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The geology of the Liberty-Orrington-Passagassawakeag/Fredericton Trough terrane boundary in the Bucksport-Orland area, coastal Maine

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THE GEOLOGY OF THE LIBERTY-ORRINGTON-PASSAGASSAWAKEAG/FREDERICTON TROUGH TERRANE BOUNDARY IN THE BUCKSPORT-ORLAND AREA, COASTAL MAINE

Abstract of

a thesis presented to the Faculty

of the University at Albany, State University of New York

in partial fulfillment of the requirements

for the degree of

Master of Sciences

College of Arts and Sciences

Department of Earth and Atmospheric Sciences

Heather A. Short

1999

ABSTRACT

The Liberty-Orrington fault separates two tectonic terranes of widely different lithologies and metamorphic grades within the Coastal Lithotectonic Belt of Maine. While the juxtaposition of the sillimanite-bearing Passagassawakeag gneiss and the chlorite grade Bucksport Formation (turbidites) requires a fault between them, field evidence for, and an understanding of, the nature of the fault has hitherto been lacking. Although the Liberty-Orrington fault has previously been interpreted as a thrust, strike-slip, and/or normal fault, the most recent debate has been centered around two models of Acadian amalgamation involving thrusting of the Passagassawakeag terrane from the southeast vs. thrusting from beneath central Maine (from the northwest) (Osberg et al., 1998; Stewart et al., 1995).

My detailed mapping shows the existence of a 250-500m wide mylonitic shear zone separating the gneiss and the turbidites in the southern portion of the study area. Foliation within the shear zone is predominantly near-vertical, with near-horizontal stretching lineations and pervasive (present orientation) sense-of-shear inidactors. The mylonites are deformed by open Acadian folds on both map and outcrop scales, and are cut by Devonian (371±2 Ma) granite. Followed eastward, this northeast-striking Passagassawakeag-Bucksport terrane boundary turns north, as do highly-strained rocks and local foliation. A thin unit of alternating layers of quartz and garnet+biotite+magnetite, previously interpreted as a stratigraphic unit showing possible orginal bedding (Rider Bluff unit), lies along the north-south striking part of the

Passagassawakeag-Bucksport boundary. Thin sections demonstrate that the layering in this unit is a tectonic fabric.

The field data suggest that the Liberty-Orrington fault is a major dextral strike-slip shear zone, with the eastern boundary as a transpressional thrust; If this is the case, the Liberty-Orrington shear zone may represent a continuum of orogen-scale dextral shear (with the Penobscot Bay and Norumbega fault zones) through the Acadian. This tectonic model is more likely than that of a folded shear zone generated by a thrust, as the sense-of-shear in the unfolded mylonites would require large-scale thrusting parallel to the orogen. This study necessitates a re-evalution of the role of transpression in the exhumation of high-grade rocks in coastal Maine during the Acadian orogeny.

University at Albany, State University of New York

College of Sciences and Mathematics

Department of Earth and Atmospheric Sciences

The thesis for the master's degree submitted by

Heather A. Short

under the title

THE GEOLOGY OF THE LIBERTY-ORRINGTON-PASSAGASSAWAKEAG/FREDERICTON TROUGH TERRANE BOUNDARY IN THE BUCKSPORT-ORLAND AREA, COASTAL MAINE

has been read by the undersigned. It is hereby recommended

for acceptance by the Faculty with credit to the amount of

6 semester hours.

(Signed)________ (Date) 28 April 1999

(Signed) W. D. Means (Date) 4/28/99

(Signed) Charles V. Guidotti (Date) 4/29/99

Recommendation accepted by the Dean of Graduate Studies

for the Graduate Academic Council

(Signed)________ (Date)________

THE GEOLOGY OF THE LIBERTY-ORRINGTON-PASSAGASSAWAKEAG/FREDERICTON TROUGH TERRANE BOUNDARY IN THE BUCKSPORT-ORLAND AREA, COASTAL MAINE

A Thesis presented to the Faculty
of the University at Albany, State University of New York
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Master of Science
College of Sciences and Mathematics
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Heather A. Short

April 1999

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Additional thanks to my field assistants in Maine: Riley Brown the Science Clown, who could always be counted on to clear all life forms from an outcrop; Brian Campbell (thanks for the sea-kayaking); Camala and Julie; Dr. Doug Reusch for many helpful discussions and suggestions in the field, and Beth for discussions after the field. Thanks also to my aunt and uncle, Connie and Sid Short for providing me with a dry and quiet place to live during the field season. Final thanks to Stew Clark, my ninth grade Earth Science teacher, for recognizing that geology was my real first language, and for teaching me how to read it in Maine.

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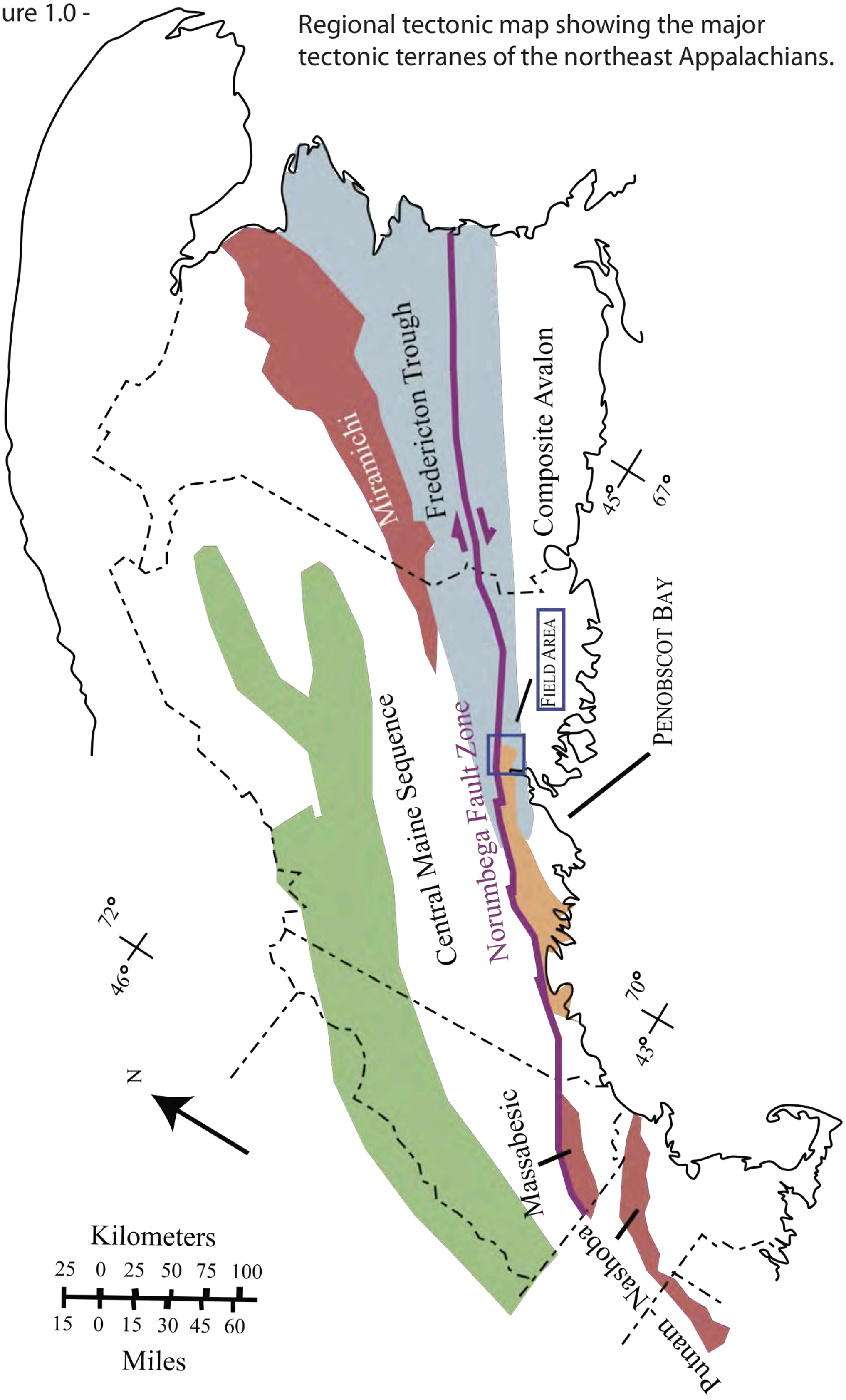
CHAPTER 1

INTRODUCTION

Purpose of the study

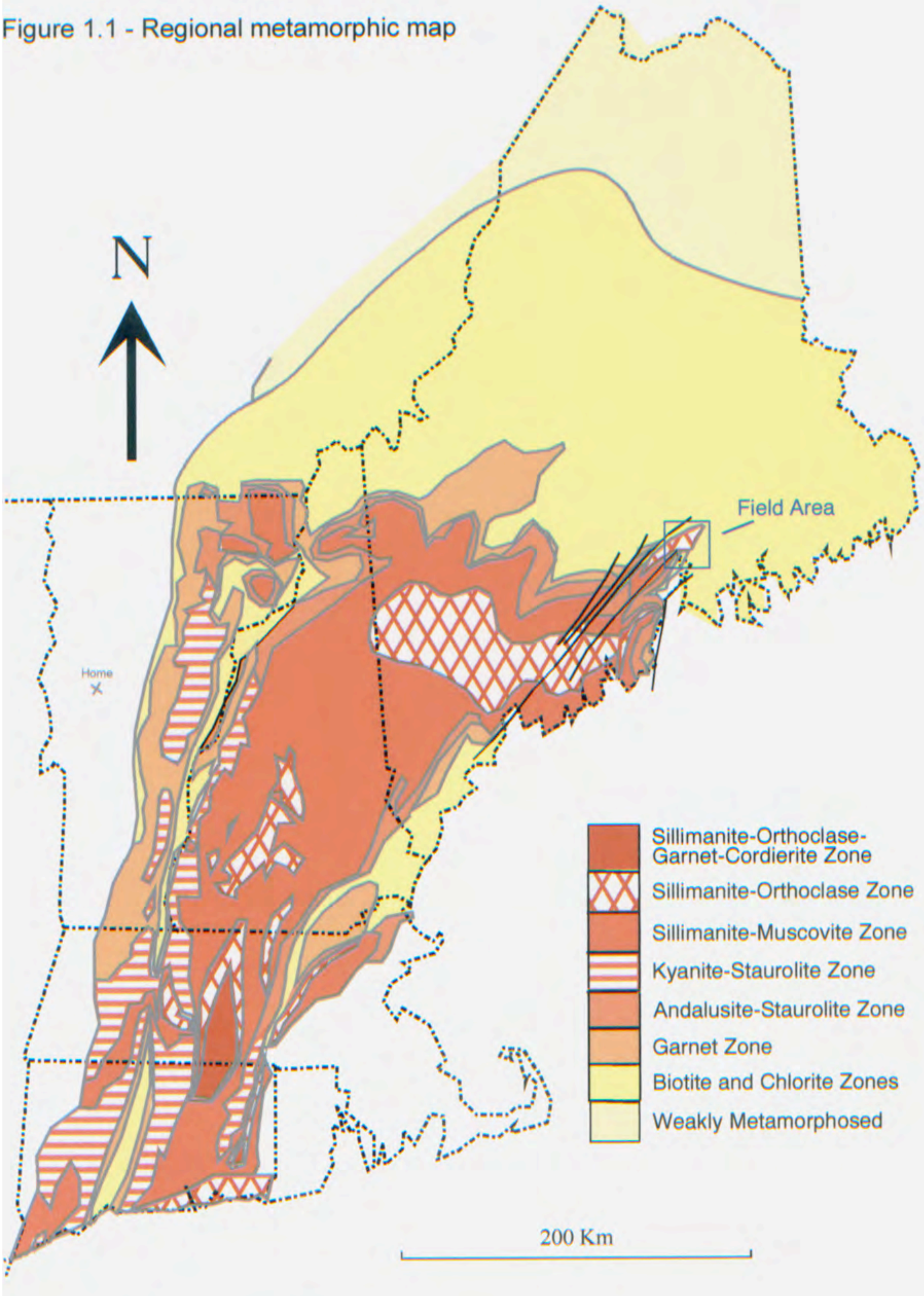
The geology of the present-day eastern margin of North America has been shaped by multiple continental and island arc collisions throughout the Paleozoic, the effects of which are preserved in the metamorphic terranes, intervening trough sediments, and extensive plutons of Maine (Figure 1). It has generally been thought that the composite terranes of eastern Maine were brought to their present configuration via perpendicular-to-orogen thrust faulting during the Devonian Acadian orogeny, and were subsequently dissected by felsic and mafic magmatism and regional strike-slip faulting along the Norumbega Fault Zone (Osberg et al., 1985). At the northern end of Penobscot Bay, mid-coastal Maine, the Liberty-Orrington Fault separates the sillimanite-grade Passagassawakeag terrane from the Fredericton Trough terrane, which consists of chlorite-grade turbidites that border the Passagassawakeag to the northwest, northeast-east, and south. This is the only location in Maine where the truncation of a major high-grade metamorphic terrane is exposed (Figure 1.1), yet the nature of the boundary fault and emplacement of the Passagassawakeag terrane is poorly understood. Previous studies failed to find any field evidence for the existence of the Liberty-Orrington Fault, and some suggested that it was even an unconformity (McSwiggen, 1978; Kaszuba and Simpson, 1989). In recent years, two models for the juxtaposition of the Passagassawakeag and Fredericton Trough terranes in the study area have been suggested

Figure 1.0 - Regional tectonic map showing the major tectonic terranes of the northeast Appalachians.



Adapted from Rast, N., and Skehan, J. W., 1993.

Figure 1.1 - Regional metamorphic map



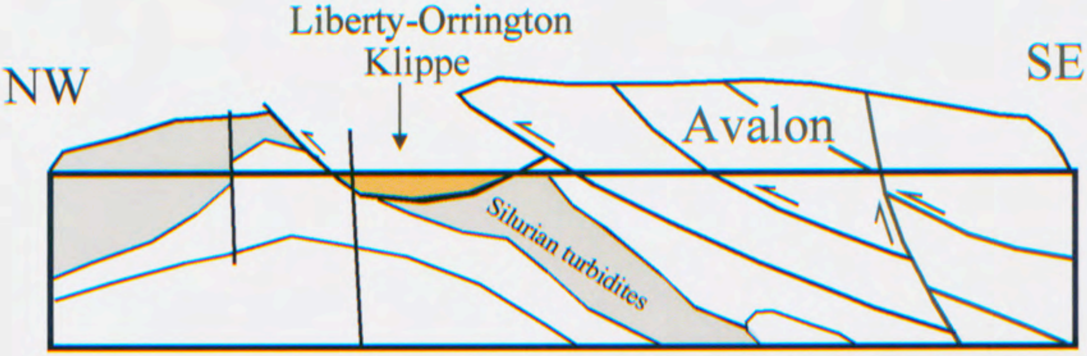
Generalized map of Acadian New England metamorphism modified from Robinson et al., 1998.

(Figure 1.2). One proposed by Stewart et al. (1995) advocates the inclusion of the Passagassawakeag terrane in the Salinic orogenic belt, now exposed from western Europe to southern New England. Late Ordovician to Early Silurian Salinic tectonic activity involved extensive thrust faulting and metamorphism, large strike-slip faults, and plutonism, all of which are represented in coastal Maine (Stewart et al., 1995). In this context, the Passagassawakeag terrane in the study area could represent a slice of the basement to this Salinic orogenic belt with the Bucksport Formation of the Fredericton Trough terrane representing turbidite sedimentation on the oceanic crust between the Salinic orogenic belt and the Avalon terrane to the east (Figure 1.2b). A contrasting tectonic model proposed for the study area does not directly contradict the existence of a Salinic orogenic belt in Maine, but contends that the Passagassawakeag rocks are a klippe of Avalonian origin (Osberg et al., 1995; 1998) (Figure 1.2a). This model is primarily based on first-order observations of coastal Maine geology, specifically that the Passagassawakeag contains Silurian age metamorphism and plutons, and the only other place in Maine that rocks with these characteristics crop out is the Avalonian rocks to the east (Berry, pers. com., 1998). Alternatively, this terrane may be entirely derived from Acadian metasediments and may not represent a basement terrane to anything.

Thus, the initial goals of this study were, firstly, to find and document field evidence for the existence of the Liberty-Orrington Fault and, secondly, to try to determine the nature of the fault and the emplacement (and possible affinity) of the Passagassawakeag terrane. Through detailed geologic mapping and petrographic analysis of a small but precisely chosen field area, I hope to contribute to the current

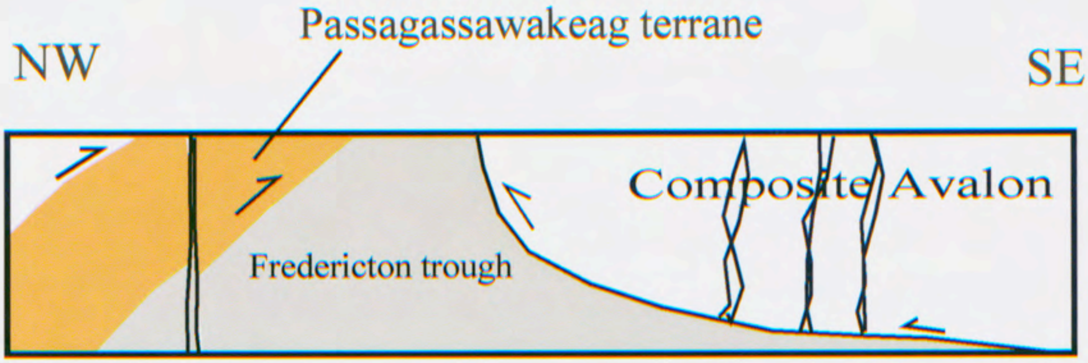
Figure 1.2 - Previously published tectonic models for the Bucksport-Orland area

a)



Osberg, Tucker and Berry (1995)

b)



Stewart, Tucker and West (1995)

understanding of terrane amalgamation in coastal Maine and the tectonic style of the Acadian orogeny.

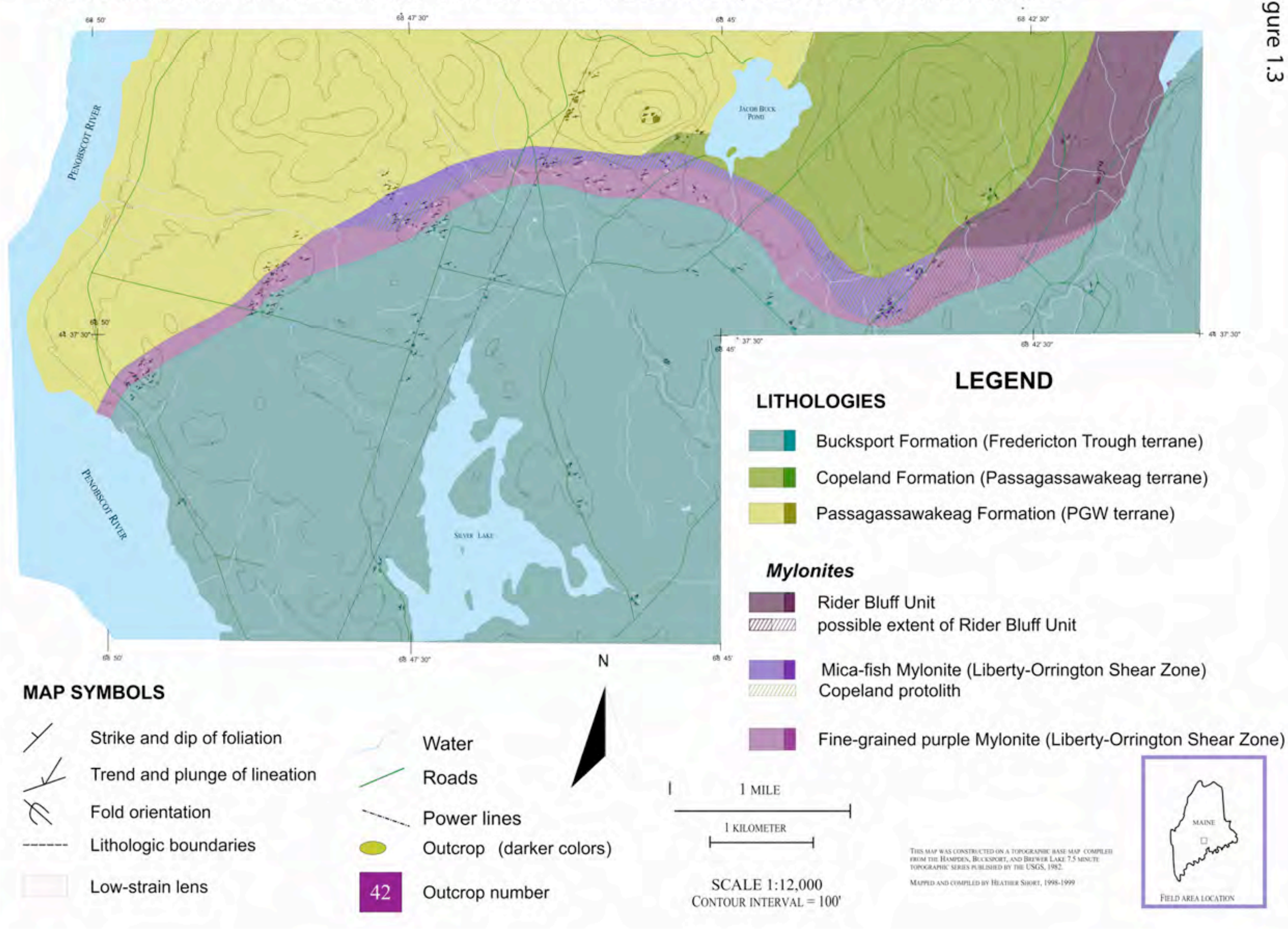
The project goals were reassessed as field work progressed, as I discovered the existence of a 250-500m wide belt of mylonitic rocks along the southern trace of the proposed Liberty-Orrington Fault, to the north of Penobscot Bay (Figure 1.3). I then focused on carefully mapping the two main types of mylonites within the shear zone, recording the orientations of foliation and lineations (Table A-3; Figure B-3), and looking for cross-cutting metamorphic and structural relationships to determine the age of mylonite formation. The vast majority of the field data from this southern extent of the terrane boundary strongly suggests that the shear zone was formed under ductile conditions during dextral strike-slip motion (Figure B-3). This interpretation is quite different from those previously suggested for the Liberty-Orrington Fault, as the most recent debate has centered on the direction from which the Passagassawakeag terrane was thrusted (northwest vs. southeast) (Figure 1.2). This thesis presents field and petrographic evidence for the dextral strike-slip nature of the Liberty-Orrington Fault along its southern extent in the field area, and attempts to explain the truncation of the Passagassawakeag terrane along its north-south striking eastern boundary with the Fredericton Trough turbidites as an overturned transpressional thrust, due to prolonged dextral strike-slip motion in the early Devonian, coupled with late Devonian to Carboniferous movement along the Norumbega Fault Zone (Ludman, 1986; West and Lux, 1993; West and Hubbard, 1997). Ultimately, this study should compel a reevaluation of the role of transpression in the amalgamation of the composite terranes of coastal Maine during the Acadian orogeny.

Location of study area

The study area lies within the Coastal Lithotectonic Belt (CLTB) of east-central Maine, a significant but poorly understood component of the Northern Appalachian Orogenic Belt (Figure 1.1). The rocks of the Maine coastal region are characterized as a group of lithotectonic terranes that underwent what was generally believed to be several episodes of mid to late Devonian regional metamorphism and deformation associated with the Acadian orogeny, although recent workers have documented Silurian metamorphism in western Penobscot Bay (West et al., 1995). This study is concerned with the Precambrian- Ordovician Passagassawakeag terrane and the Ordovician-Early Silurian Fredericton Trough terrane, in the region stretching from the middle of Silver Lake, approximately 2 km north of Penobscot Bay, northward to the Norumbega Fault Zone, bordered on the west by the Penobscot River, and the east by the Lucerne Pluton (Figure 1.3). This particular field area was chosen because it is for the most part free of significant contact metamorphism, and because previous attempts by other workers at determining the nature of this terrane boundary to the east were inconclusive. Essentially, the southern boundary between the Passagassawakeag and Fredericton Trough terranes within the study area had not been examined in 20 years, and never in detail.

Figure 1.3

GEOLOGIC MAP OF THE BUCKSPORT-ORLAND FIELD AREA, CENTRAL COASTAL MAINE



Regional geology

The western boundary of the Coastal Lithotectonic Belt of eastern Maine is approximated by the right-lateral Norumbega Fault zone. To the west of it is the Kearsarge- Central Maine ‘Synclinorium’(Central Maine Sequence) of the Medial New England terrane rocks that have been affected only by mid to late Paleozoic orogenic activity (Rankin, 1994). Along strike to the south of the CLTB, the Late Precambrian Avalonian terrane of southern New England is typified by late Paleozoic metamorphism and deformation of the overprinting Alleghanian orogenic event (Wintsch et al., 1992). Northeast of the Maine CLTB in the Atlantic Provinces of Canada, as well as in western Penobscot Bay, new research has shown Silurian tectonism and metamorphism to be an integral part of the accretionary history of those areas (Van Staal, 1994; West et al., 1995; Stewart et al., 1995).

According to early work by Stewart and Wones (1974) the CLTB is a composite of several geologically distinct terranes each with different stratigraphy, metamorphic grades, and tectonic history. The Penobscot Bay area contains five of these terranes, from southeast to northwest: the Cambrian-Early Ordovician Ellsworth terrane, the Precambrian-Ordovician Penobscot terrane, the Cambrian St. Croix terrane, the Devonian-Early Silurian Fredericton Trough terrane, the Precambrian-Ordovician Passagassawakeag terrane, and the Devonian-Ordovician Vassalboro terrane (Kaszuba and Simpson, 1989; Osberg et al., 1985). The boundaries between each of these terranes have all been referred to in the past as both unconformities and faults (Stewart and Wones, 1974; Stewart et al., 1995; Osberg et al., 1985; 1998). Three major faults in the area are now thought to be the boundaries between four of the above mentioned terranes: the Senebec Pond Fault between the St. Croix and Fredericton terranes, the Liberty-Orrington Fault between the Fredericton Trough and Passagassawakeag terranes, and the Hackmatack Fault between the Passagassawakeag rocks and those of Medial New England (Osberg et al., 1985; 1998; Pankiwskyj, 1996). Felsic and mafic Devonian plutons cut the Paleozoic sequences and some faults within the CLTB, and some were later deformed locally by late Paleozoic fault reactivation (Kaszuba and Simpson, 1989; Ludman, 1986).

The application of terrane analysis and the concept of accretionary tectonics is not new to Maine geology. Perhaps the earliest attempt to separate terranes foreign to North America in coastal Maine was by Zen (1983), who included the Passagassawakeag gneiss as a candidate for an 'exotic terrane' and correlated it with the Nashoba gneiss complex of eastern Massachusetts. Subsequent workers have produced numerous models for the timing of accretion of various terranes within Maine and adjacent areas affected by Early Paleozoic orogenies (Keppie, 1989; Ludman, 1986; Ludman et al., 1993; Rast and Skehan, 1993; Boone and Boudette, 1989; Rankin, 1994; Osberg et al., 1995; Stewart et al., 1995; Mac Niocaill et al., 1997; Bradley et al., 1998; and many others). Most models generally involve the slow closing of a large ocean between Laurentia and Gondwana, with intervening island arcs, microcontinents, and back arc basins, and with collisions between these various tectonic objects sometimes occurring in mid-ocean, then accreting to Laurentia or Gondwana as composite terranes. In Maine, the tectonic objects involved have long been limited to Laurentia versus the Avalonian arc and/or composite terrane brought together during the Acadian orogeny, with the possible exception of the Chain

Lakes Massif in northwestern Maine. It has in recent years become accepted that the geology of Maine is indeed the product of the amalgamation of various terranes to North America beginning with the Taconic orogeny and continuing through the Acadian and Alleghanian orogens, with the Penobscottian and Salinic as ‘internal’ (between the Taconic and Acadian) orogenies.

Previous work

The first detailed geologic map of the Penobscot Bay region relevant to the study area was published in 1950 by J. M. Trefethen, a former Maine State Geologist. He was the first to suggest that the Bucksport Formation is distinct from the Vassalboro Formation of the Medial New England terrane (see definition below) to the west. He was also the first to map some of the calc-silicate layers in the Passagassawakeag gneiss and to distinguish the Liberty-Orrington Antiform. However, he did not delineate the nature of the boundary between the Bucksport and Passagassawakeag formations within the study area.

An unpublished MS thesis by McSwiggen (1978), from the University of Maine at Orono entitled “Stratigraphy, Structural Geology, and Metamorphism of the Northeast extension of the Liberty-Orrington Antiform, south-central Maine,” produced a 1”=1/2 mile scale structural map showing four calc-silicate layers within the Passagassawakeag Formation multiply folded into a general shape suggesting the nose of an antiform. On his accompanying geologic map, McSwiggen shows the Copeland and Rider Bluff as separate formations within the antiform, with the Copeland Formation extending along the southeast margin of the Passagassawakeag terrane and cropping out along the east side of the Penobscot River. A regional amphibolite isograd in the Vassalboro (now Bucksport) Formation ends at the contact with the Passagassawakeag rocks. That contact was interpreted as a stratigraphic unconformity. He also portrayed the Norumbega Fault Zone as a couple of discontinuous faults with only vertical displacement.

A 1:62,500 scale general geologic map of the Bucksport Quadrangle, Maine, was published in 1991 by D. R. Wones. The map shows the Bucksport and Vassalboro Formations as separate units, and portrays the boundary between the Passagassawakeag terrane and the Bucksport Formation as a northwest dipping thrust fault. The Passagassawakeag, Copeland, and Stricklen Ridge formations lack internal lithologic detail on this map, and no structural cross sections accompany the map. Work on the map was done by Wones prior to 1984, and was later compiled by Kaszuba, Stewart, and Bateman without any additional field work or checking, thus it lacks metamorphic isograds, detailed petrologic interpretations, and structure cross-sections.

