STRUCTURAL ANALYSIS OF THE GONIC FORMATION

IN BERWICK, MAINE

Abstract of

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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
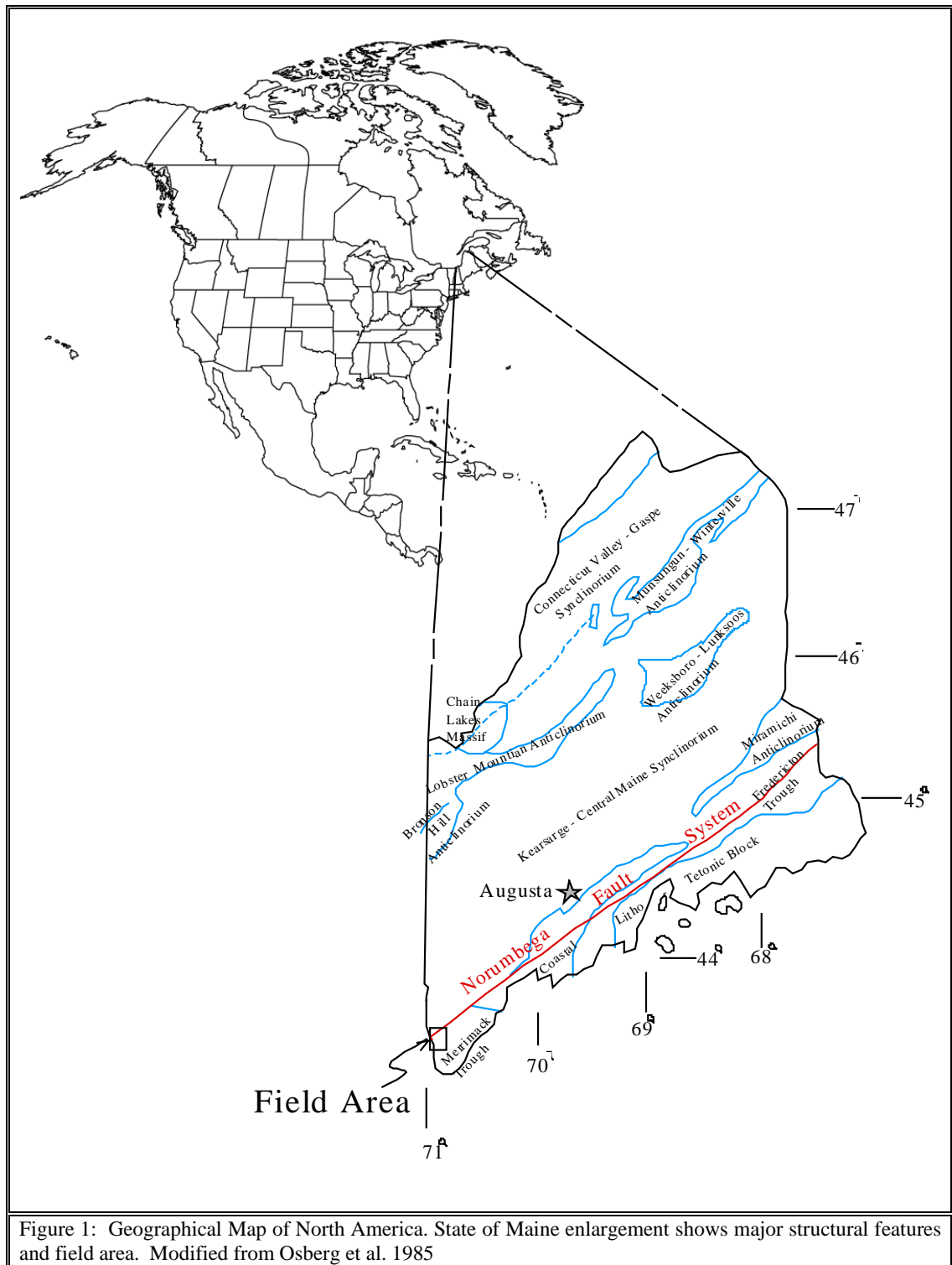
composite peri-Gondwanan terrane to North America in Late Silurian to Early Devonian time. The earliest Norumbega related dextral shear deformation occurred at this time (West, 1999; Ludman et al. 1999). In south-central Maine $^{40}Ar/^{39}Ar$ age dating of hornblende has constrained the latest amphibolite 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 Paleozoic 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.

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Connecticut Valley - Gaspe Synclinorium

Munsungun - Winterville Anticlinorium

Weeksboro - Lunksoos Anticlinorium

Chain Lakes Massif

Lobster Mountain Anticlinorium

Miramichi Anticlinorium

Kearsarge - Central Maine Synclinorium

Bronson Hill Anticlinorium

Fredericton Trough

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Norumbega Fault System

Tetonic Block

Augusta ☆

Litho

Coastal

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Merrimack Trough

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Field Area |

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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 NRF/KCMS 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 Tough and Gonic Formation. Map modified from Osberg, 1985.
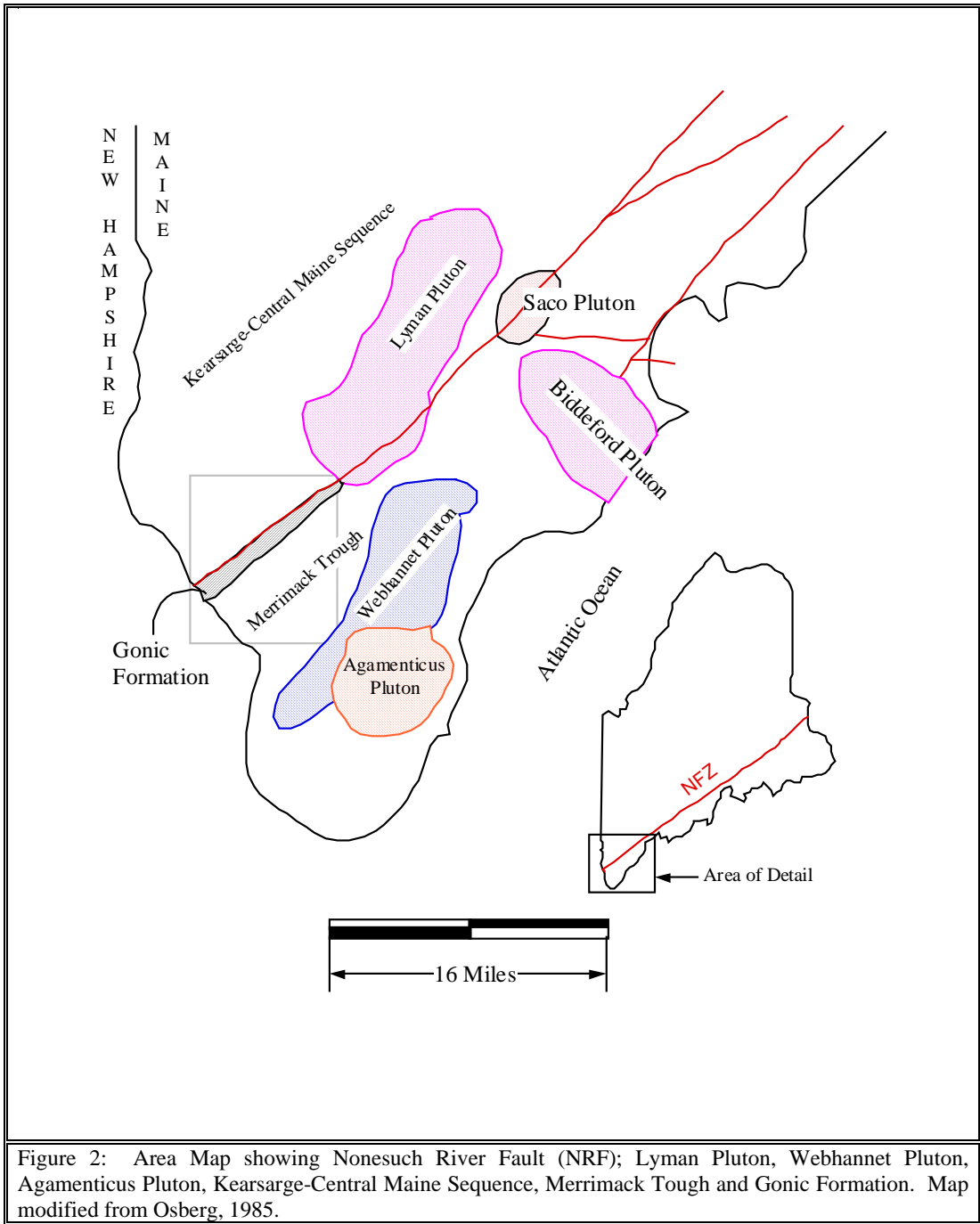
Early Models of the Norumbega Fault System

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.
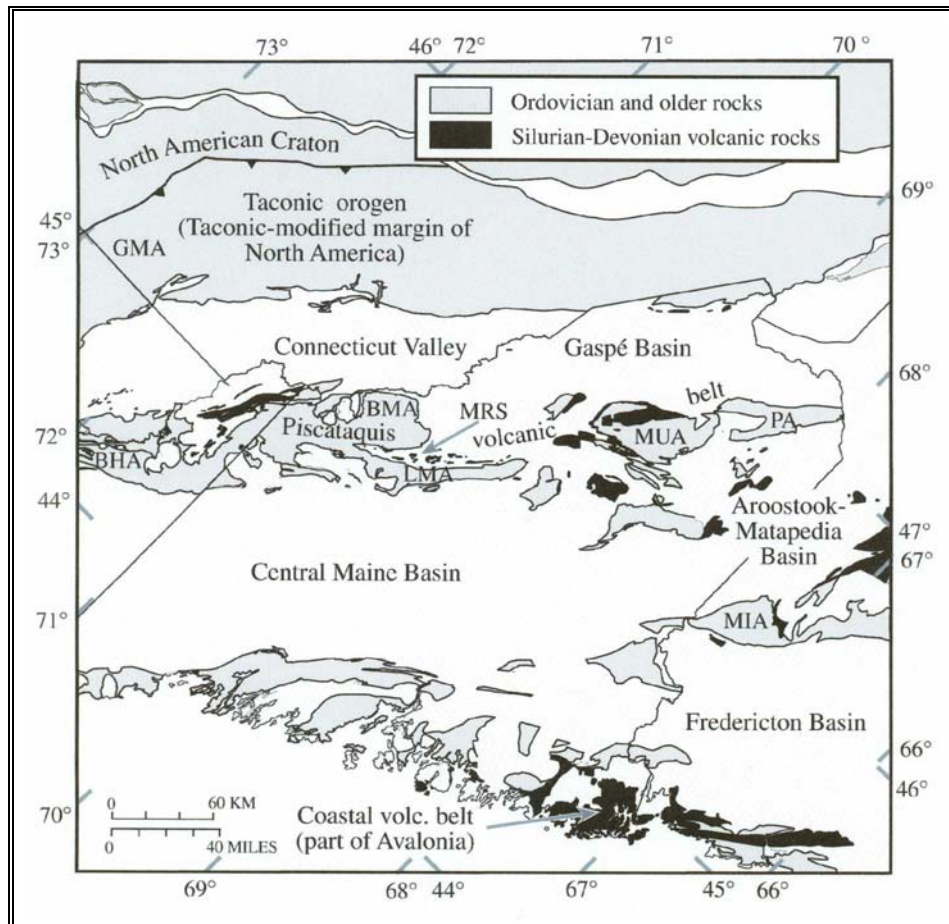
Figure 3: Maine and adjacent parts of New Brunswick, Quebec, New Hampshire and Vermont, showing distribution of major Silurian-Devonian paleogeographic elements. BHA, Bronson Hill anticlinorium; BMA, Boundary Mountains anticlinorium; GMA, Green Mountain-Sutton Mountain anticlinorium; LMA, Lobster Mountain anticlinorium; MIA, Miramichi anitclinorium; MRS, Moose River synclinorium; MUA, Munsungun anticlinorium; PA, Pennington anticlinorium. Bradley et al 2000.

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).

