet porphyroblasts are described with chlorite reaction rims, a retro-metamorphic reaction.

In a couple of northern locations at Windy Hill, andalusite cores were still detected. These partial pseudomorphs also appear to have been stretched (extension) by a deformation event prior to and/or during the re-crystallization phase.

Approximately 1 mile north of the intersection of Sand Pond Road and Morrells Mill Road on the Sanford 7.5 minute quadrangle (#985.3), an andalusite porphyroblast can be observed stretched into pod like shapes (Figure 31).
Furthermore, each pod is enveloped by a reaction rim of muscovite with pieces of staurolite and garnet, indicating that a period of extensional deformation preceded re-metamorphism. This order of deformation/metamorphism was determined because had recrystallization occurred prior to extension, a truncation of the reaction rim would be present.

As a result two types of extension were observed; ductile extension followed by re-crystallization and re-crystallization followed by brittle extension. This, for the Windy Hill area, yields event sequences as:

- Staurolite growth → Re-metamorphism → brittle extension; and
- Andalusite growth → ductile extension → Re-metamorphism.

Based on geographical proximity to the Lyman Pluton, and the relationship between metamorphism and deformation; the reaction rims can be attributed to Lyman Pluton emplacement but the pseudomorphs could have undergone change earlier. The reaction rims also indicate a hydrous type
metamorphism consistent with the introduction of water and heat related to the intrusion of the Lyman. As a result, crystal modifications shown in Figures 29, 30 and 31 have to be synchronous or subsequent to the 322 my. age of the Lyman Pluton.

**Petrography**

Multiple steps were taken to orient rock samples that were collected for thin section analysis. Methodologies to orient and cut thin sections followed those described by Passchier and Trouw (1998).

Two methods are used to illustrate thin section structures; 1) photomicrographs and 2) traced illustrations, to show a larger field of view. First, discussion of structures observed in photomicrographs is presented, followed by structures shown in illustration. Illustrations were drawn by tracing a projected image of the thin section through a modified microfiche viewer.

Figure 32 is a thin section in plain light of a schistose sample obtained from Diamond Hill (DH). The dominant foliation at Diamond Hill is N60E and the section was cut normal to the foliation, parallel to lineation. However, out of respect for the property owner this sample was chosen from an adjacent cobble pile and not orientated. This thin section was **not** used to determine shear sense.
The right half of the thin section in Figure 32 is a staurolite crystal. The left side is schist matrix of the Gonic Fm. Passing left to right is the pervasive foliation (S1). The foliation continues through the staurolite crystal, an indication of staurolite growth after, or at least after initiation of, foliation formation (post or syn-kinematic). This thin section also contains zonal crenulation cleavage (S2). The S2 cleavage forms a microfold of S1. However, S2 deflects around a staurolite crystal, indicating development of S2 followed staurolite growth. Therefore:

\[ S1 \rightarrow \text{staurolite growth} \rightarrow S2. \]
Two types of garnet porphyroblasts are present, those without internal foliation (Type I) and those with internal foliation (Type II). In a crossed-polars photomicrographic thin section from the Buttonwood Hill area cut parallel to lineation and perpendicular to foliation (LR1; Figure 33), the core of a garnet porphyroblast appears to have small inclusions of quartz. The apparent alignment of the quartz appears to define an earlier foliation. Signifying the garnet grew as a syn- or post tectonic porphyroblast.

The outer rim of this garnet porphyroblast also shows lobate recrystallization to quartz. Although not visible in the photomicrograph, the upper left corner shows an asymmetric quartz tail. Assuming the matrix foliation and the foliation within the garnet are the same this arrangement of internal foliation and asymmetric tailing suggests counter-clockwise rotation of the garnet.
porphyroblast of approximately 25 degrees to the prominent foliation as expected in sinistral shear.

Other garnet porphyroblasts in the same thin section (LR1; Figure 34), under plain light, show a reaction rim of chlorite where in contact with muscovite. The ~1mm garnet porphyroblast does not appear to contain an internal foliation. However, the chlorite rim appears to show the foliation from the matrix. This perhaps indicates Type I garnet development preceded foliation development, which was synchronous with chlorite growth.