Kaszuba and Simpson (1989), conducted a detailed petrologic and structural investigation (but with little emphasis on lithostratigraphy) of the Passagassawakeag and Bucksport terranes just northeast of the present study area (Figure 1.5) entitled “Polyphase deformation in the Penobscot Bay area, coastal Maine.” They recognized that the two terranes shared four phases of ductile deformation and therefore must have been joined early in the tectonic history of the area. However, they were not able to establish the nature of the boundary between the two terranes, noting that they could find no structural or metamorphic gradient which coincided with it, and concluded that their study did not prove or disprove the existence of a premetamorphic thrust fault at that boundary. The ambiguity of their results is probably due to the local overprint by the contact aureole of the Lucerne pluton, and overprinting deformation associated with the Norumbega Fault Zone.

The Bedrock Geologic Map of Maine (Osberg et al., 1985) portrays the study area at 1:500,000 scale. It shows the boundary between the Passagassawakeag terrane and the Fredericton Trough terrane as a northwest-dipping thrust fault, and portrays the Passagassawakeag terrane as a klippe in structural cross-section. However, the Passagassawakeag rocks are correlated with the metavolcanic rocks of the Casco Bay Group and Ellsworth Formation to the east, and it is designated as having Avalonian affinity. This latter interpretation is now questioned by Osberg himself (Osberg et al., 1995; Stewart pers. com., 1998).

In the NEIGC 1995 field trip guide book, Stewart et al. (1995) show a simplified geologic map of the Penobscot Bay region and structural cross-sections based in part on vertical incidence seismic reflection lines. They show the Liberty-Orrington Fault dipping northwest at a steep angle (~50°) in cross-section, implying that they interpret the Passagassawakeag terrane as not a klippe or even a low-angle thrust sheet, but a tectonic ‘slice’ from the west (Stewart et al., 1995) (Figure 1.2b).

Finally, a paper presented at the 1998 Northeast GSA section meeting by Osberg et al. (1998) entitled “Acadian tectonics along coastal Maine and southern New Brunswick,” advocated the old idea that the geology of eastern Maine is organized into a series of thrust sheets, dismembered by younger faults. They refer to the Passagassawakeag terrane as the Liberty-Orrington klippe (Figure 1.2a), and correlate the sillimanite-grade rocks of this terrane with those of the chlorite-grade Miramichi anticlinorium of northeastern Maine and southern New Brunswick (Figure 1), and therefore they should belong to the Medial New England terrane (Laurentia). Oddly, Osberg et al. (1998) maintain that the Passagassawakeag terrane was transported from the southeast (present coordinates) within the interval 422-418 Ma, even though its proposed source terrane is to the northwest of its present location, across a major tectonic boundary (Norumbega Fault Zone).

Format of this study

In this thesis, I present evidence for the existence of the Liberty-Orrington Fault and the subsequent nature of the Passagassawakeag/Fredericton Trough terrane boundary by first describing in Chapter 2 the lithologies present in each terrane, and in Chapter 3, the newly identified fine-grained and mica-fish mylonites of what is herein referred to as the Liberty-Orrington shear zone. Sense-of-shear indicators within and outside of the Liberty-Orrington shear zone are discussed, and cross-cutting relationships between structural and metamorphic fabrics are documented for later discussion.

Chapter 4 is a discussion of the timing of mylonitization and concomitant exhumation of the Passagassawakeag terrane as determined by cross-cutting relationships (detailed in Chapters 2 & 3), in conjunction with qualitative P-T and T-t paths derived from petrographic analysis. The orientation of the stress field responsible for the creation of the macro and microscopic structures found in the field area is also discussed on both local and regional scales in an attempt to show that dextral shear was maintained long enough during the early Devonian in coastal Maine to create and eventually overturn the transpressional thrust that truncates the northeastern end of the Passagassawakeag terrane on the eastern side of the field area. Chapter 5 is a discussion and evaluation of the possible tectonic models that could explain the geology and tectonic evolution of the Bucksport-Orland and surrounding areas. In accordance with the new field evidence presented in this thesis, a model of prolonged dextral shearing in a transpressional orogen is suggested to explain the juxtaposition of the Passagassawakeag and Fredericton Trough terranes. While the idea of transpressional tectonics and major dextral faulting in coastal Maine is not new, this study documents major dextral strike-slip movement during the Devonian, so that the Liberty-Orrington shear zone may represent a part of a continuum of Acadian transpression from the Silurian to the Carboniferous.

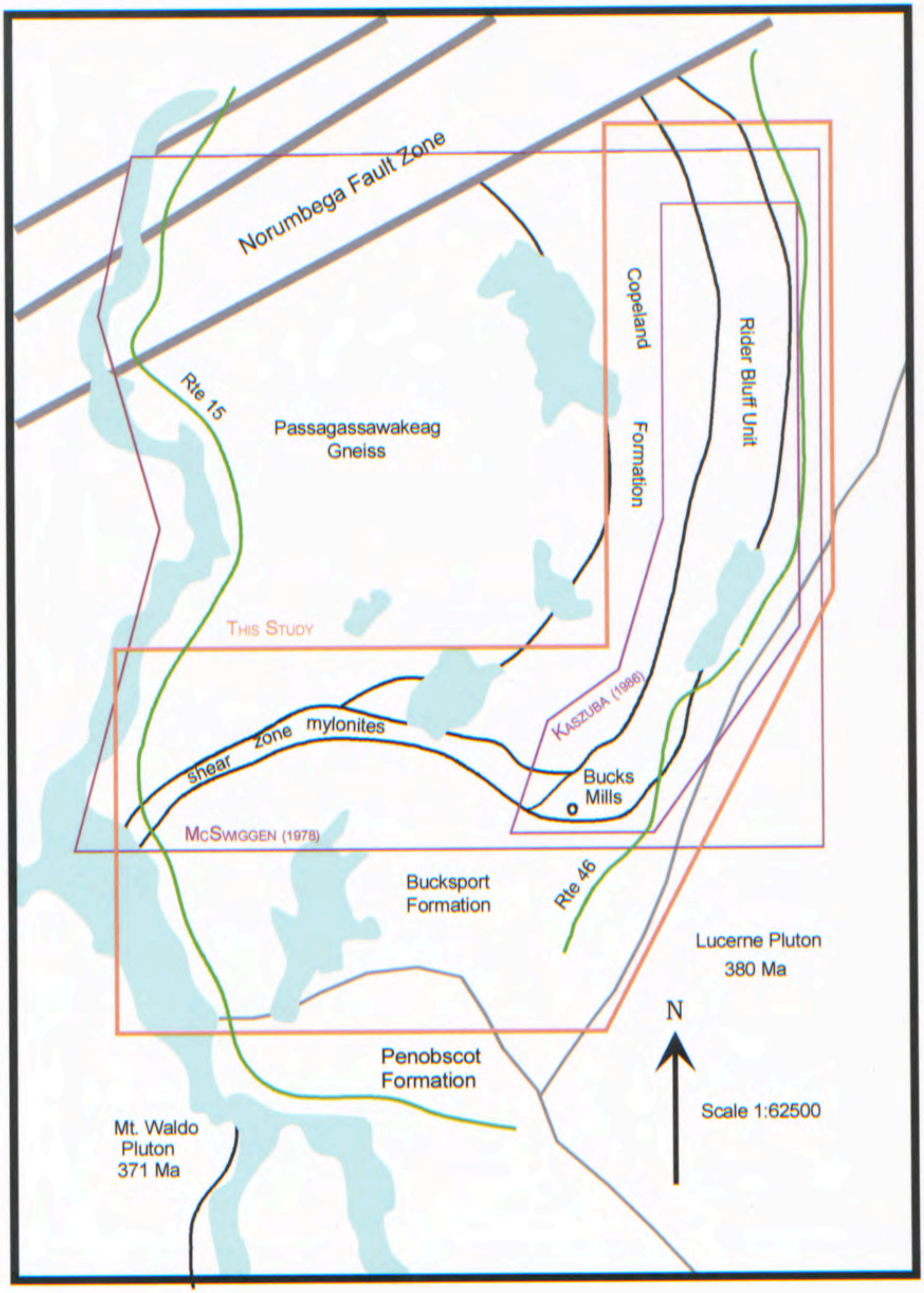
CHAPTER 2

LITHOLOGIES

Passagassawakeag terrane

This terrane consists of the sillimanite-bearing Passagassawakeag gneiss, the Copeland Formation (schist & quartzite), and the Rider Bluff member of the Copeland (formerly an independent unit), all of early Paleozoic age (Figure 2.0). Isotopic ages for these units are not recent and have large error margins, but for the most part the terrane is considered to be Precambrian to Ordovician in age. This estimate is based on Late Silurian (time scale of Harland et al., 1990) or Early Devonian (time scale of Tucker et al., 1998) ages for intraformation migmatites (412± 14 Ma, Winterport Granite; 412± 16 Ma, Stricklen Ridge Granite; Zartman and Gallego, 1979), and the high metamorphic grade of the Passagassawakeag Gneiss (Stewart et al., 1995). This study is primarily concerned with the Passagassawakeag gneiss and the Rider Bluff, as they are the units in contact with the surrounding turbidites of the Bucksport Formation. Discussion of the Copeland Formation and the Rider Bluff member is restricted to outcrops in the eastern portion of the study area, as this is where type sections of the lithologies occur. Both formations are discussed in the context of the Liberty-Orrington shear zone in the section of this chapter labeled as such.

Figure 2.0 - Location map of this study area and previous studies



Passagassawakeag Formation

The Passagassawakeag Formation is a complexly folded quartz-feldspar-biotite-sillimanite-garnet gneiss with a minor volume of moderately continuous calc-silicate layers consisting of diopside-hornblende-plagioclase and pyrophyllite. In the study area, it most often crops out as a grey, pelite-rich layered gneiss with intrusions of the migmatitic Stricklen Ridge garnet-bearing leucogranite and/or small dikes of the Mt. Waldo Pluton (Figure 2.1a). Where the pelitic variety occurs with bands of the calc-silicate lithology, the formation is distinguished by differential weathering causing the calc-silicate layers to form small ridges in outcrop. Grain size varies within and between outcrops from very fine in strained calc-silicate layers to 2-7cm diameter plagioclase porphyroclasts in what I call the ‘popcorn’ augen gneiss (Figure 2.1b). The abundance of the migmatite intrusions increases to the north and east so that the top of Jacob Buck Mountain is almost entirely granite. The gneiss and granite are also cut by pegmatite dikes, and in some places by small, tourmaline-bearing aplite dikes. It is important to note that the gneiss is characterized by at least two distinct lithologies: a medium to coarse-grained pelitic unit with gneissic layering generally defined by alternating plagioclase + quartz and biotite + hornblende layers, and a fine-grained calc-silicate unit of plagioclase + quartz + hornblende + biotite.

The Passagassawakeag has been correlated on the basis of metamorphic grade or approximate age with several different units of southeastern Maine, and its correlation is still under dispute. Hussey (1988) correlates it and the Copeland Formation (Hogback Schist of older literature) with the Cape Elizabeth Formation of the Casco Bay area near Portland, which consists of a thin to medium layered quartz-plagioclase-biotite-muscovite

Figure 2.1 - a) Passagassawakeag gneiss-pelitic lithology. b) Augen gneiss lithology.

a)

b)

schist or phyllite with some local sillimanite, staurolite, garnet, and andalusite, and discontinuous layers of chloritized amphibolite. In the same paper, it is also suggested that the rocks of the Passagassawakeag terrane could be correlated with the Cushing Formation which consists of high metamorphic grade metavolcanic and volcanic sedimentary rocks that underlie the Cape Elizabeth Formation in the Casco Bay area. Obviously, the relationship between the Cushing and Cape Elizabeth formations is unclear, and Rb-Sr metamorphic cooling ages for the two formations (494± 25 Ma & 481± 40 Ma for the Cushing, 485± 30 Ma for the Cape Elizabeth; Hussey, 1988) do not offer much help. Regardless, these rocks are thought to be of Avalonian affinity, and both correlations support the status quo hypothesis that the Passagassawakeag rocks are a klippe from the east.

Other workers correlate the Passagassawakeag Formation with slightly younger, Cambrian metasediments of the Miramichi anticlinorium (Figure 1) of northeastern Maine and southwestern New Brunswick on the basis of lithologic similarities, placing it in the Medial New England terrane, which is suggested to represent a terrane at the eastern edge of North America in Silurian-Lower Devonian time, separated from Avalonia by a shrinking ocean (Osberg et al., 1998; Osberg et al, 1995). This correlation is placed in a context of the klippe-from-the-east hypothesis, although it is puzzling how rocks of older age and higher metamorphic grade than the ones they are correlated with (Miramichi) could be emplaced along a shallow-dipping thrust with no trace of the younger rocks that should have been on top. Alternatively, if one considers this correlation in the context of the Late Ordovician-Early Silurian Salinic orogen, it could be said that the Passagassawakeag rocks are the basement to the Miramichi rocks and that the Passagassawakeag terrane was emplaced along a steeply-dipping thrust fault from underneath the Medial New England rocks to the west (Stewart et al., 1995, Stewart, pers. com., 1998).

On an orogen-scale, the Passagassawakeag terrane (Casco Bay Belt of Hussey, 1988; and Robinson et al., 1998), has been correlated with high-grade gneisses of southern New England such as the Massabesic gneiss of southeastern New Hampshire and the Putnam-Nashoba terrane of eastern Massachusetts and Connecticut (Figure 1) (Zen, 1983; Keppie, 1989; Rankin, 1994). The Passagassawakeag terrane has also been correlated on the basis of similar age and lithology with gneisses of the Gander zone (terrane) of Newfoundland along strike to the northeast (Rankin, 1994).

Structures

Quartz ribbons, isoclinal folds, and sigmoidal feldspar porphyroclasts are abundant and a dextral sense of shear is commonly found at the outcrop scale. Foliation is most often vertical with a strike of 040 to 070 (Figure B-2; Table A-3), which is consistent with the general regional trend. The gneiss lacks well-developed microstructures other than gneissic layering, with only weak S-C foliation present in rocks near the trace of the Liberty-Orrington fault. Quartz occurs as a matrix mineral and in ribbons and veins where it has irregular grain boundaries, displays undulose extinction, and is dynamically recrystallized. Some deformation bands were also observed. Samples adjacent to the Liberty-Orrington terrane boundary have late fractures through the quartz approximately perpendicular to gneissic layering and that offset other phases. Biotite often displays markedly different properties in the same sample, with a fine-grained, subhedral, brownish-red to pale green pleochroic variety defining foliation and an orangy-red, anhedral biotite phase oriented approximately 30° to the north of the foliation defining a probable S-foliation. Hornblende also defines the gneissic layering in the C-foliation, and inclusions of quartz in slightly larger grains preserve the older S foliation, indicating dextral sense of shear.

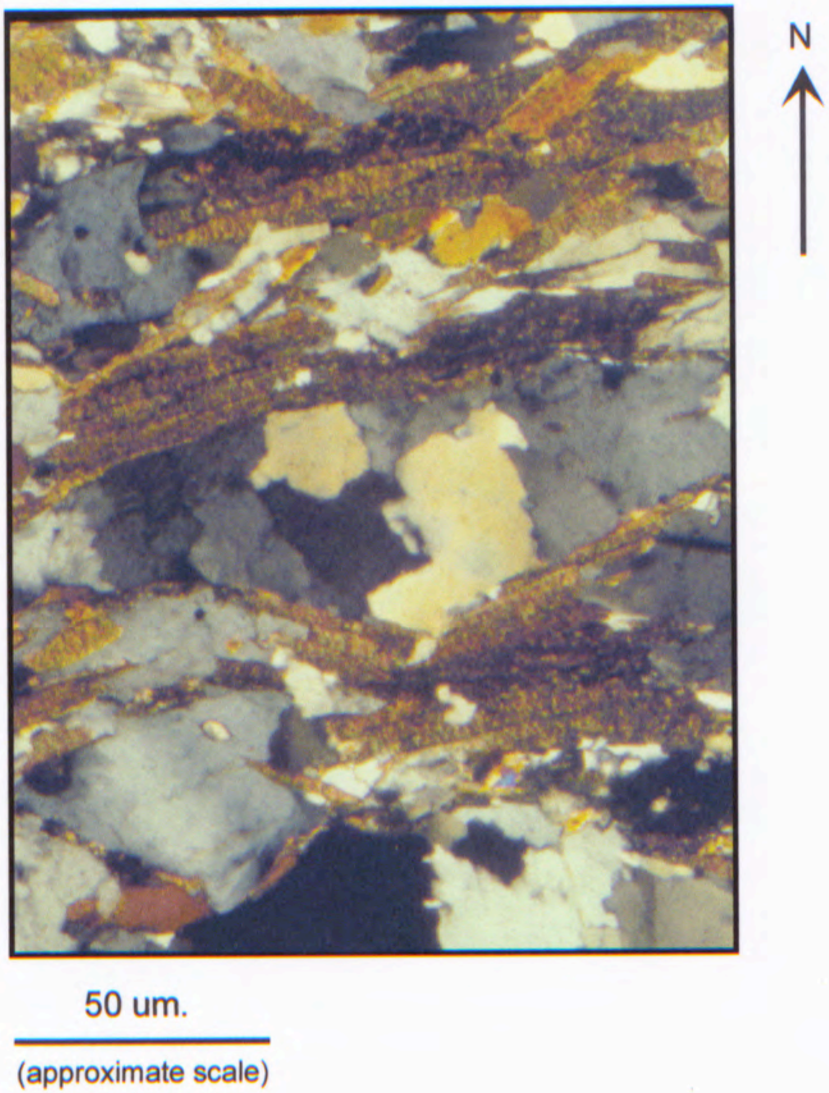
Stretching lineations are difficult to find in outcrop due to the steep dip of foliation (in mostly pavement outcrops) and annealed minerals common to this formation near the terrane boundary between the Passagassawakeag gneiss and the Bucksport turbidites. Lineations here are near-horizontal, and become steeper away from the boundary as the dip of the foliation in the gneiss shallows. Near-horizontal attitudes of the foliation (gneissic layering) occur even further away from the Liberty-Orrington boundary, along Rte. 15 and the Penobscot river to the west. Isoclinal folds of quartz layers and ribbons have trends and plunges concordant with the strike and dip of foliation in outcrops away from the terrane boundary (Figure B-7; Table A-4), while z-folds are present in the gneiss adjacent to the boundary. Unfortunately, many of the good pavement exposures of the gneiss occur in areas underneath power lines that are used in the summer as commercial blueberry fields, and due to spring burning of the fields, the majority of the gneiss exposures were covered with soot, making detailed structural analysis impossible. Any map-scale structure within the gneiss defined by the orientations of the calc-silicate ‘units’ was not mapped during this project, as attention was paid to the nature of the boundary between the Passagassawakeag terrane and the Bucksport turbidites (see *Previous work*, Chapter 1).

Metamorphism

The Passagassawakeag Formation within the study area represents the northeastern terminus of high-grade metamorphism in New England (Figure 1.2) (Guidotti, 1989). It is assigned to the high-rank amphibolite facies on the Maine generalized map of regional metamorphic zones (Guidotti, 1985), and the sillimanite-orthoclase zone by Robinson et al. (1998). The Passagassawakeag is thought to be polymetamorphic due to its high grade, the presence of migmatites and multiple deformations. While the initial grade of metamorphism is not known, it is estimated to have undergone at least two periods of amphibolite facies metamorphism (West et al., 1995).

Although sillimanite was never observed in outcrop in the present study, it is present in several thin sections of the pelitic portion of the Passagassawakeag gneiss as fibrolitic inclusions in quartz and feldspar (Table A-1). Both pelitic and calc-silicate varieties of the gneiss display annealed grain boundaries, suggesting that the minerals were recrystallized after formation of the gneissic layering (Figure 2.2). Chlorite is not a major phase, and usually occurs in late, cross-cutting extensional fractures, demonstrating low-grade alteration. The presence of dark red-brown matrix biotites (defining the S-direction), and hematite and some allanite as accessory minerals implies a high Fe^{3+} content of the host rock, while the presence of calcic-amphibole (hornblende), sphene, and albite to anorthite plagioclase imply a high Ca content and a high degree of metamorphism. A later, less-Fe-rich biotite that defines the gneissic layering may represent a separate phase of metamorphism coincident with the deformation that produced the C-fabric.

Figure 2.2 - Passagassawakeag gneiss; photomicrograph; crossed polars, thin section cut parallel to lineation and perpendicular to foliation.



Copeland Formation

Along the eastern margin of the Passagassawakeag gneiss, the Copeland Formation crops out in an arcuate map pattern, trending roughly north-south (Figure 2.0). It consists of alternating layers of bluish-grey, coarse-grained muscovite schist and clean quartzite, with layers ranging from a few centimeters to several meters thick (Kaszuba, 1986). The schist consists mostly of muscovite, plagioclase, and quartz, with lesser amounts of biotite and calcic amphibole, and accessory amounts of garnet, epidote, sphene, and tourmaline. The quartzite is almost entirely white quartz, with accessory amounts of biotite and opaque minerals. The Copeland has undergone regional metamorphism to at least staurolite grade, and andalusite and sillimanite are present near intrusions of the Stricklen Ridge granite (Kaszuba, 1986). Local amphibolite lenses are probably boudins of a previously continuous metavolcanic unit. Nowhere in the present study area or the two previous study areas of McSwiggen (1978) and Kaszuba (1986), is the contact between the Copeland and the Passagassawakeag formations exposed, so their relationship remains speculative. Despite this, the relative age of the Copeland has been estimated to be Cambrian to Ordovician based on its high metamorphic grade, intrusion by the Silurian Stricklen Ridge granite, and correlation on the basis of similar lithology to early Paleozoic formations along strike to the southwest.

On the most recent map of the northern Penobscot Bay area by Wones (1991), the Copeland Formation also occurs in fault-bounded slices along the Norumbega Fault Zone, to the northwest of the present study area. On the same map, it is interpreted to mantle the gneiss along the eastern margin of the Passagassawakeag terrane beginning in the north at the Norumbega Fault Zone and continuing south where it pinches-out just southwest of Jacob Buck Pond (Wones, 1991; Kaszuba, 1986). Excluding the Rider Bluff member (formerly the Rider Bluff Formation), its map width ranges from 7 km in the north to an average of 4km near Long Pond, whereas it is portrayed as a thin smear of at most 2 km width along the eastern terminus of the Liberty-Orrington Fault on the Bedrock Geologic Map of Maine (Osberg et al., 1985). An unpublished Master's thesis by McSwiggen (1978), in which the Passagassawakeag Formation was mapped in detail as the 'Liberty-Orrington Antiform,' (Figure 2.0) shows the Copeland wrapping around the nose of this antiform, with its southern limb forming the southern boundary with the Vassalboro Fm. (now Bucksport), which he interpreted as an unconformity even though "locally the formation is finer grained, not layered, and not as schistose, particularly along the southern limb of the antiform." McSwiggen (1978) also distinguished a 'basal member' of the Copeland Formation which he named the South Orrington Member, consisting of a fine-grained quartz-plagioclase-biotite granulite (probably a gneiss) with abundant concordant quartz veins and rods, that occurs on the northern 'limb' of the 'antiform' and pinches-out near the nose. However, examples of the same general lithology and textural relationships occur near the southern boundary of the Passagassawakeag terrane in outcrops of the gneiss, and subsequent workers (Wones, 1991; Kaszuba, 1986) mapped this lithology as undifferentiated Passagassawakeag gneiss. Considering also that McSwiggen's (1978) type locality of the South Orrington member actually occurs very close to a splay of the Norumbega Fault Zone, it is most likely that this unit is simply a high-strained, and possibly hornfelsed version of the Passagassawakeag gneiss.

The Copeland Formation has been correlated on the basis of similar lithology with the Hogback Schist, the Ordovician Appleton Ridge Formation, and the Late Precambrian to Ordovician Cape Elizabeth Formation (described above) of the Casco Bay area near Portland, Maine. According to the Bedrock Geologic Map of Maine, it crops out to a much greater extent along the Norumbega Fault Zone to the southwest and is bounded on the east by a thrust fault (Osberg et al., 1985). The contact between the Copeland and the Passagassawakeag formations is not exposed in the eastern portion of the study area, but it may occur within the mylonites that define the Liberty-Orrington shear zone in the southern part of the study area, to the west of Jacob Buck Mountain.

Structures

Type exposures of the Copeland do not occur within the southern part of the study area, but to the east along Rte. 46 it bears a well-developed schistosity that is cut by open folds and a discontinuous crenulation cleavage. Compositional layering here consists of 1cm-20cm thick quartzite layers alternating with 1cm-40cm thick greenish-blue pelitic schist. Only very thin quartzite layers are affected by the crenulation, which trends generally northwest. Primary schistosity is difficult to measure due to the outcrop-scale open folds, but an attitude taken on a quartzite bed in the nose of one fold is 290, 80SW. Stretching lineations in quartzite of the same layer trend 320 and plunge 30SE, and are probably due to slip between the compositional layers during folding (Table A-3). The trends of the major fold axes range from 010 to 335, and plunge very steeply to the north. Crenulation appears to have occurred prior to folding, as the trend of the second foliation changes along the folds (~348 in nose, 013 to 030 on western limbs, 000 in the far west; a cleavage fan).

Further north, crenulation is absent from the Copeland, and the schist and quartz veins are multiply folded with quartz rods and late fractures along the axes of the folds. In some outcrops, quartz-filled fractures have been deformed to a sigmoidal shape indicating dextral shear, while the axial planes of small tight folds trend 020, and plunge 60SW (Table A-4). Late brittle fractures trend 033 and cut both foliation and folds, with a small dextral displacement (Table A-5). One pavement outcrop along Rte. 46 displays ductile folding involving both the quartzite and schist layers with large Z and small S-folds, large feldspar augen, and a small aplite intrusion, also involved in the folding. Sinistral and dextral movement both appear to be involved here, but the relationship between the two is not certain. It is germane to note that nowhere along the eastern portion of the field area and terrane boundary were quartz ribbons, boudins, or other microstructures typical of the high-strain rocks of the southern boundary observed in the Copeland unit.

Metamorphism

The Copeland Formation is of a similar metamorphic grade as the Passagassawakeag gneiss, although nowhere does it display gneissic layering, and the source of the Stricklen Ridge migmatite is thought to be the Passagassawakeag, even though it intrudes the Copeland as well. Outcrops along the eastern terrane boundary are usually very fine-grained and green to dark blue-grey in color. No large porphyroblasts were observed in the outcrops surveyed during this study, but Kaszuba (1986) reports euhedral to subhedral garnet porphyroblasts up to several millimeters in diameter that overgrow primary foliation, and sometimes contain an internal foliation subparallel to it. This observation is in agreement with the thin section petrography of samples of the

Copeland from the eastern terrane boundary of the present study. Elongate garnets in pelitic layers are actually composed of a mass of tiny euhedral garnets that have coalesced into a linear shape and apparently represent primary textures (Kaszuba, 1986). Staurolite ghosts, replaced by sericite and fibrolitic sillimanite, were observed in one thin section, and Kaszuba (1986) reported staurolite mantled by optically continuous andalusite, with both phases mantled by mats of fibrolitic sillimanite. Sillimanite is more common near intrusions of the Stricklen Ridge (Kaszuba, 1986), suggesting that the metamorphic event that produced sillimanite grade in the Copeland was related to the formation of the migmatite, and perhaps a relatively static event.

Rider Bluff

The Rider Bluff member of the Copeland Formation was first described as such by Stewart and Wones (1974) on the basis of lithologic similarities, and mostly occurs as a green, finely-laminated metapelite. It crops out in an arcuate ≤ 2 km wide belt, on the eastern side of the Copeland Formation from just south of the Norumbega Fault Zone south, to where the Liberty-Orrington shear zone turns sharply to the west (Figure 2.0). It is unique in that it, and/or a correlative formation, is not known to occur anywhere else in Maine, and its origin is speculative. At its type locality on the top of Rider Bluff, it is fine-grained, finely-laminated with consistent 2 mm-wide alternating laminae of quartz + plagioclase and biotite + garnet + magnetite, which have previously been interpreted to possibly represent bedding (Kaszuba and Simpson, 1989; Stewart, pers. com., 1998) (Figure 2.3). Kaszuba and Wones (1985) interpreted the Rider Bluff as ductily deformed Copeland Formation, but later concluded that the two units are lithologically distinct even though deformed Rider Bluff is almost indistinguishable from deformed Copeland

Formation (Kaszuba, 1986). The basis for this distinction is not detailed by Kaszuba (1986), or subsequent workers, and nowhere in the study area is the contact between the two units exposed.