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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.
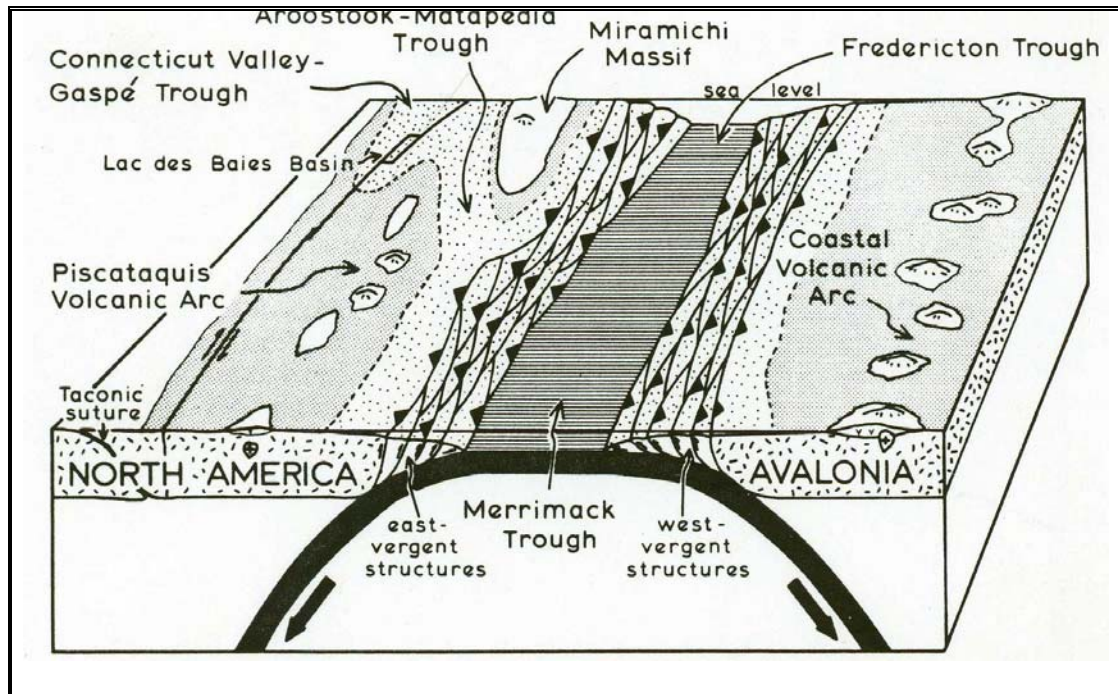
Figure 4: Proposed reconstruction of the Acadian Orogen in the late Silurian illustrating the convergence of Avalonia and North America, closure of the intervening ocean, the double subduction hypothesis, and the formation of the Piscataquis and Coastal Volcanic Arcs. Bradley, 1983.

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.

<u>Berwick Formation</u>

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;

(4)   medium purplish gray, rather granular quartz-biotite schist, locally containing elongate biotite porphyroblasts which give a gneissic structure and lineation to the fabric;

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

(6)   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).

Figure 5: Generalized Map of Regional Metamorphic Zones (Guidotti, 1985)

▮ (yellow)	Greenschist facies
▮ (light orange)	Epidote-amphibolite facies
▮ (orange)	Low rank amphibolite facies
▮ (dark orange)	Medium rank amphibolite facies
▮ (red)	High rank amphibolite facies
▮ (dark gray)	Plutonic rock with isotopic age determination
▮ (light gray)	Plutonic rock without isotopic age determination

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.

Figure 6: Topographic map showing alignment of hills within the Gonic Formation. (1) Windy Hill, (2) Beech Ridge, (3) Diamond Hill, (4) Buttonwood Hill will, (5) Small Hill and (6) Pine Hill. Reduced USGS 7.5' Minute Topographic Quadrangle, Somersworth, Maine- N.H. Green lines approximate outline of the Gonic Formation. North is up.
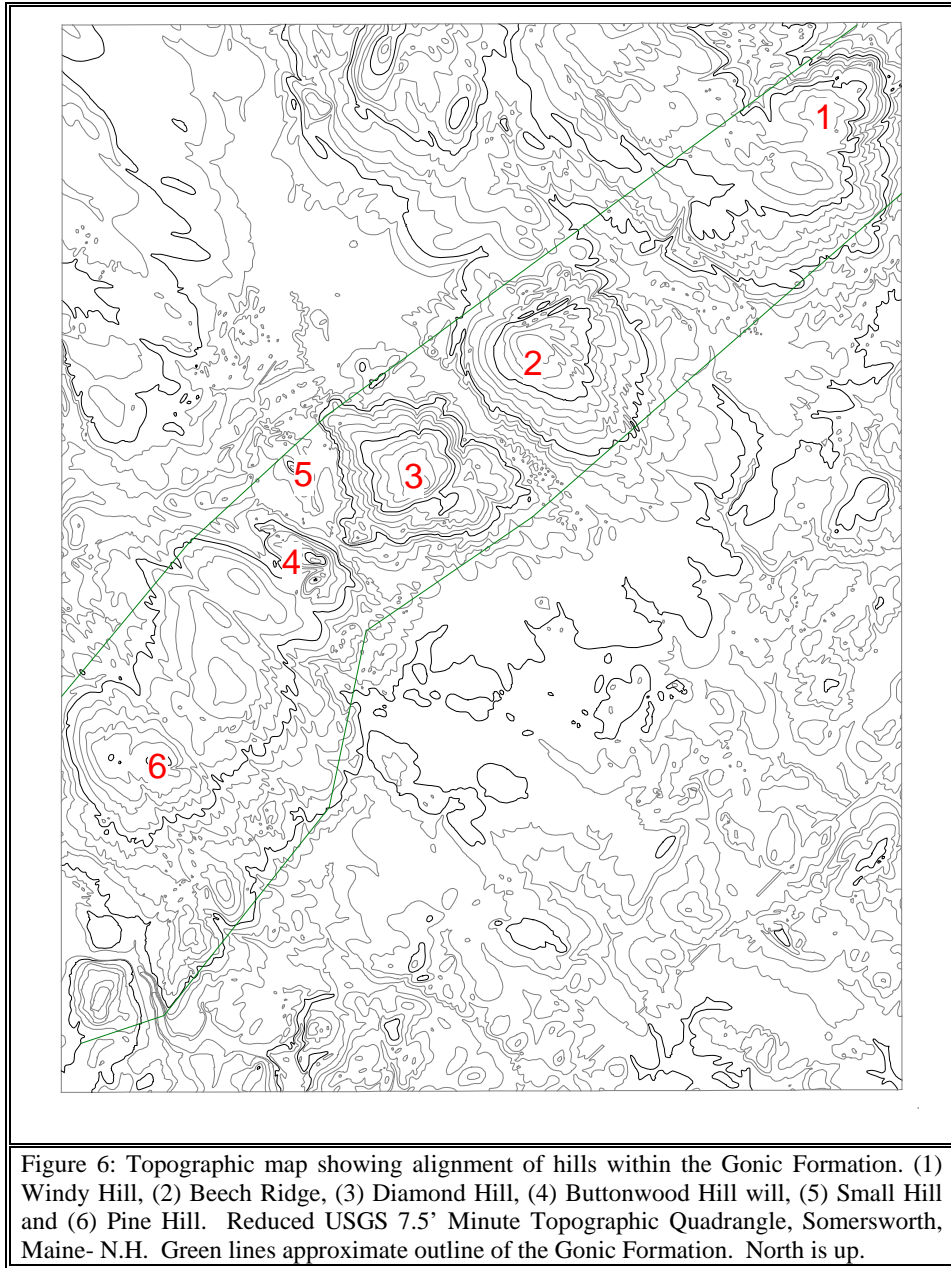
The Gonic Formation is characterized as pelitic schist consisting of two dominant lithologies. They are:

(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 km^2; 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. $\pm$ 3 (Aleinikoff et al. 1985). The Pennsylvanian age of the Sebago pluton correlates with the age of the Lyman pluton (322 $\pm$ 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

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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

Figure 7: Stereonet Diagram. Foliated granite found with the Gonic Fm. Equal area projection. N= 4.
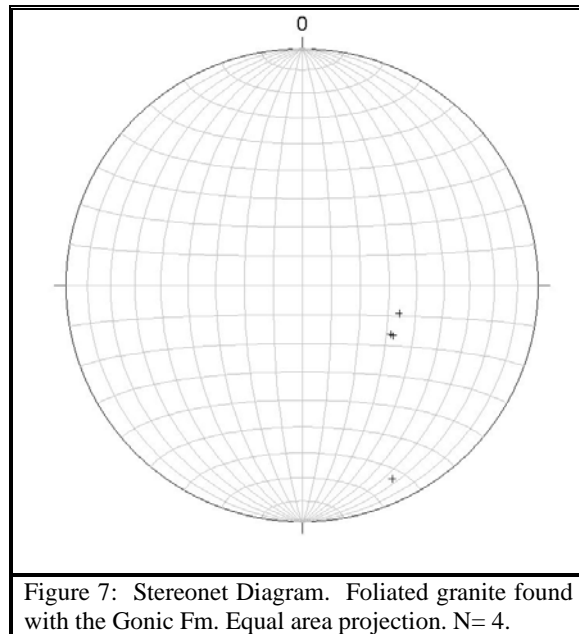
glance the rock in outcrop appeared to possess a gneissic structure. Measurements of the foliation of LR3.5 and another nearby granite outcrop with a weak foliation, revealed a similar strike and dip. These measurements plot exceptionally close to that of a foliated granite sample found within the Gonic Fm. (at 803 Morrills Mill Road) approximately 3 miles north of Windy Hill (Figure 7).

Table 1: Point Count Results from Granitiod Samples in percentages.

Sample ID	Quartz (SiO$_2$)	Plagioclase (NaAlSi$_3$O$_8$ & CaAl$_2$Si2O$_8$)	Biotite (K$_2$(Mg, Fe)$_3$ AlSi$_3$O$_{10}$ (OH, O, F)$_2$)	Muscovite (KAl$_2$(Si$_3$O$_{10}$)(OH)$_2$)	Other *	Total %
LR3.15	47.98	26.75	5.53	20.32	-	100.49
LR3.5	51.8	13.2	0.57	34.4	-	99.97
DHD	53.7	5.57	3.71	36.3	0.6	99.88
% Ratios						
	Plag../ Qtz	Bt./Muscov.	Muscov./ Qtz.	Bt./ Qtz.		
LR3.15	0.558	0.272	0.424	0.115		
LR3.5	0.255	0.017	0.664	0.011		
DHD	0.104	0.102	0.676	0.069		
* 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 → S1→ 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

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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)
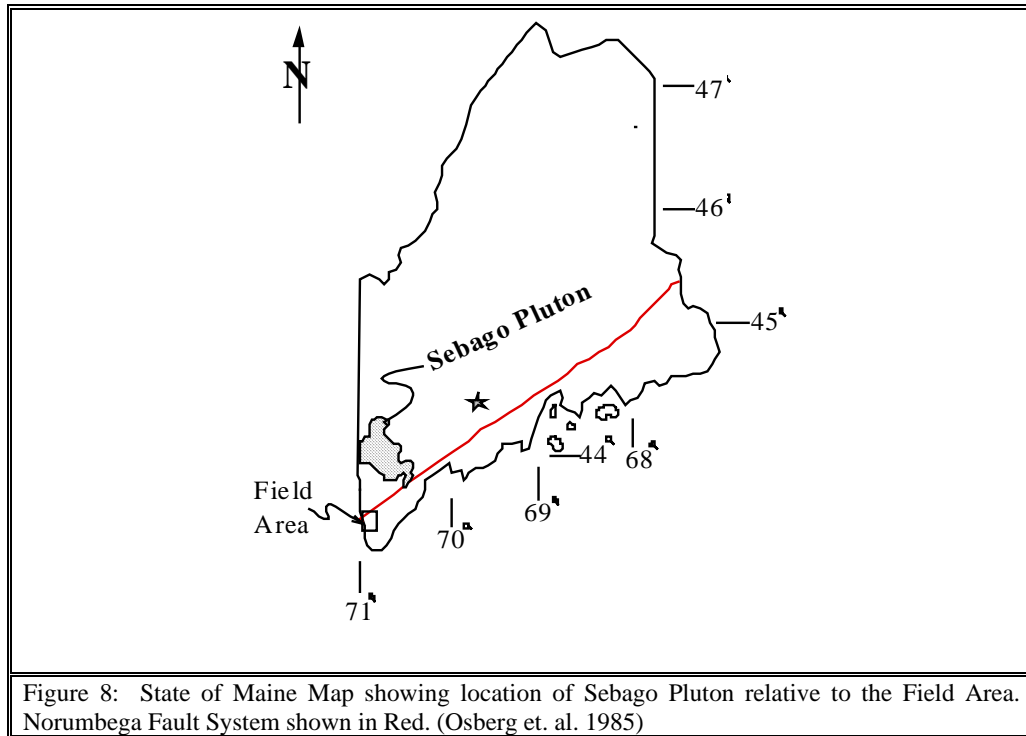
CHAPTER 4

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 S_0 surfaces and F_2 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) D_1, discontinuous bed parallel cleavage (S_1) and rare isoclinal folds (F_1);

2) D_2, upright to overturned east- directed Class 2 folds (F_2) with subhorizontal hinges and poorly developed axial plane cleavage (S_2);

3) D_3, map-scale anastomosing ductile shear zones with both dextral and sinistral kinematic indicators; interference of S_3 shear and F_2 folds produced steeply plunging sheath folds (F_3);

4) D_4, characterized by shallow east-dipping spaced cleavage (S_4) that cut both S_2 and S_3; west directed F4 folds locally well developed in the Eliot Formation;

5) D_5, 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.