A sketch of LR1 thin section was drawn in order to show a larger perspective of the slide. In Figure 35 the garnet crystals are shaded pink, the chlorite rims are light green, and sericite is a beige color. The garnet in the upper right quadrant of the illustration exhibits asymmetric quartz tails. The orientation of the tails implies a sinistral sense of shear. Within the tails where three quartz
grains interact, 120° boundary angles can be seen. This implies a period of static
recrystallization annealing followed by the tail-forming metamorphic/deformation
phase. Within four garnet porphyroblasts a poikiloblastic texture is evident,
mainly at the cores. Nucleation of these garnets, following the Passchier and
Trouw (1998) version of relative crystal order, as discussed in their Porphyroblast
section, these crystals formed as inter- or syn-tectonic. However, the kinematic
usefulness of these porphyroblasts is questionable because of opposing indicators.
This may be an effect of the proximity to adjacent garnet porphyroblasts. The
left-most garnet porphyroblast shows no internal structure, contrasting with the
other garnet porphyroblasts, which do. This garnet also has the most well
developed chlorite reaction rim. Chlorite rims around the garnet are present
where in contact with muscovite. It appears that where the garnet is ‘shielded’ by
quartz, chlorite rims did not develop.
The sericite crystals seen in thin section show a subhedral to anhedral crystal shape and appear to be pseudomorphs after staurolite. The muscovite and biotite crystal alignment wraps around the large porphyroblast.

In thin section BWH2, annealing of quartz grain crystals with 120° grain boundaries (Figure 36) is also present. Development of this type of boundary angles implies a period of static recrystallization followed re-heating.

![Image of thin section BWH2 showing C-S foliation structure](image)

Figure 36: Crossed-polars photomicrograph from thin section BWH. Development of 120° boundary angles on quartz crystals suggests static recrystallization. Photomicrograph is approximately 3mm across.

Thin section BWH2 also shows a C-S foliation structure (Figure 37). The foliation is defined by muscovite with quartz clasts. Very little biotite is present in this sample. Inspection of this fabric suggests a sinistral shear direction, where the C-plane is parallel to the shear zone boundaries and the S-plane is perpendicular to the stress direction.
The porphyroblast in the center of Figure 38 (BWH) is a chloritoid crystal ~1mm in length. The porphyroblast appears to be twinned like feldspar. The porphyroblast also overprints the foliation defined by the muscovite, an indication that porphyroblast growth was subsequent to foliation development.
The thin section illustration of Gonic schist in Figure 39 shows a staurolite porphyroblast with an internal foliation oblique to the predominant foliation plane. An apparent rotation of ~40° between the staurolite foliation and matrix foliation has been measured. The upper left and lower right of the porphyroblast exhibits asymmetric tails composed of biotite. This biotite contains no relict foliation. The location of the biotite tails suggests counter-clockwise rotation, consistent with sinistral shear. Below and to the left of the staurolite porphyroblast, gashing of the foliation and subsequent quartz formation and recrystallization has occurred. The foliation defined by muscovitic deflects through this gashed area and is oblique to the main foliation. This could be defining a C-S foliation or an effect of crystal rotation.

Figure 39: Illustration from BWH of staurolite crystal showing internal foliation at an acute angle (~40°) to matrix foliation, suggesting sinistral motion. Foliation direction is N48E 66SE.
Two additional illustrations were made of thin sections from Buttonwood Hill (BWH4; Note, slides were reversed during sketching, therefore actual sense of displacement is opposite of that shown). Figure 40A shows a garnet porphyroblast with asymmetric tails composed of quartz grains. Figure 40B shows a fragmented quartz grain aligned with muscovite where the original grain segments have moved in a right-lateral direction with respect to the parent grain. A reconstructive measurement has determined the grain expansion to be approximately 20% (+5%). Shear sense determined from these kinematic indicators is dextral. The opposing shear sense seen in this thin section is likely related to position of the sample on the limb of a F2 fold. Additionally, macroscopic observation throughout the slide shows a pytgmaitc folding structure and the brittle deformation of the fragmented quartz grain (40B) suggests a later stage and probably cooler deformation event.
Figure 41 is a plain light view of a sample from the Gonic Formation schist north of Windy Hill. The foliation is orientated N40E 16NW and is cut by a crenulation cleavage lineation orientated 14° N37E. The foliation evident within the biotite is oblique to the main foliation (yellow line). The asymmetric shape of the porphyroblast indicates a dextral shear sense (red arrows). Also note that in the upper left of center of the porphyroblast a segment of the biotite has dislodged during shearing and has moved sinistrally with respect to its parent porphyroblast. This sample is ambiguous with respect to other kinematic indicators in the field area. The geographic location of this sample provides a constraint on deformation sense.

