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STRATIGRAPHY AND STRUCTURAL GEOLOGY OF THE WYTOPITLOCK AND  
SPRINGFIELD FIFTEEN-MINUTE QUADRANGLES, EASTERN MAINE

by

JOHN HOPECK

A dissertation submitted to the Graduate Faculty in Earth and Environmental Sciences in partial fulfillment of the requirements for the degree of Doctor of Philosophy, The City University of New York.

1998

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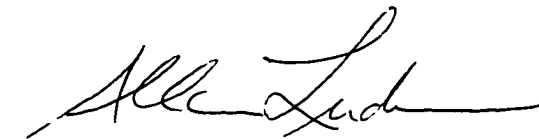
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This manuscript has been read and accepted for the Graduate Faculty in Earth and Environmental Sciences in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

1/26/98


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THE CITY UNIVERSITY OF NEW YORK

## Abstract

STRATIGRAPHY AND STRUCTURAL GEOLOGY OF THE WYTOPITLOCK AND  
SPRINGFIELD FIFTEEN-MINUTE QUADRANGLES, EASTERN MAINE

by

John Hopeck

Advisor: Professor Allan Ludman

Study of the boundary of the Aroostook - Matapedia Belt and Miramichi Anticlinorium reveals that the two tracts show very similar post-Caradocian stratigraphies and that the boundary represents the edge of a relatively shallow marine basin developed in the Late Ordovician. Broadly similar sections of Ashgillian-and-younger rocks described elsewhere in northeastern Maine imply formation of similar basins on the Miramichi volcanic basement subsequent to its accretion to North America in the Middle Ordovician. These small basins were blanketed by regionally extensive deep-water sandstones and shales, representing a clastic wedge derived from the Avalonian continent, in the Late Silurian. Structures within the rocks of these basins record slumping within the accumulating sediment, compression of the basins, and development of a series of dextral oblique-slip faults in the Early Devonian. Similarities between the stratigraphies and structures of northeastern Maine and the Central Maine Belt and Fredericton Trough suggest a generally common history for these supracrustal blocks from the latest Ordovician onward, and that the St. Croix Belt therefore represents the most inboard portion of the Avalonian landmass in the supracrustal section. Brittle structures and pegmatites in the Bottle Lake Pluton indicate that the dextral oblique-slip faults developed in a transtensional regime which coincided with and may be related to the intrusion of this and

other Devonian plutons in Maine, and probably reflects regional stresses developed during oblique convergence of Avalon and North America. Early, regionally distributed dextral tension eventually localized in the Norumbega Fault Zone as convergence continued to the south and southwest. This study therefore describes the evolution of the North American margin from the Late Ordovician through at least the Middle Devonian.

## PREFACE

This work would not have been possible without the inspiration and dedication of my advisor, dissertation committee, other faculty and staff of the City University, and geologists and students from many other institutions. Their contributions to this work cannot be measured; any errors or misstatements which are here are mine and not a reflection on their review and assistance. This work would also have been impossible without the support of friends and family throughout this long process; not only this document, but the steps leading to it could not have been taken without them, whether they know it or not. This is especially for Bert Kay, who was there for the start of this long journey, but not for the end of it.