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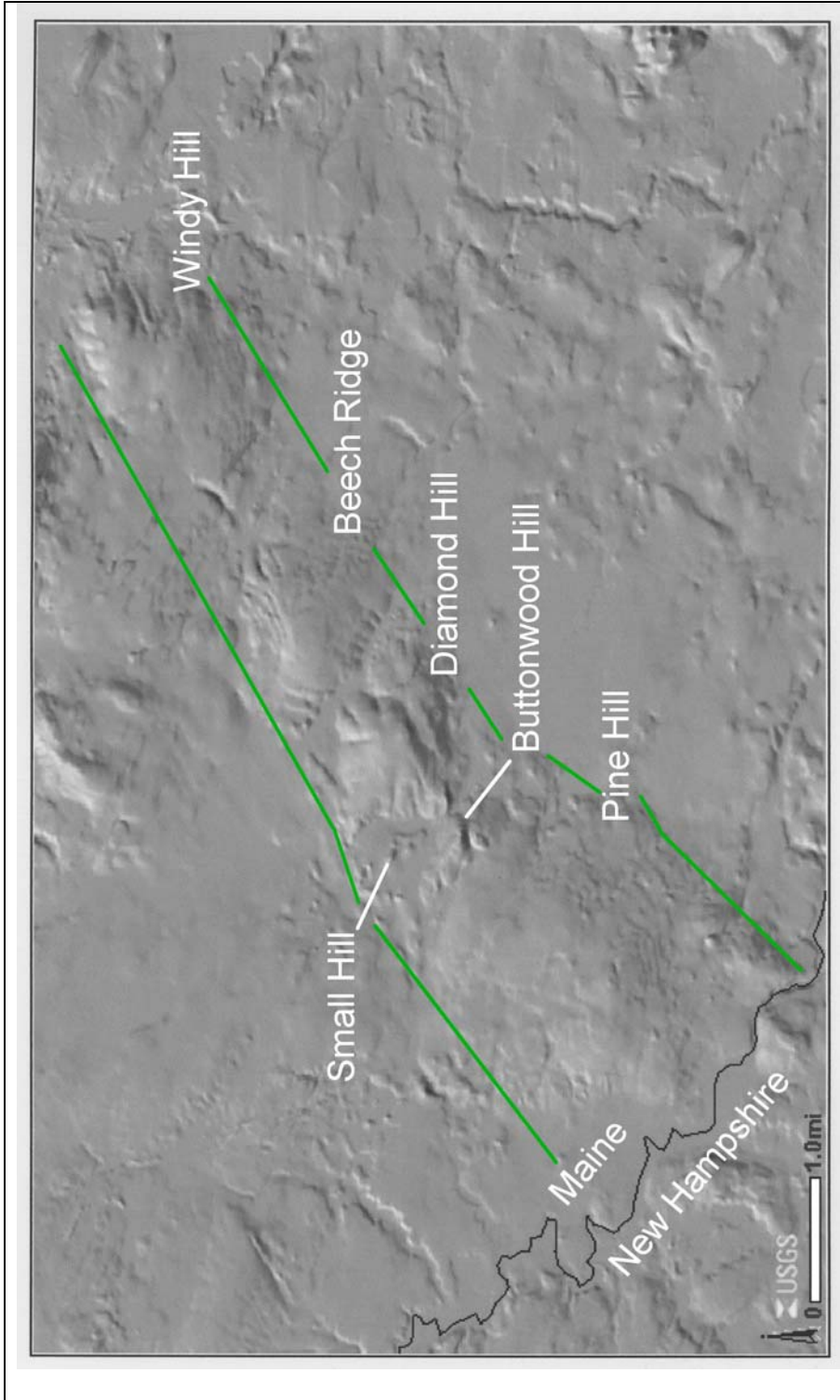
Figure 9: Shaded Relief Map of the low-lying hills that define the Gonic Formation. Glacial transport direction is from the northwest to the southeast. Map depicts variations in elevation based on a specified position of the sun. Areas in the sun are bright, while areas in shadow are dark. Generated from the National Elevation DataSet. (USGS National Map Viewer, 2003)

F_3 folding is observed in the field by deflections in the primary foliation direction and variance in measured F_2 fold axis lineations. F_3 was recognized after mapping because of the dense vegetation and soil cover. The general trend of F_3 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 F_3 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.

Figure 10: Transposition of Bedding. (A) Flexural folding of bedded sequence of stiff (black) and soft (white) layers. (B) Tight folding and onset of cleavage development. (C) Attenuation and rupture of fold limbs. (D) Flattening of sequence and creation of pseudostratigraphy. (Modified from Turner and Weiss, 1963)

      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
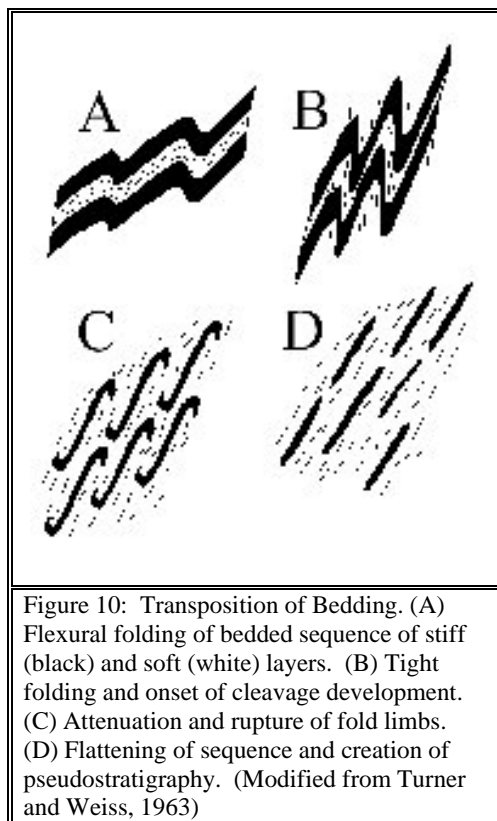
observed to terminate as both a 'pinch out' (Figure 10) and a feathered gradational pattern.

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.

Macroscopic Transposition

Figure 11a:

Photo 1 shows transposition in the Windy Hill area. Quartzite layers (outlined in yellow) appear as non-continuous layers that 'pinch out' parallel to foliation. Foliation and quartzite band strike are roughly N55E. Quartzite layer is approximately 18 centimeters wide at bottom of photo.

Figure 11b: View is normal to foliation (N16W 27 SW) shows tight folding of a quartzite layers (fold axis N20W). Outcrop is located ~0.4 kilometers north of the intersection of Morrells Mill Road and Sand Pond road on the Sanford 7.5 minute quadrangle. Camera lens cover is 5.5 centimeters across.

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.
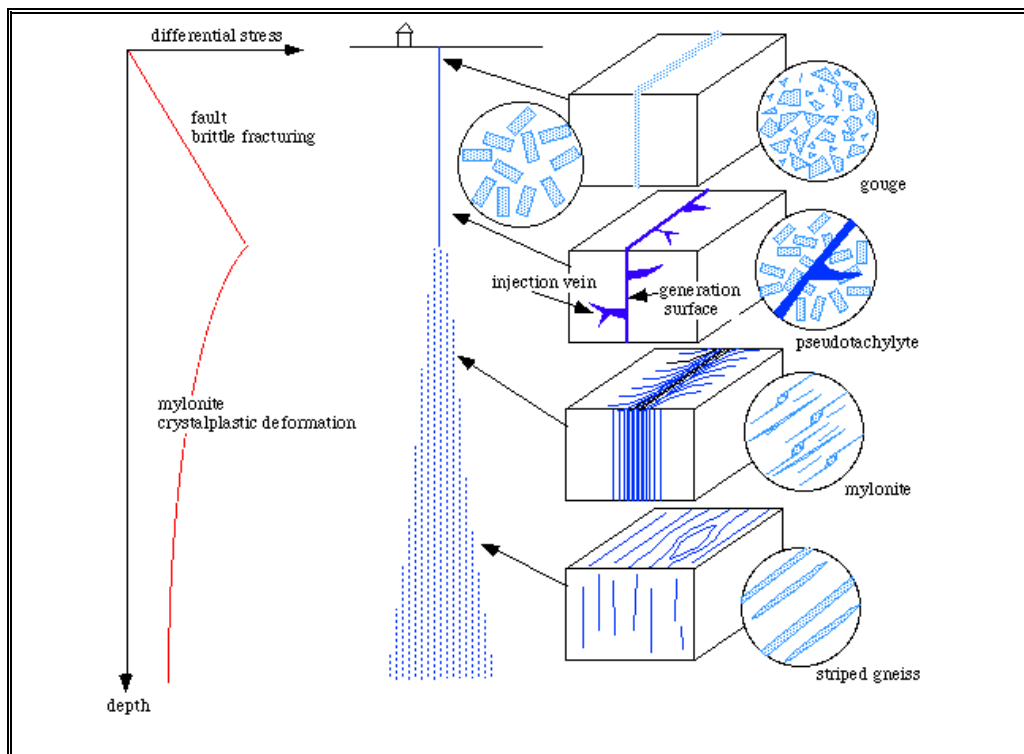
Figure 14. Distribution of the main types of fault rocks with depth in the crust. **Left and Center)** Schematic cross section through a transcurrent shear zone. The zone may widen, and changes in geometry and dominat type of fault rock occur with increasing depth and metamorphic grade. **Right)** Schematic representation of four typical fault rocks (not to scale) and the locale 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 compostion, geothermal gradient, bulk strain and other factors. Diagram from Passchier and Trouw, 1998.

Table 2: Textural Classification of Fault Rocks

			Random Fabric			Foliated		
Incohesive			Fault Breccia (visible fragments >30% of rock mass)			?		
Incohesive			Fault Gouge (visible fragments <30% of rock mass)			Foliated Gouge		
Cohesive	Nature of Matrix	Tectonic reduction in grain size dominates grain growth by recrystallization and neomineralization	Glass-devitrified glass	Pseudotachylite		?		
			Crush Breccia ………… (Fragments > 0.5cm) Fine Crush Breccia ……..(0.1 <fragments <0.5) Crush Microbreccia …….(fragments <0.1cm)				0 – 10	Percent of Matrix
			Cataclasite Series	Protocataclasite	Mylonite Series	Protomylonite	10 - 50	
				Cataclasite		Mylonite (Phylonite Series)	50 – 90	
				Ultracataclasite		Ultramylonite	90 - 100	
	Grain Growth Pronounced		?			Blastomylonite		

Sibson's (1977) classification as modified by Scholz (1990)

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.

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
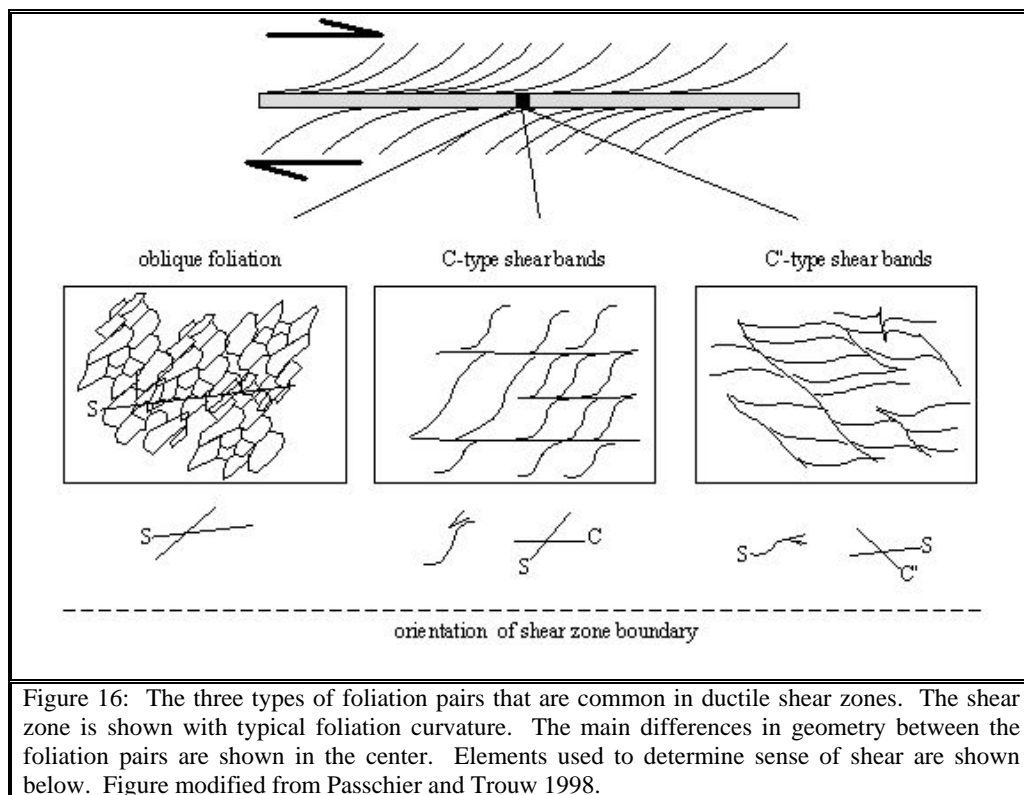

Figure 16: The three types of foliation pairs that are common in ductile shear zones. The shear zone is shown with typical foliation curvature. The main differences in geometry between the foliation pairs are shown in the center. Elements used to determine sense of shear are shown below. Figure modified from Passchier and Trouw 1998.

and C-C` planes.