One thin section, S1090, was derived from the Rindgemere Formation (Figure 42; Note; slide shown in reverse mount). The outcrop exposure has a dominant foliation orientated N31W 50SW. A kink band was also observed with a 39°
deflection of foliation. A fold hinge was observed orientated 25° S50W. A faint crenulation cleavage lineation was observed orientated 9° S15W. The thin section was cut parallel to lineation and perpendicular to foliation. Figure 42 shows two asymmetric quartz structures, which would have with sinistral shear sense in outcrop. Quartz minerals within the lower asymmetric shape show nearly perfect 120° boundary angles, a sign that static recrystallization after deformation occurred. This agreement of shear sense between the Rindgemere and Gonic Formations could be indicating that shearing was not disrupted by the brittle NRF or more likely that shearing occurred prior to development of the brittle NRF. If further evidence of this is observed it could show that regional shearing is distributed throughout both formations. However, this study did not focus on this relationship and sufficient data to better prove this contention was not collected.

Figure 42: Illustration of thin section S1090. Rindgemere Formation. Quartz grains showing asymmetric structure. Tails are outlined in RED. Lower shape contains quartz grains with 120° boundary angles. Sinistral Shear.
Conclusions

Field observations and microstructural analysis has both confirmed and provided insight into the deformation and metamorphic history of the Gonic Formation. F<sub>1</sub> recumbent folding was not directly observed but evidence such as the generally horizontal schistosity (S<sub>1</sub>), transposition, and kinematic indicators contrary to regional deformation suggest the presence of larger scale structures, in addition to deformation not directly related to the Norumbega Fault Zone. F<sub>2</sub> upright folding of S<sub>1</sub> schistosity is well documented, indicating the occurrence of later shortening deformation (D<sub>2</sub>). F<sub>3</sub> folding was observed at the map scale as variations in foliation direction and F<sub>2</sub> axis lineations.

Evidence that F<sub>2</sub>, crenulation cleavage, and quartz vein folding developed during the same deformation event is supported by the strong similarity of the trend and plunge of F<sub>2</sub> hinges towards the southwest (Figures 22 A, B; 23 A, B; 24B & 26).

Sense of shear appears to be strike-slip in lieu of present foliation dip. Samples collected for kinematic indicators were collected where foliation dip was sub-vertical. Microscopic and outcrop scale shear sense indicators, in the Buttonwood Hill, Small Hill, and Diamond Hill areas, show good evidence for sinistral sense of shear. This result is contrary to previously reported regional deformation patterns and may be related to earlier deformation or the intrusion and subsequent displacement related to intrusion of the Lyman Pluton.

Relationships of porphyroblasts to foliations were established for the Gonic Formation through thin section analysis. At Diamond Hill, staurolite crystals with a strong internal foliation, which deflects S<sub>2</sub> crenulation cleavage,
define an $S_1 \rightarrow$ staurolite growth $\rightarrow S_2$ development scheme. The two garnet types (with and without internal foliation) show that Type I (without internal foliation) garnet growth preceded $S_1$ development. This was followed by a re-metamorphism that formed chlorite rims on these garnets. The Type II garnets (with relict internal foliation) developed after $S_1$. Evidence of internal foliation was only observed at the core of the garnets.