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## INTRODUCTION

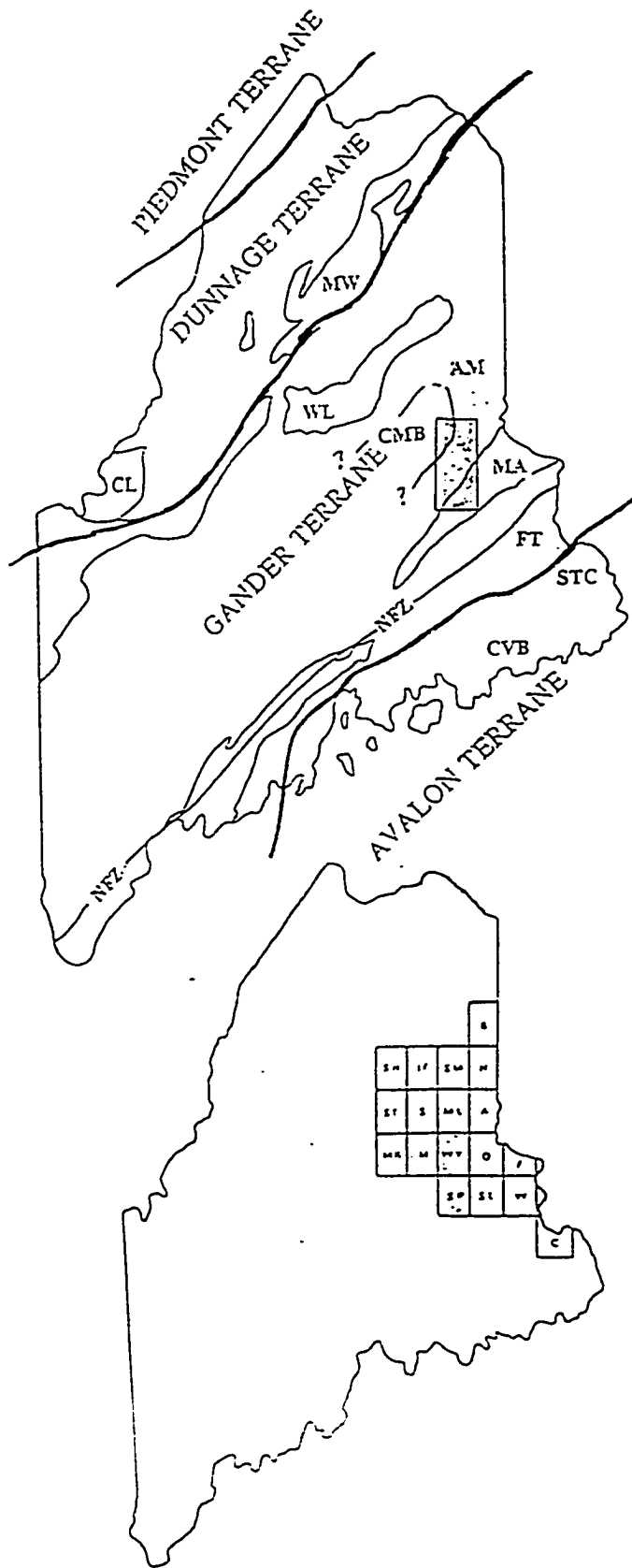
This report presents the first detailed analysis of the geology of the Wytovitlock and Springfield 15-minute quadrangles. The study area includes parts of three of the lithotectonic blocks of Maine's supracrustal sequence (Figure 1); understanding the relationships between these blocks is critical to describing the Early Paleozoic evolution of eastern North America. The study reveals that the distinctions among these blocks are less clear than previously thought, and that their stratigraphies and structures record the accretion of a composite terrane onto the eastern edge of North America in the late-middle Ordovician, and the subsequent complex evolution of that terrane through the Devonian Acadian Orogeny.

### Physical and Political Description

The study area lies in Aroostook, Penobscot, and Washington counties in east-central Maine. Detailed mapping was conducted in the eastern halves of the two quadrangles, with reconnaissance or detailed reconnaissance work in their western halves and in parts of the Scraggly Lake, Danforth, Amity, Mattawamkeag, Houlton, and Smyrna Mills 15-minute quadrangles. The area is sparsely settled, with population concentrated in the small villages of Bancroft, Wytovitlock, Kingman, and Springfield. Farms and homes are scattered along paved roads, principally Route 6, with residences less common along Routes 169, 170, and 171 and connecting gravel roads, and relatively uncommon along Route 2A. An extensive network of unpaved roads, constructed for timber harvesting and access to lake properties, provides access to much of the area.