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 ($\leq$ 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

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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 F_2 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.
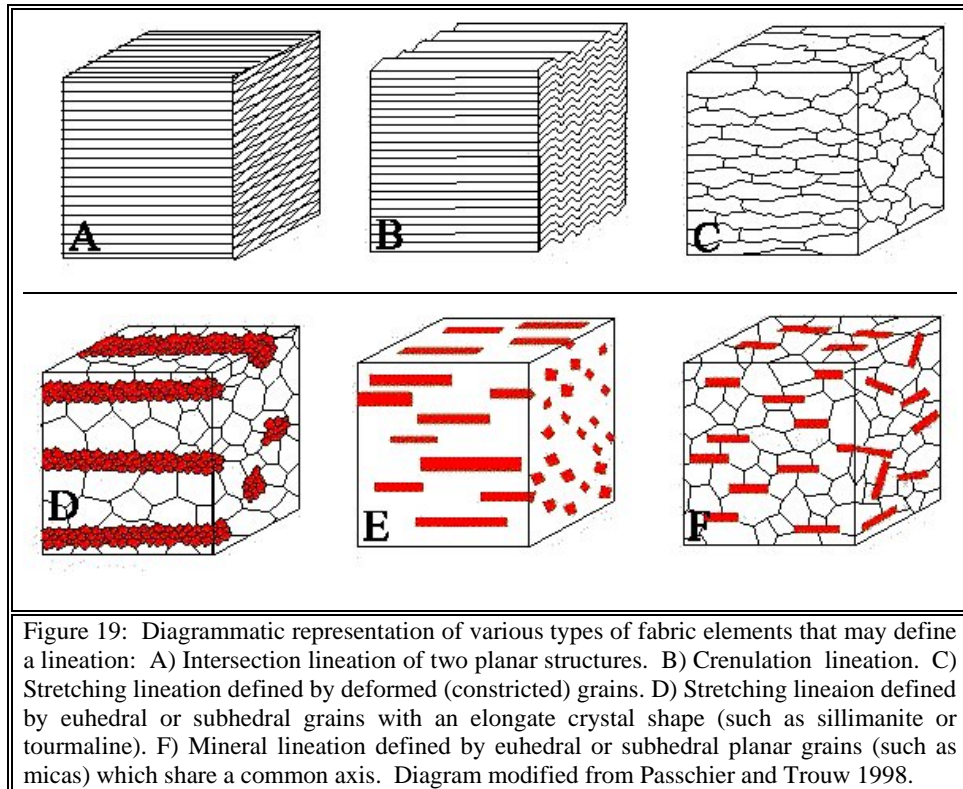
Figure 19: Diagrammatic representation of various types of fabric elements that may define a lineation: A) Intersection lineation of two planar structures. B) Crenulation lineation. C) Stretching lineation defined by deformed (constricted) grains. D) Stretching lineaion defined by euhedral or subhedral 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

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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 Porphyblasts

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 (σ) and delta (δ) 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.
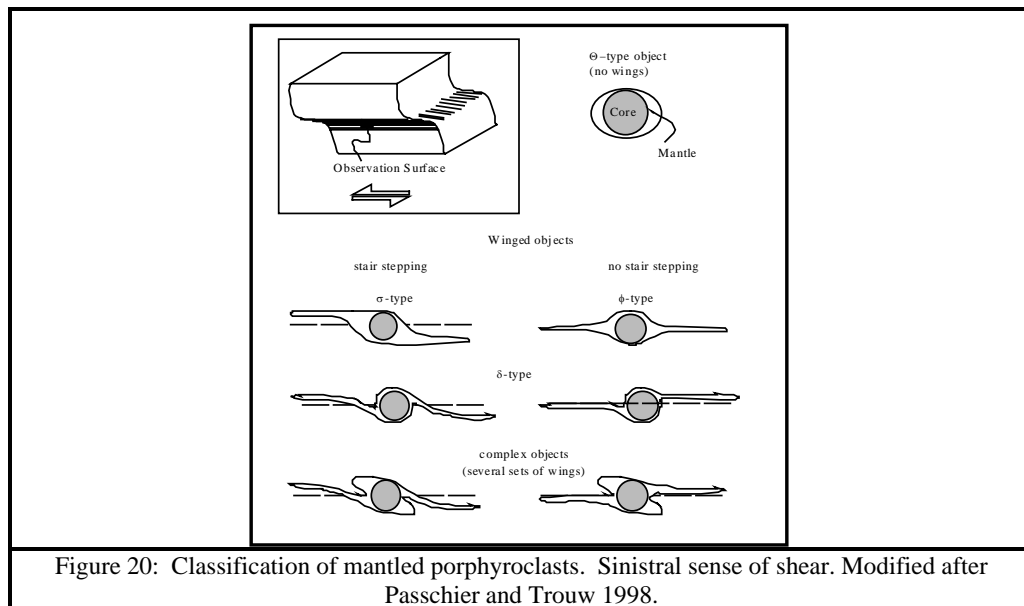
Porphyroblasts

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).

deformation does not cause folding of matrix foliation

A

1   2

3

4

B

1   2

3

C

D

deformation causes folding of matrix foliation

2

1

2

E

1   2   3

4

F

G

-presence of strain shadows common
-always deflection of Se around porphyroblast
-distinction between pre- inter- and syn-kinematic porphyroblasts is only possible if inclusions are present

-no strain shadows
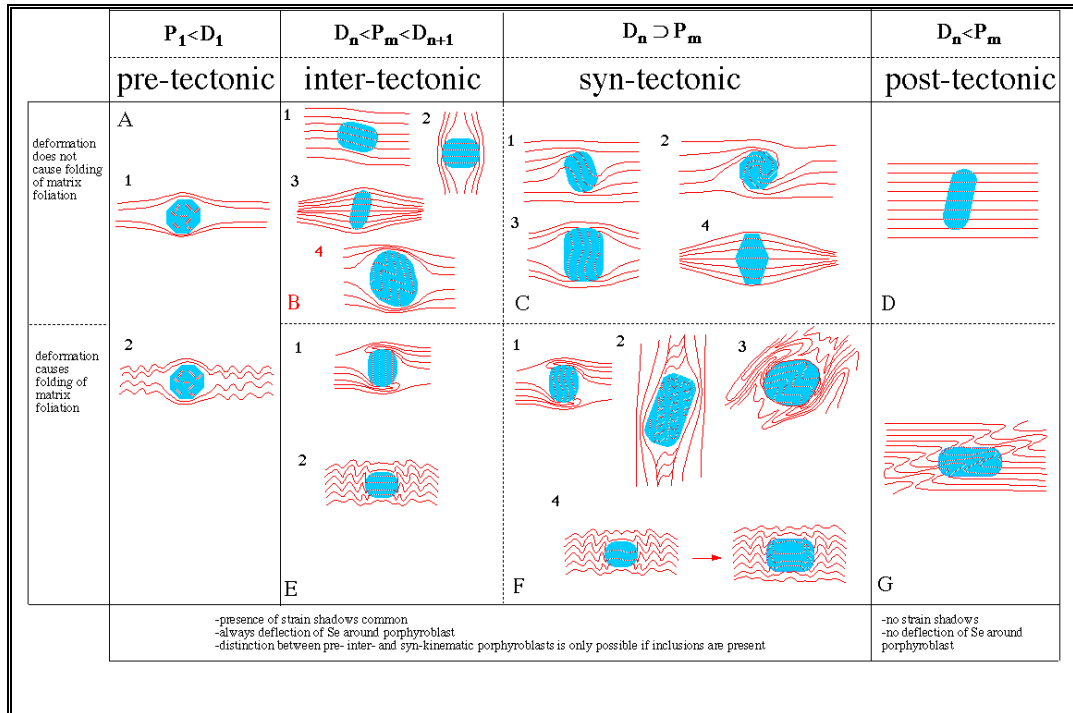-no deflection of Se around porphyroblast

Figure 21: Schematic representation of pre-, inter-, syn-, and post tectonic growth. The left-hand part of the diagram refers to deformation resulting in a single foliation or deformation of an earlier foliation without folding; the right-hand part considers deformation resulting in crenulation of an older foliation. Pretectonic porphyroblasts (A and B) show strong foliation deflection and randomly oriented inclusions. Intertectonic porphyroblasts (C and D) grew passively over a fabric in absence of deformation, and protect the resulting inclusion pattern from later deformation. Inclusion patters are usually straight but more complex situations (C4) are also possible. C2 and E3 are known millipede structures. Syntectonic porphyroblasts (E and F) have grown during a phase of deformation. Inclusion patterns are usually curved and continuous with the fabric outside the porphyroblast, and show evidence of having been modified during porphyroblast growth. The distinction between syn and intertectonic porphyroblast is usually difficult since transitions occur and differences are subtle (cf. C1 and E1; C3 and E4; C4 and F1). Post-tectonic porphroyblasts (G and H) have grown after cessation of deformation. The inclusion patter is identical to and continuous with the external fabric. No strain shadows, strain caps or deflection of foliation are developed. (Passchier and Trouw, 1998)

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.

Windy Hill Foliation

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^o 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^o 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

Figure 23: Equal area projection, lower hemisphere. Windy Hill area. **A.** Measured crenulation lineations showing dominance for southwest directed plunge. N=23 **B.** Measured F_2 quartz vein fold hinge directions showing dominance for southwest directed plunge. N=17
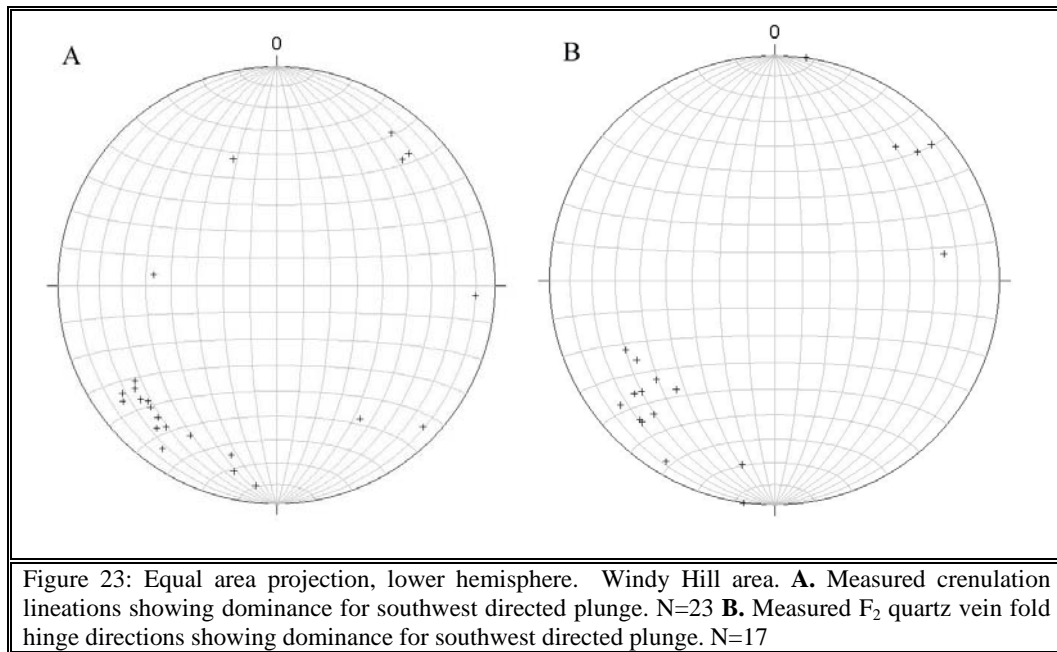
Orientations of crenulation lineations and fold hinges in quartz veins in the Windy Hill area show strong similarities (Figures 23a and 23b). Both stereonet diagrams show predominance of southwest-directed plunges with a lesser component of northeast-directed plunge suggesting that the formation of crenulation 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.