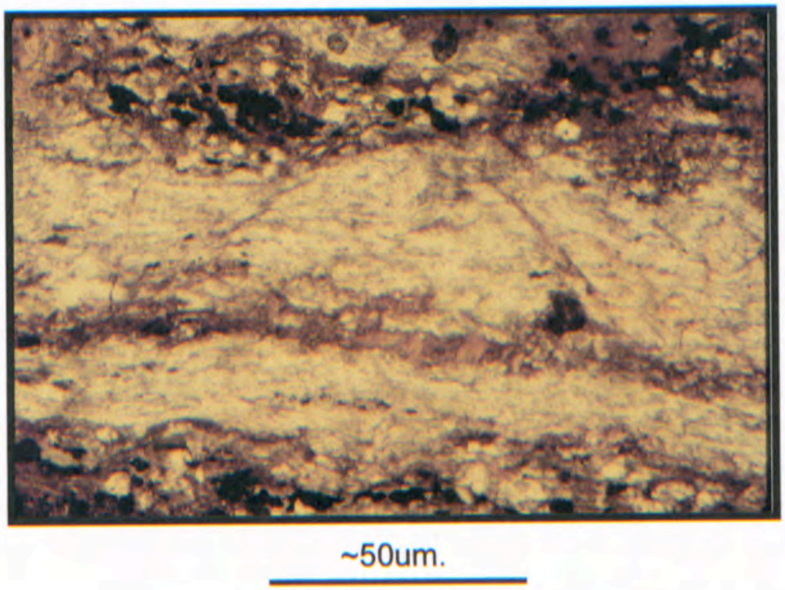
Structures

In outcrop, the Rider Bluff always displays the above described very fine compositional lamination of light and dark minerals, and is folded in small to moderate sized open folds with axes trending fairly consistently 060, plunging ~50E. At the top of Rider Bluff, a stretching lineation perpendicular to the strike of foliation (lamination) is strong, with quartz rods and late fractures occurring along the axes of folds (Table A-4). Dip of foliation is consistently to the east, and strike in less-folded outcrops changes from slightly northwest in the north, to approximately due north in the central portion of its map pattern (north of Long Lake; Table A-3), to slightly northeast in the south, where it grades into the Liberty-Orrington shear zone (Wones, 1991).

Thin sections from the type locality at the top of Rider Bluff show that the quartz and plagioclase bands are fine to coarse-grained, extensively dynamically recrystallized with subgrain development, and display undulatory extinction and deformation bands oriented approximately perpendicular to compositional banding (Figure 2.4).

Figure 2.3 - Hand sample of Rider Bluff unit showing quartzo-feldspathic and biotite-magnetite laminations. Sample was cut parallel to stretching lineation and perpendicular to foliation.

Figure 2.4 - Photomicrograph of the Rider Bluff unit showing compositional laminations (foliation), twinned biotite, and late C' foliation. Section cut parallel to lineation and perpendicular to foliation.



Biotites are arranged in two main orientations, one with the C-axis perpendicular to lineation so that only basal sections are seen in the thin section, and the other with the C-axis parallel to lineation. The perpendicular biotites display deep red-brown to orange pleochroism, are sometimes twinned, and large, almost poikilitic, with abundant inclusions of quartz, zircon, and opaques. The opaque inclusions are grouped such that the biotites have an anastomosing striped appearance (~60° to compositional banding) and display undulose extinction, suggesting that these biotites grew or recrystallized during deformation (Figure 2.4). Biotites with C-axis parallel to foliation/compositional layering seem to grow around and fill in space between the orange biotites, are subhedral, small, and display very strong pale beige green to dark brown pleochroism (=Mg-rich). They also display typical bird's-eye extinction with high-order interference colors, and contain ilmenite inclusions perpendicular to compositional layering regardless of biotite orientation. Garnet porphyroclasts are small, fractured dodecahedrons within the biotite bands. Magnetite is more abundant in the biotite bands, but is also common to the quartz/plagioclase bands.

Because of the deformation evident in the biotite grains perpendicular to lineation (parallel to foliation) and the recrystallization in the quartz/plagioclase bands, I suggest that the compositional lamination characteristic of the Rider Bluff defines a foliation and is therefore tectonic in origin. This foliation is cut by chlorite-filled extensional shear bands (C') indicating a thrust sense of shear (in present orientation, Bucksport over Passagassawakeag). In some areas, there appears to be an older, gneiss-over-Bucksport C' foliation defined by a sharp alignment of micas and fine-grained quartz. Although these two C' fabrics do not clearly intersect, the former type is dominant and chloritized, and therefore presumed to be younger. Further discussion of the structure and significance of this unit is continued in the section on the Liberty-Orrington shear zone later in this chapter.

Metamorphism

Garnet porphyroblasts are the highest grade metamorphic mineral observed in the Rider Bluff unit, and appear to have regrown after foliation, as some are subhedral but have clearly been rotated. Some garnets are moderately replaced by chlorite. Considering that the formation this unit is assigned to achieves sillimanite grade very close to outcrops of garnet-grade Rider Bluff, it seems unwise to assume that the two lithologies experienced the same amount and/or type of deformation and metamorphism. Given the petrographic relationships between the phases described above, the most likely sequence of events that created the type lithology of the Rider Bluff appear to be: 1) foliation of a pelitic parent rock defined by alternating compositional laminations in a Passagassawakeag -over-Bucksport sense, probably with biotite grade metamorphism; 2) metamorphism to garnet grade producing garnet and biotite porphyroblasts and growth of new, Mg-rich biotite (greenish), preserving a fabric defined by inclusions of opaque minerals parallel to lineation and perpendicular to foliation; 3) development of extensional shear bands in a Bucksport- over-Passagassawakeag sense, coincident (?) with a retrograde metamorphism that produced chlorite growth in the C’ direction and some replacement of garnet. Timing of these events with respect to the rest of the field area is discussed in more detail in Chapter 4.

The Fredericton Trough terrane

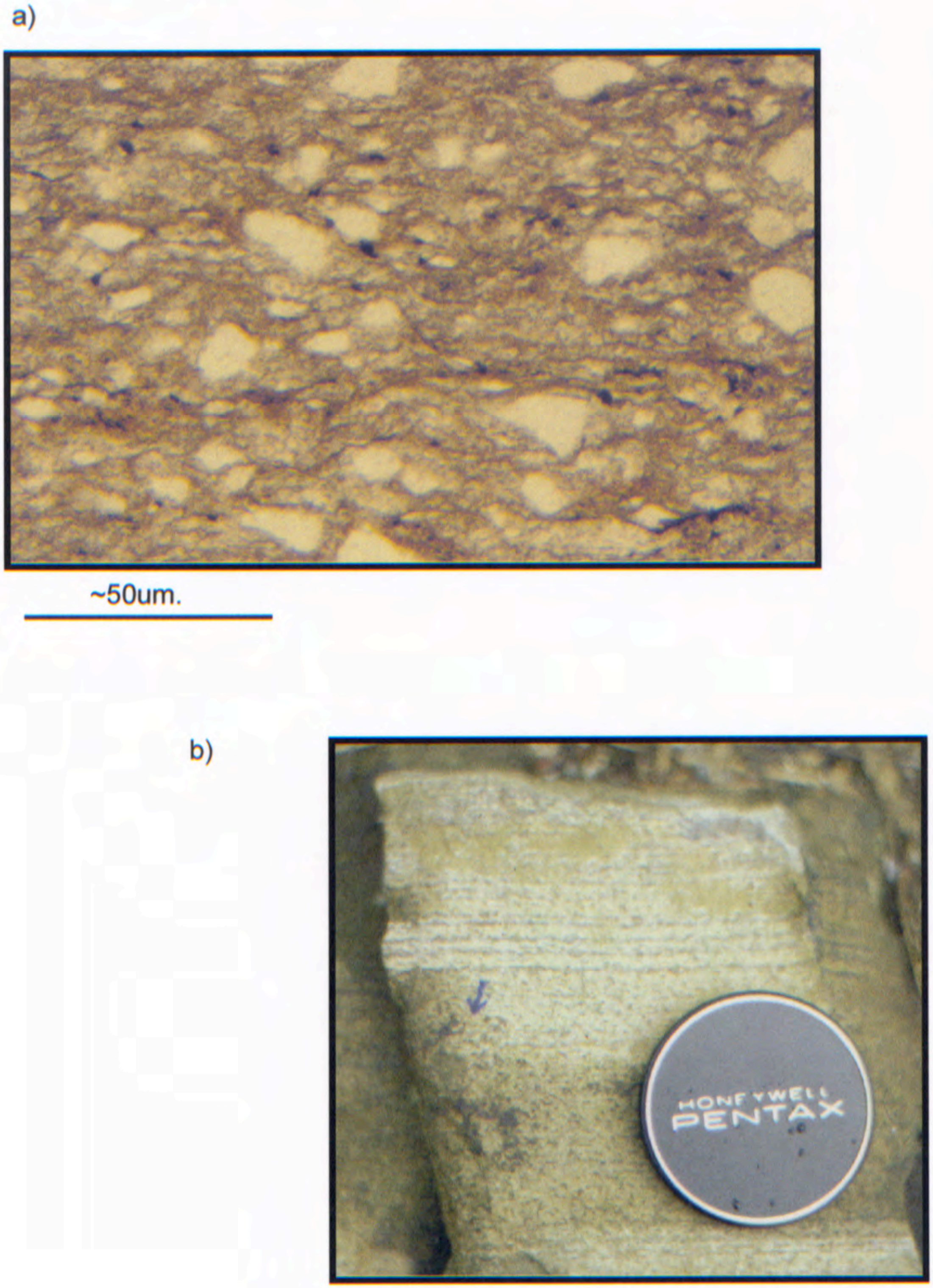
In the present field area, the Fredericton Trough terrane is represented by the metaturbidites of the Bucksport Formation (Figure 2.0). These turbidites were deposited in a basin between the Taconic modified margin of Laurentia and the composite Avalon terrane on what is believed to have been the last remaining oceanic crust in the area after the close of the Taconic orogen (Ludman et al., 1993). In northeastern Maine and New Brunswick, an estimated 3000m of calcareous quartzofeldspathic wackes and shales of the Kingsclear and Flume Ridge formations fill the trough, the former containing Wenlock-Ludlow graptolites (Robinson et al., 1998). Other formations within the trough are devoid of fossils, including the Bucksport Formation, but are cut by late Silurian and Devonian plutons, requiring an age of Silurian or older. The source of sediment in the Fredericton Trough in Maine is dominantly from the east, and it spreads westward and interfingers with turbidites of the Central Maine basin just south of the Miramichi uplift. Both basins have stratigraphies that can be generally characterized by a change from local heterogeneous sedimentation (sandstones and coarse conglomerates) to regional homogeneous sedimentation (quartzofeldspathic wackes), but defining an internal stratigraphy in the Fredericton Trough has proved difficult (Robinson et al., 1998; Ludman et al., 1993). The rocks that make up the Fredericton Trough have been regionally metamorphosed to greenschist facies within the study area and along strike to the northeast. Along strike to the southwest, the Bucksport Formation. and equivalents have undergone up to high rank amphibolite facies regional metamorphism, and have been contact metamorphosed (Guidotti, 1985). Structures common to this terrane are isoclinal folds with a penetrative axial-plane cleavage (Table A-4), and the turbidites are almost everywhere in fault contact with adjacent terranes (Bradley et al., 1998).

Bucksport Formation

As part of the youngest and least deformed terrane in coastal Maine, the Bucksport Formation within the study area consists of calcareous siltstones and pelites metamorphosed to greenschist facies, and contact metamorphosed by the intrusion of the Devonian Mt. Waldo Pluton. It crops out in the far southern and eastern portions of the study area where it is in contact with the Passagassawakeag and the Rider Bluff member of the Copeland formations (Figure 2.0). It is typically characterized by greenish-grey layers of pelite and siltstone 1-10cm thick containing fine-grained quartz, muscovite, biotite, plagioclase, and calcite, with minor amounts of ilmenite, tourmaline, hematite, zircon, and apatite dispersed throughout (Table A-1). In the least-deformed, least-hornfelsed outcrops, the lithology consists of a very fine-grained micaceous matrix with larger clasts of quartz, plagioclase, and tourmaline, with calcite as a probable original cement (Figure 2.5a). In outcrops within the contact metamorphic aureole of the Mt. Waldo pluton, the lithology is characterized by a purple and green compositional layering defined by alternating quartz + large biotite and muscovite + hornblende + biotite layers.

The Bucksport Formation is lithologically similar to the Vassalboro Fm. of the Medial New England terrane and has in the past been correlated with it (McSwiggen, 1978; Osberg, 1980). It has also been correlated with the Late Silurian-Early Devonian Flume Ridge Formation (the youngest of the Fredericton Trough) of northeastern Maine on the basis of lithologic similarities (Kaszuba and Simpson, 1989). For reasons I have

Figure 2.5 - a) Photomicrograph of least-deformed Bucksport Formation (OC#84). Clasts are of plagioclase, matrix mostly micas and quartz. b) Field photo of hornfelsed Bucksport; blue arrow indicates North.

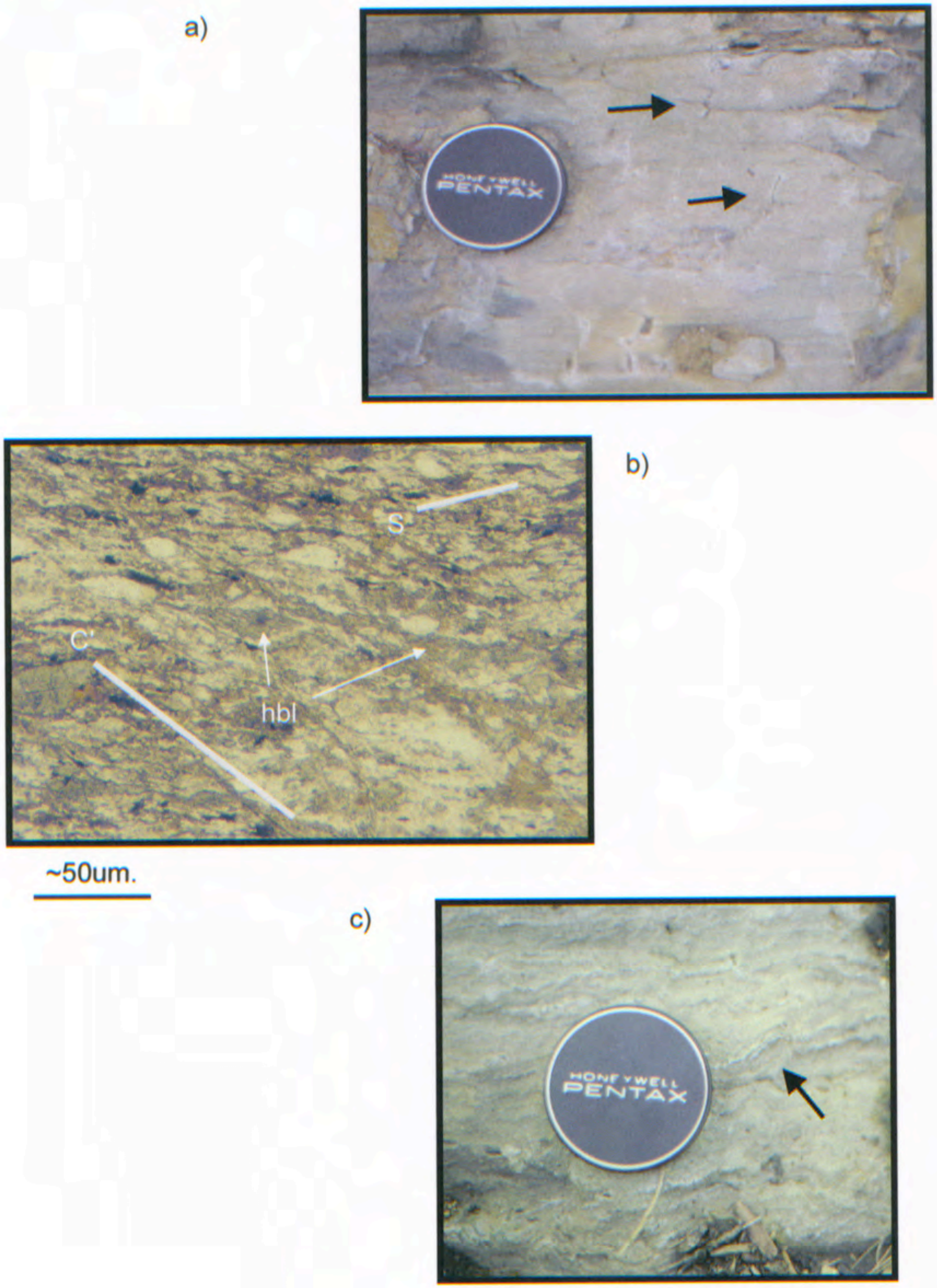


yet to understand, Hussey (1988) correlates the Bucksport with the Precambrian-Ordovician (?) Sebascodegan Formation, which is a biotite calc-silicate granofels that is stated by Hussey (1988) to conformably underlie the Cape Elizabeth Formation (correlated with the Passagassawakeag terrane) in the Casco Bay area. Hussey (1988) defends this correlation with the assertion that Bucksport-like rocks in the Boothbay Harbor area (midway from Penobscot to Casco Bay) are conformably overlain by the Cape Elizabeth Formation as well. Stewart (pers. com., 1988) disagrees with this correlation on the basis that differences in layering style between the Sebascodegan and the type-locality of the Bucksport are significant. Also problematic is that with this correlation, the greenschist-facies Bucksport would have to be older than the sillimanite grade Passagassawakeag gneiss in the study area, which calls for truly creative tectonic scenarios for coastal Maine.

Structures

The least deformed Bucksport Formation within the study area occurs on the eastern side of Silver Lake, just north of the village of Bucksport. It shows only slight foliation defined by small zones of preferentially oriented micas, with some elongate muscovite (Figure 2.5a). Northeast-trending, steeply plunging folds are common in outcrops at least 0.35 miles from the Liberty-Orrington fault, and an axial plane cleavage occurs with them(Table A-4; Figure B-7). Closer to the fault, particularly in the southern portion of the study area, the amount of deformation in the Bucksport increases. Foliation becomes stronger toward the Liberty-Orrington fault, manifested by compositional layering and a weak foliation trending ~25° to the northwest of layering, with some hornblende and/or quartz-filled fractures approximately perpendicular to foliation (Figure

Figure 2.6 - a) Bucksport Formation with hornblende-filled fractures nearly perpendicular to compositional layering (foliation). b) Photomicrograph of S-C' foliation in Bucksport. c) Field photo of folded hornblende-fractures.

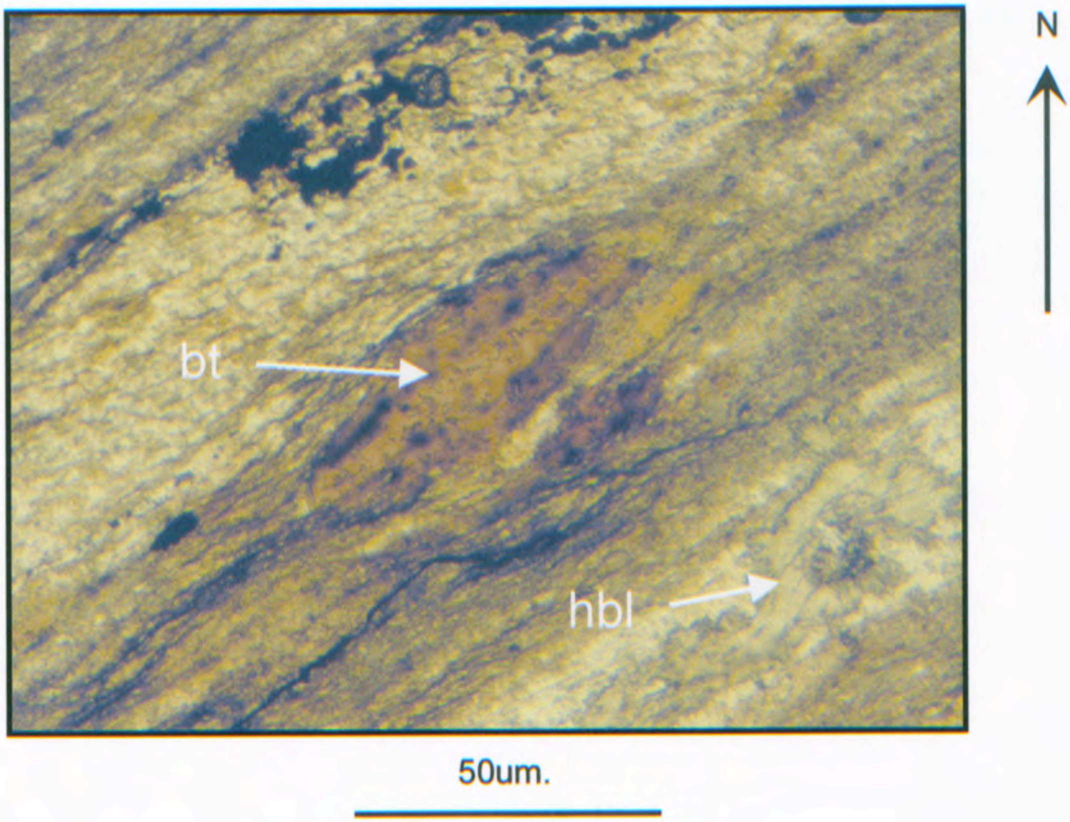


2.6a). Still closer to the Liberty-Orrington fault, the Bucksport shows S-C' foliation (C' is poorly developed) defined by micas and quartz (which displays undulose extinction) with late quartz or hornblende-filled fractures oriented in the S-direction (45-60° E of foliation) (Figure 2.6b). Finally, close to the contact with the Passagassawakeag terrane, the Bucksport is still distinguishable as such but is very strained, displaying an S-C' foliation that obliterates the compositional layering, sigmoidal-shaped biotite porphyroclasts, and boudined/on-lapped quartz ribbons, all indicating dextral shear. Some outcrops in close proximity to the Liberty-Orrington fault exhibit small and moderate-scale z-folds involving compositional layers, foliation, and hornblende -filled fractures (Figure 2.6c). More highly strained Bucksport is considered part of the Liberty-Orrington shear zone and is described in the section of this chapter on mylonites.

Metamorphism

Within the present study area, rocks considered by the author to be of true Bucksport lithology are regionally metamorphosed only up to chlorite or biotite grade, with much of the chlorite present as a secondary or disequilibrium feature (replacing biotite). Previous workers reported traces of garnet present in the Bucksport, although this was probably a fine-grained mylonite mistaken as Bucksport (McSwiggen, 1978). Along strike to the southwest on the other side of the Mt. Waldo pluton, the Bucksport Formation is of a much higher grade and its assignment to this formation is doubted by some (Stewart, pers. com., 1997). Within the contact metamorphic aureole of the Mt. Waldo pluton in the study area, the Bucksport Formation may be at epidote-amphibolite facies, as hornblende and calcic amphiboles are abundant and chlorite occurs only along late fractures and C' shear bands. Hematite always occurs with chlorite, suggesting a

Figure 2.7 - Photomicrograph of biotite porphyroblast in the Bucksport Formation. Note that biotite overgrows foliation.



retrograde replacement of biotite. Calcite is never observed within hornfelsed Bucksport, and amphiboles occur both in the matrix and as late radial bunches in qtz veins (Table A-1). In some samples outside of the hornfelsed area, biotite occurs both as small matrix grains and as larger, almost poikilitic basal-section porphyroblasts (?) that overgrow and preserve foliation (Figure 2.7).

The metamorphic grade of the Bucksport observed in this study does not directly conflict with the grade shown on the 1985 Generalized Map of Regional Metamorphic Zones (Bedrock Geologic Map of Maine; Osberg et al., 1985), where it is shown at greenschist facies. However, the map of 'Acadian' metamorphism in Robinson et al. (1998) shows the Bucksport Formation in the study area as belonging to the garnet zone; it is not clear whether this is attributed to regional or contact metamorphism, but in either case, the observed grade of the Bucksport by the present author does not warrant this assessment.

CHAPTER 3

THE LIBERTY-ORRINGTON SHEAR ZONE

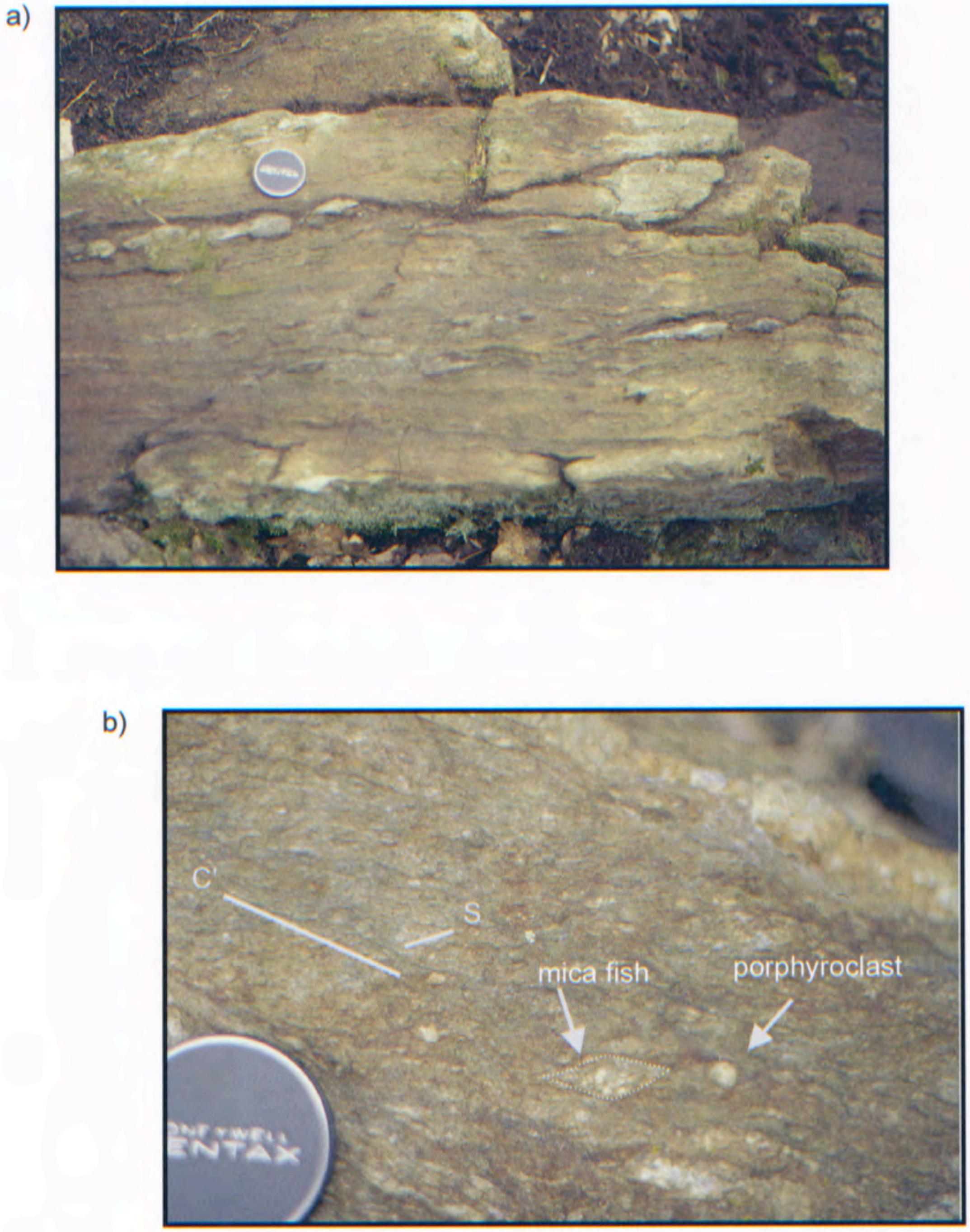
Within the southern portion of the study area, the trace of the Liberty-Orrington fault, previously thought to be a pre-metamorphic thrust, crops out as a continuous band of at least two distinct types of mylonites (mica-fish and fine-grained) between the Passagassawakeag terrane to the north and the Bucksport Formation to the south (Figure 1.4). The band of mylonites varies from 250 to 500m in width, and because of its extent and mappable lithologies is referred to in this document as the Liberty-Orrington shear zone (Plate 1). Within the study area, the shear zone extends from the east side of the Penobscot River near the Mt. Waldo pluton in an east-northeast direction to where the terrane boundary turns sharply north, near Bucks Mills (Figure 2.0). In this 'bend' area, the mylonite lithologies of the southern margin of the shear zone are replaced by mylonitized and highly-strained metapelites that exhibit both ductile and some brittle deformation. It is important to note that while I have grouped the mylonites of the southern boundary into two, generally recognizable map units, mylonites of either type do not necessarily have the same protolith, or vice versa. Along the eastern north-south trending trace of the Passagassawakeag/Bucksport terrane boundary, high-strain rocks are represented by the Rider Bluff unit, which I argue are mylonites that also largely record movement along a continuation of the Liberty-Orrington shear zone. Because of the lithologic and structural differences between the 'southern' and 'eastern' traces of the Passagassawakeag/ Bucksport terrane boundary, lithologies, structures, and metamorphic grade of the boundary rocks are described and discussed separately.

This significant area was last mapped more than twenty years ago, as part of a master's thesis (McSwiggen, 1978) (Figure 2.0), but more attention was paid to the structure of the Passagassawakeag gneiss, and the mylonites were not recognized as such and were interpreted as a strange part of the Copeland Formation. Since then, the presence of a fault separating the two terranes has become accepted, although no further field work apart from this study has been done to determine the nature of it. It is not known whether correlative mylonites exist on this boundary along strike to the southwest, although the late Silurian Lincoln Sill that intrudes the boundary in the vicinity of Liberty, Maine is strongly foliated with cracked and broken feldspar phenocrysts (Stewart, pers. com., 1999). This implies post-late Silurian shearing along the Passagassawakeag/ Bucksport boundary in at least one area outside of the present study area.

Mica-fish mylonites- southern boundary

A coarse-grained grey, and in places white micaceous mylonite occurs as a mappable unit within the Liberty-Orrington shear zone. In the field, it is generally characterized by an abundance of mica fish (foliation fish in a largely pelitic rock; hence the informal name), quartz ribbons and boudins, and small porphyroclasts of garnet and/or tourmaline (Figure 3.0). The mica fish lithology fairly consistently occurs on the north side of the shear zone, adjacent to the Passagassawakeag gneiss and Stricklen Ridge granite, although nowhere is a clear contact exposed. In the vicinity of Jacob Buck Mtn., the mica fish lithology occurs as sigmoidal-shaped lenses intertwined with fine-grained, grey mylonite (Figure 3.1).

Figure 3.0 - a) Typical outcrop of mica-fish mylonite showing foliation and large boudined quartz veins. b) Photo of mica-fish mylonite showing mica fish, S-C' foliation, and feldspar porphyroclasts.