Maximum relief is approximately 800 feet, although this reflects a few hills with elevations over 1000 feet; relief of 500 feet or less is perhaps more representative. Two

Figure 1: Figure showing the relation of the lithotectonic belts in Maine (after Osberg et al., 1985) to the tectonostratigraphic terranes of Williams (1978); the area of the present study is shaded. NFZ = Norumbega Fault Zone. Key to lithotectonic belts: CL = Chain Lakes Massif; MW = Munsungun - Winterville Anticlinorium; AM = Aroostook - Matapedia Belt; WL = Weeksboro - Lunksoos Lake Anticlinorium; CMB = Central Maine Belt; MA = Miramichi Anticlinorium; FT = Fredericton Trough; STC = St. Croix Belt; CVB = Coastal Volcanic Belt. Inset shows the location of 15-minute quadrangles identified in this study; the Wytovitlock and Springfield 15- minute quadrangles are shaded. B: Bridgewater; H: Houlton; SM: Smyrna Mills; IF: Island Falls; SH: Shin Pond; A: Amity; ML: Millinocket Lake; S: Sherman; ST: Stacyville; V: Vanceboro; F: Forest; D: Danforth; WY: Wytovitlock; M: Medway; MK: Millinocket; K: Kellyland; W: Waite; SL: Scraggly Lake; SP: Springfield; C: Calais; BL: Big Lake; WL: Wabassus Lake.



roughly linear zones of higher elevations (Figure 2) divide the study area into three drainage basins. Hills in the eastern third of the Wytovitlock quadrangle form the eastern drainage boundary of the Mattawamkeag River; land to the east of these hills drains to Baskahegan Stream, which is a tributary to the Mattawamkeag. North and west of the Mattawamkeag, the land slopes gradually toward the river, or to extensive flood plains along the river banks, best developed in the southeastern quadrant of the Wytovitlock quadrangle. The hills in the eastern part of the quadrangle continue south into the Springfield quadrangle, where they merge with an east - west trending zone of higher elevations across the approximate middle of the quadrangle. Water north of this zone flows to the Mattawamkeag River or Baskahegan Stream, while water in the south flows to the Passadumkeag River and thence to the Penobscot River, or into a network of lakes leading ultimately to the Grand Falls Flowage and St. Croix River.

The drainage reflects the distribution of lithologies and of the tectonostratigraphic blocks (See Plates I and II). The hills to the east of the Mattawamkeag River are underlain by Middle Ordovician - Silurian sandstones, siltstones, conglomerates, and volcanic rocks, while flood plains and wetlands along the river, and the lower, gentle hills farther west, are underlain by Late Ordovician - Silurian argillaceous carbonates, siltstones, and pelites of the Aroostook - Matapedia Belt. More pronounced hills in the west and northwest of the Wytovitlock quadrangle reflect the fine-to-medium grained sandstone bedrock of the Madrid (Osberg et al., 1985) or Lawler Ridge (Roy, 1987) formations of the Siluro-Devonian Central Maine Belt. The southerly drainage is underlain by granitic rocks and minor amphibolites of the Mid-Devonian (Ayuso and Arth, 1983) Bottle Lake Plutonic Complex. The hills forming the divide between the northerly and the southerly drainage have the highest elevations in the study area, and are underlain by resistant biotite-rich hornfels and calcsilicate rocks.

## Methods

The study area is mantled by till, alluvial sediment, and swamp deposits (Holland, 1986; Holland and Newman, 1986), which limit bedrock exposure to perhaps no more than one percent of the land surface; pavement outcrops are the most common exposures, particularly along the unpaved lumber roads. Most outcrops occur where the glacial cover has been removed by stream erosion or road construction; there are few significant road cuts. Road ditches and gravel pits provided some exposures. Field mapping and data collection occurred over a total of approximately 48 weeks during the summer months from 1986 through 1989. Off-road traverses were conducted up stream channels and across steep slopes or extrapolated contacts; most streams and steep slopes yielded at least some exposures. Orientations of planar and linear fabrics were recorded at all exposures where they were evident, but only trends could be obtained at many pavement exposures, and some outcrops provided evidence only of lithology.

Analysis of field data was supplemented by petrographic study of lithologies and microstructures. Seismic data from the U.S. Geological Survey and the Maine Geological Survey, provided supporting evidence for structural and tectonic interpretations, as did isotopic data compiled by Pamela Brock (1989, 1993). Samples collected for study at representative exposures and exposures of particular interest were slabbed and thin sections prepared for analysis at Queens College.