Buttonwood Hill

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.
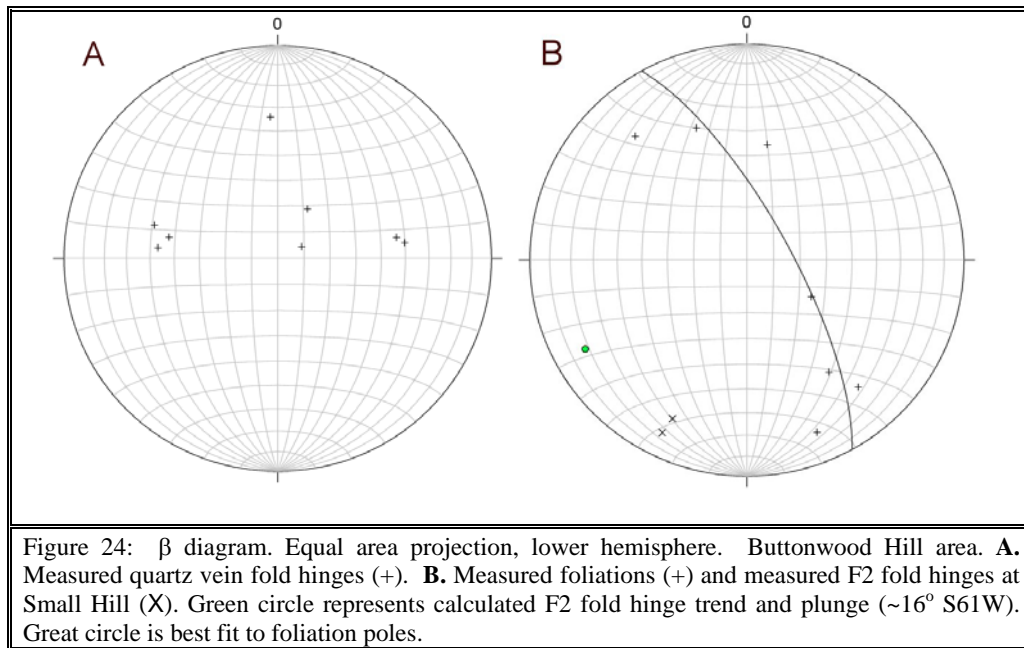
Figure 24A shows quartz vein fold hinge lineations measured at Buttonwood Hill. Three orientations of fold axis are evident. One orientation plunges to the west, one to the east and a third is sub-vertical. These three groupings of quartz vein fold hinge plunge are likely reflected in the ptymatic folding of quartz veins observed in this area (Figure 25).
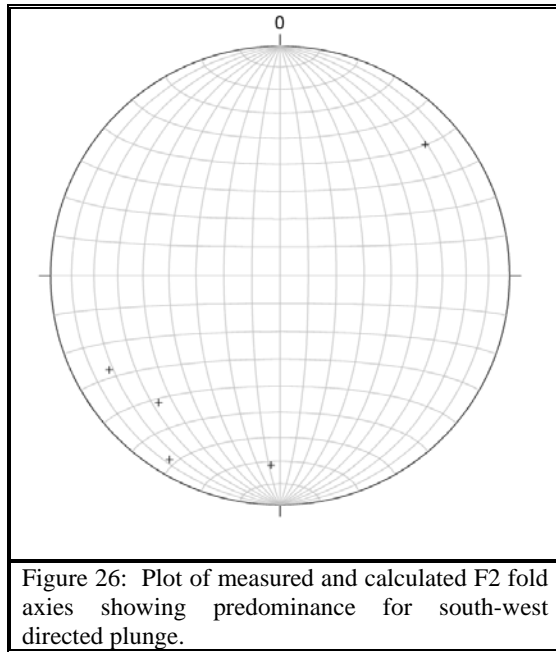
Figure 25: Plunging ptymatic folding of quartz veins at Buttonwood Hill. Direction of ruler is ~N86W and is approximately 10 cm long.
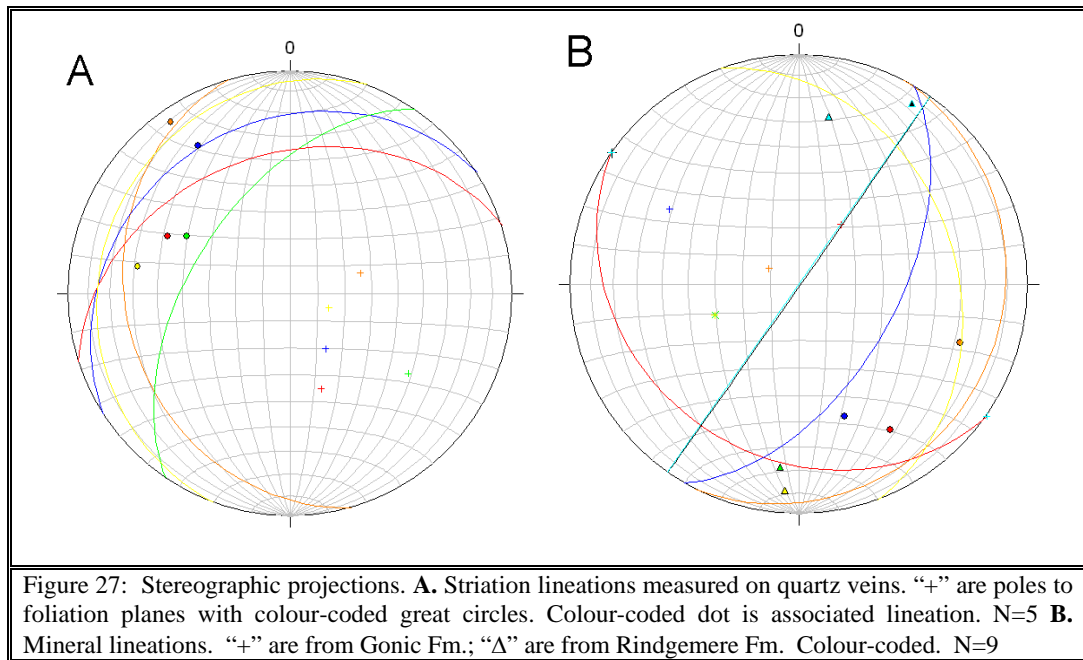
Poles to foliation at Buttonwood Hill show that northeast-southwest trending strikes are dominant. The stereonet projection (Figure 24B) illustrates a folded foliation. The limbs of a fold are evident; a best-fit π-circle is shown. The two groups of foliation data represent separate limbs of a fold, 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 ~16° 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 F2 fold axies 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.; "Δ" 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
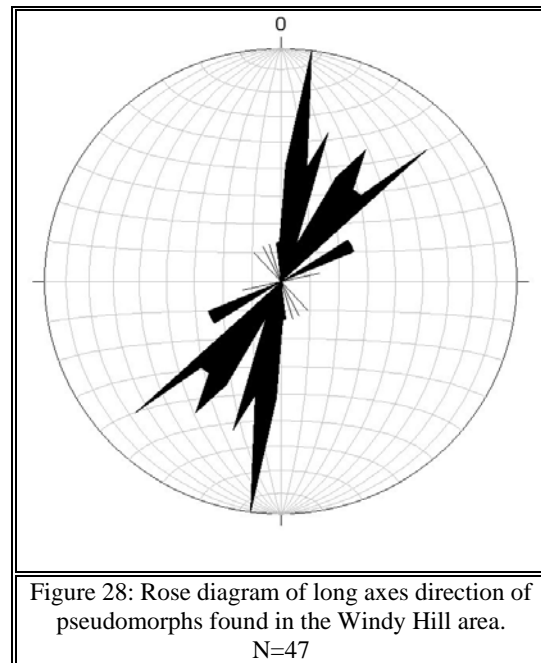
Figure 27B appears to have been folded. This is consistent with the calculated F_3 fold axis of Eusden et. al 1987. The mineral lineations in the Gonic are consistent with F_2 folding in the Windy Hill area. These mineral lineations formed during a recrystallization event prior to F_2 and could be synchronous 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.

Figure 28: Rose diagram of long axes direction of pseudomorphs found in the Windy Hill area. N=47

The purpose of these measurements was to investigate the

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 → 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.
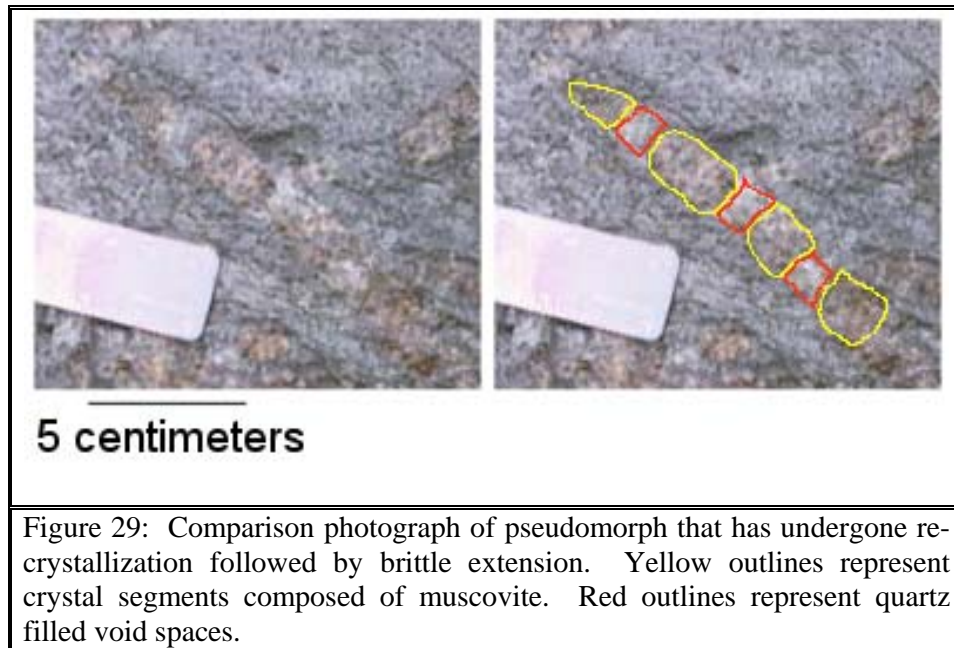
Figure 30: Windy Hill area. Andalusite porphyroblast with muscovite reaction rim. Camera lens cover = 5.5 cm diameter.

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.

Figure 31: Pseudomorph crystal that underwent extension followed by recrystallization. Figure A is field photograph. Figure B has been retouched to emphasise andalusite core (left pod, staurolite and garnet cores (middle and right pods) and muscovite enveloping each pod.
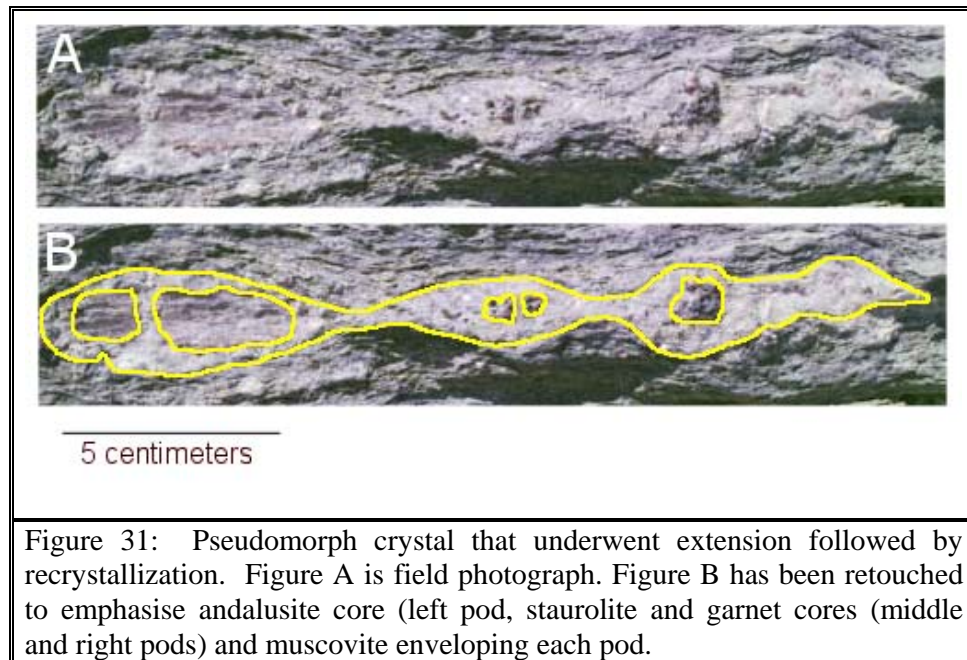
As a result two types of extension were observed; ductile extension followed by re-crystallization and re-crystallization followed by brittle extension. This, for the Windy Hill area, yields event sequences as:

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
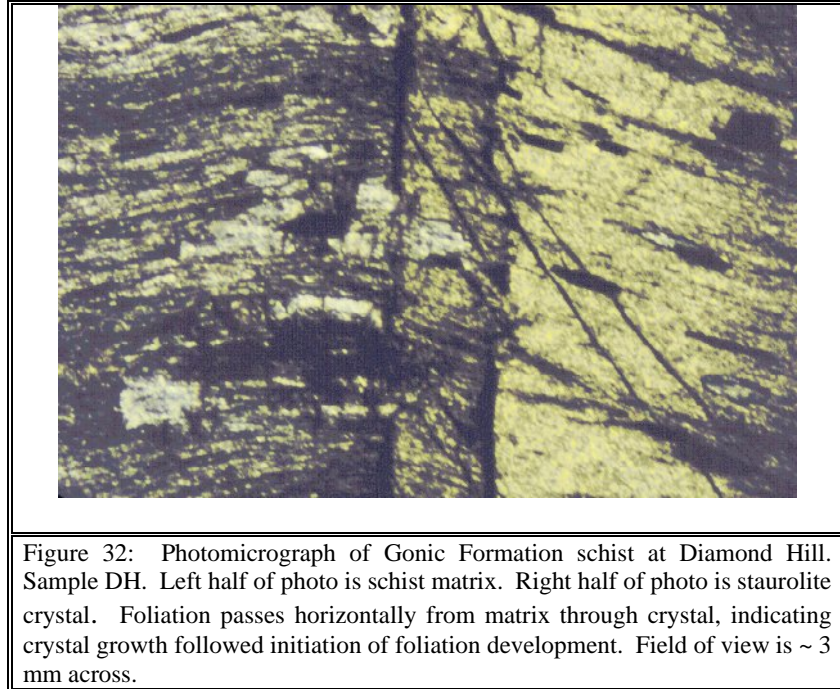
metamorphism consistent with the introduction of water and heat related to the intrusion of the Lyman. As a result, crystal modifications shown in Figures 29, 30 and 31 have to be synchronous or subsequent to the 322 my. age of the Lyman Pluton.