Grey mica fish mylonites are most common and consist of mostly quartz, plagioclase, and muscovite with accessory amounts of chlorite, garnet, tourmaline, hematite, zircon, and opaques, and trace amounts of biotite and sillimanite (Table A-1). Quartz and plagioclase occur as very fine-grained, dynamically recrystallized matrix grains, boudined ribbons, and cross-cutting late veins. Muscovite is large and forms mica fish. Garnet is pale pink and forms small, oblong or broken porphyroclasts concordant with foliation or large subhedral porphyroclasts with abundant fractures, some torn apart. White mica fish mylonites have the same mineralogy listed above, but never contain biotite and have very few opaques.

Structures

Mylonitic foliation within the shear zone is consistently near-vertical, and stretching lineations are consistently near-horizontal (Figure B-3). Stretching lineations are defined by aligned tourmalines, which prove to be porphyroclasts in thin section, so the lineation seen in hand-sample is not an intersection or mineral lineation. The strike of foliation changes from ~050 in the west to ~070 on the west side of Jacob Buck Mtn., to ~330 on the east side of Jacob Buck Mtn., to 000-020 along the eastern boundary, implying that the map-scale folding occurred after movement along the shear zone had ceased (Plate 1). All coarse-grained mylonites have gorgeous muscovite mica fish, all showing dextral sense of shear (Figure 3.0). Most samples display a compositional segregation into quartzofeldspathic + pelitic domains, but it is not known if this texture represents an earlier foliation or not. Some samples also have plagioclase fish (mesoscopic and microscopic porphyroclasts), and quartz ribbons folded in z-folds. All show a well-developed S-C foliation (Figure 3.2) locally overprinted by a crenulation

Figure 3.1 - a) Field sketch of relationship between fine-grained and mica fish mylonites west of Jacob Buck Mtn. b) Close-up of outcrop #5d.

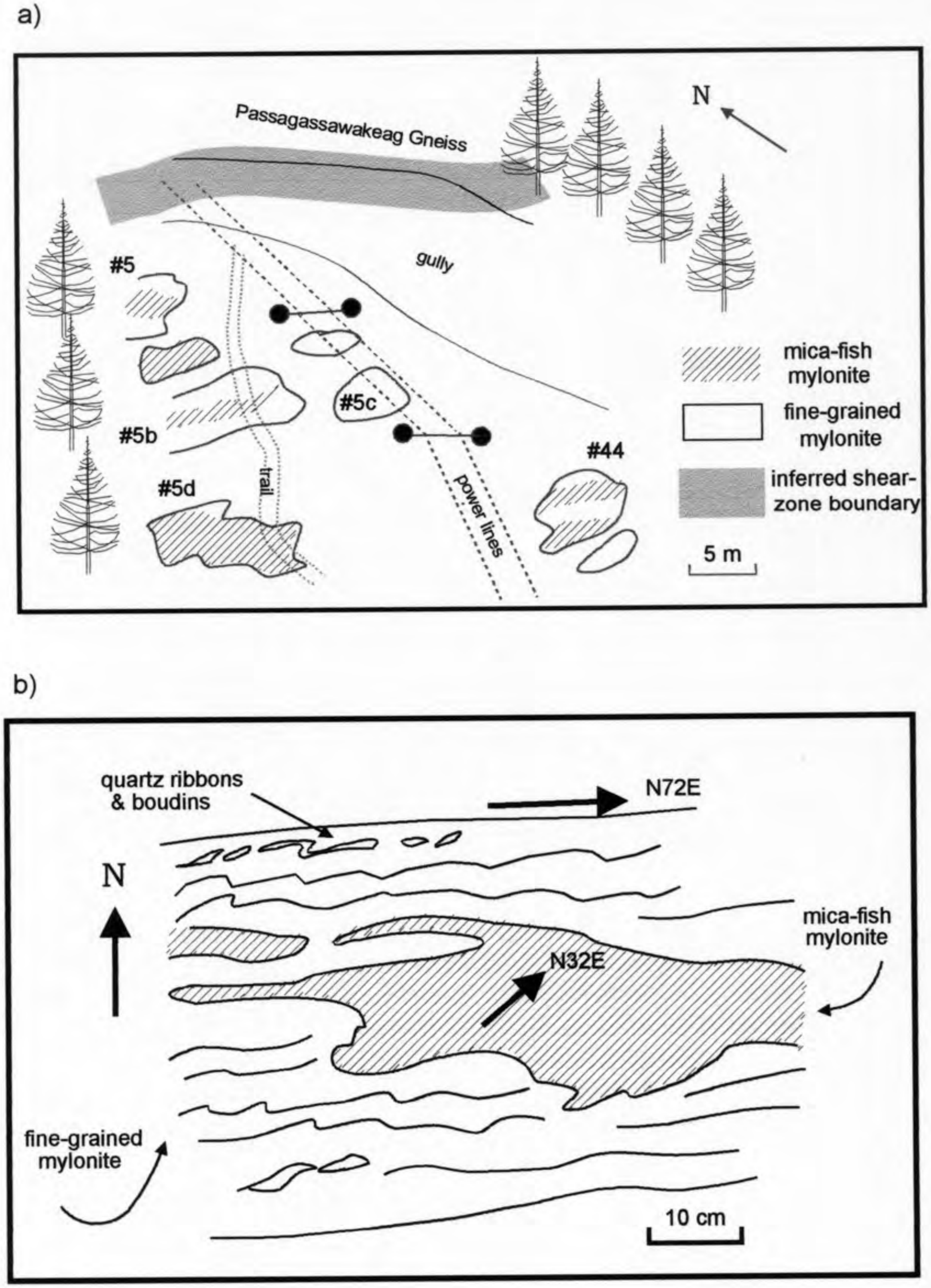
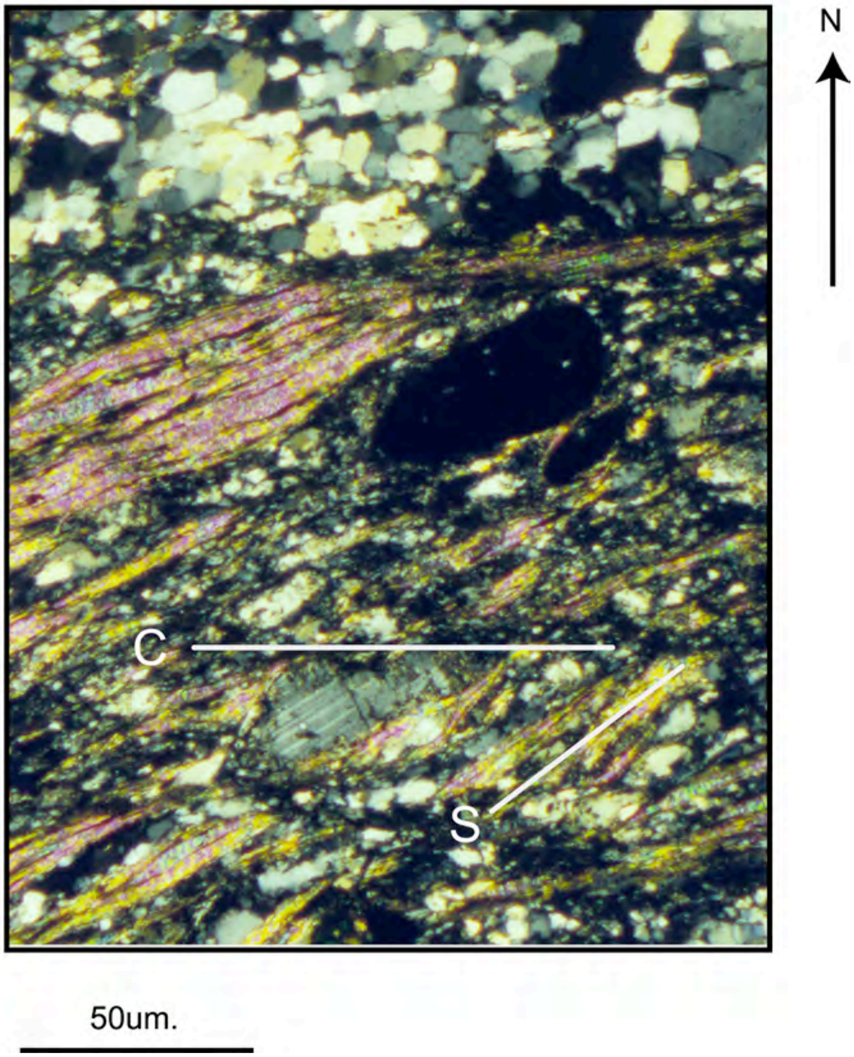


Figure 3.2 - S-C foliation in mica fish mylonite.Thin section cut parallel to lineation and perpendicular to foliation. Dextral sense of shear.



foliation, possibly due to local folding. Samples without crenulation present show a weak to strongly developed C' foliation defined by smaller micas (Table A-2). In all samples, quartz is dynamically recrystallized (Figure 3.3) with elongate grains oriented ~45° to the northeast of the main S-foliation, and rotated garnet porphyroclasts have recrystallized mica tails, all indicating dextral shear. One sample within the contact metamorphic aureole of the Mt. Waldo pluton (outcrop #55) has abundant euhedral tourmaline porphyroclasts (with detrital cores) oriented in two main directions. Crystals oriented with the c-axis perpendicular to lineation behaved as rotated porphyroclasts complete with mica tails, while crystals oriented with the c-axis parallel to lineation are lath-shaped, define the S-direction, and are often broken (Figure 3.4).

Metamorphism

Mylonitic rocks within the shear zone are categorized into two main groups: those within the contact metamorphic aureole of the Mt. Waldo pluton and those outside of it. Within the contact metamorphic zone, the highest prograde metamorphic mineral found is garnet, which occurs as small, elongate and broken clasts and as large, subhedral clasts. The elongate garnets are probably the result of tiny coalesced clumps of garnet that were later annealed along with the larger clasts during contact metamorphism (Figure 3.5). Chlorite appears to be a later, possibly retrograde phase, as it replaces muscovite in areas of stronger shear and grows in the shadows of rotated garnets. Cordierite (?) occurs as larger, bluish clasts with abundant inclusions and is altered to pinite around grain

Figure 3.3 - Dynamically recrystallized quartz in mylonite.

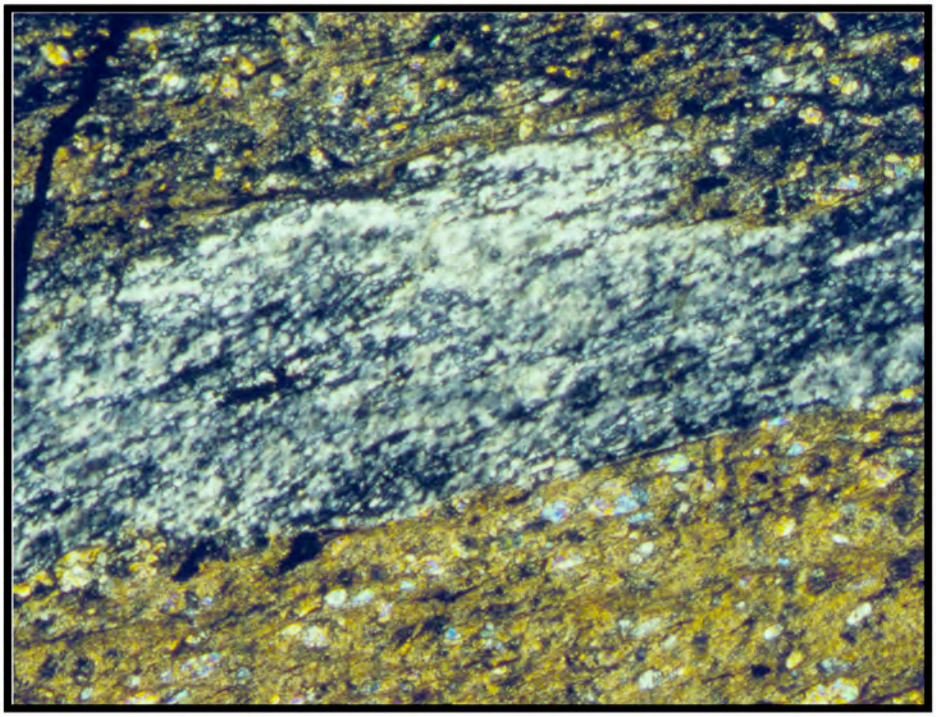


Figure 3.4 - Tourmaline porphyroclasts in mylonite.Dark green crystals have c-axis perpendicular to plane of view; light green = parallel with lineation & pov.

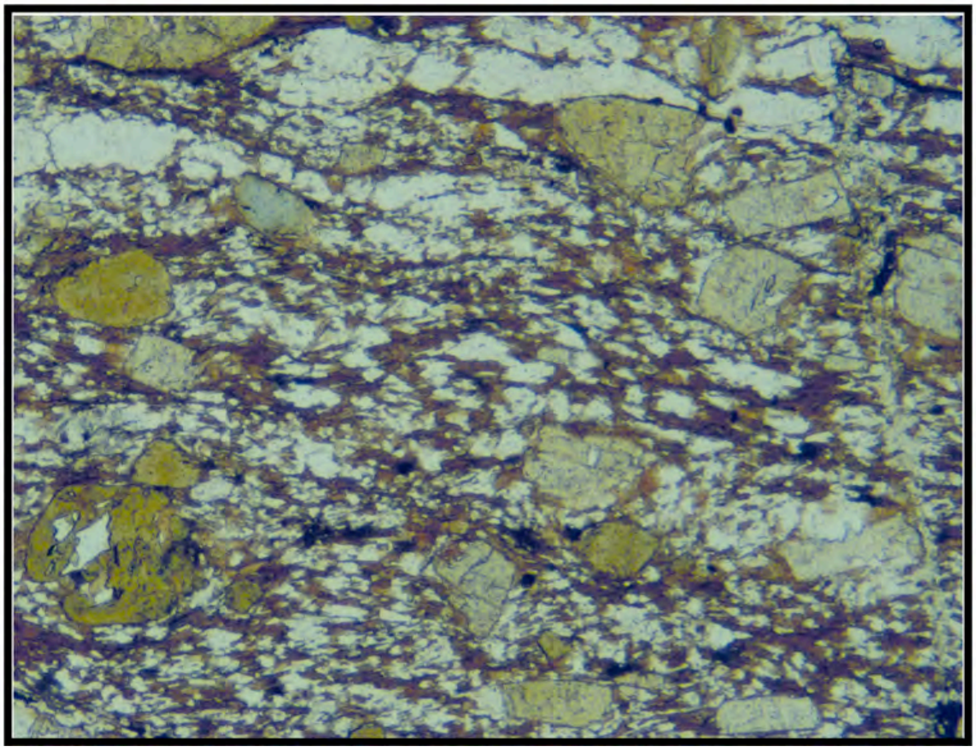
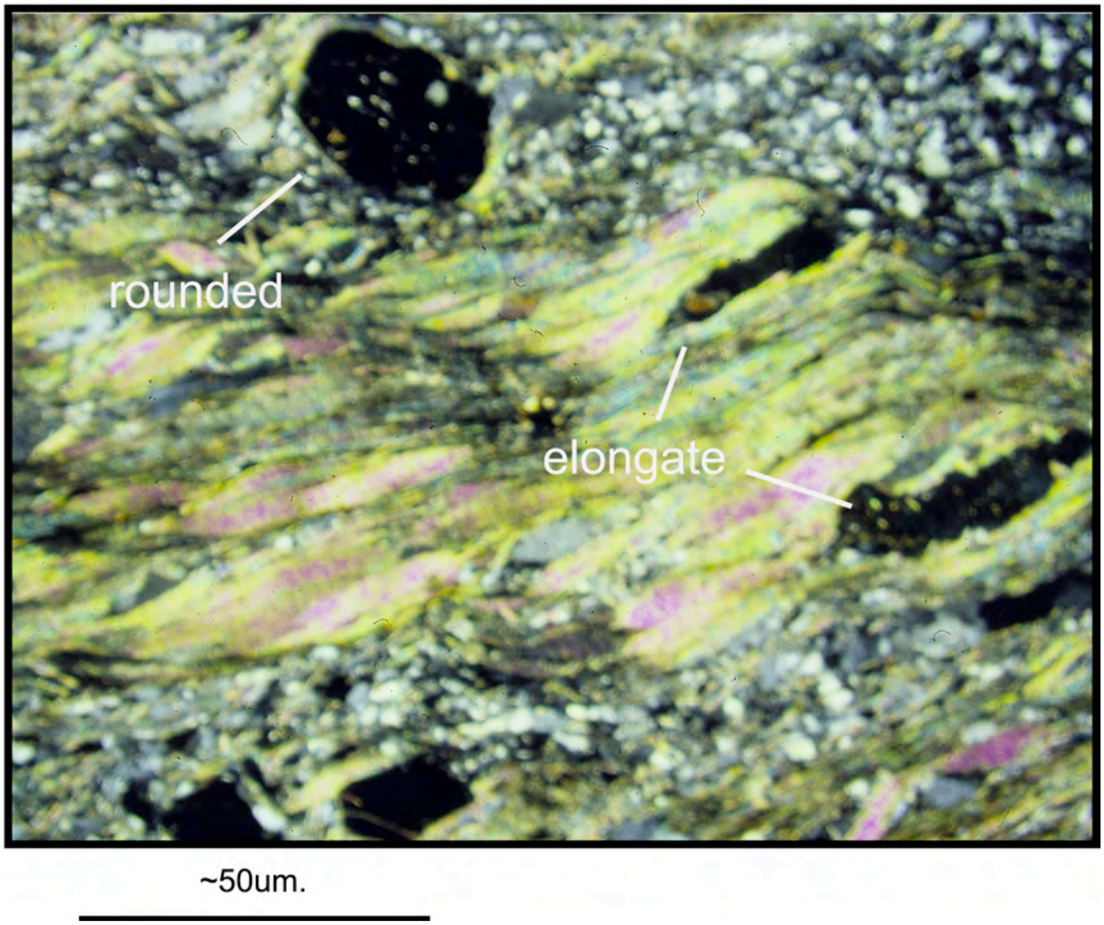


Figure 3.5 - Elongate and rounded garnets in a mica fish mylonite.



boundaries. In one sample (outcrop # 61), chlorite forms most of the matrix (probably replacing biotite) and is a strange deep yellow color in plain light (Table A-1). In the same sample, plagioclase clasts are highly altered to pyrophyllite, and possibly contain sphene.

The metamorphic mineral assemblage of rocks outside of the Mt. Waldo aureole is much the same as those within it with a few exceptions. Fibrolitic sillimanite occurs as mats of tiny prisms in the matrix where it is involved in foliation and as inclusions in quartz where it appears to overgrow foliation. Garnets are subhedral to anhedral and are almost always fractured and torn apart. Chlorite occurs as small blebs in the matrix, as fine recrystallized laths in S-oriented shear zones, and around garnets where it clearly represents a retrograde phase (Table A-1).

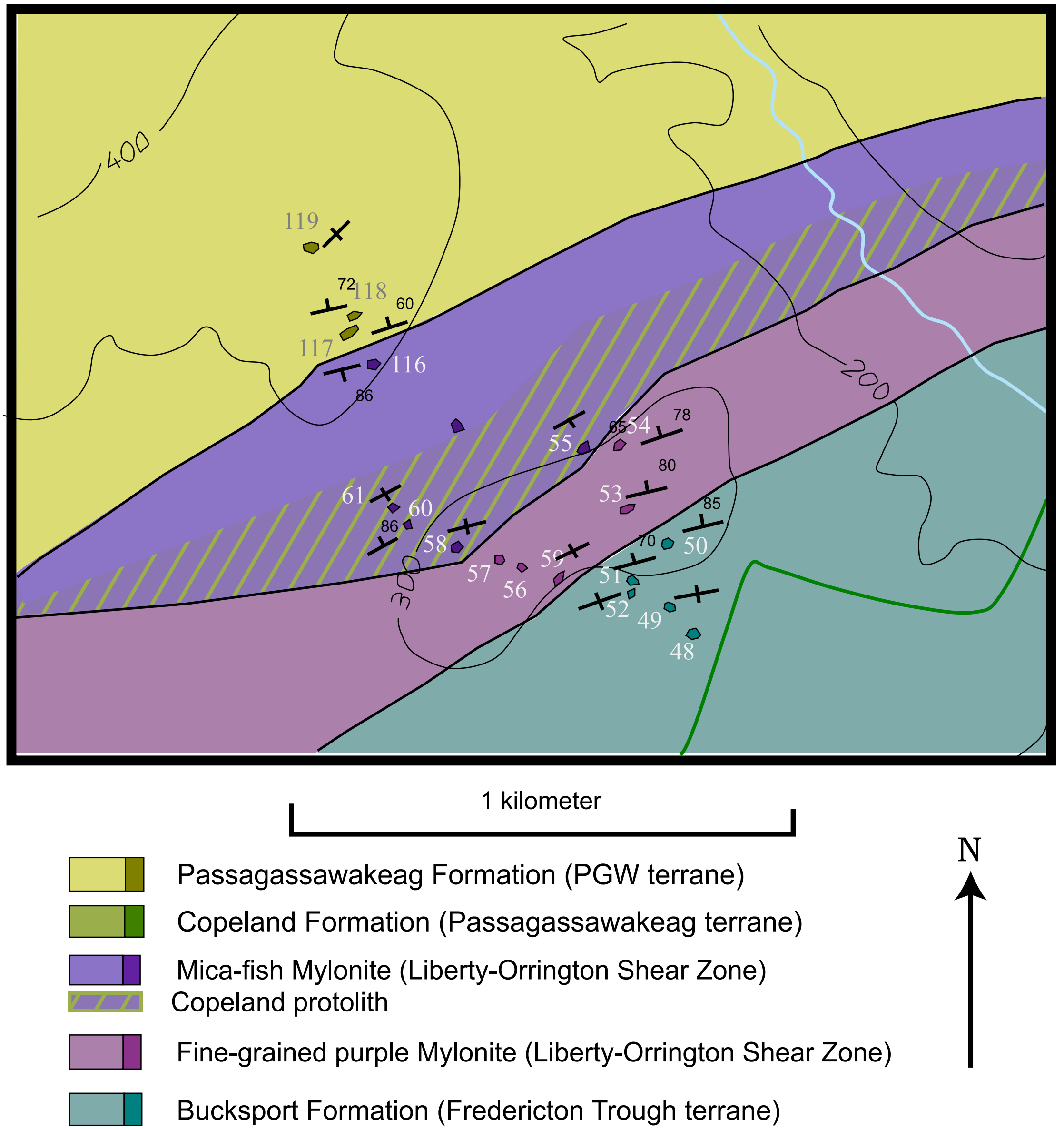
Protoliths

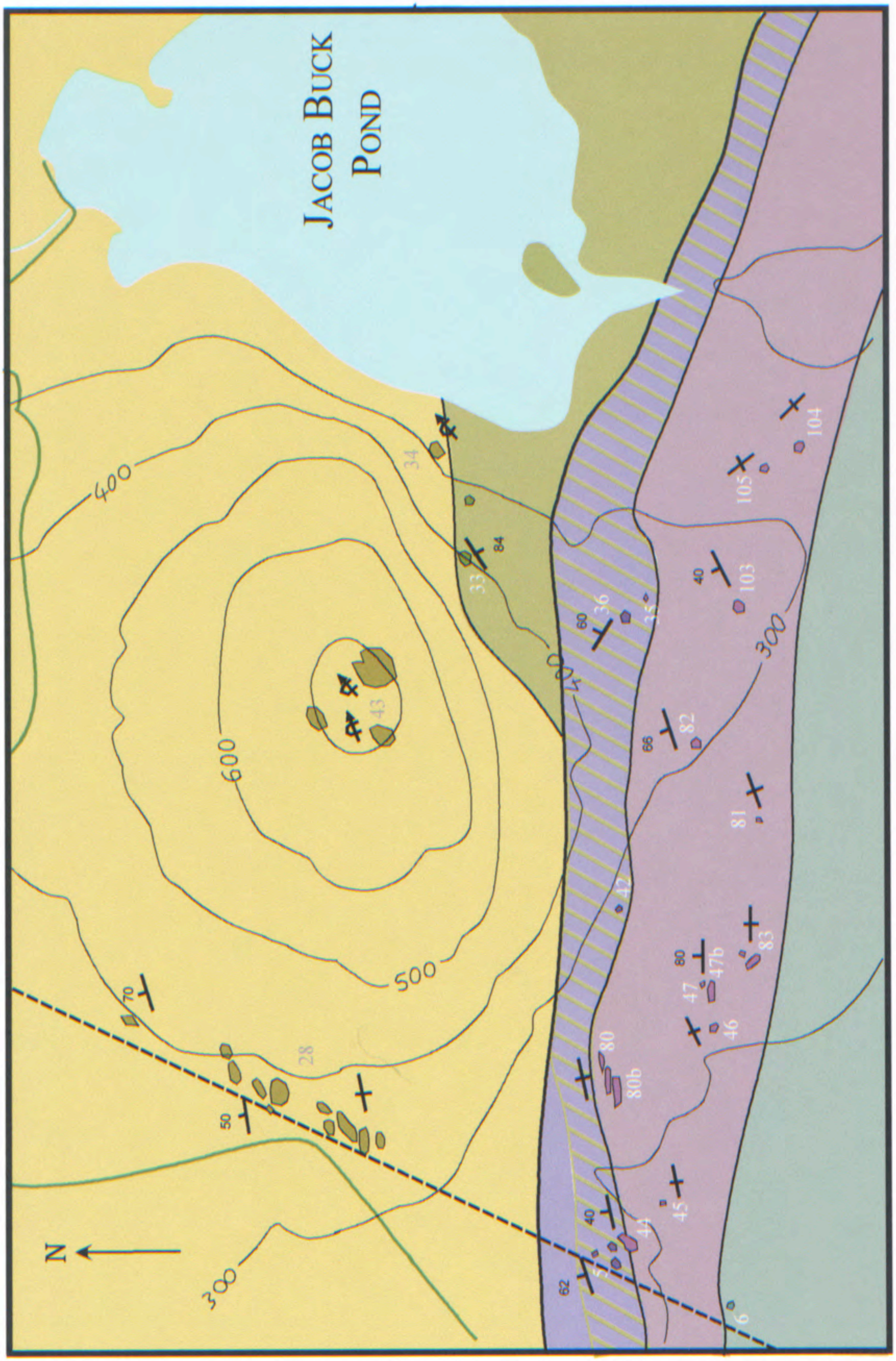
Based on the mineralogy of the thin sectioned mylonite samples, each has been assigned a tentative protolith (pre-mylonitization), although it is understood that in a long-lived reactivated shear zone such as this, most protolith signatures may have been obliterated. In general, mica fish lithologies that contain very little biotite and opaques, or lack them, are considered to be derived from granite that intruded the Passagassawakeag or Copeland formations. The grey mica fish mylonites are considered to be derived from the Copeland Formation for several reasons. The paucity of biotite, lack of amphibole and calcite, and the presence of chlorite as an apparent primary phase rule out a Bucksport protolith. In addition to the reasons listed above, the fine-grained matrix nature of the plagioclase and quartz casts doubt on the Passagassawakeag gneiss as a protolith. The mineralogy of the grey mica fish mylonites is in agreement with the mineralogy of the pelitic portion of the Copeland Formation, and its high mica content provides an appropriate zone of relative weakness for a shear zone to develop. A complete list of thin sectioned samples and their protoliths is provided in Table A-1, and areas where they occur are outlined on Plate 1 and Figure 3.6a.

Fine-grained mylonites- southern boundary

The most abundant type of mylonite in the Liberty-Orrington shear zone is a fine-grained, grey (to purple where hornfelsed) mylonite/phyllonite, that typically crops out along the southern portion of the shear zone, adjacent to the Bucksport Formation. A fine-grained mylonite is also present near Jacob Buck Mountain, which may have been derived from the fine-grained calc-silicate unit of the Passagassawakeag gneiss (Figure 3.6b). These mylonites are characterized by an extremely fine-grained, sugary texture often with very fine, boudined quartz ribbons (Figure 3.7). Foliation is usually difficult to identify, although when present it is crenulated and/or defined by purple and green compositional layering. Because of the extreme fine-grained nature of some of these mylonites, it is almost impossible to determine the protolith or even the degree of deformation in the field, therefore thin sections were made of all fine-grained lithologies in doubt. The mineralogy of fine grained mylonites is variable but, all contain quartz, plagioclase, biotite, and hematite, and depending on the protolith and/or metamorphic grade amphibole, tourmaline, sphene, allanite, calcite, ilmenite, chlorite, muscovite, garnet, and sillimanite (Table A-1).

Figure 3.6 - a) Local site map of locations of thin-sectioned samples; Numbers in white and grey are outcrop numbers, in black are dip numbers. b) Next page- Site map of outcrop locations near Jacob Buck Mountain.