Intrusion of the Lyman pluton had some effects on the Gonic Formation. Shortening at Buttonwood Hill as evidenced by $S_2$ development and deformed conjugate quartz veins set hints that some north-south, sinistral compression may have occurred. Suggesting timing of the intrusion is approximately equal to $F_2$.

The pseudomorph crystals found only in the Windy Hill area and boudinaged andalusite with reaction rims approximately 1 mile north of Windy Hill imply a metamorphic event occurred subsequent to andalusite development and extensional deformation (Figure 31). Furthermore, the reaction rims are the result of a hydrous type metamorphic reaction. This is consistent with the introduction of water and heat from granite such as Lyman Pluton.
Conjugate quartz veins at Buttonwood Hill imply a similar north-south shortening direction (Figure 43). The S1 foliation direction is ~N45E. One vein is planar and relatively undeformed with a N60E trend. This vein represents the zone of extension. The second quartz vein shows approximately 30% shortening and trends N32E. It represents the zone of shortening, orientated ~N18-46E. In pure shear system, these conjugate quartz veins suggest a sinistral deformation. Interestingly, the Lyman Pluton is approximately 32° the east of Buttonwood Hill.

During this study two types of granite were observed occurring within the Gonic schist. One generation of granite intruded prior to development of S1 foliation. The second generation intruded after S1. The source of the granites was not determined. However, the line of hills that topographically defines the Gonic Formation trends (northeast-southwest) between the Lyman pluton and the Massabesic pluton in New Hampshire. This suggests that the hills topographically defining the Gonic Formation could be an effect of granite intrusions and not just
erosional resistance of the Gonic as concluded by Hussey (1962) but of the granite.

The Nonesuch River Fault as a brittle structure was not directly observed during the course of this study due to heavy vegetation and little outcrop exposure. A USGS shaded relief map (Figure 9) shows prominent northeast-southwest lineaments through Diamond Hill and Buttonwood Hill. This could be reflecting a fault or more likely, $F_2$ folding of lithic layering. Striation lineations on several foliation-parallel quartz veins imply that late normal slip has occurred most likely related to Mesozic rifting.

A chart of known relationships has been assembled to simplify the geologic history of the Gonic Formation (Table 3).

<table>
<thead>
<tr>
<th>Table 3: Geological Relationships -simplified</th>
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<td></td>
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<tr>
<td>Granite dike intrusion</td>
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<td></td>
</tr>
<tr>
<td>Granite intrusion</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Garnet growth Type I</td>
</tr>
<tr>
<td>Andalusite growth</td>
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<tr>
<td>Andalusite growth $\rightarrow$</td>
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</table>
A deformation and metamorphism sequence of events within the Gonic Formation has been established. Transposition, folding of bedrock, folding of quartz veins, foliations, boudinage and reaction rims all point to an active geologic past. However, evidence for Gonic Formation deformation linked to broad scale Norumbega Fault Zone deformation could not be directly established. This could lend support to the contention of Hussey et al. (1999) that the southwestern continuation of the Norumbega Fault System is directed offshore, signifying that deformation within the Gonic occurred independently or prior to NFZ activity.
References


Berthé, D., Choukroune, P. and Jegouzo, P., 1979, Orthogneiss, mylonite and non coaxial deformation of granites: the example of the South Armorican Shear Zone: Journal of Structural Geology, v. 1, no. 1, p. 31-42.


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Swanson, M.T., 1994, Minimum dextral shear strain estimates in the Casco Bay area of coastal Maine from vein reorientation and elongation: Geological Society of America Abstracts with Programs, v. 26, p. 75.


United States Geological Survey; Somersworth, Maine, 7.5-minute series topographic quadrangle.


Appendix A

Geological Time Scale
Appendix B

Data Tables
<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Location</th>
<th>Rock Type</th>
<th>Foliation</th>
<th>Lineation</th>
<th>Fold Hinges</th>
<th>Remarks</th>
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<td></td>
<td>GristMillBridge</td>
<td>fn. gr schist</td>
<td>N20W  32NE</td>
<td>N4E   11SW</td>
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