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 <u>not</u> used to determine shear sense.

Figure 32: Photomicrograph of Gonic Formation schist at Diamond Hill. Sample DH. Left half of photo is schist matrix. Right half of photo is staurolite crystal. Foliation passes horizontally from matrix through crystal, indicating crystal growth followed initiation of foliation development. Field of view is ~ 3 mm across.

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→staurolite growth→S2.

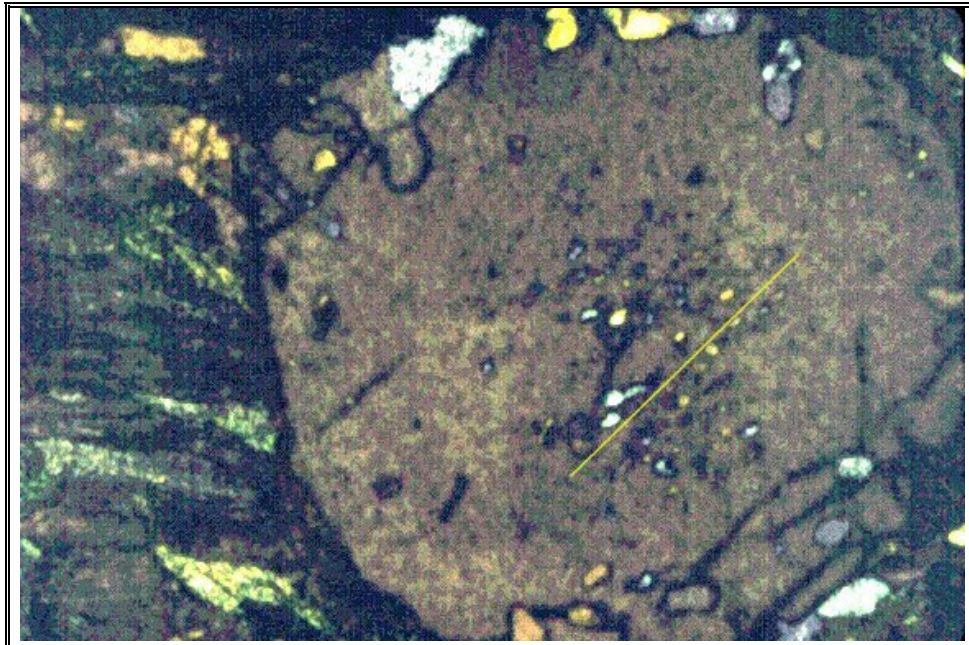Two types of garnet porphyroblasts are present, those without internal

Figure 33: Buttonwood Hill area. Sample LR1. Sample shows garnet crystal with internal foliation (Type II) oblique to matrix foliation. Yellow Line. Note lobate recrystalization on upper right of garnet. Although not evident in photo garnet also shows asymmetric tails indicative of sinistral motion. Field of view is ~3 mm.

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 recrystallzation 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

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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.
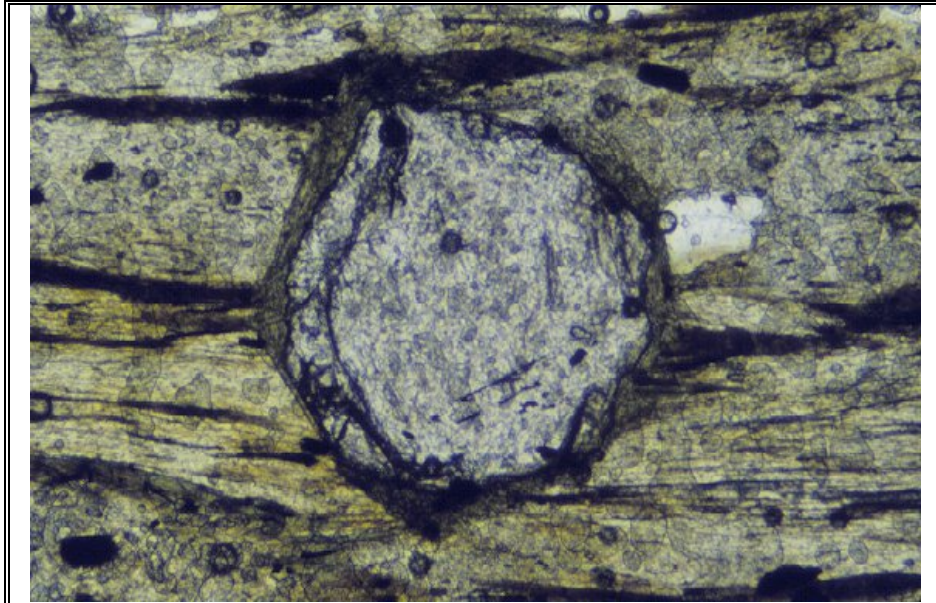
Figure 34: Buttonwood Hill area. Plain light image of a garnet porphyroblast in Gonic Schist showing chlorite reaction rim with muscovite. Schistosity (S1) horizontal. Garnet shows no internal foliation (Type I). Garnet is ~1 mm across.

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

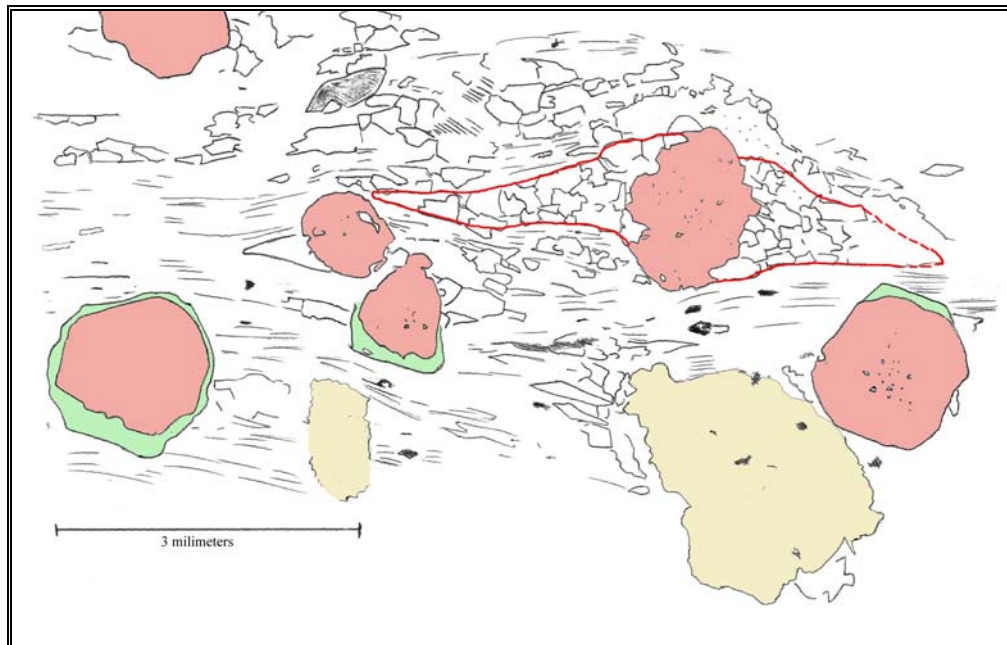Figure 35: Illustration of thin section LR1 from the Buttonwood Hill Area. Garnets are red color; Chlorite rims are green; Sericite is beige. Matrix is composed dominantly of muscovite and biotite. Asymmetric tails on garnet in upper right quadrant is annealed quartz. Black are opaque minerals.

grains interact, 120° boundary angles can be seen. This implies a period of static recrystallization annealing followed 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.

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The sericite crystals seen in thin section show a subhedral to anherdal 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.

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.
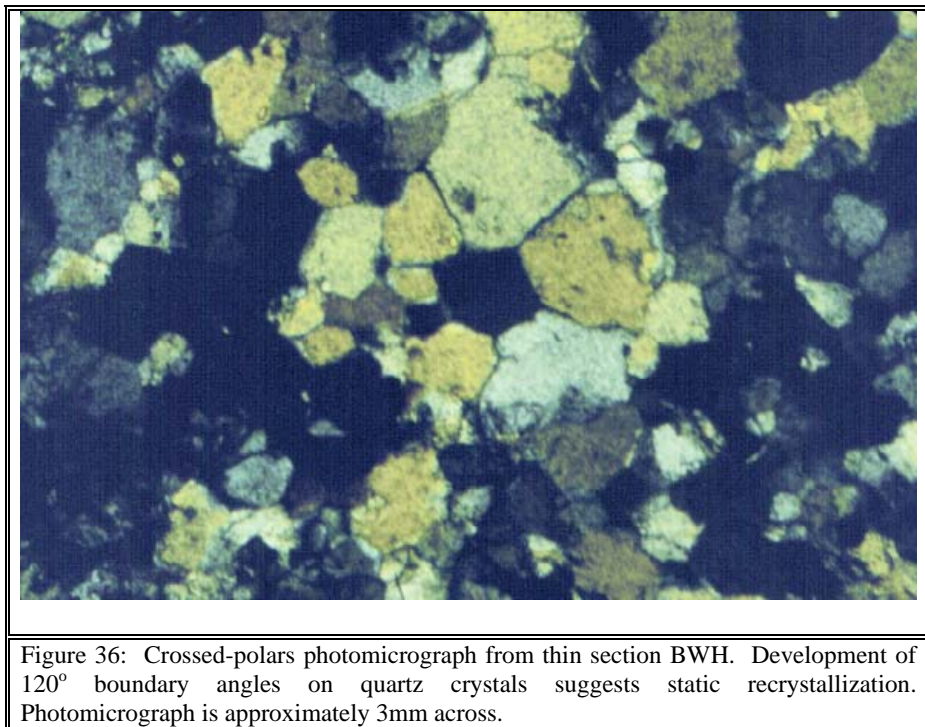
Thin section BWH2 also shows a C-S foliation structure (Figure 37). The foliation is defined by muscovite with quartz clasts. Very little biotite is present in this sample. Inspection of this fabric suggests a sinistral shear direction, where the C-plane is parallel to the shear zone boundaries and the S-plane is perpendicular to the stress direction.
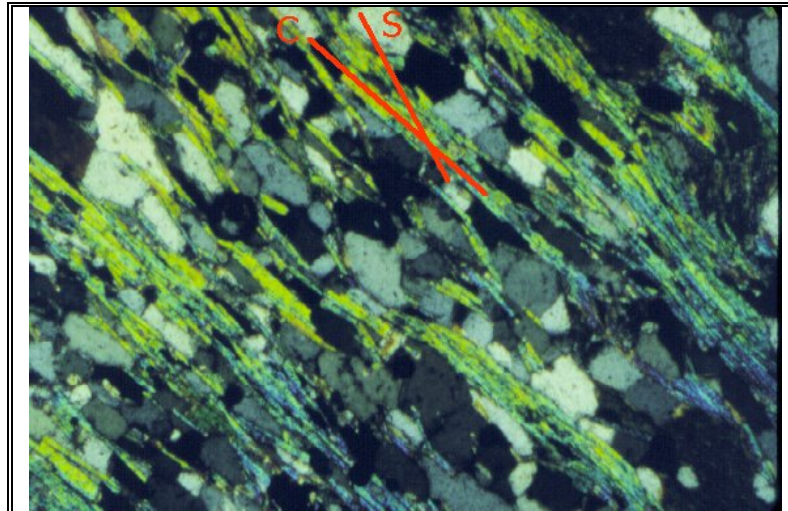
Figure 37: Crossed-polars photomicrograph from BWH showing C-S fabric elements defined by muscovite. Field of view is ~3 mm across.