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47b
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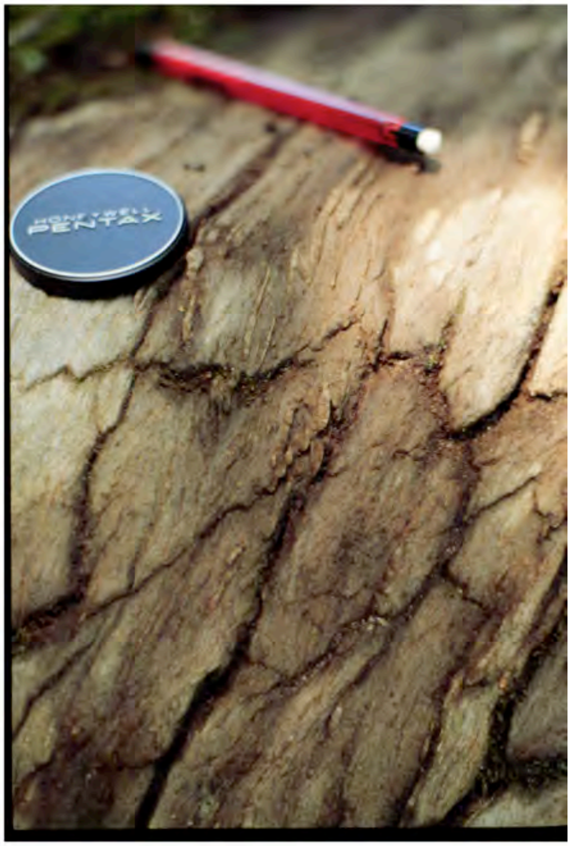
Figure 3.7 - a) Outcrop of boudined quartz ribbons in fine-grained mylonite. Pencil indicates North. b) Field sketch of boudined quartz ribbons and S-C foliation in a fine-grained mylonite (OC#52).

a)



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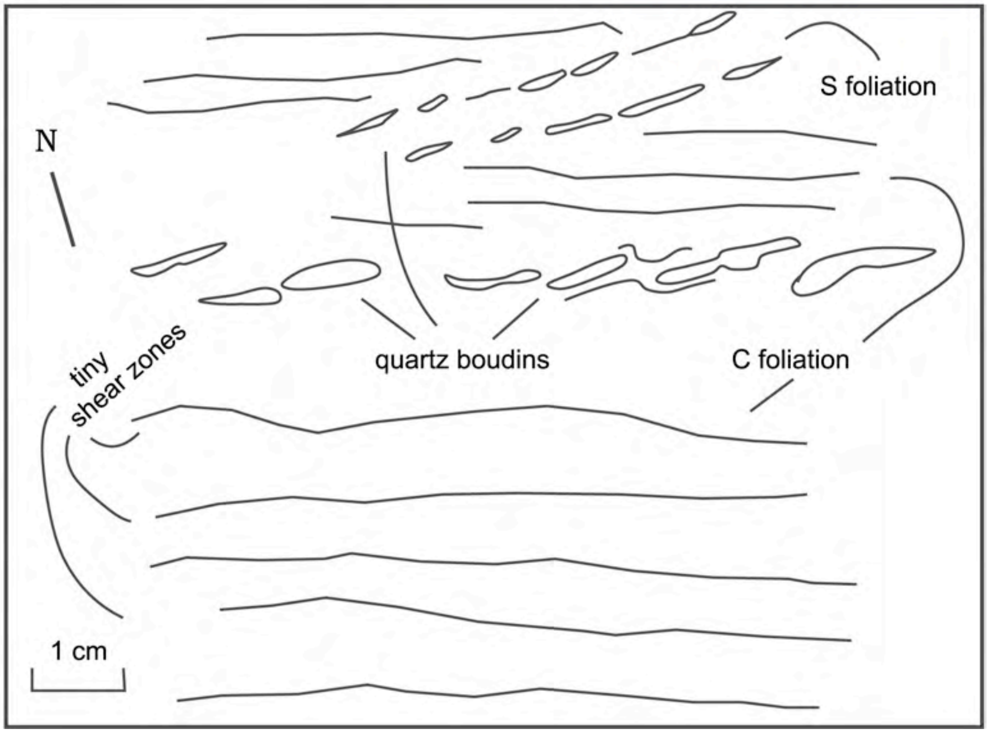


Structures

In outcrop, obvious structures such as foliation and lineations are not easily identified in this rock type, and are somewhat rare. The majority of fine-grained mylonites strike 050 to 060 in the western end of the field area, change to 080 near Jacob Buck Mountain, and to 325 east of Jacob Buck Mountain, with near vertical dips and near-horizontal stretching lineations (Plate 1). This map pattern is nearly identical to that shown by the mica-fish mylonite, and considering that both types of mylonites occur along the length of the shear zone and even in the same outcrop, they probably formed at the same time, prior to regional folding. In thin section, all fine-grained mylonites exhibit a well-developed dextral S-C foliation with the S-direction defined by quartz and/or amphiboles, and the C-direction defined by micas except in samples where quartz is the main phase (Table A-2). C' foliation is also developed in more pelitic samples and layers, and when present, is usually dominant. In some cases, amphibole and quartz are stretched and sigmoidal, indicating dextral shear. Quartz ribbons are folded, boudined, and on-lapped, and late dynamically recrystallized quartz veins occur in the S-direction. In the western portion of the study area, late fractures (locally a crenulation) cut all foliation nearly perpendicular to C-foliation (Figure B-6). In samples that contain garnet porphyroclasts, foliation bends around them or forms mica tails, and the garnets themselves are abraded with numerous inclusions. Some garnets are elongate and appear deformed, while others form tectonic fish. Large tourmalines also occur as porphyroclasts (Figure 3.8).

Figure 3.8 - Boudined tourmaline oriented in the C'-direction in a fine-grained mylonite. Note inclusions of matrix minerals in tourmaline overgrowth versus the inclusion-free core.

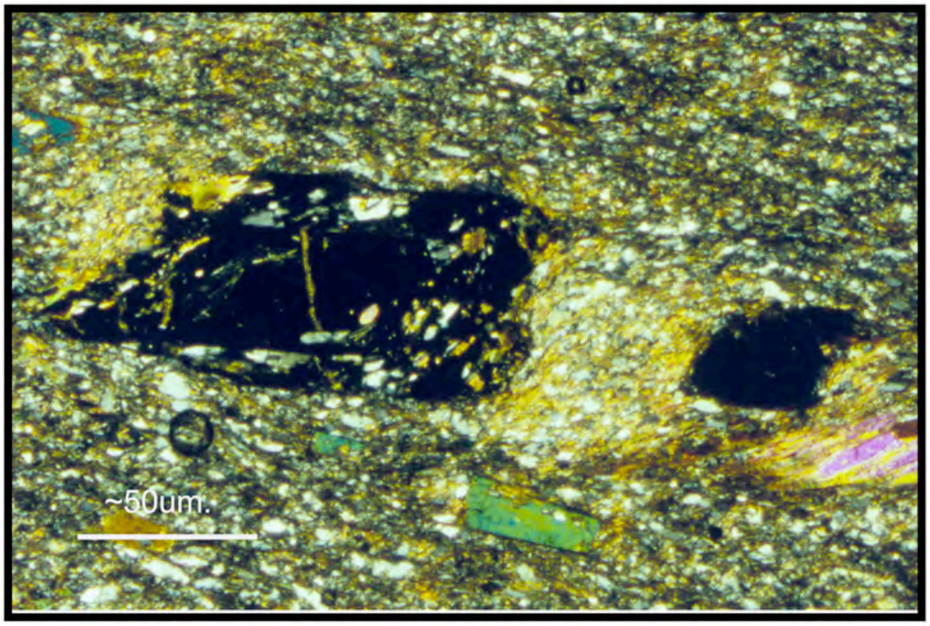
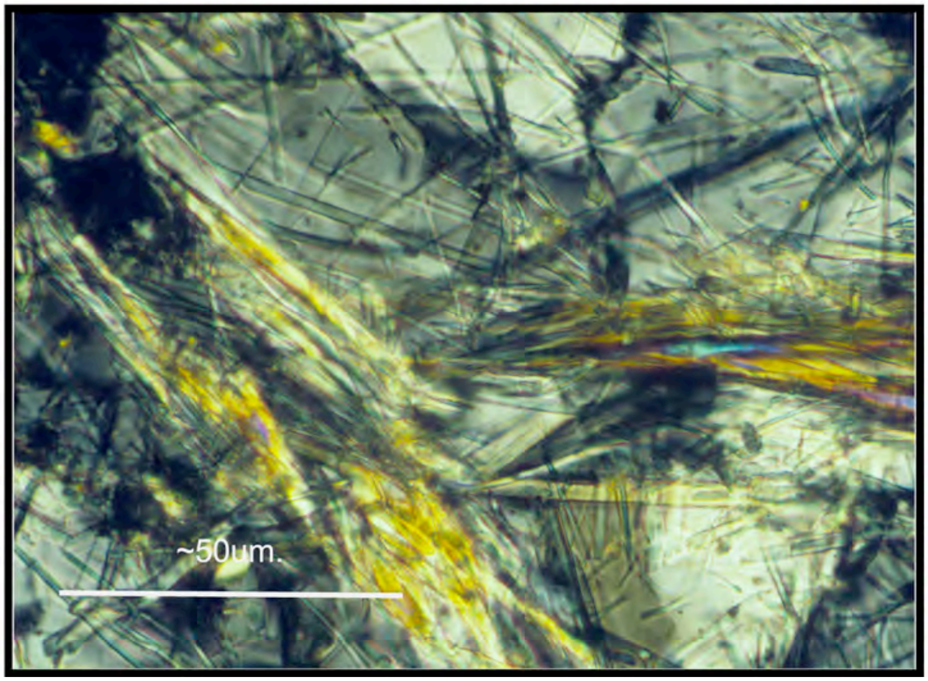


Figure 3.9 - Sillimanite in quartz of fine-grained mylonite.



Metamorphism

The degree of metamorphism of the fine-grained mylonites is generally coincident with the metamorphic grade of the protoliths, with the exception of the hornfelsed mylonites in the western portion of the study area (Table A-1). Small prismatic sillimanite needles are present in the mylonite on the south side of Jacob Buck Mountain (Figure 3.9), and garnet is present in a few samples from the western end of the study area. Mylonites within the contact metamorphic aureole of the Mt. Waldo pluton are hornfelsed, as shown by larger hornblende, biotite, and tourmaline crystals that appear to grow in preferred orientations. Chlorite appears to be a late phase in all samples, occurring along quartz veins and fractures, and sometimes extensively replacing biotite.

Protoliths

Fine-grained mylonites were assigned to protoliths based on their mineralogy and relative position within the shear zone. The one sample that contains sillimanite is probably highly-strained Passagassawakeag gneiss, as the abundance of hornblende rules out the Copeland. Samples with garnet are derived from either the Copeland or Passagassawakeag formations. Mylonitic Bucksport contains a fair amount of hornblende and/or calcic amphiboles and calcite, although in higher-strained varieties calcite is absent. It is also characterized by a lack of aluminum-silicate minerals and tourmaline. Fine-grain size in mylonites with a Bucksport protolith might perhaps be a function of the original fine grain size of the Bucksport Formation, while fine-grained mylonitic Copeland or Passagassawakeag probably indicates areas of higher strain.

Low-strain zones

A couple of areas within the Liberty-Orrington shear zone consist of relatively low-strain, highly chloritized rock in places exhibiting evidence for vertical movement, such as small boudins and axes of quartz vein folds parallel to foliation. In one outcrop, original Passagassawakeag gneissic layering is preserved apparently in contact with fine-grained, hornfelsed Bucksport Formation (outcrop # 15) (Plate 1). I refer to these lithologies as 'fault rock' and believe that they represent low-strain lenses within the shear zone. Locations of the low-strain lenses are shown on Plate 1.

Eastern boundary mylonites

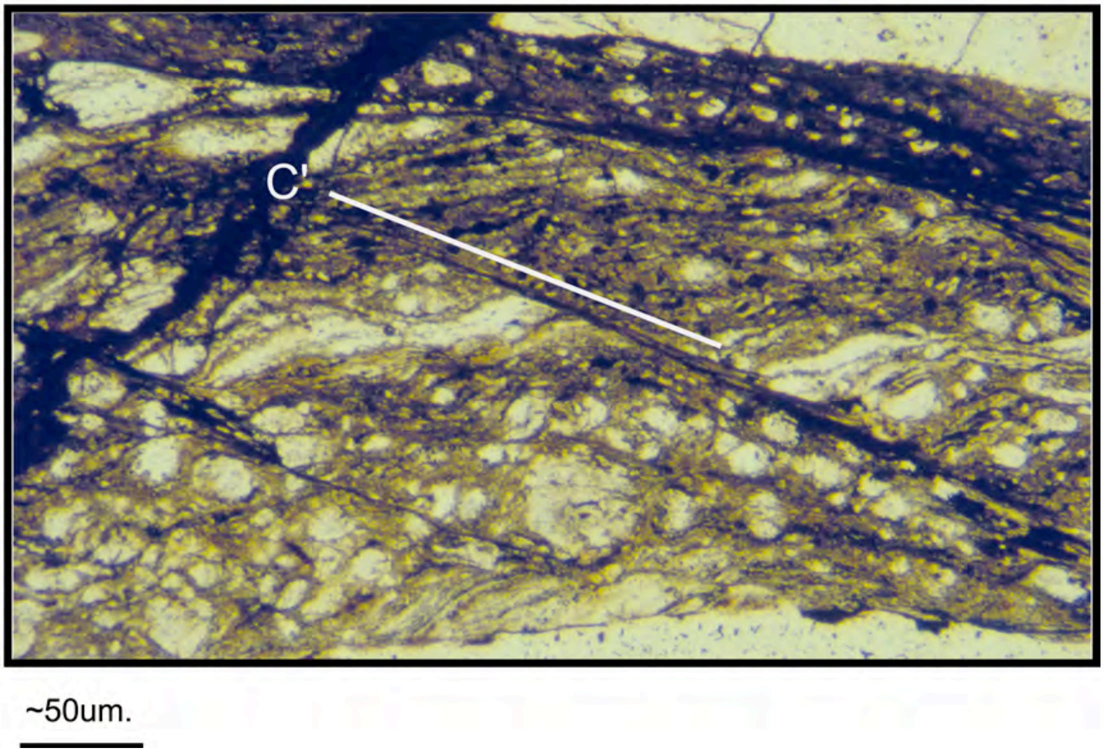
Perhaps the most significant outcome of this study is the recognition that lithologies that occur along the eastern trace of the Liberty-Orrington fault are distinct from the mylonites mapped in the shear zone along the southern boundary, and may have formed in different manners. Because the host lithology (Passagassawakeag gneiss vs. Copeland schist/quartzite, or Bucksport?), style, and present sense-of-shear orientation are different along this boundary, and because of a scarcity of outcrops, it is not possible to categorize these mylonites like the mylonites along the southern trace of the fault. Consequently, eastern-boundary mylonites are described by geographic location rather than lithology. Fine-grained mylonites of the southern boundary extend to the east as far as Jacob Buck Pond (Plate 1). The inferred trace of the shear zone from this area passes to the northeast of Whites Brook at the base of Orcutt Mountain, a till-covered and heavily forested area with no outcrop. The next outcrops to the east are near Bucks Mills, where several distinct fine-grained mylonites and a low-strain lens occur (outcrops #88,

#115, #107). These lithologies are individually described in Table A-1 , and are derived from Copeland, Rider Bluff, or Bucksport formations. From here, the Liberty-Orrington fault trace turns sharply northeast and the mylonitic fault rocks are represented by the Rider Bluff unit (formerly a member of the Copeland Formation), which may be mylonitized Copeland or even Bucksport formation. The strike of foliation also turns north, even in relatively undeformed Bucksport outcrops adjacent to the fault trace (outcrop #101). Because of poor exposure and the discovery of the mylonites along the southern Liberty-Orrington trace, mapping of the eastern trace was not a priority, and only those outcrops that are easily accessible were visited.

Structures

All mylonites in the 'bend' area are fine-grained and micaceous with a sugary texture and small quartz ribbons. One outcrop has small S-folds, but in most the sense of shear is indeterminate at outcrop scale. The general strike of foliation is north-northeast, while dip is near-vertical at the bend and is consistently to the east once the boundary turns to the north. In thin section, slight pelite + quartzofeldspathic domains are developed in most samples, and C' foliation is clearly defined by matrix micas, quartz ribbons, and tectonic fish (Figure 3.10). All quartz is extensively dynamically recrystallized with elongate subgrains oriented in the S-direction. Some quartz veins exhibit z-folds, and some quartz ribbons are boudined and isoclinally folded. Porphyroclasts of plagioclase and garnet are abundant, and while plagioclase grains are rounded and deformed, garnet grains are less abundant and extensively fractured and displaced, with the fractures filled by chlorite (Figure 3.11a&b).

Figure 3.10 - C' foliation in a mylonite near Bucks Mills. Large rounded porphyroclasts are plagioclase, ribbons are quartz, and matrix is mostly micas.



All ductile deformation features indicate a dextral sense of shear (present orientation). In quartzo-feldspathic rich parts of the samples, brittle deformation appears to be dominant, with broken and displaced garnet and plagioclase porphyroclasts, microlithons, and broad as well as brittle folding of the ductile foliation.

Macro and micro structures present in the Rider Bluff unit are described in detail above with the Passagassawakeag lithologies. The highly-deformed and recrystallized quartz and biotite layers characteristic of this unit are a tectonic fabric and do not represent original sedimentary bedding. The unit has a very strong stretching lineation almost perpendicular to the strike of foliation, with well-developed C' foliation in a Bucksport-over-gneiss thrust sense(Table A-2). It is highly unlikely that original sedimentary bedding of such a fine scale (~ 2mm) would survive the strain required to create the stretching lineation, as this same kind of strain-induced compositional layering is evident in slightly deformed Bucksport Formation within the study area (outcrop # 97).

Metamorphism

The highest grade index mineral observed in the mylonites of the transition and eastern boundary zones (Rider Bluff) is garnet (Figure 2.4). This is consistent with the reports of previous workers (McSwiggen, 1978; Kaszuba, 1986). Garnet porphyroclasts are subhedral to anhedral and are abraded or fractured with green biotite (Mg-rich) filling the fractures (Figure 3.11b). This magnesium-rich biotite occurs as fracture fill in other phases, and may be the result of regional retrograde metamorphism, possibly an intermediate phase between biotite and chlorite. Considering this, and that chlorite is concentrated along the C' shear bands in the Rider Bluff unit, a regional retrograde a)

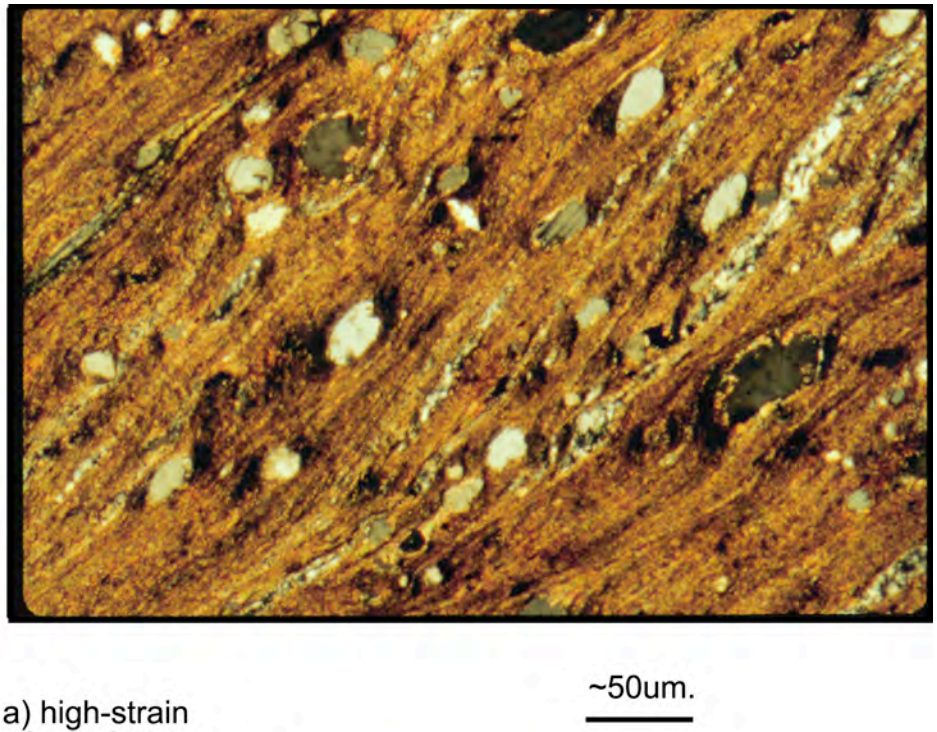
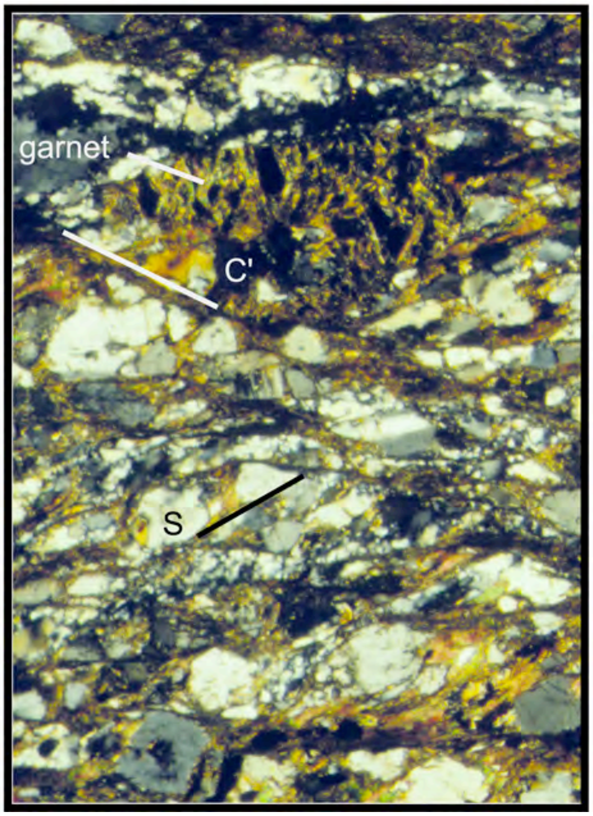


Figure 3.11 - a) high-strain mylonite with plagioclase porphyroclasts in a mica matrix. b) Fractured garnet being replaced by chlorite in a lower-strain portion of the same thin section. OC#91.

b)



metamorphism may be associated with the brittle deformation observed in the eastern boundary rocks.

Summary of eastern boundary mylonites

It is curious that the Rider Bluff unit (and the transition mylonites) are only at garnet grade, when the lithology that they are supposedly derived from and/or part of is at sillimanite grade (Copeland Formation), and there does not appear to have been a retrograde event severe enough to downgrade the rocks from sillimanite to garnet grade. Also, nowhere does the Stricklen Ridge migmatite intrude the Rider Bluff unit, and it has not been observed to intrude the 'bend' mylonites either. It is odd that a unit whose outcrop pattern is very thin and parallels a fault trace, has a unique tectonically-derived layering, and is bordered on the west (for ~15 kilometers) by a high-grade migmatitic schist but exhibits a significantly lower metamorphic grade, should be considered anything except the manifestation of a major fault.

It is quite plausible that the Rider Bluff unit is mylonitized Bucksport Formation and that the entire unit is a fault zone. The present composition of the Rider Bluff may or may not reflect that of the original protolith. It most closely resembles the Bucksport, but is not pelitic enough to be considered part of the formation, and may be derived from a lithology not exposed at the surface (a highly-ferrugenous argillite?). The abundance of magnetite and hematite imply that the protolith was iron-rich (possibly of hydrothermal origin), or that the iron was secondarily introduced through solution transfer processes. The Rider Bluff is clearly highly-strained, so pelitic material and magnetite could have been concentrated in the unit due to circulating fluids during shearing.

It is also relevant to note that the Rider Bluff exhibits late Bucksport-over-gneiss shear (C’ foliation) superimposed on early ductile deformation (compositional layering), while mylonites of the ‘bend’/transition area have brittle deformation superimposed on older, clearly dextral ductile deformation (S-C foliation; present orientation). Both later deformations coincide with a retrograde metamorphism. I suggest that the eastern-boundary mylonites record the same general kind of deformations and metamorphism, but with different kinematics, as the ductile dextral shear in the mylonites of the Liberty-Orrington shear zone, and that they were formed along a thrust continuation of the Liberty-Orrington shear zone.

CHAPTER 4

TIMING OF MYLONITIZATION AND EXHUMATION OF THE PASSAGASSAWAKEAG TERRANE

As is typical of most polydeformed and polymetamorphosed areas, deformation associated with initial movement along the Liberty-Orrington shear zone is probably obscured by subsequent tectonic events. However, it is possible to estimate the relative time of formation of the earliest preserved fabric by establishing a sequence of tectonic events recorded by the rocks through overprinting relationships, from the microscopic to regional scale. It is clear from inspection of the samples of mylonites and gneiss taken in this study that they show a complex history of ductile dextral shear along the Liberty-Orrington shear zone sometime between the early (deformed Stricklen Ridge granite) and late (cross-cutting Mt. Waldo pluton) Devonian, with metamorphism both accompanying and occurring in-between deformations. Therefore, the Passagassawakeag and Fredericton Trough terranes in northern the Penobscot Bay area were juxtaposed close to the beginning of the Acadian orogeny, and perhaps even earlier. Depending on when motion began on the Norumbega Fault Zone, there may have been a hiatus between when shearing ceased along the southern boundary of the Liberty-Orrington shear zone (~371 Ma) and when movement was taken up along the Norumbega to the north.

Relationships between metamorphism and deformation

Regional scale -Overprinting relationships

At the northern end of Penobscot Bay, the Liberty-Orrington shear zone is cross-cut by the 371±2 Ma Mt. Waldo pluton (Tucker et al., in press). Although the author has not directly observed the Mt. Waldo granite intruding the mylonites of the shear zone, granite dikes clearly intrude and hornfels the Bucksport Formation within the western portion of the study area. Both the fine-grained and mica-fish mylonites near here appear to be hornfelsed as well, evidenced by the growth of new metamorphic minerals in these rocks within the contact metamorphic aureole of the Mt. Waldo granite as well as the growth of existing minerals over the mylonitic foliation. Specific petrologic evidence for the hornfelsed mylonites is discussed in detail below. Further detailed mapping of the Mt. Waldo pluton and its relationship to the Liberty-Orrington shear zone, particularly south of the present study area, would provide additional support for the sequence of tectonic events seen here.

The Stricklen Ridge granite is thought to be anatectic, so its 412± 14 Ma age may also be the age of the most recent metamorphic event experienced by the Passagassawakeag terrane (Zartman and Gallego, 1979). Because dikes of the Stricklen Ridge granite are involved in mylonitization in the Liberty-Orrington shear zone, this date also provides a lower limit on the age of the earliest preserved deformation associated with movement within the shear zone. The high metamorphic grade of the Passagassawakeag gneiss and adjacent mylonites is most likely the result of multiple metamorphisms (McSwiggen, 1978; West et al., 1995). Consequently, it is also likely that the 412± 14 Ma sillimanite-bearing mineral assemblage within the mylonites that overprints foliation, may obscure older metamorphic and deformation events.

Microscopic scale- petrographic analysis

The relationships between metamorphic and tectonic episodes are more clearly delineated at the microscopic scale, but only show a relative and qualitative sequence of events without microprobe and other detailed chemical analysis. Mineral overgrowths, late porphyroblasts, and the present coexistence of chlorite with higher-grade metamorphic phases in the mylonites of both the southern and eastern boundary zones indicates that the rocks mostly preserve a retrograde metamorphic sequence. The metamorphic minerals in both types of mylonites do not appear to be in equilibrium, as chlorite replaces biotite and garnet, and plagioclase is altered to sericite. Consequently, a detailed account of prograde metamorphic reactions and their relationship to deformation is not observed. Although the later sequence of deformation and metamorphism obscures the prograde/burial path through P-T (Figure 4.0) and T-t (Figure 4.1) space, it does provide a record of Devonian movement along the Liberty-Orrington shear zone and, subsequently, the exhumation of the Passagassawakeag terrane.