## Background of the Present Study

Maine's bedrock may be divided into subparallel lithotectonic belts (see Figure 1, adapted from Osberg et al., 1985). These belts have distinctive internal stratigraphies and are entirely or partially fault-bounded. Each, therefore, could be considered a "terrane" in

a very loose sense, and accretion models of the Appalachian Orogen (for example, Osberg, 1978; Williams and Hatcher, 1983; Zen, 1983) have posited some or all of these belts, or composite terranes including them, as exotic or suspect terranes. Some of the boundary faults are therefore candidate sutures or megashears.

The study plan was to focus on the contact of the Miramichi Anticlinorium and Aroostook - Matapedia Belt. Reconnaissance mapping by Ludman (1985, pers. comm.) had identified a fault along this boundary near the town of Bancroft, where thinly layered and intensely deformed argillaceous micritic carbonates on the west bank of the Mattawamkeag River are juxtaposed with massive feldspathic conglomerate on the eastern bank. The carbonate rocks were tentatively correlated to the Late Ordovician (?) - Silurian Carys Mills Formation of the Aroostook - Matapedia Belt, while clasts of sedimentary rocks and felsic volcanic rocks in the conglomerate were comparable to Cambro-Ordovician volcanic and clastic rocks of the Miramichi Anticlinorium (Sayres and Ludman, 1985). Both blocks lie within the Gander Terrane (see Figure 1) of Williams (1978), a belt of polydeformed and metamorphosed rocks that may have developed on the opposite side of a major ocean from the ancestral North American margin (Williams and Hatcher, 1983). They include both the Cambrian and Ordovician basement rocks of the Gander Terrane proper and overlying sequences of Late-Ordovician-and-younger volcanic and clastic rocks. The area of mapping was extended into the northern portion of the Bottle Lake Complex (Ayuso, 1982), during evaluation of the intrusive body for a nuclear waste repository. This mapping was conducted simultaneously with seismic and gravity studies by other workers

#### Outline of Significant Findings

Depositional facies suggest that the post-Caradocian section consists of debris shed from topographic highs underlain by the Cambrian and Ordovician volcanic and clastic rocks of the Miramichi belt, so that the Aroostook - Matapedia and Miramichi blocks are less distinct than previously thought; the stratigraphic units of the two terranes may be essentially equivalent, from at least Late Ordovician (Ashgillian?) time onward. The Late Ordovician - Silurian sedimentary rocks grade from relatively coarse rocks in the east into finer-grained sediments in the Aroostook - Matapedia Belt. Other lithotectonic belts - the Weeksboro - Lunksoos Lake (Neuman, 1967) and Munsungun - Winterville (Hall, 1970) Anticlinoria - show similar stratigraphies in which coarse clastic rocks adjacent to Cambrian and Ordovician sedimentary and volcanic rocks grade into finer-grained but clearly equivalent strata over relatively short distances. The Cambrian and Ordovician volcanic and clastic rocks may, therefore, form the basement of much of the Gander Terrane, underlying both the Aroostook - Matapedia and Central Maine belts.

All tracts in the study area record identical structural histories from the latest Ordovician onward, beginning with localized disruption of the unlithified, semi-consolidated deposits. The lithified sequence was compressed during the Acadian Orogeny in three phases: (1) early east-vergent thrust faulting; (2) development of upright north-northeast trending folds with a strong axial-planar foliation; and (3) a final phase of west-side-up reverse faulting. Later in the Devonian, these reverse faults were reactivated as dextral strike-slip faults; motion on these faults was synchronous with intrusion of the Bottle Lake Complex, and deformational fabrics associated with this faulting event are found within all rocks in the study area, including the intrusive rocks. Dextral strike-slip motion occurred first along northerly trending faults, then along northeast-trending faults, and finally along east-northeast trending faults, including the Norumbega Fault Zone (Wones and Stewart, 1976). Radiometric ages of the Bottle Lake Complex and of metamorphic biotites along the Norumbega Fault are close enough in age to suggest that

these faulting events are related to the early-Devonian intrusion of the plutons. This change in the direction of slip may, in turn, reflect a change in the regional stress field associated with continued Acadian convergence in southern New England and the Middle Atlantic states. All fabrics are offset by a late, northwest-trending sinistral slip cleavage and associated kink bands of uncertain tectonic significance.