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.
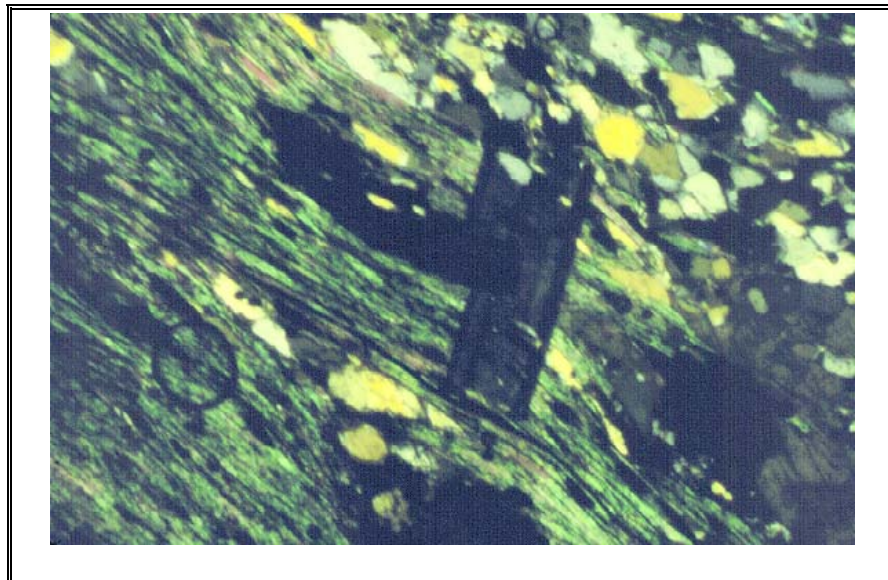
Figure 38: Crossed-polars photomicrograph from thin section BWH of a chloritoid crystal. Foliation, defined by muscovite, can be seen passing through chloritoid crystal indication crystal growth occurred after foliation development. Therefore: S1→chloritoid. Chloritoid crystal is approximately 1mm in length.

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.
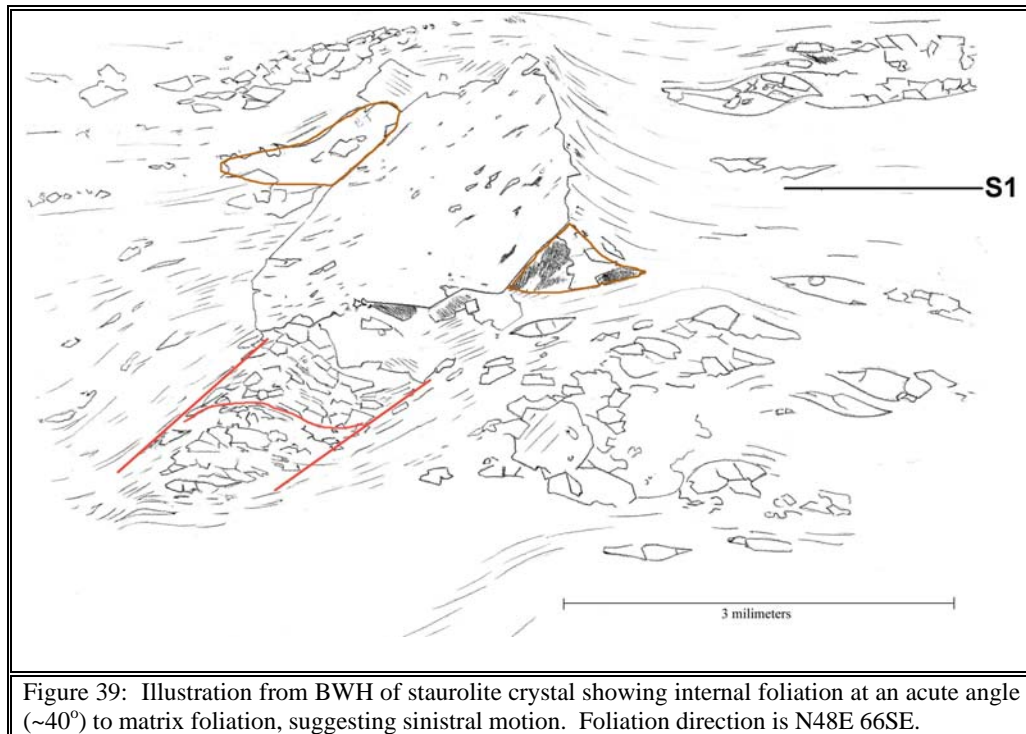
Figure 39: Illustration from BWH of staurolite crystal showing internal foliation at an acute angle (~40°) to matrix foliation, suggesting sinistral motion. Foliation direction is N48E 66SE.

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% ($\pm$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 ptygmaitc folding structure

and the brittle deformation of the fragmented quartz grain (40B) suggests a later

stage and probably cooler deformation event.

Figure 40:
Note Slides were reversed during sketching, therefore displacement sense is opposite of shown.

A: Garnet porphyroblast (gray shading) with asymmetric tails composed of quartz grains. Foliation defined by alignment of muscovite and biotite.

B: 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% ($\pm$5%)

A.

3 milimeters

B.

3 milimeters

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.

Figure 41: North of Windy Hill area. Mica-fish. Biotite with cleavage (yellow line) oblique to matrix foliation. Asymmetric crystal shape is indicative of dextral motion. Photo is ~ 5mm across.
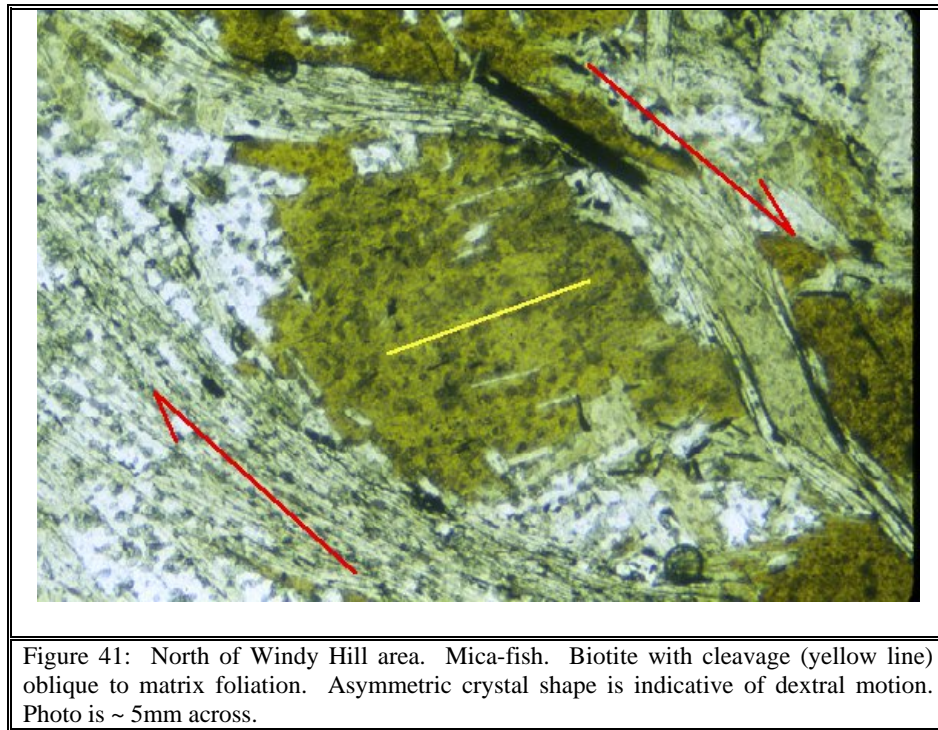
One thin section, S1090, was derived from the Rindgemere Formation (Figure 42; Note; slide shown in reverse mount). The outcrop exposure has a dominant foliation orientated N31W 50SW. A kink band was also observed with a 39°

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
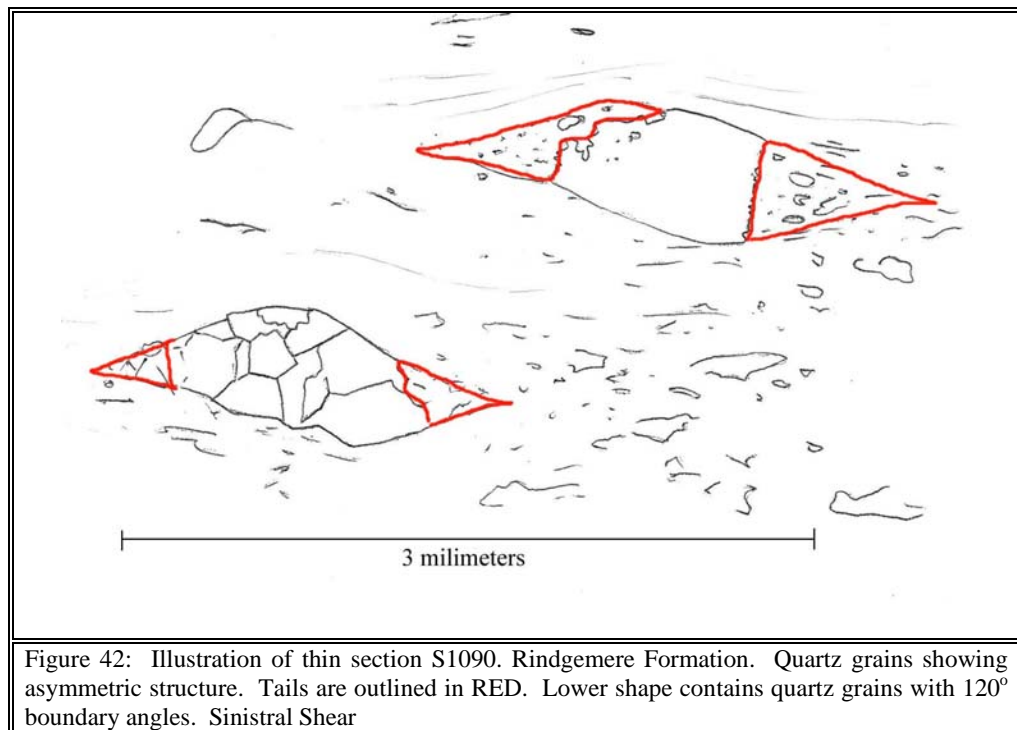
Conclusions

Field observations and microstructural analysis has both confirmed and provided insight into the deformation and metamorphic history of the Gonic Formation. F_1 recumbent folding was not directly observed but evidence such as the generally horizontal schistosity (S_1), 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_2 upright folding of S_1 schistosity is well documented, indicating the occurrence of later shortening deformation (D_2). F_3 folding was observed at the map scale as variations in foliation direction and F_2 axis lineations.

Evidence that F_2, 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_2 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 folation, which deflects S_2 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.

Figure 43: Buttonwood Hill. Conjugate quartz veins. Deformed vein trends N32E and shows approximately 30% shortening. This vein represents a zone of shortening between N18 to 46E. The undeformed vein trends N60E and represents the zone of lengthening. Primary foliation N45E, parallel with pen. Pen is 16cm long.

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 S_1 foliation. The second generation intruded after S_1. 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 3: Geological Relationships -simplified			
	S_1→	Staurolite growth→	S_2
	S_1→	Chlorite growth	
Granite dike intrusion →	S_1→	Granite intrusion	
	S_1→	F_2→	Dip Slip
Garnet growth Type I→	S_1→	Re-metamorphism	
	S_1→	Garnet growth Type II	
Andalusite growth→	Extensional Deformation →	Re-metamorphism	

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.