Southern boundary

Sillimanite is present in the Passagassawakeag gneiss and portions of the southern mylonites, and is both involved in and overgrows mylonitic foliation (Figure 3.9). Because the Stricklen Ridge migmatite is derived from and cross cuts the gneiss, it is assumed that the sillimanite formed during prograde metamorphism which culminated in partial melting, at or near 412±14 mya (Zartman and Gallego, 1979). Although the

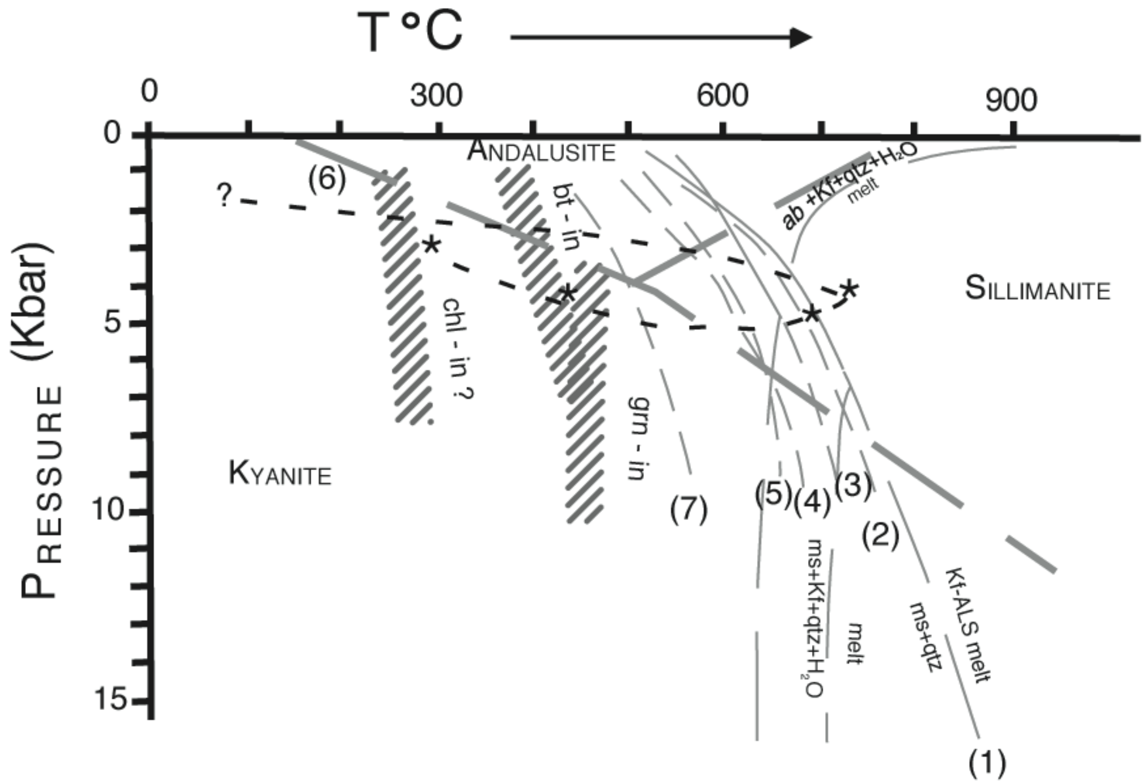
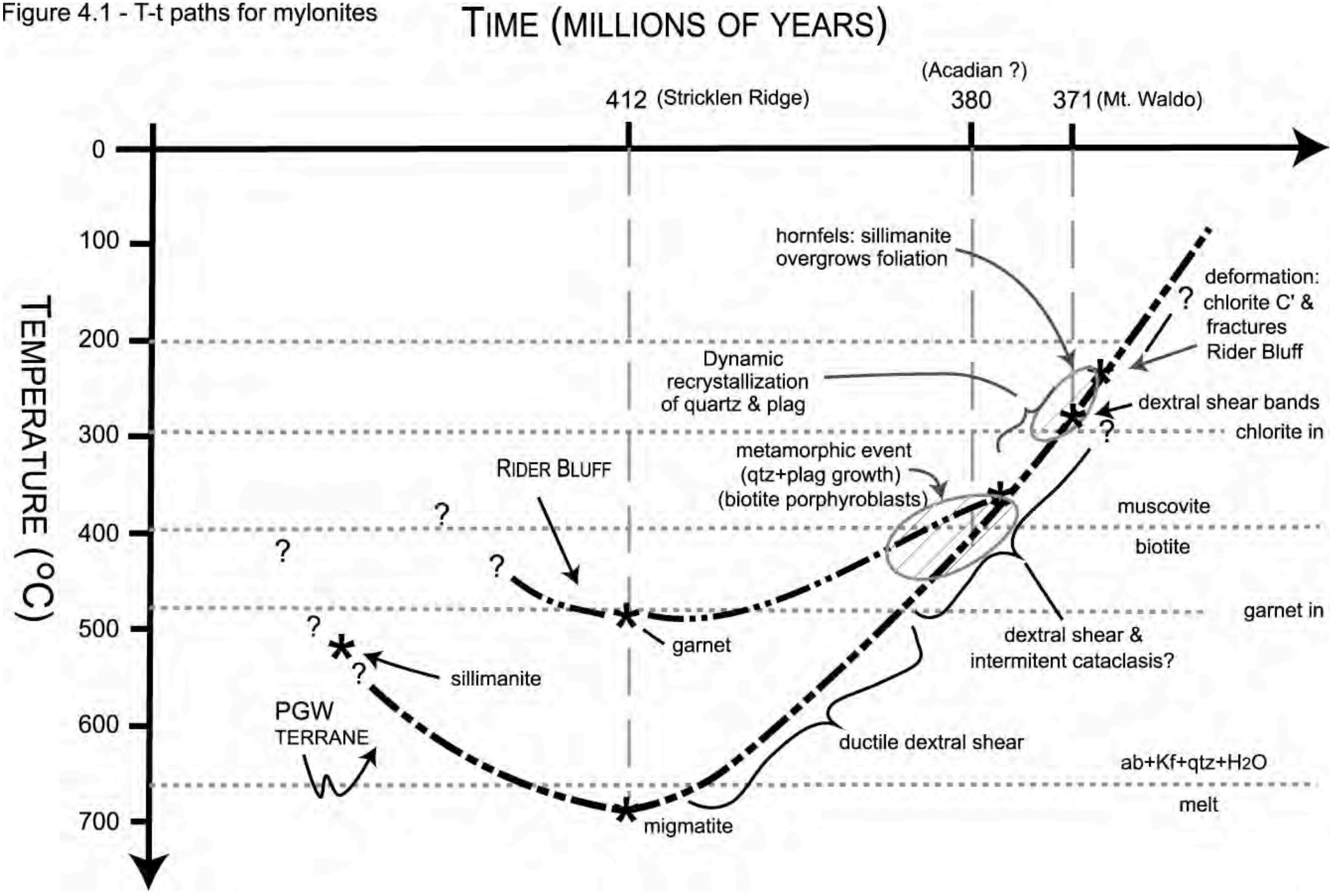


Figure 4.0 - Petrogenetic grid for metasediments of Passagassawakeag with P= PH_2O. Abbreviations used are: ab=albite; ALS=aluminum silicate; bt=biotite; chl=chlorite; grn=garnet; Kf=K-feldspar; ms=muscovite; qtz=quartz. Positions of reaction curves are from Guidotti (1974) and Yardley (1995). The dotted line indicates the approximate path of the Passagassawakeag Gneiss based on existing mineral assemblages, marked by (*). The prograde path is not seen. Numbered reactions are as follows: (1) ms+qtz= Kf-ALS melt; from right to left: (2) silica+Kf=ms+ab; (3) (4) (5) silica+bt=staurolite+chl; (6) aluminum silicates; (7) staurolite+bt=grn+chl.

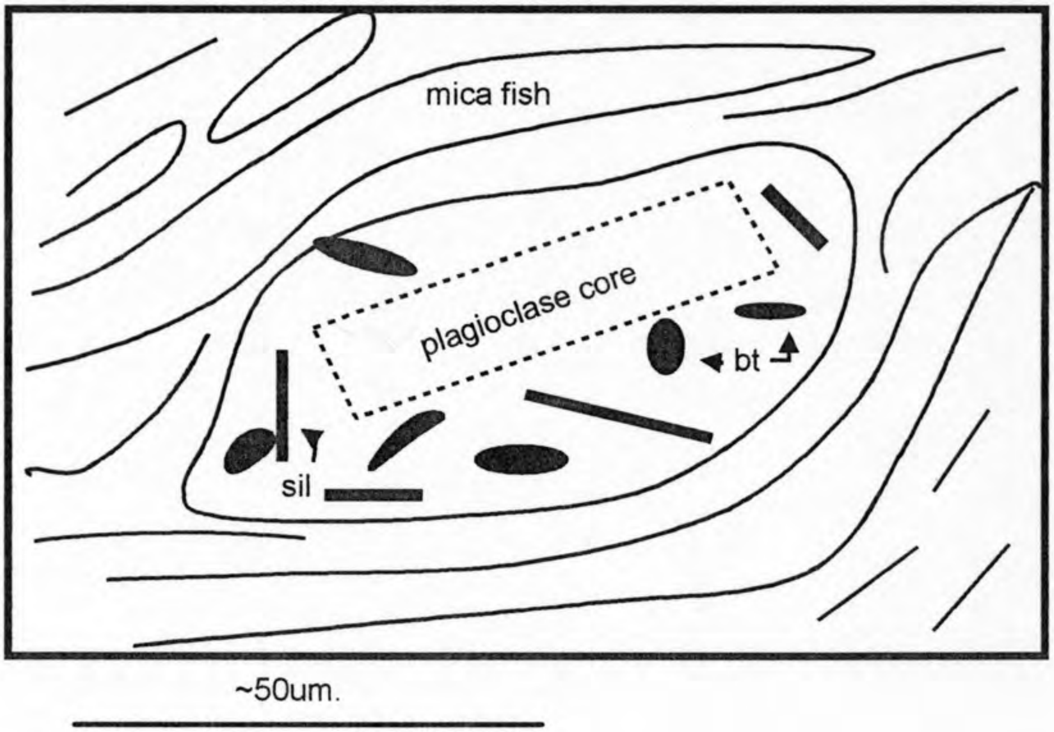
Figure 4.1 - T-t paths for mylonites



dextral shear preserved in the southern mylonites deforms the migmatite and is therefore younger than it, dikes and sills of the migmatite appear to intrude the non-mylonitic gneiss outside the shear zone in a manner concordant with the gneissic layering and also showing dextral shear indicators, implying that the strain pattern resembling that of the shear zone was in place at 412±14 mya.

The dextral shear responsible for the formation of the southern mylonites began sometime after peak metamorphism and anatexis of the Passagassawakeag gneiss, hence in the early Devonian (Figure 4.1). Strike-slip motion by ductile shear is inferred through the early part of the Devonian, as evidenced by the ductile structures in the mylonites described in Chapter 3. Quartz and plagioclase porphyroclasts in the fine-grained and mica-fish mylonites contain inclusions of randomly-oriented red biotite and sillimanite needles. Because the original plagioclase grain boundaries in the porphyroclasts are still evident, the plagioclase and inclusions are probably all originally matrix minerals, with the biotite and sillimanite being incorporated into the plagioclase during a metamorphic event. One explanation for the random orientation of the inclusions is that they record local cataclasis within the shear zone, which destroyed the previous ductile mylonitic foliation. Shortly after this, the rock was metamorphosed, causing matrix quartz and plagioclase to overgrow and preserve the randomly oriented sillimanite and biotite. Dextral movement then resumed, transforming the porphyroblasts into clasts and restoring mylonitic foliation (Figure 4.2). Another explanation for the inclusions is that the porphyroclast is simply a lithic fragment from the Passagassawakeag gneiss, with the biotite and sillimanite incorporated during a static metamorphic event. While this is

Figure 4.2 - Sketch of plagioclase porphyroclast with random inclusions of biotite and sillimanite in overgrowth of original grain as evidence for cataclasis during mylonite formation. Also see Figure 3.4 (matrix inclusions in tourmaline).



certainly possible, it seems unlikely that the matrix minerals in a strongly deformed gneiss would be randomly oriented.

Mica-fish mylonites are characterized by an abundance of muscovite mica-fish and a paucity of biotite. This may reflect protolith bulk composition, or it may indicate a prolonged deformation event when the mylonites were approximately at 400° C (~ 16 km depth; based on an average 25°/km thermal gradient), as this is the temperature at which biotite is replaced by muscovite through the continuous reaction: garnet + biotite + quartz + H_2O = chlorite + muscovite (Yardley, 1995). If the latter is the case, then the southern boundary mylonites were approximately at 4.8 kbar and 400° C shortly after peak Acadian metamorphism (Figure 4.0) (presumed to be 380 Ma; Tucker et al., in press). As an alternative to protolith, the occurrence of two types of mylonites in the Liberty-Orrington shear zone may reflect differences in the H_2O content of the shear zone rocks, as water is required to drive the above reaction.

In mylonites in the 'bend' area of the southern boundary, late chlorite-filled shear bands with a dextral sense cut all previous mylonitic foliation, and along with the dynamic recrystallization of quartz and plagioclase, probably represent the last portion of dextral movement along the Liberty-Orrington shear zone. Some garnets are fractured and filled with chlorite, suggesting the retrograde reaction in the previous paragraph was still taking place. I infer that this dextral C' foliation formed prior to intrusion of the Mt. Waldo granite (Figure 4.1), because the granite cuts (in large scale) the shear zone (just south of the study area) and is not known to have undergone ductile strain.

After formation of the mica-fish mylonites and C’ foliation, rocks within the western half of the southern boundary were hornfelsed during the intrusion of the 371±2 Ma Mt. Waldo pluton (Figure 4.1). Garnets, tourmalines, and sillimanite needles all overgrow mylonitic foliation to various degrees, and their occurrence extends from the Penobscot River east, to Jacob Buck Pond. The adjacent Bucksport Formation is also noticeably hornfelsed, manifested through growth of amphiboles and biotite porphyroblasts that also overgrow foliation.

Eastern boundary

The mylonites of the Rider Bluff unit follow a similar T-t path as that described above for the southern boundary mylonites, except they may have only reached a maximum pressure and temperature of ~6 kbar and 475° C, as garnet is the highest-grade phase present. As with the southern boundary mylonites, the prograde metamorphic history of the Rider Bluff unit has been obscured by peak and later deformation and metamorphism (Figures 4.0 and 4.1).

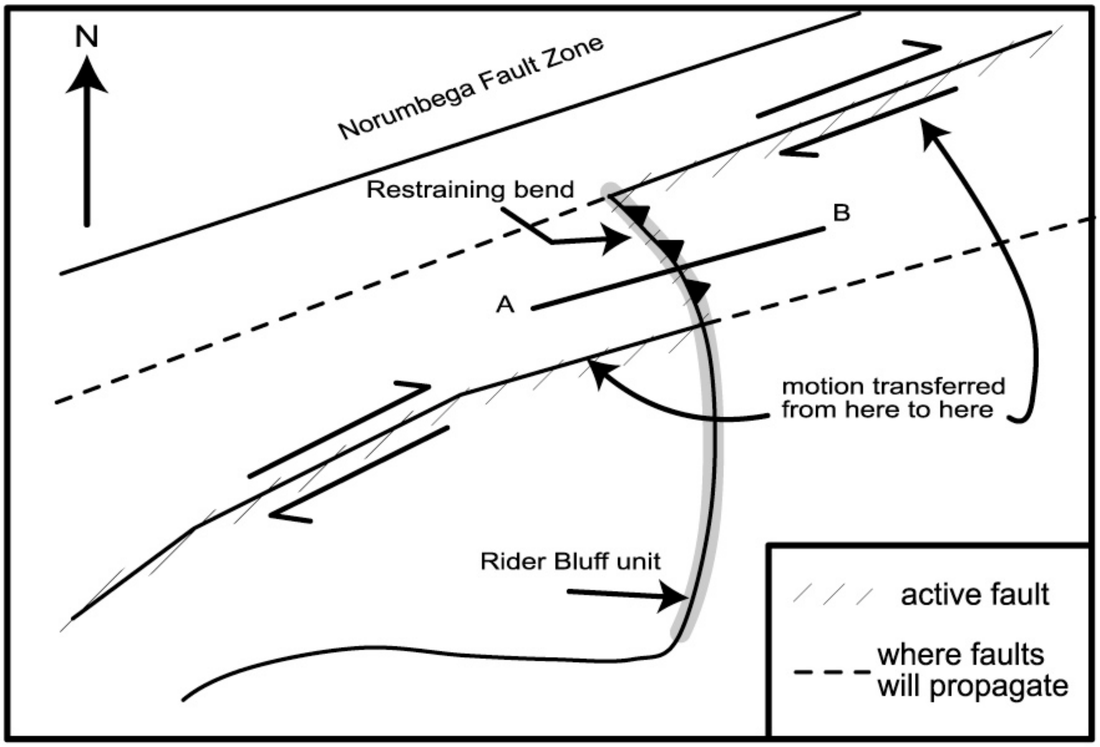
The most striking feature of the Rider Bluff mylonite is its fine compositional layering, described in Chapter 3 and defined as the primary mylonitic foliation. The presence of garnet porphyroclasts indicates that the present foliation formed after garnet formation, presumed to be sometime in the early-mid Devonian (Figure 4.1). A small but recognizable amount of chlorite is involved in the primary foliation, indicating that the dextral movement that produced it continued through a temperature of 350° C, which the mylonites experienced shortly after peak Devonian metamorphism (Figure 4.1) (presumed 380 Ma; Tucker et al., in press).

Biotite porphyroblasts nucleate from and overgrow the primary compositional foliation (Figure 2.4), and may have grown in response to the intrusion of the Lucerne pluton, so foliation must be older than 380 Ma (Bradley et al., 1998). Some garnets are nearly euhedral, yet are clearly involved as porphyroclasts in the foliation, so were probably annealed and/or overgrown during the same metamorphic event. Because the chlorite involved in the primary foliation must have formed sometime after 380 Ma, porphyroclast/blast growth within this boundary was probably syn-kinematic (Figure 4.1).

A younger C' foliation cuts the compositional layering and biotite porphyroblasts, is chlorite-filled, and displays the opposite sense of shear (Bucksport over Passagassawakeag) than the earlier shear zone, where they do not occur. These chlorite shear bands are most prevalent in the northern portion of the eastern boundary mylonites where the rocks are in close proximity to the Norumbega Fault Zone, decrease in occurrence to the south, and are not present near the 'bend' in the mylonite outcrop pattern, near Bucks Mills. Because this foliation is the youngest structural and metamorphic feature in the Rider Bluff unit, it is most likely related to later, post-Acadian strike-slip motion along the Norumbega Fault Zone after movement along the Liberty-Orrington shear zone had ceased (Figure 4.1).

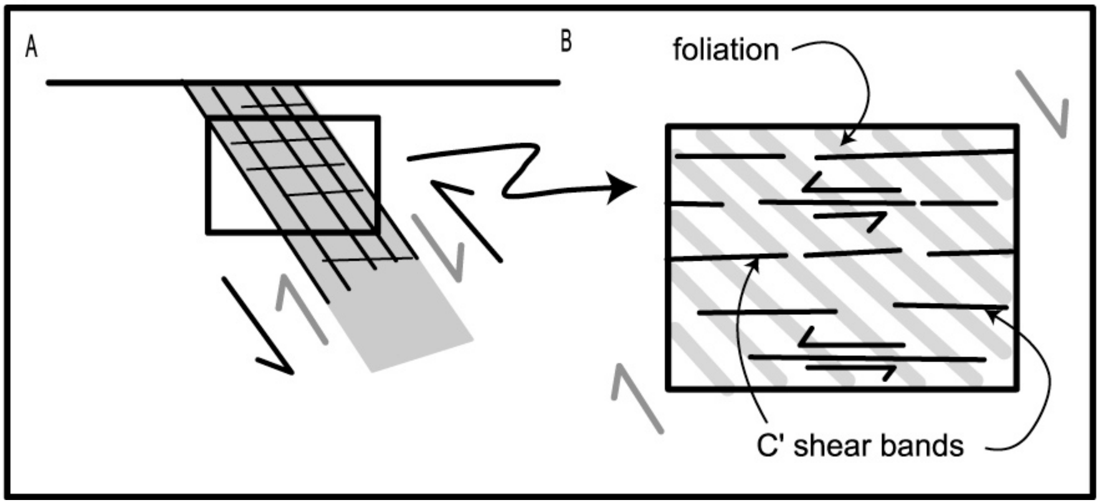
Figure 4.3

a)



a) Cartoon of Bucksport-Orland study area showing the structural conditions under which late C' shear bands may have developed, with the northern portion of the Rider Bluff unit as a thrust fault (east over west sense) along a restraining bend between two dextral strike-slip faults of the Norumbega Fault Zone. b) cross-section showing the present orientation of foliation and late C' shear bands in the Rider Bluff.

b)



CHAPTER 5

TECTONIC EVOLUTION OF THE BUCKSPORT-ORLAND AREA

Tectonic models

The Liberty-Orrington shear zone juxtaposes two lithotectonic terranes of very different metamorphic grade and age that crop out in the midst of the wide suture zone of the Acadian orogeny. With the discovery of a wide mylonite belt along the trace of this terrane boundary (Figure 1.4; Plate 1), it is clear that the two terranes are separated by a major fault, the nature of which is discussed below.

Both tectonic models for the region proposed by Stewart et al. (1995) and Osberg et al. (1998) invoke a pre-metamorphic thrust fault as the mechanism for emplacement of the Passagassawakeag terrane during the early Acadian or earlier (Figure 1.3). If this were the case, one would expect to see mylonitic foliation with steeply pitching stretching lineations indicating movement of the Passagassawakeag terrane either from the northwest or the southeast (present coordinates). As described in Chapter 3, throughout the southern boundary mylonites, foliation is consistently vertical or near vertical with near-horizontal stretching lineations. Mylonitic foliation in the Rider Bluff unit of the eastern boundary has very strong stretching lineations oriented perpendicular to its strike, suggesting a thrust fault. Given only this information, it is arguable that the Liberty-Orrington Fault could be an elaborately folded pre-metamorphic, pre-Acadian-deformation thrust fault. However, the entire eastern boundary dips moderately to the east, and when ‘unfolded’, along with the vertical foliation of the southern boundary, the kinematic indicators present require along-strike transport of the Passagassawakeag terrane from the southwest (Figure 5.0). It is unlikely that the dextral shear present in the Liberty-Orrington southern mylonites is an overprinting of earlier thrust motion, as any other direction of movement is not reconcilable with the direction and sense of shear in the eastern mylonites, which could not have formed through orogen-parallel dextral shear (Figure 5.1).

The simplest tectonic model that explains the macro and micro structures, outcrop pattern, and kinematic indicators of the Liberty-Orrington shear zone is one in which the southern boundary mylonites represent prolonged dextral movement along a strike-slip shear zone, with the eastern boundary mylonites representing an overturned transpressional thrust (formed along a restraining bend in the shear system), along which the Passagassawakeag terrane was exhumed (Figure 5.2). The overturning of the eastern thrust boundary may be due to regional folding, prolonged strike-slip motion along the southern boundary, late dextral motion along the Norumbega Fault Zone, or a combination of any of the above. As the pervasive dextral shear in the southern boundary mylonites requires prolonged strike-slip motion, and petrographic analysis of the mylonites shows that dextral shearing did occur through most of the Devonian, this is the most feasible explanation.

The difference in mylonite lithology between the southern and eastern boundaries lends further support to the dextral shear zone + transpressive thrust tectonic model proposed here in that different strain regimes (strike-slip vs. thrust) may well produce different mylonites. Foliation in the southern mylonites turns north at the ‘bend’ in the map pattern, and dip of the foliation makes a transition from near-vertical or steeply

Figure 5.0 - Cartoon of the tectonics of the Bucksport-Orland area. Colors correspond to colors on Figure 1.4 and Plate 1. Cross-section lines refer to positions of cross-sections in Figure 5.2.

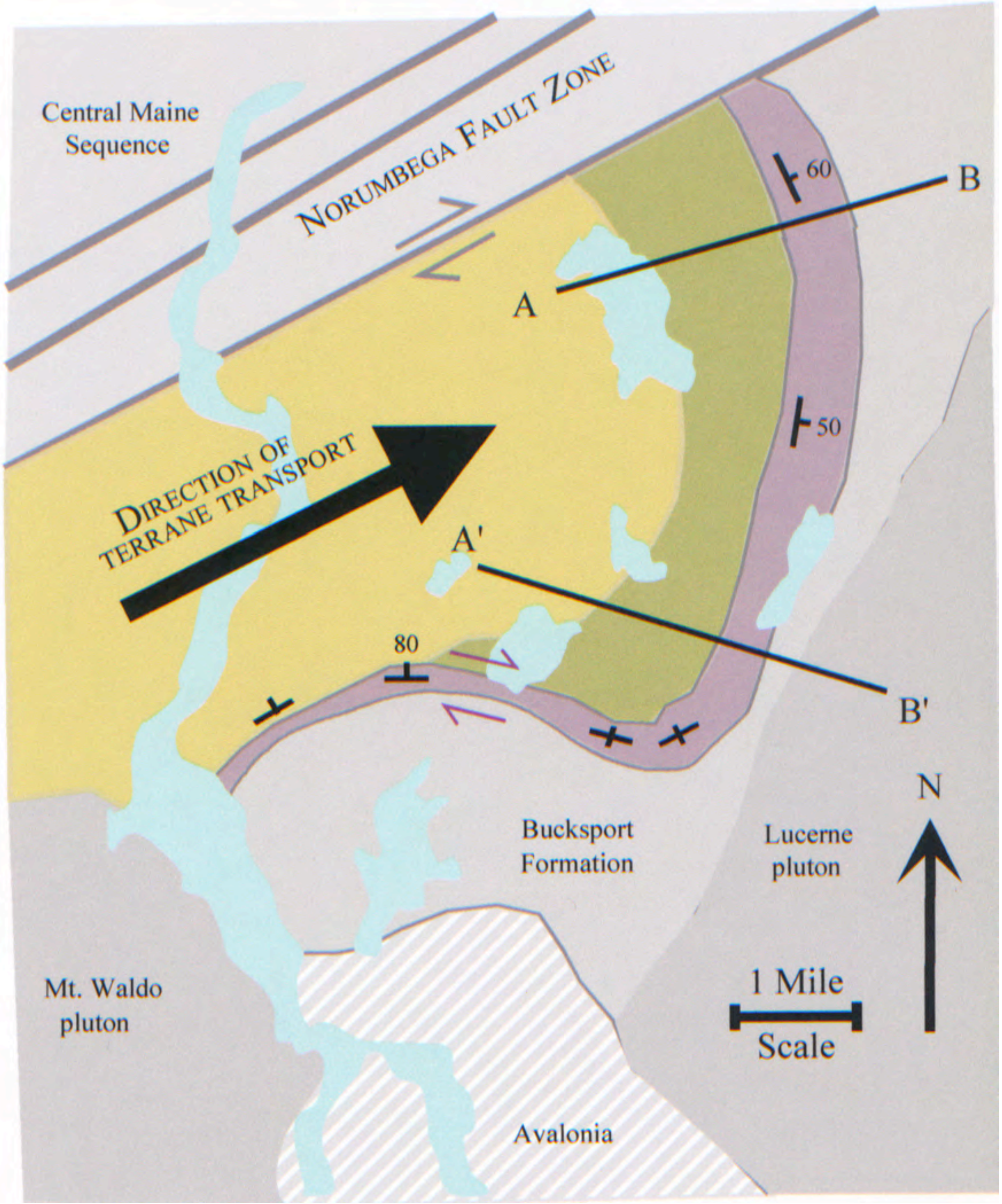
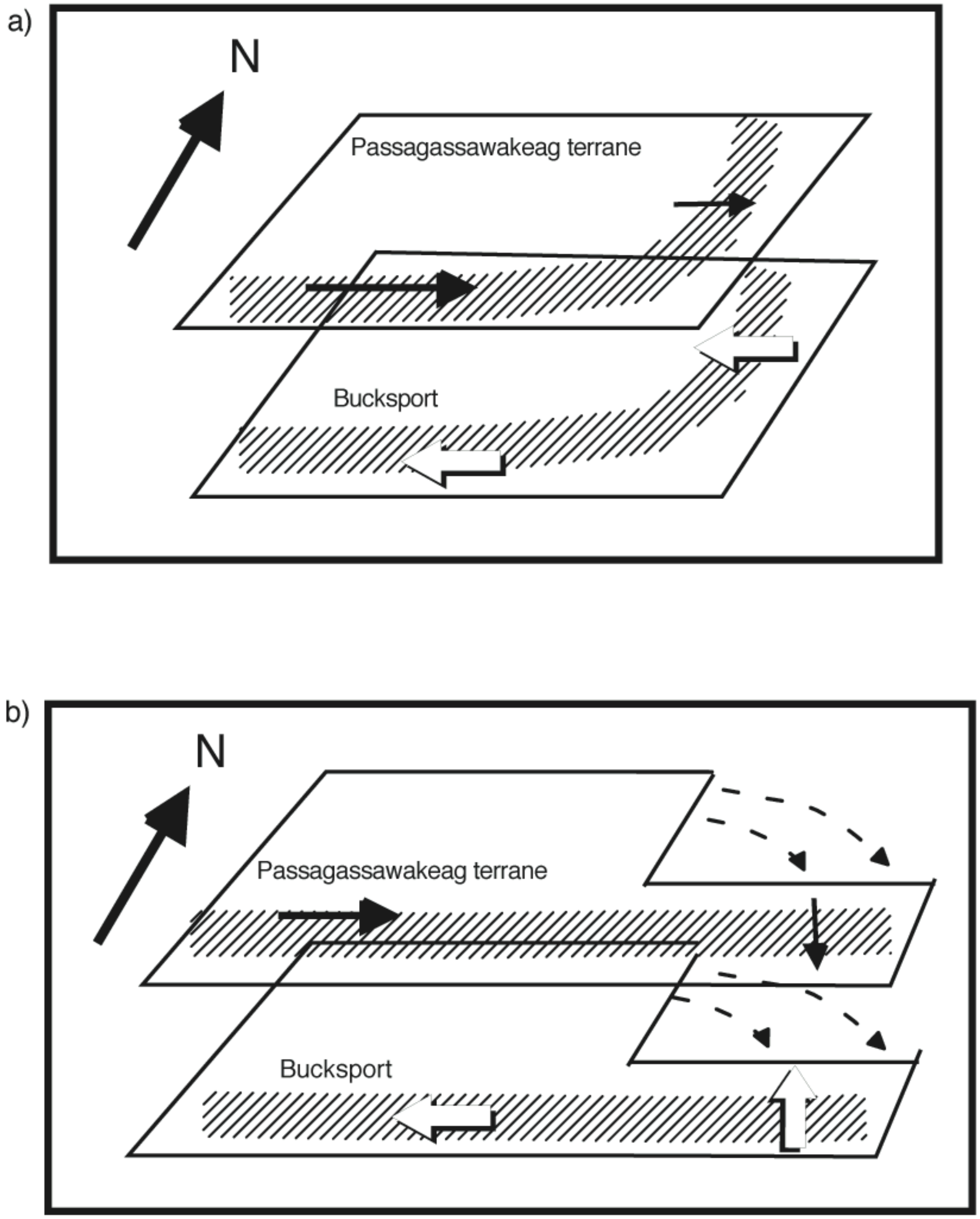


Figure 5.1 - Schematic diagram showing kinematics of both boundaries when 'unfolded'; black arrows indicate direction of movement of the Passagassawakeag terrane relative to the Bucksport Fm.; white arrows indicate motion of the Bucksport Fm. relative to the PGW; hatched area is an approximation of the shear zone. a) Sense of shear in mylonites after unfolding dip of foliation to horizontal. b) Sense of shear in mylonites after straightening the eastern boundary, as if it were an extension of the southern boundary, formed in the same manner and orientation.



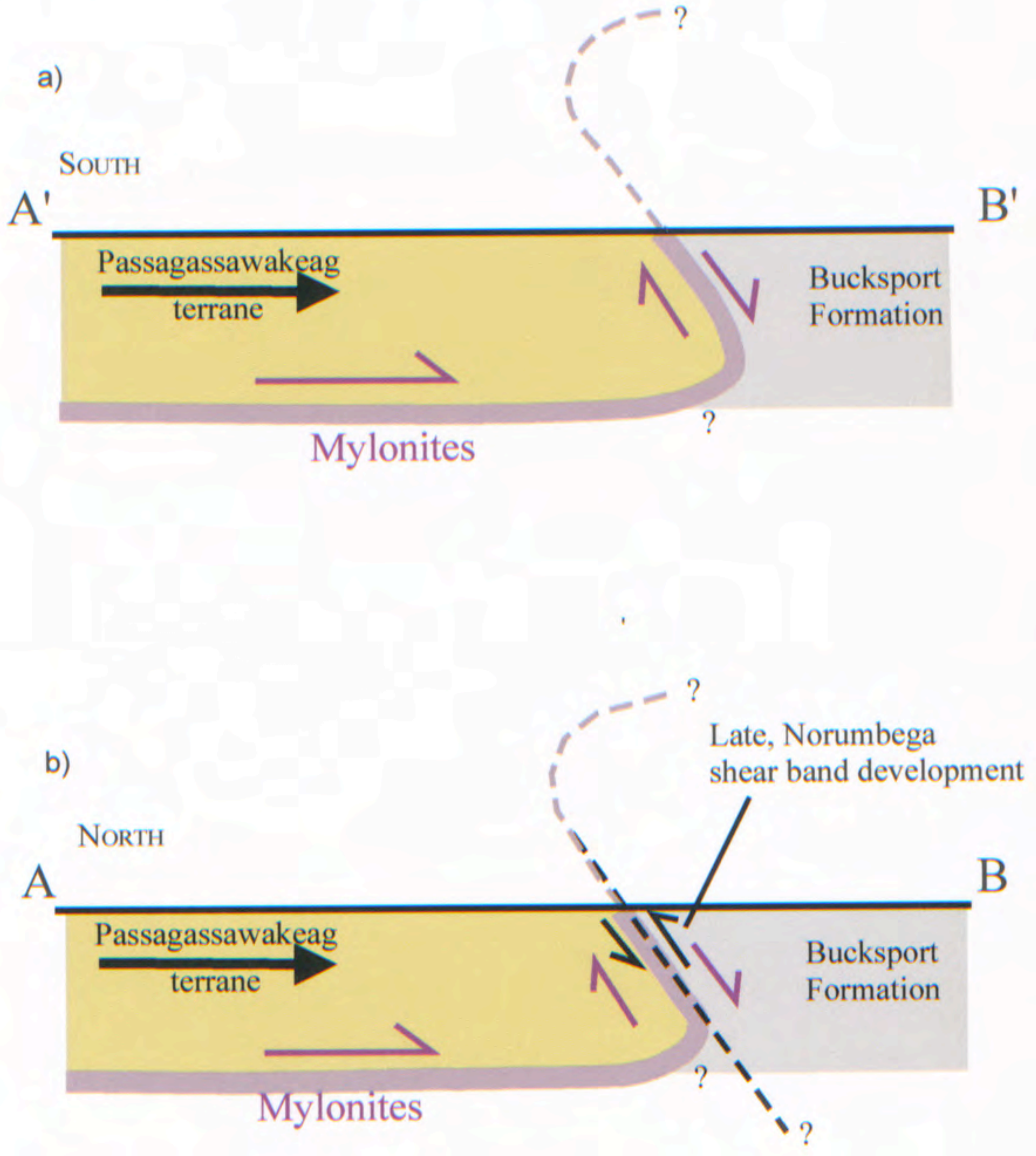
north-dipping in the southern boundary to vertical at the ‘bend’, to east-dipping along the eastern boundary, indicating a mechanical continuity between the two boundaries (Figure 5.0). Kinematic indicators in the mylonites from the ‘bend’ area appear less systematic but the rocks remain highly-strained, implying that these rocks represent a transition from a region of strong dextral shear to one of thrusting. This apparent structural if not lithologic continuity at the bend in the Liberty-Orrington shear zone requires a similar geometry at depth, with transition mylonites occurring between the strike-slip and thrust components of the shear zone.

The role of transpression in the Acadian orogeny

The majority of the tectonic models for the amalgamation of coastal Maine have been focused on the nature of the initial collisions and sutures between terranes, all thought to be major thrust faults (Robinson et al., 1998; Osberg et al., 1995). The Norumbega Fault Zone has long been considered a late, although possibly reactivated feature with moderate dextral offset that has obscured the original terrane boundary relationships in coastal Maine (Keppie, 1989; Osberg et al., 1989; Ludman, 1986).

In recent years, extensive, long-lived dextral strike-slip fault systems have been described for coastal Maine (Stewart et al., 1995; Swanson, 1995; West and Hubbard, 1997). While many of these fault systems are still considered secondary tectonic features, a Silurian strike-slip fault system in Penobscot Bay is recognized as the primary mechanism of terrane amalgamation, in conjunction with a major thrust fault at depth (Stewart et al, 1995). The Penobscot Bay-Smith Cove-Blue Hill dextral strike-slip fault

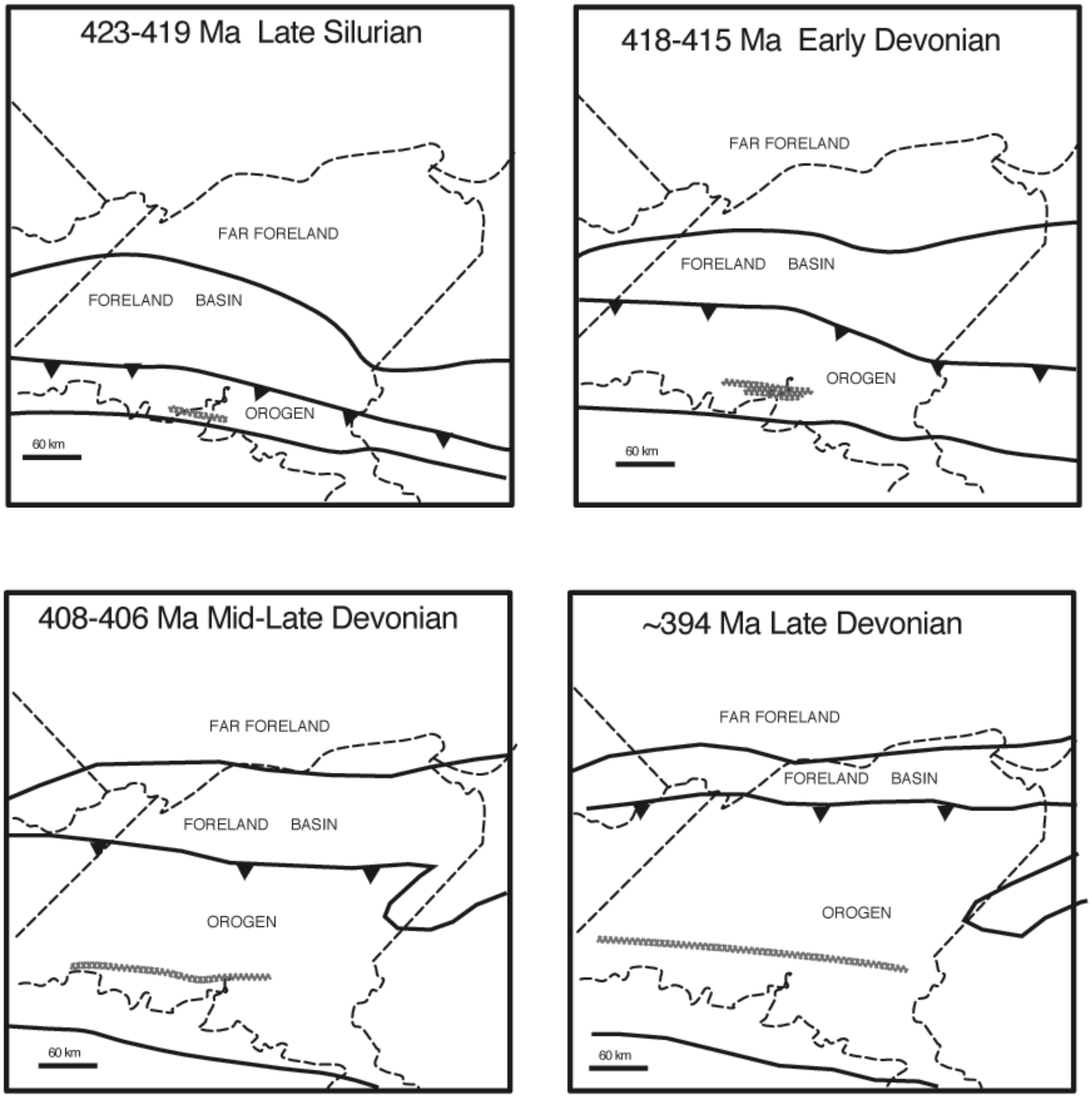
Figure 5.2 - Cartoon cross-sections of the Passagassawakeag- Fredericton Trough terrane boundary as determined by this study. a) section across the southern end of the eastern boundary showing thrust sense and present orientation. b) section across the northern end of the eastern boundary showing late C' shear band development superimposed on older overturned thrust.



zone is 3 km or more wide, and juxtaposes Avalonian and peri-Gondwanan rocks. This fault is believed to be the earliest active fault in the Penobscot Bay region (before 419.5± 1 Ma, U-Pb age of a cross-cutting intrusive suite; Stewart et al., 1995), and dextral movement migrated northward (present coordinates) throughout the later part of the Silurian. West and Hubbard (1997) describe a wide zone of dextral shear along a major splay of the Norumbega Fault Zone to the southwest of Penobscot Bay, interpreted to represent a major episode of Late Devonian (360 Ma) to Early Carboniferous (320 Ma) transpressive tectonism. Dextral strike-slip movement along the Liberty-Orrington shear zone fills both a geographic and temporal gap in the progressive migration of strike-slip motion northward (present coordinates) during the Acadian orogeny, and provides a means for the exhumation of the high-grade Casco Bay- Passagassawakeag terrane.

This migration of strike-slip deformation northward during the Silurian and Devonian fits well with a new model for the migration of the Acadian orogen proposed by Bradley et al. (1998). A comparison of the first-order migration of the dextral strike-slip shear zones discussed above with the position of the Acadian orogen as shown by Bradley et al., (1998; Figure 12) suggests that the shear zones developed near the hinterland-side of the orogenic wedge, and moved inland with the orogen (Figure 5.3). This relationship implies that orogen-parallel motion was an integral part of the Acadian orogeny and must be taken into consideration when reconstructing the nature of the amalgamation of lithotectonic terranes in coastal Maine and New England (Moecher and Wintsch, 1994; Peterson and Robinson, 1993).

Figure 5.3 - Schematic maps showing dextral ductile shearing in the Acadian orogen through time; cross-hatched areas indicate dextral strike-slip motion. Modified from Bradley et al. (1998).



Transpressional tectonics have long been recognized in other portions of the Appalachians and equivalents in the Canadian Maritimes, Newfoundland, Scandinavia, and the British Isles (Doig et al., 1990; Piasecki, 1995; Van Staal et al., 1998; Stewart et al., 1999). Interestingly, all evidence for strike-slip accretion of exotic terranes in all of these areas is of a sinistral sense, opposite of that documented for the northern U.S. Appalachians in this thesis. The 435.5±1.5 Ma (Early Silurian) Kingston Dyke complex of southern New Brunswick was injected during sinistral movement between Avalon and Laurentia (Doig et al., 1990). In Newfoundland, Piasecki (1995) documented complex ductile shearing early (Ordovician to Silurian) in the development of the boundaries between the Gander, Dunnage, and Humber zones of both sinistral and dextral sense. The Great Glen Fault Zone of the Caledonian orogenic belt of the British Isles has been shown to be a major, sinistral shear zone active between 428 Ma and 390 Ma (Stewart et al., 1999). This sinistral shearing would have taken place along strike to the northeast (present coordinates) of the concomitant dextral shearing in Penobscot Bay and the Liberty-Orrington shear zone in coastal Maine. While it is clear that ductile shearing produced by orogen-parallel motion was ubiquitous, the plate kinematics required to produce this motion in opposite directions appears more complex than simple oblique collision, and probably would involve escape tectonics.

CHAPTER 6

SUMMARY

Coastal Maine consists of a conglomeration of distinct lithotectonic terranes separated by faults that were juxtaposed during a complex, multi-component Paleozoic orogen (Bradley et al., 1998; Van Staal et al., 1998). The purpose of this study was to find and document evidence for the existence of one of these faults and to try to determine its nature and, subsequently, the nature of the relationship between the Passagassawakeag and Fredericton Trough terranes that it separates. Because the Passagassawakeag (Liberty-Orrington/Casco Bay) terrane is regionally extensive, the nature of its emplacement into the Bucksport turbidites of the Fredericton Trough has significant implications for the style of amalgamation of the Coastal Lithotectonic Block of Maine and the Acadian orogeny.

Abundant evidence for the existence of the Liberty-Orrington fault was found in the form of an extensive and continuous belt of mylonites along its trace. Foliation in the mylonites is vertical or near-vertical with near-horizontal stretching lineations. Kinematic indicators include feldspar and biotite porphyroclasts, z-folds, coarse mica-fish, quartz ribbons, boudined quartz veins, and delta and sigma-type porphyroclasts of garnet, feldspar + quartz, and tourmaline, all displaying consistent and strong dextral shear. A localization of strain as the shear zone is approached is clearly demonstrated in the biotite-grade turbidites of the Bucksport Formation, as hornblende-filled fractures originally normal to foliation become oblique and are eventually involved in the foliation and small z-folds. This evidence clearly dictates that the Liberty-Orrington fault is a major shear zone with right-lateral strike-slip kinematics in its present orientation.

As the shear zone is followed to the east of Jacob Buck Pond, the mylonites turn north, and the sense of shear becomes more complex. Foliation is vertical in this transition zone, and eventually dips moderately to the east along the entire eastern boundary, interpreted in this thesis as an over-turned transpressional thrust. Here, the original thrust sense of the primary foliation (the Rider Bluff unit) is overprinted by late, chlorite-filled shear bands displaying a Bucksport-over-Passagassawakeag thrust sense that are most prominent in the northern part of the eastern boundary. I interpret this C' fabric with a younger-on-top-of-older sense as developing due to its proximity to the Norumbega Fault Zone.

The transition between the southern boundary and the eastern boundary mylonites is continuous, and the intense deformation found within the Liberty-Orrington shear zone does not extend east-northeast into the surrounding Bucksport turbidites at the transition-bend, as would be expected if the boundaries were entirely separate faults. When considering the southern and eastern boundaries as a continuous fault system, the kinematics simply do not allow for the entire shear zone to have originated as a thrust fault, as most previous workers have proposed, unless the thrust was directed from the southwest along strike, in which case the root zone is missing.

Time constraints on the development of the Liberty-Orrington shear zone are provided by the cross-cutting late Devonian Mt. Waldo pluton, and the early Devonian migmatitic Stricklen Ridge granite, which is involved in the shear zone deformation. Petrographic analysis reveals a sequence of metamorphic and deformational events through which the exhumation of the Passagassawakeag terrane can be qualitatively traced through T-t space. Essentially, the earliest preserved movement within the shear zone occurred sometime in the Early to Middle Devonian, during the Acadian orogeny.

The Liberty-Orrington shear zone is in some part responsible for the exhumation of a major high-metamorphic grade terrane in coastal Maine, extending from the present study area south at least to the vicinity of Portland, Maine. Major dextral strike-slip fault systems have been described for the Silurian in Penobscot Bay, across strike to the south, and for the Late Devonian- Carboniferous Norumbega Fault Zone, across strike to the north (Stewart et al., 1995; West and Hubbard, 1997). I interpret the Liberty-Orrington shear zone to represent a part of a more extended continuum of dextral shear during the early part of the Acadian orogeny, which migrated north with the orogenic wedge (Bradley et al., 1998). The evidence presented in this thesis strongly suggests that transpressive tectonism due to oblique collision was a major component of the Acadian orogeny, and that dextral strike-slip shearing played an integral part in the amalgamation of the terranes in coastal Maine.

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APPENDIX A - TABLES

TABLE A-1 - Mineralogy of Thin Sectioned-samples

Sample #	Major minerals	Accessory minerals	Metamorphic grd (observed)	Formation /protolith
5-7-20	pl, qtz, ms, chl*	grt, tur, bt, zrn, ap	≥ garnet	mylonitized Stricklen Ridge Granite
10-6-15	qtz, pl, bt, chl, grt	mag	≥ garnet; recryt bt+chl w/defm.	Rider Bluff: mylonitized Copeland
16-7-24	qtz, pl, bt, hbl, ms	ill, hem, zrn	biotite; slightly hornfelsed	Bucksport
17-7-24	qtz, pl, bt, hbl, Fe-amphibole	spn, hem, ill	biotite; hornfelsed	Bucksport
19-7-24	qtz, pl, bt, hbl, cal	chl, ill, ap, zrn	biotite-chlorite?	Bucksport
28-6-19	pl, qtz, sil, bt, hbl, spn	hem, zrn	sillimanite	PGW gneiss, calc-silicate unit
36-6-19	pl, qtz, ms, bt, chl, grt, sil	hem, tur, glt, aln, zrn	sillimanite	Mica-fish mylonite: Copeland?
49-6-29	qtz, pl, bt, cal, hbl	tur, aln, hem, ill	≥ biotite hornfelsed?	Bucksport (near shear zone)
50-6-29	qtz, pl, bt, hbl	hem, aln, tur, cal?, chl*, zrn	~ biotite; prob. hornfelsed	Bucksport (near shear zone)
51-6-29	qtz, pl, bt, hbl, cal	hem, tur, mag, zrn	~ biotite; prob. hornfelsed	Bucksport or calc-silicate unit of PGW
53-6-29	qtz, hbl, bt, cal, pl?	hem, aln, prl	≥ chlorite (crd)	Bucksport (?)
54-6-29	qtz, bt, pl, grt	hem, tur, chl*, zrn	≥ garnet	fine-grained schisty mylonite: Copeland
55-6-29	qtz, ms, pl, grt	tur, chl*, zrn, hem, ill	≥ garnet	Mica-fish mylonite: Copeland (?)
56-6-29	qtz, pl, chl, bt, hbl, tr	aln, hem, prl	≥ biotite	Fine-grained mylonite: Bucksport (?)
57-6-29	qtz, pl, bt, Fe-hbl, ms	hem, zrn, ill	≥ biotite; hornfelsed	Fine-grained mylonite: Bucksport or PGW
58-6-29	qtz, pl, bt, tur, grt	chl*, hem, zrn, prl	≥ garnet; hornfelsed	Fine-grained mylonite: Copeland
59-6-29	qtz, bt, pl, chl*, ms?	hem, aln	≥ biotite; hornfelsed?	Fine-grained mylonite: Bucksport
61-7-1	qtz, pl, prl*,	hem, zrn,	≥ biotite;	Schisty-mylonite(?):

Sample #	Major minerals	Accessory minerals	Metamorphic grd (observed)	Formation /protolith
	chl*, bt	spn, tur	hornfelsed?	SRG
65-7-6	qtz, pl, bt, ms, cal, tur, grt, sil	aln, hem, ill, chl*	~ sillimanite; hornfelsed?	Fine-grained mylonite: PGW
71-7-7	qtz, pl, ms, cal	hem, bt, tur	biotite	Bucksport
80b-7-10	qtz, pl, hbl, aln, spn, sil	hem, zrn, chl*	~sillimanite	Fine-grained mylonite: PGW
84-7-13	qtz, ms, bt, cal, pl	chl*, mag, aln, tur	biotite	Bucksport
90-7-11	hbl, qtz, pl	sil, ill, ap, zrn	~sillimanite	amphibolite lens of the Copeland
91-7-13	bt, pl, qtz, green biotite	ms, grt, ill, hem, zrn, ap	≥ garnet	Rider Bluff
97-7-15	qtz, pl, bt, ms	hbl, ill, hem, chl*	biotite-chlorite	Bucksport, strained, hornfelsed?
99-7-16	qtz, pl, bt, ms	hbl, hem, ap	≥ biotite	Bucksport, strained, hornfelsed (?)
100-7-16	qtz, pl, bt	zrn, hem, chl*, ap	biotite-chlorite	Bucksport, strained, hornfelsed (?)
101-7-16	qtz, ms, bt, pl?	hem, tur, zrn, opaq.	biotite	Bucksport
113-7-21	qtz, pl, bt, ms, hbl	ap	≥ biotite	Bucksport, strained (comp. banding)
115-7-24	ms, qtz, alb, tur, grt, bt	hem, ill?, zrn	≥ garnet	Fine-grained mylonite: Copeland?
117-7-24	qtz, alb, hbl, spn, mc, sil	hem, bt, chl, zrn	~ sillimanite hornfelsed?	PGW or sheared SRG
119-7-24	qtz, alb, bt, hbl, mc	spn, hem, mag, zrn	≥ biotite; hornfelsed?	PGW gneiss

Mineral abbreviations according to Kretz: Symbols for rock-forming minerals: qtz=quartz, pl=plagioclase, bt=biotite, hbl=hornblende, ms=muscovite, grt=garnet, mag=magnetite, ill=illmanite, hem=hematite, zrn=zircon, spn=sphene, chl=chlorite, sil=sillimanite, cal=calcite, tur=tourmaline, aln=allenite, prl=pyrophyllite. (≥) indicates that the observed metamorphic grade is lower than previously reported, and the sample probably did not contain key phases such as garnet or sillimanite. * indicates that the phase is secondary.

TABLE A-2 - Summary of structures in thin-sectioned samples

Sample #	macrostructures	strike & dip	lineations (pitch)	microstructures	SOS	Formation & location
5-7-20	highly strained, mica-fish	N70E, 90	17E	S-C foliation (micas + inclusions= S; micas = C); bands of Q & P domains; foliation overprinted by crenulation	dextral	mylonitized Stricklen Ridge Granite, west side of Jacob Buck Mtn.
10-6-15	2mm light & dark mineral bands, small open folds, qtz rods	N320W, 60NE; fold axes 60°	strong, 87N	chl-filled C' fabric cuts bands of pl+qtz+chl & bt+qtz+mag; over-printing older C' fabric of opposite sense of shear	sinistral, cutting dextral	Rider Bluff, top of Rider Bluff on eastern boundary
16-7-24	Weak foliation at an angle to comp. banding; late hbl-filled fracts.; one large pl+qtz augen	c. b. N10E, 90; fol.= N348W, 90, frac. N69E	none	late qtz-filled fractures ~ 60°- 45° from foliation = extensional shear bands ?	dextral	Bucksport, Silver Lake Rd
17-7-24	Comp. banding intersected by foliation	N332W, 82E	none apparent	slight S- foliation with small shear zones developed around calc-silicate 'pod'		Bucksport, Silver Lake Rd
19-7-24	Foliated, fissile in places, concordant hbl-filled fracts. , qtz veins, and small folds	N40E, 62SE	16NE	S-C' foliation; qtz has undulose ext., micas in C' dir., qtz & late qtz veins in S dir.	dextral	Bucksport, intersection of State Farm Rd. & Silver Lake Rd.
28-6-19	Gneissic banding, fine-grained, intruded by SR granite	N70E, 50N-70N	30E	foliation defined by compositional banding; minerals are annealed	dextral	Calc-silicate unit of Passagassawakeag gneiss, west side of Jacob Buck Mtn.
36-6-19	Crenulated schist with qtz ribbons	N298W 60NE	mica fish	Mica fish & boudined qtz ribbons; S-C foliation, cut by crenulation (local?)	dextral	Mica fish mylonite, Copeland; south side of Jacob Buck Mtn.
49-6-29	Comp. banding, moderate foliation, late hbl-filled veins	N68E, 90; v. N46E-N58E	03W	Chaotic: initial fol. is S-C', with C' dominant; late hbl-fracts. oriented in S direction	dextral	Bucksport, SE of Cobb Hill

Sample #	macrostructures	strike & dip	lineations (pitch)	microstructures	SOS	Formation & location
50-6-29	Foliated, boudined & overlapped qtz ribbons	N68E, 85NW	07E	Looks ‘chewed up’: primary S-C’ fol. defined by matrix mica, qtz ribbons, & stretched hbl. Locally intersected by a weak crenulation ~45° to the C dir.	dextral	Moderate-high strained Bucksport; SE of Cobb Hill
51-6-29	Very fine-grained, foliated	N67E, 70NW	05W	Nice S-C foliation (micas & hbl), late C’ fabric is dominant; small isoclinal folds	dextral	Fine-grained mylonite: Bucksport or calc-sil. PGW; SE of Cobb Hill
53-6-29	Fine-grained, sugary texture, foliation defined by qtz ribbons	N68E, 81NW	07E	Clear S-C fol. (qtz=S, fine micas= C), w/C’ developed in pelitic layers; comp. banding, late pervasive fracts. in S dir.	dextral	Fine-grained mylonite: Bucksport or calc-sil. PGW; SE of Cobb Hill
54-6-29	Foliated schist, very fine crenulations, qtz ribbons	N62E, 78NW	08W	S-C & C’ foliation with beautiful grt porphyroclasts w/mica tails, some grt fish; cordierite porphyroclasts	dextral (and how)	Mica-fish mylonite: pelitic PGW or Copeland
55-6-29	Mylonitic schist, mica fish ‘eyes’, qtz ribbons, grt porphyroclasts	N50E, 65SE	08E	Gorgeous S-C & C’ foliation, loads of mica fish, dynam. recrys. qtz, rotated grt porphyroclasts	dextral	Mica-fish mylonite: pelitic PGW or Copeland; SE of Cobb Hill
56-6-29	Fine-grained mylonite, surgery texture, boudined qtz ribbons, porphyroclasts	N59E, 82N	05E	Nice S-C & C’ foliation, qtz ‘fish’ in S dir., bt & chl in C & C’ dirs. All foliation is cut by a late crenulation	dextral, late sinistral?	Fine-grained mylonite: Bucksport; SE of Cobb Hill
57-6-29	Comp. banding, fine-grained, heterogeneously strained	N52E, 86N	00	S-C & C’ foliation defined by micas, δ pl porphyroclast, boudined qtz ribbons; qtz veins cut fol., late fracts. cut all fol. ~ ⊥, hbl & qtz ‘fish’	dextral	Fine-grained, hornfelsed mylonite: Bucksport or calc-sil. PGW; SE of Cobb Hill
58-6-29	Very fine-grained mylonite w’ tur & grt porphyroclasts	N54E, 90	07W	S-C & C’ fol. defined by micas; grt porphyroclasts are rounded or oblong w/ δ-type foliation tails; large tur cross-cut fol. but are also broken by it; all fol. is cut by late, ⊥ qtz fractures	dextral	Fine-grained mylonite: Bucksport or pelitic PGW; SE of Cobb Hill
59-6-29	Mylonitic texture, large dextral indicators	N56E, 90	13E	S-C foliation defined by micas, boudined & folded qtz ribbons, dyn. recrys. qtz matrix, chl fish & ribbons	dextral	Fine-grained mylonite: Bucksport or pelitic PGW; SE of Cobb Hill
61-7-1	Mylonite schist, qtz ribbons	N60E, 90	02W	extensive pl fish, qtz ribbons w/Z-folds, C’ ?, heterogeneous strain- areas of brittle deformation	dextral	Mylonite (?): PGW or granite; SE of Cobb Hill

Sample #	macrostructures	strike & dip	lineations (pitch)	microstructures	SOS	Formation & location
65-7-6	Very fine-grained, foliated, stretching lineations	N54E, 86NW	06NW	cal & ms fish, micas & tur define a faint S-fabric, qtz horizons = C; subtle folds cut S-C foliation	dextral	Mylonitic, hornfelsed Bucksport (?); Rte. 15-blueberry field
71-7-7	Sandy & pelitic, open folds, strong horizontal mineral lineation	N54E, 84S	17W	Only horizons of foliation, a few of qtz ribbons	dextral	relatively undeformed Bucksport
80b-7-10	Fine-grained, grey mylonite, qtz ribbons	N80E, 80N	31W	S-C & C' foliation (elongate hbl & micas = S; qtz & pl = C; micas = C'); late qtz/crd ribbons; chl/qtz veins cut S-C fol.; all cut by crenulation/ folding, with qtz recrys. along axes	dextral	Fine-grained mylonite: PGW (?); S side of Jacob Buck Mtn.
84-7-13	Slightly foliated (?)	N325W, 54SW	90	slight foliation defined by small zones of preferentially oriented micas; some recrys. elongate ms; smushed sigmoidal qtz & pl		relatively undeformed Bucksport
90-7-11	very finely-laminated, alternating bands of light & dark minerals	N42E, 64N	63W	foliation defined by alternating bands of hbl & qtz+pl =C, larger hbl grows ~40° to fol.=S; slight C'; very late extensional fractures cut all foliation	dextral	strained amphibolite lens of Copeland
91-7-13	very fine-grained, small s-folds	N41E, 84N	06W	S-C & C' foliation defined by matrix micas, qtz ribbons, & mica fish; qtz ribbons are boudined & isoclinaly folded; pl & grt porphyroclasts, grt is broken; C'= green biotite; brittle & ductile deformation	dextral	ductile & brittle deformed Copeland or Rider Bluff, mylonitic
97-7-15	strained, with hbl-filled fractures	N20E, 66SE	35S	S-C (?) foliation (weak overall, heavy on C) defined by micas & qtz veins w/hbl; qtz is dynam. recryt. large bt has undulatory extinction, overgrow foliation & appear deformed; C' fol. w/ opposite sense (?)	dextral and sinistral?	moderately foliated Bucksport with one, strong foliation
99-7-16	foliated w/ hbl-filled fractures	N62E, 72NW	35W	weak S-C foliation defined by bt w/ hbl-fractures cutting fol. at ~45-60°	dextral	strained Bucksport near shear zone
100-7-16	strong foliation w/ concordant	N73E,	05E	S-C' foliation, biotite porphyroclasts	dextral	strained Bucksport near

Sample #	macrostructures	strike & dip	lineations (pitch)	microstructures	SOS	Formation & location
	calc-silicate pods, boudined qtz veins	60S		with sigmoidal shape		shear zone
101-7-16	Foliated, very fine-grained	N354W, 64E	04N	slight segregation of P & Q domains; micas define C', no obvious S-C; late hem-filled C' fabric of opposite sense	dextral, then sinistral	Bucksport; out of field area near Hancock Pond, at 'bend' in terrane boundary
113-7-21	finely-laminated	N08E, 58SE	85SE	diffuse bands of P & Q domains = foliation; poikolititc bt porphyroclasts	dextral	moderately strained Bucksport
115-7-24	Fine-grained, small qtz ribbons	N34E, 84NW	03W	Z-folded qtz veins, porphyroclasts of pl; boudined/stacked qtz ribbons; ms mica fish; strong C' in pelitic layers; S-C fol. is broadly folded (brittle & ductile); fractures along fold axes	dextral: ductile then brittle	Mylonite: Bucksport or Copeland; just off Rte 46, Bucks Mills
117-7-24	Gneissic banding	N64E, 60NW	29NE	Foliation defined by alignment of bt & hbl, layers of qtz veins, dyn. recrys. qtz w/ undulose extinction	dextral	sheared, hornfelsed granite; Cobb Hill
119-7-24	Gneissic banding, stretching lineations ~⊥ to bands	N36E, 90	90	weak S-C foliation (bt = S, qtz & pl = C)	dextral	Passagassawakeag gneiss; Cobb Hill

TABLE A-3 - Attitudes of foliations and stretching lineations

Outcrop #	Strike	Dip	Lineation: pitch	trend	plunge	Formation
1-6-15	N48E	70NW				mylonite
2-6-15	N47E	72NW				Bucksport
3-6-15	N56E	80SE				“
4-6-15	N50E	75S				“
4b-6-15	N37E	65S				“
5-7-20	N70E	90	17E	N70E	17E	mylonite-granite
5-7-20	N72E	62NW	03W	254W	03W	mylonite
7-6-15	N79E	87N				PGW- pelitic
8-6-15	N77E	46N				Copeland
9-6-15	N70E	80N				“
10-6-15	N334W	60E	87N	N68E	60NE	Rider Bluff
12-6-16	N68E	79N	13NW	N66E	13N	mylonite
13-6-16	N40E	84SE	27W	217W	27SW	Bucksport (?)
14-6-16	N40E	84SE				“
15-6-16	N292W	70NE				fault rock
16-6-17	N10E	85W				Bucksport
17-6-17	N332W	82E				“
17b-6-17	N26E	85NW				“
18-6-17	N45E	87N				“
19-6-17	N40E	80SE	16NE	N44E	16N	“
22-6-18	N78E	25NW				Copeland (?)
23-6-18	N42E	50NW				PGW-pelitic
25-6-18	N58E	30N				“
26-6-18	N78E	50NW	09SW	264W	07SW	PGW- calc-silicate
27-6-18	N78E	52N				PGW- pelitic
28-6-19	N70E	60N	30E	N55E	26NE	PGW- calc-silicate
29-6-19	N75E	70N				“
30-6-19	N82E	40NW				PGW- pelitic
31-6-19	N326W	59N	69SE	N274W	53E	“
32-6-19	N50E	64N	20NE	N41E	18NE	“
33-6-22	N44E	84S				PGW (?) mylonite
36-6-22	N298W	60NE	03W	N300W	03NW	Copeland mylonite
37-6-23	N54E	86SE	16E	N55E	16NE	Bucksport?