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Appendix A

Geological Time Scale

Appendix B

Data Tables

Sample No.	Location	Rock Type	Foliation	Lineation	Fold Hinges	Remarks
S1090*	Rindgemere	Rusty Phyllitic Schist	N31W 50SW	Cren. N15E 9SW	N50E 25SW	Carl Broggi Hwy.
	GristMillBridge	fn. gr schist	N20W 32NE	N4E 11SW	N/A	
	GristMillBridge	Gonic like	N20W 32NE	N5-8E 21SW	N/A	
GrmB*	GristMillBridge	more yellow than Gonic	N20W 32NE	north 34W	N/A	
GrgH		gray fn. Gr. Q. Mica Schist	N15E 76NW	N/A	N/A	
	Diamond Hill	Gonic	N55E 70SE	cren. N75E 15SW, N86E 34SW		
		gonic	main N47E		rk. N85E 47SW qtz. N74W 42SE	
Cemetary	Pine Hill	gonic	N50E nodip	cren. N70E ??		
LR1	Little River Road	rindgemere	N35E 90 N10E 27NW N28E 26NW	N32E 8SW		
Lor1	Loring R.	gonic	N56E 30NW			
Lor2	Loring R.	gonic	N56E 50NW			
WH2	West 5 Log R.	gonic	N59E 55NW			
BWH	Buttonwood	Gonic schist	N48E 66SE	Cren. N48E 22SW	N/A	
BWH2	Buttonwood	Gonic schist	N49E 67NW	N/A	nose N31E 68SW	
BWH3	Buttonwood					

Sample No.	Location	Rock Type	Foliation	Lineation	Fold Hinges	Remarks
8.29.99 BWH1	Buttonwood	Gonic ptymagic qtz. vein	N18E	N85W 43NW	N85W 43NW N79W 47NW N80E 43 NE N83E 40 NE	
		Gonic shearband zone	main N35E & N69E N77E 53NE		N70E 57NE N75E 36SW N76E 11SW, N73E	
		dark bands in shear zone bt. Between dk. Bands	N71E N82W		6SW	
622LR1.1	Windy Hill	Gonic schist	N55E 35NW	N/A	N/A	
622LR1.2	Windy Hill	Gonic schist	N10W 35NW	N/A	N/A	
622LR1.3	Windy Hill	Gonic schist	N18E 15NW	N/A	N/A	possible boulder
	bakof 622lr1.3	Gonic schist	N/A	N/A	N50E 32SW	bands gneiss type fol
	bakof 622lr1.3	Gonic schist	N/A	N/A	N42E 35SW	bands gneiss type fol
	bakof 622lr1.3	Gonic schist	N/A	N/A	N44E 15SW	bands gneiss type fol samp. Show tex.
622LR1.4	Windy Hill	Gonic schist	N5E 40NW	N/A	N43E 15SW	Change
Glh	Small Hill	granite fn. Gr. Q,Mu,Bt,Feld	N/A	N/A	N/A	

Sample No.	Location	Rock Type	Foliation	Lineation	Fold Hinges	Remarks
LR3.1	Small Hill	Gonic schist	N32E 29SE	N/A	N26E 12SW N25E 20SW	
LR3.2	Small Hill	Gonic schist	N30E 55SE	Cren. N19W 39SE	N/A	
LR3.3	Small Hill	Gonic schist	N19E 54SE	N/A	N/A	
LR3.4	Small Hill	Gonic schist	N55E ??	N/A	Q.vein N3W 34NW	
LR3.5	Small Hill	Gneiss	N29E 36NW	N/A	N/A	
LR3.6	Small Hill	granite pegmatite	N/A	N/A	N/A	no fol. Chunky
LR3.7	Small Hill	gonic schist	N90E 71SW	N/A	N/A	samp.
LR3.8	Small Hill	Gonic schist	N35E 0	cren. N50E no plunge	N/A	
LR3.9	Small Hill	granite pegmatite ~same as lr3.6	N/A	N/A	N/A	N8W 38SW unsure of orientations
LR3.10	Small Hill	Gneiss +Gonic contact?	N/A	N/A	N/A	
LR3.11	Small Hill	granite fine grained	weak N29E	N/A	N/A	
LR3.12	Small Hill	gonic schist	N72E 37NW	N65W 39NW	N/A	
LR3.13	Small Hill	granite fine grained	N/A	N/A	N/A	
LR3.14	Small Hill	granite fine grained	N/A	N/A	N/A	
LR3.15	Small Hill	granite fine grained	N/A	N/A	N/A	
LR3.16	Small Hill	gonic schist	N/A	N/A	N/A	
985.1	985 Morrils Mill Rd.					
985.2	985 Morrils Mill Rd.	gonic schist	N16W 27SW	N35W 7NW	N/A	
985.3	985 Morrils Mill Rd.	gonic schist	N40E 16NW	cren N37E 14NE	N/A	
985.4	985 Morrils Mill Rd.	gonic schist	N55W 26SW	N32W 26SE	smeared garnet (pic) fol. N35W 28SW	
985.5	985 Morrils Mill Rd.	gonic schist	N35W 17SW	N/A	N/A	
985.6	985 Morrils Mill Rd.	gonic schist	N35W 27SW	N/A	N/A	
985.7	985 Morrils Mill Rd.	gonic schist	N35W 24SW	N/A	N/A	

Sample No.	Location	Rock Type	Foliation	Lineation	Fold Hinges	Remarks
7.14.99 I1	WindyHill log road	granite weatered pegmati	N/A	N/A	N/A	lots of feldspar
7.14.99 I2	WindyHill log road	gonic schist	N70W 81SW	cren. N32W 29SE	N/A	
7.14.99 I4	WindyHill log road	granite weatered pegmati	N/A	N/A	N/A	lots of feldspar
7.14.99 I5	WindyHill log road	gonic schist	N35E 16SE	N/A	N/A	
7.14.99 I6	WindyHill log road	granite weatered pegmati	N/A	N/A	N/A	lots of feldspar
7.14.99 I7	WindyHill log road	gonic schist	N47E 27SE	N/A	N/A	
7.12-1*	WindyHill log road	gonic schist	N60W 34SW	N/A	N/A	*7.12A
7.12-1a	WindyHill log road	gonic schist	N83E 65SE	N/A	N/A	
7.12-1b	WindyHill log road	gonic schist	N70E 38SE	N/A	N/A	
7.12-2	WindyHill log road	gonic schist		N54E 21SW	N/A	
7.12-3	WindyHill log road	gonic schist	N57E 24NW	N32W 23NW	N81E 23SW q.v.	
				cren N46E 21SW	N/A	
7.12-5	WindyHill log road	gonic schist	N55E 22NW	N/A	N/A	
Odd xlls C-axis direction		N65E, N40E, N4E, N70W, N13W, N60W, N70W, N27E, N15E, N64W, N15E, N5W, N65E, N14W				
Staurolites replaced by mica		N6E, N5W, N67W, N70W, N15W, N4W, N8W, N5E, N70W, N57W, N42E, N19E				
7.12-6	WindyHill log road	gonic schist	N25E 27NW	cren N53E 13SW		mylonite+gonic
7.15.7	WindyHill log road	gonic schist				rapakivi?
7.20.7	WindyHill log road	gonic schist	N5W 6SW		N/A	sample of odd xlls

Sample No.	Location	Rock Type	Foliation	Lineation	Fold Hinges	Remarks
7.12-8	WindyHill log road	mylonite	N10E 26NW	N/A	N/A	interbed w/gonic like7207
7.26.00.1	Turkey Rd.	gonic	N64E 66SE			
7.26.00.2	Turkey Rd.	gonic	N32E 82SE	cren. N65E 5NE		qtz., bt., st., muscov., gt.
BB1	Sanford Quad	granite	fracture N5W 77NE	N5W 50S		qtz, feld, hornblend, muscov., bt., gt.
		schist w/ def. Granite vein	So N35E 43SE	on So N55W 43SE mineral line. On granite N6E 58SW, N60W 65SE, N25W 37NW		
	Devils Den	granite	joints; N80E 67SE, N20E 49SE			qtz., feld., hornblend, muscov, gt.
	Putnam Lumber	gonic	N20E 15NW	N80W 31SE on qtz.		qtz. Muscov., bt., gt., feld. In muscov.
	Putnam Lumber	gonic	N65W 50SW			muscov. Pseudomorphs
	Putnam Lumber	gonic	N48E 37SE			muscov. Pseudomorphs
	Putnam Lumber	gonic	N80W 67SW			
	Putnam Lumber	gonic	N51E 26SE			
	Putnam Lumber	gonic	N31W 51SW pesudomorphs	cren. N20W 21SE N3W 25SE, N43W 7SE, N27W 18SE, N16W 18SE, N7W 17SE		

Sample No.	Location	Rock Type	Foliation	Lineation	Fold Hinges	Remarks
7.12-9	Windy Hill log rd.	gonic	N21E 5NW	cren N55E 15SW	q.v. N42E 21SW	
7.12-10	Windy Hill log rd.	gonic	N24E 42SE	cren N45E 16NE	N/A	
7.12-11	Windy Hill log rd.	mylonite	N15E 32NW	N/A	N/A	
7.12-12	Windy Hill log rd.	granite pegmatite	N/A	N/A	N/A	
7.12-13	Windy Hill log rd.	mylonite	N52E 15NW	N/A	N/A	collected 7.22.99 F2 fold hinge
7.12-14	Windy Hill log rd.	gonic	N51E 0	N/A	gentle N48E 16NE q.v. N49E 9SW	coll.7.22 collected 7.22.99
7.12-15	Windy Hill log rd.	gonic	N62E 6SE	N/A	N/A	collected 7.22.99
		mylonite	N47E 2SE	N/A	N/A	collected 7.22.99 boulder?pseudomylo
7.12-16	Windy Hill log rd.	gonic	N86W 15SW	N/A	N/A	nite
7.12-16a	Windy Hill log rd.	gonic	N35E 6NW	N/A	N/A	collected 7.22.99
7.12-18	Windy Hill log rd.	granite pegmatite	N/A	N/A	N/A	collected 7.22.99

Sample No.	Location	Rock Type	Foliation	Lineation	Fold Hinges	Remarks
8.3.99.1	Windy Hill	gonic	N60E 74NW	Intersection line. Needs checking N52E 26NE		
		mylonite	N85W 39NE			
8.3.99.2	Windy Hill	mylonite	N40E 51NW			
			odd xll c-axis N21E			
8.3.99.3	Windy Hill	gonic	N41E 75NW			
8.3.99.4	Windy Hill	mylonite	N34E 54NW			
		Qtz Vein		N61W 46SE		
		Qtz Vein		N79W 45SE		
		Qtz Vein	strike N34E 54NW			
8.3.99.5	Windy Hill	mylonite	N80E 45 SE	Cren. N56E 23 SW		
		oddxlls N46E, N61E		Cren. N87W 10SE		
8.3.99.6	Windy Hill	gonic	N60E 46NW		qtz. vein N51E 21SW, N51E 13SW	
8.16.1	Windy Hill	mylonite	N70E 17NW	cren. N40E 16 SW	qtz. vein N50E 24 SW	
8.16.2	Windy Hill	mylonite	N31E 60 SE		N31E 7 SW	
			N31E 42SE			
8.16.3	Windy Hill	mylonite	N54E 25SE			
			feldspar, qtz, muscov.			
8.16.4	Windy Hill	granite peg.	Little bt.			
8.16.5	Windy Hill	granite peg.				
8.16.6	Windy Hill	granite peg.				
8.16.7	Windy Hill	granite peg./gonic	N50E 27NW			contact
8.16.8A	Windy Hill	gonic	N46E 26NW			
356	Windy Hill	gonic	N30E 13 SE	N35E 10SW		
	Ford Quint	rindgemere?	N19E 25SE	N30E 22SW		

Sample No.	Location	Rock Type	Foliation	Lineation	Fold Hinges	Remarks
		mylonite?	N27E 12 SE			
		rindgemere?	line.	N70W 26SE		
			cren. Line	N38E 19 SW		
			2nd cren. line	N46W 8 SE		
			small grains; Feld, Bt.			
8.24.1	Windy Hill	granite	Qtz			
			small grains; Feld, Bt.			
8.24.2	Windy Hill	granite	Qtz			
8.24.3	Windy Hill	gonic	N42E 79NW			contact
		granite	N56E 79NW			
8.24.5	Windy Hill	granite/gonic	contact strike N52E			
				mineral line. N15-30E		
8.24.6	Windy Hill	gonic	N43W 18NE			
8.24.6a	Windy Hill	gonic	N62W 21NE	cren. N42E 20SW	qtz. N65E 28SW	
					N60E 30SW	
8.24.7	Windy Hill	gonic	N10E 53SE			
8.24.8	Windy Hill	gonic	N60E			
8.24.9	Windy Hill	gonic	N85E 40 NW	cren. N45E 20SW		
8.24.10	Windy Hill	gonic	N75E 14SE			
8.24.11	Windy Hill	gonic	N30W 13NE			
8.24.12	Windy Hill	gonic	N45E 14NW			
8.24.13	Windy Hill	gonic	N38E 26NW			
		odd xlls	N75E, N35E, N45E, N20E, N45E, N58, N80W, N80E, N48E, N33E			
			N39E, N35W, N7E, N41E, N36E, N84W, N25E, N33E			
8.24.14	Windy Hill	gonic	N73E 16NW		N8E NE plunge	
8.25.1	Windy Hill	gonic (myl)	N40E 5SE	cren. N6E 9SW		St. xlls. Re-meta parallel w/ fol.
8.25.2	Windy Hill	gonic (myl)	N28E 7NW			
		st. band in gonic	N12E 31SW			
8.25.3	Windy Hill	gonic (myl)	N11E 12SE			qtz. Veining/ odd xlls.
8.25.4	Windy Hill	gonic (myl)	N66W 17NE			
8.25.5	Windy Hill	gonic (myl)	N32E 12SE	cren. N15E 21SW	qtz. N10E 18SW	grt. St.
8.25.6	Windy Hill	gonic	N18E 14NW	N13E 14SW		
		odd xlls	N56E, N13E, N12E, N11W, N25W, N6E, N19E, N5E, N60E			
			N26E, N46E, N9E, N12E, N33E, North, N31E, N2E, N3E			