Outcrop #	Strike	Dip	Lineation: pitch	trend	plunge	Formation
38-6-23	N60E	68NW	17NW	246W	16SW	“
39-6-23	N59E	60NW	22W	246W	19SW	fault rock
40-6-23	N62E	82N	08W	243W	08SW	PGW- pelitic
44-6-25	N70E	40N	10E	N61E	07NE	mylonite
45-6-25	N55E	90				ultra(?)mylonite
46-6-25	N52E	90	07E	N52E	07NE	mylonite
47-6-25	N75E	80N	24W	260W	24SW	“
47b-6-25	N90E	80N				“
49-6-29	N68E	90	03W	N68E	03W	Bucksport
50-6-29	N68E	85N	07E	N67E	07E	“
51-6-29	N67E	70N	05W	249W	05W	mylonite
52-6-29	N62E	60N				“
53-6-29	N68E	80N	07E	N68E	07E	“
54-6-29	N62E	78N	08W	244W	08W	“
55-6-29	N50E	65S	08E	N54E	07E	“
56-6-29	N59E	82N	05E	N58E	05E	“
57-6-29	N52E	86N	00	N52E	00	“
58-6-29	N54E	90	07W	234W	07W	“
59-6-29	N56E	90	13E	N56E	13E	“
60-7-1	N53E	87NW				“
61-7-1	N60E	90	02W	240W	02W	“
63-7-6	N30E	90				Bucksport?
64-7-6	N60E	64N				“
65-7-6	N54E	86N	06W	234W	06W	mylonite
66-7-6	N43E	83NW	05SW	224W	05SW	“
66b-7-6	N44E	80N	20SW	228W	20SW	“
67-7-6	N35E	70NW				mylonite?
68-7-6	N42E	74N	08SW	225	08SW	mylonite
69-7-6	N60E	80N	04NE	N60E	04NE	“
71-7-7	N54E	84S	17W	232W	17SW	Bucksport
72-7-7	N60E	79S				“
73-7-9	N46E	70N	19NE	N39E	18NE	mylonite
74-7-9	N48E	42N				“
75-7-9	N42E	70N				“
76-7-9	N50E	75N				“
77-7-9	N48E	81N				“
78-7-9	N56E	90	00	N56E	00	“
79-7-9	N42E	52N				foliated granite
80-7-10	N80E	90				mylonite
80b-7-10	N80E	80N	31W	266W	30SW	“
81-7-10	N62E	86S				“
82-7-10	N70E	66N	05SW	252W	04SW	“

Outcrop #	Strike	Dip	Lineation: pitch	trend	plunge	Formation
83-7-10	N90E	90				“
84-7-13	N325W	54SW	90	234W	54SW	Bucksport
85-7-13	N312W	45NE				“
86-7-13	N66E	52N				“
88-7-13	N06E	50NW	18N	354W	14NW	mylonite
90-7-13	N42E	64N	63W	262W	52SW	Rider Bluff?
91-7-13	N41E	84N	06W	222W	06SW	mylonite
92-7-13	N28E	62SE	07N	N25E	06N	Rider Bluff
93-7-15	N286W	64SW	25NW	274W	22NW	Bucksport
94-7-15	N16E	70SE				Copeland
95-7-15	N24E	76SE	08SW	202W	08SW	Bucksport
96-7-15	N36E	86S				“
97-7-15	N20E	66SE	35SW	186W	32SW	“
98-7-16	N28E	84NW	17SW	210W	17SW	“
99-7-16	N62E	72NW	35W	254W	33SW	“
100-7-16	N73E	60S	05E	N75E	05NE	“
101-7-16	N354W	64E	04N	356NW	04NW	“
102-7-16	N10E	60E				“
103-7-17	N60E	40NW				mylonite
104-7-17	N320W	90				“
105-7-17	N330W	90				“
106-7-17	N30E	40SE				“
108-7-20	N40E	76NW				PGW-pelitic
109-7-21	N27E	68SE				Bucksport
110-7-21	N24E	84NW				“
111-7-21	N00	50E				“
112-7-21	N40E	50SE				Rider Bluff
113-7-21	N08E	58E	85SE	108E	62S	Bucksport
114-7-21	N60E	88NW				Copeland?
115-7-24	N34E	84NW	03W	214W	03SW	mylonite
116-7-24	N62E	86SE	09W	240W	09SW	foliated granite
117-7-24	N64E	60NW	29NE	N49E	24NE	fol. granite & PGW
118-7-24	N72E	72NW	48E	N56E	45NE	“
119-7-24	N36E	90				“

TABLE A-4 - Orientations of fold axes

Outcrop #	Fold axes	Notes
10-6-15	N60E, 60NE	fractures along axes, qtz rods in same orientation
11-6-16	N28E, 72NE	near shear zone
12-6-16	N04E, 80NE	in mylonites
15-6-16	N335W, 20N	
19-6-17	N40E, 80SW	Bucksport
30-6-19	N40E, 53NE	PGW
34-6-22	N46E, 87NE	PGW/SRG
35-6-22	N16E, 81NE	Bucksport?
39-6-23	N52E, 60NE	
41-6-23	N42E, 27NE	small sheath fold; pegmatite involved
41b-6-23	N32E, 31NE	beautiful Z-folds
43-6-24	N40E, 77NE	PGW, multiply folded
43b-6-24	N78E, 82NE	“
43c-6-24	N58E, 76NE	“
46-6-25	N292W, 90	Z-folds, parasitic
62-7-3	N10E, 80SW	Copeland; crenulation N346
63-7-6	N31E, 90	Bucksport?
66-7-6	N02E, 81NE	mylonite
70-7-7	N06E, 86NE	Bucksport
71-7-7	N29E, 84SW	Bucksport
76-7-9		small Z-folds
81-7-10		small Z-folds
84-7-13	N25E, 51NE	Bucksport, farthest from shear zone
85-7-13		S-fold
86-7-13		Z-folds
87-7-13	N22E, 87NE	parasitic Z-folds
88-7-13	N06E, 52NE	Z-folds, Bucks Mills
90-7-13	N00, 64N	eastern boundary
91-7-13		small S-folds, & Z-folds
92-7-13	N17E, 62NE	Rider Bluff?
94-7-15	N20E, 60NE	Copeland
96-7-15	N36E, 86SW	Bucksport?
106-7-17	N346W, 40NW	eastern boundary
107-7-17	N42E, 48SW	weird outcrop
109-7-21	N53E, 25SW	large, upright
110-7-21	N24E, 30NE	Bucksport, east
111-7-21		small Z-folds
112-7-21	N40E, 50SW	small, isoclinal, Rider Bluff
115-7-24	N00, 28S; and N24E, 20SW	eastern boundary; north-trending folds overprint small NE folds

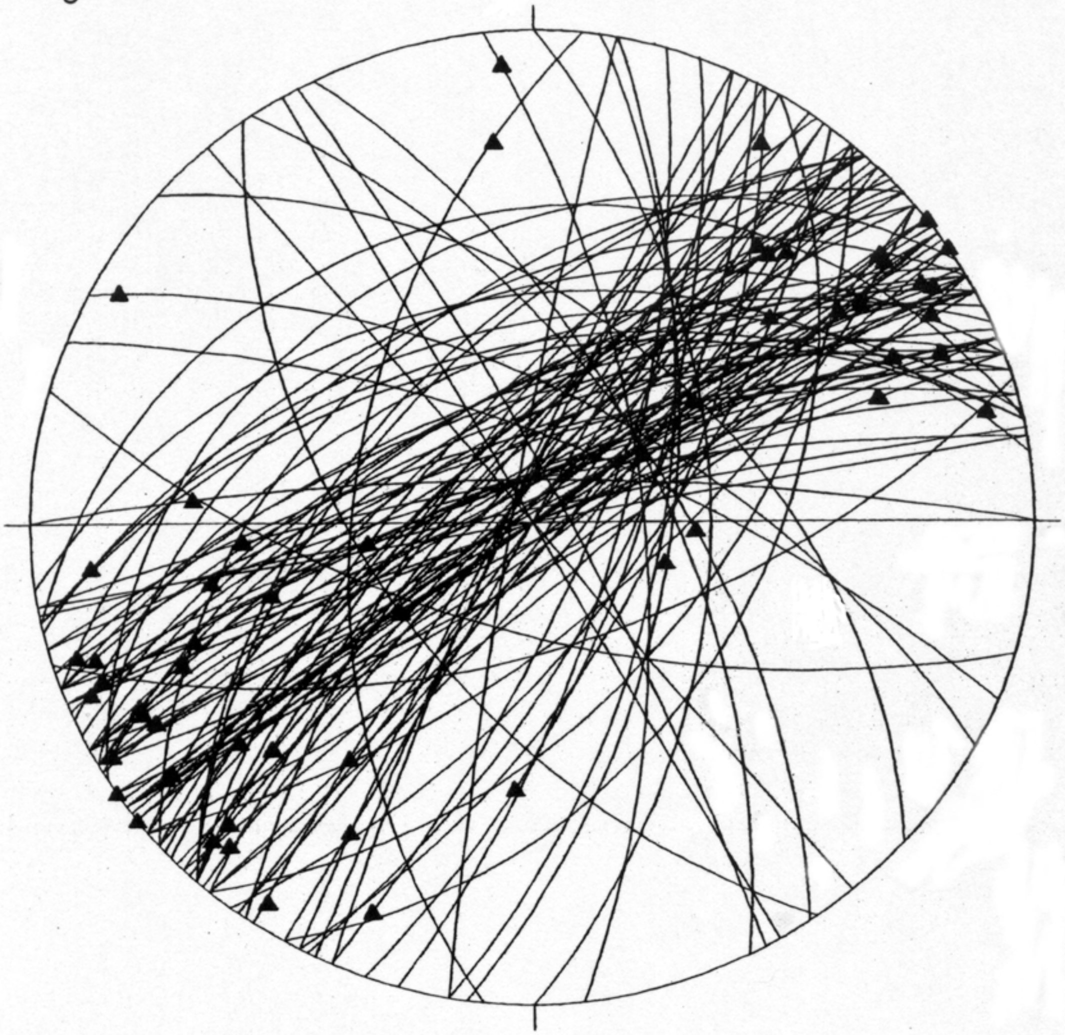
TABLE A-5 -Orientations of late fractures and veins

Outcrop #	Feature	Strike	Dip	Formation	Notes
2-6-15	fractures	1) N316W 2) N338W 3) N22E		Bucksport	#1 appears offset by foliation
3-6-15	qtz vein	N34E	54SE	“	22° N from fol.
3-6-15	fractures	N273W		“	several
4-6-15	qtz veins	N30E		“	20° N from fol.
10-6-15	qtz-filled fractures	N60E	60NE	Rider Bluff	along fold hinges
16-6-17	fractures	N69E		Bucksport	59° E from fol.; hbl-filled
17-6-17	fractures	N332W	82NE	“	hbl-filled
17b-6-17	“	N292W & N356W		“	“
18-6-17	“	1) N296W 2) N64E 3) N27E		“	
19-6-17	qtz veins	N40E	80SE	“	with foliation
19-6-17	fractures	1) N296W 2) N316W 3) N292W 4) N72E	84NW 70SE	“	
27-6-18	dike	N32E		PGW-pelitic	granite, small
28-6-19	fractures	N284W & N324W		PGW- calc-silicate	late, cuts everything
29-6-19	sill	N64E	70NW	“	SRG, with fol.
46-6-25	fractures	N18E		mylonite?	hbl-filled, folded in places
46-6-25	“	N358W	40E	“	cut fol. & hbl fracs.
47-6-25	“	N354W & N318W	90	“	very late conjugate shears (?)
47b-6-25	“	N64E		“	hbl-filled
49-6-29	“	N46E to N58E		“	“
52-6-29	“	N51E	90	mylonite	“
86-7-13	fractures	N318W to N324W		Bucksport	hbl-filled, near ⊥ to foliation
93-7-15	qtz veins	N312W	30SE	“	several, boudined
93-7-15	chert veins	N290W	70SE	“	~8mm ‘veins’ of black chert

Outcrop #	**Feature**	**Strike**	**Dip**	**Formation**	**Notes**
94-7-15	fractures	N33E		Copeland	late
97-7-15	"	N300W to N324W		Bucksport	near ⊥ to foliation; hbl-filled
99-7-16	"	N340W		"	near ⊥ to foliation; hbl-filled
100-7-16	qtz veins	N56E		"	~20° N from fol.

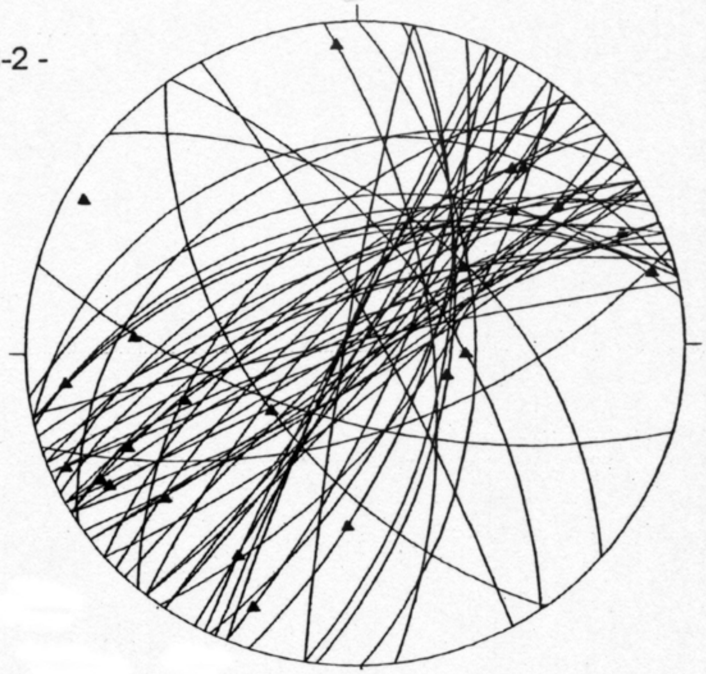
APPENDIX B – STEREOPLOTS

Figure B-1 -



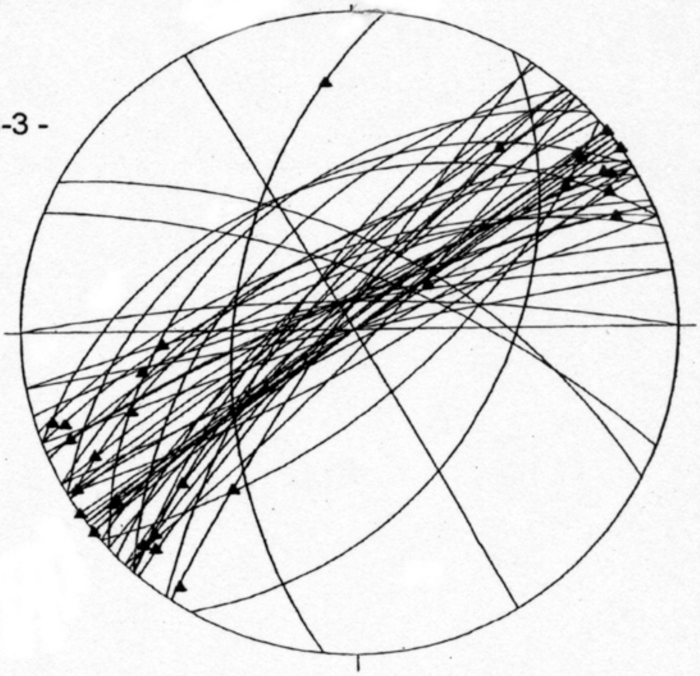
Equal angle projection, lower hemisphere showing strike & dip of foliation; pitch of stretching lineations for all outcrops in the Bucksport-Orland area shown on Plate 1 and listed in Table A-3.

Figure B-2 -



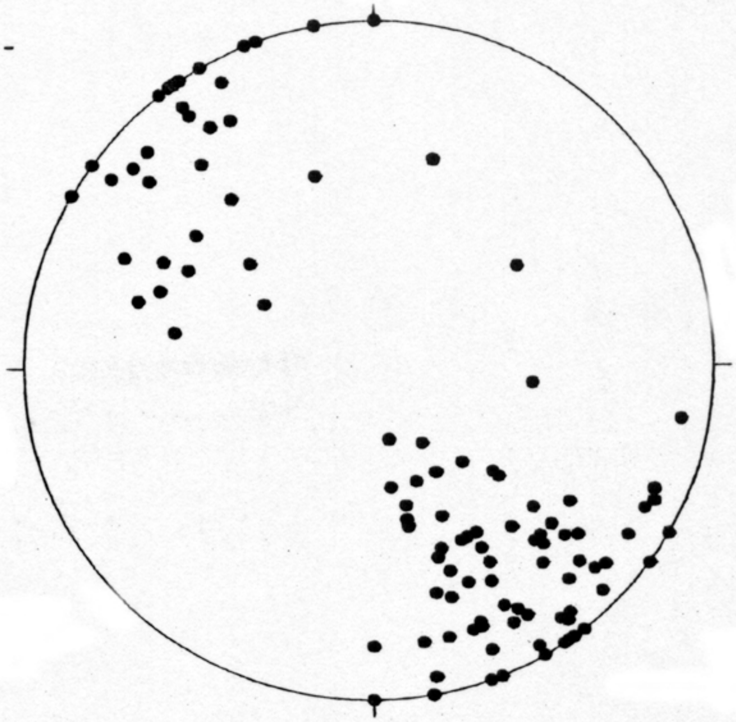
Equal angle projection, lower hemisphere showing strike & dip of foliation and pitch of lineations in the Passagassawakeag, Bucksport, or Copeland formations listed in Table A-3.

Figure B-3 -



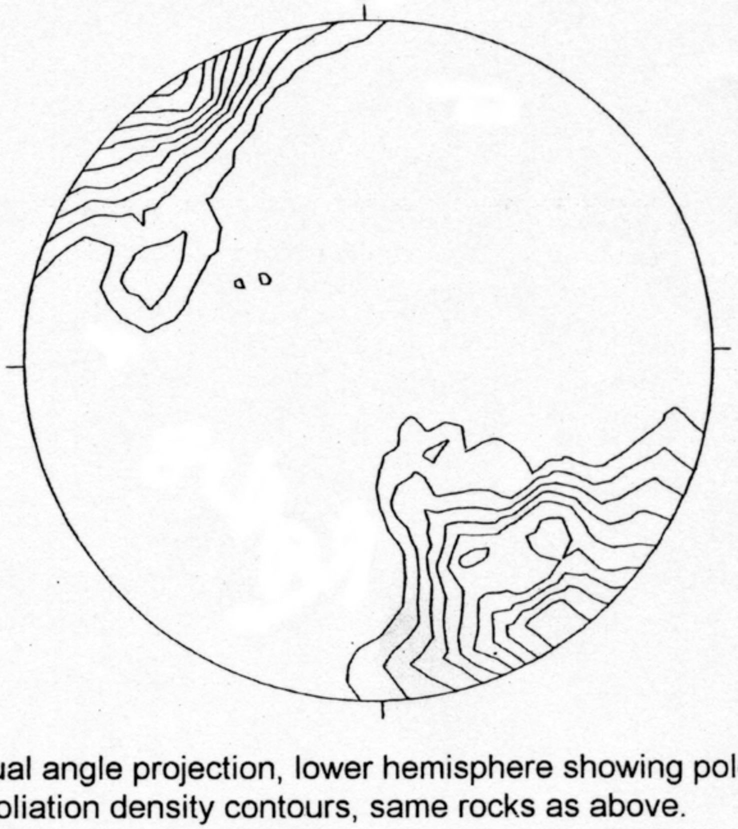
Equal angle projection, lower hemisphere showing strike & dip of foliation and pitch of lineations in mylonites shown on Plate 1 and listed as mylonite or Rider Bluff on Table A-3.

Figure B-4a -



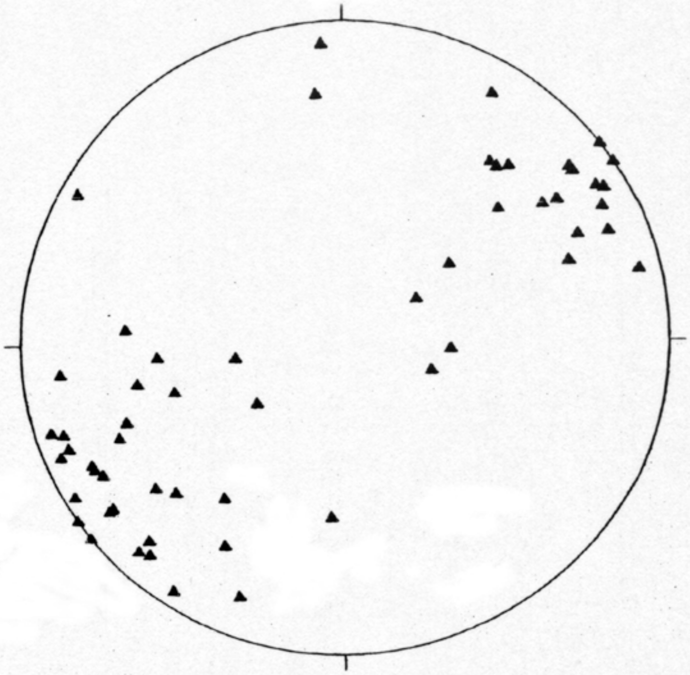
Equal angle projection, lower hemisphere showing poles to foliation of mylonites shown on Plate 1 and listed as mylonite or Rider Bluff in Table A-3.

Figure B-4b -



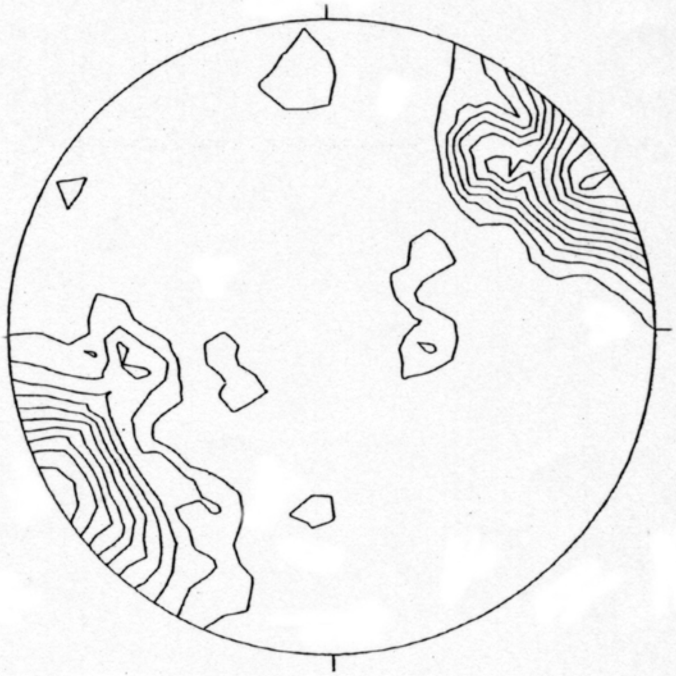
Equal angle projection, lower hemisphere showing poles to foliation density contours, same rocks as above.

Figure B-5a -



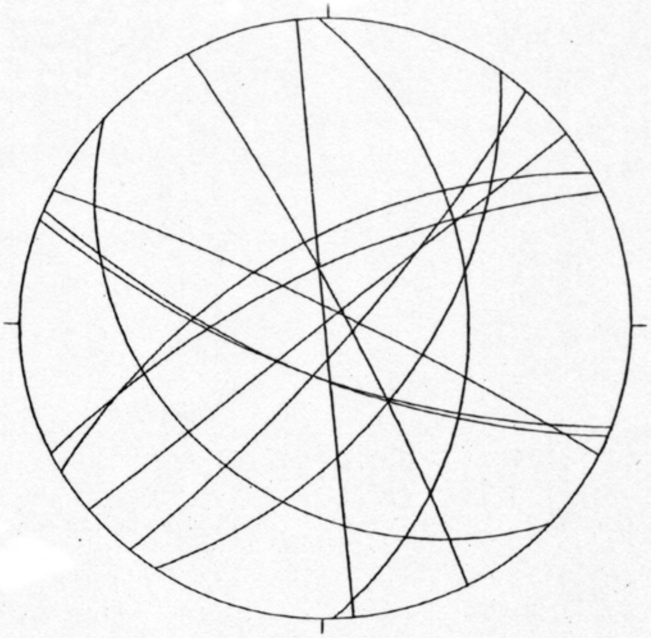
Equal angle projection, lower hemisphere showing orientations of stretching lineations in foliated rocks shown on Plate 1 and listed in Table A-3.

Figure B-5b -



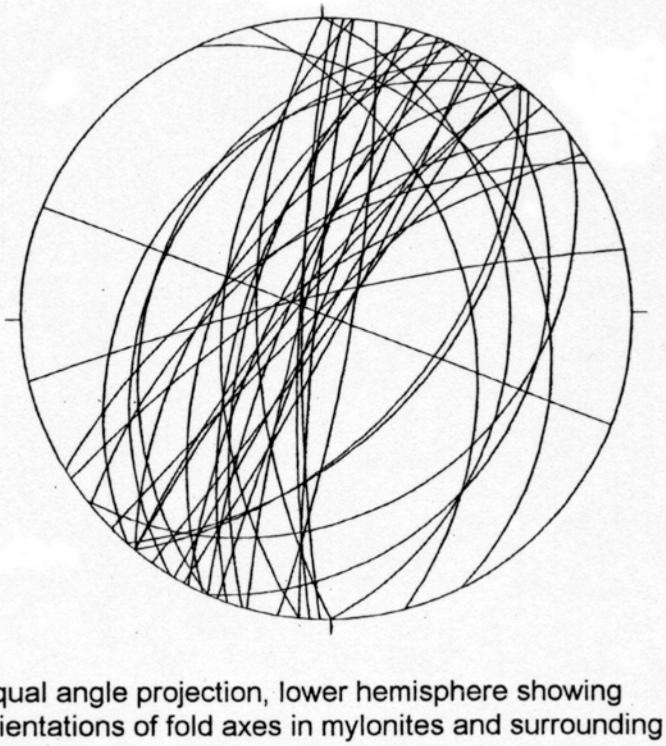
Equal angle projection, lower hemisphere showing stretching lineation density contours, same rocks as above.

Figure B-6 -



Equal angle projection, lower hemisphere showing orientations of fractures and veins in mylonites and surrounding rocks shown on Plate 1 and listed in Table A-5.

Figure B-7 -



Equal angle projection, lower hemisphere showing orientations of fold axes in mylonites and surrounding rocks shown on Plate 1 and listed in Table A-4.