The final chapter synthesizes the findings of this research with a review of geochemical and geophysical data by Brock (1989, 1993), to develop a plate tectonic model for the assembly of the North American margin in the New England - Maritimes region. Brock's analysis reveals that hypothetical terranes defined largely by the supracrustal section, whether the lithotectonic belts shown in Figure 1, or the zones of Williams (1978), may not provide the most accurate picture of the lithospheric blocks which comprise the orogen. Isotopic data allow division of the basement in the New England - New Brunswick area into parallel belts of continental and island-arc affinity, based on the apparent ages of source rocks for plutons intruding the supracrustal section (Brock, 1989, 1993). Synthesis of this view of the basement with the structural and stratigraphic data described below suggests that the Gander terrane developed during the Cambro-Ordovician as a composite block at some distance from North America. This terrane was accreted to North America in the mid-to-late Ordovician, and the rock units and fabrics described in this study developed on that accreted block. Consequently, the events described in this study record the geologic evolution of the North American margin during the interval between the "Taconian" orogenic phase and at least the end of the Acadian phase.

## STRATIGRAPHY

### PREVIOUS WORK

Modern work on the stratigraphy of the study area dates to Larrabee and Spencer (1963), Griscom and Larrabee (1963), and Larrabee et al. (1965), who described an internally conformable Ordovician - Silurian section of slate, sandstone, conglomerate, and magnetite-bearing volcanic rocks. Their basal unit of black slate and siltstone (Os) was overlain by black, graptolitic, locally pyritic slate and shale (Oss) interbedded with thin black chert and chalky-weathering rhyolitic tuff. Oss passed conformably upward into gray and black thin-bedded slate and siltstone with minor granule conglomerate (Sss), underlying most of the Wytovitlock quadrangle, and locally, a conglomerate containing fragments of "post-Ordovician" corals and crinoids with pebbles and cobbles of micritic limestone and gray siltstone (Sl). Coarse conglomerates were reported along the outlet of Lower Hot Brook Lake. Above this, but found only east of the Mattawamkeag River, was a unit of chloritic quartzite, quartzite conglomerate and gray and green slate and siltstone (Sq), overlain by poorly exposed gray slate, siltstone, argillaceous quartzite, and thin-bedded siltstone. Unit ages were based on interpretation of the structure and on Caradocian graptolites found in Os carbonaceous pelite.

### Pre-Ashgillian Section

Subsequent detailed work in the Danforth and Scraggly Lake quadrangles by Mangini (1981), Sayres (1985), and Ludman (1985) demonstrated the equivalency of the eastern part of this section to the Pre-Ashgillian volcanic and sedimentary rocks of the Tetagouche Group in New Brunswick (Venugopal, 1978; Lutes, 1979; Fyffe, 1982).

### Baskahegan Lake Formation

The Baskahegan Lake Formation (Ludman, 1985) is a unit of thick-bedded, noncalcareous, feldspathic turbidite wackes, commonly interbedded with slate and minor amounts of grit. It is correlated to the Cambro-Ordovician Chain of Rocks Formation, the basal part of the Miramichi Group (van Staal and Fyffe, 1991). Grit and quartz-granule conglomerates occur locally, as either distinct beds or Bouma A-units. A distinct and regular spaced cleavage, described by Ludman (1985) as “bread-slicer cleavage”, is common in many exposures of the wackes. Most outcrops are off-white or pale gray, but fresh surfaces are gray or greenish gray; some exposures, interpreted to belong to an older member of the formation (Ludman, 1988), are red or green, and either less feldspathic, or sufficiently high in chroma to mask the chalky weathering.

#### Early Ordovician through Caradocian Rocks

The Baskahegan Lake Formation is unconformably overlain (Ludman, 1989) by a sequence of interbedded volcanic and clastic sedimentary rocks, the detailed stratigraphy of which is discussed by Mangini (1981), Sayres (1986), and Ludman (1985, 1990, 1991) (Figure 2), and the age and composition of which are comparable to those of the Upper Tetagouche Sequence of the Miramichi terrane (Fyffe, 1982) and the Tetagouche Group of van Staal and Fyffe (1991). The basal unit (Bowers Mountain Formation of Ludman, 1991) is composed of carbonaceous and sulfidic pelites and wackes, and mafic volcanic rocks, including both tuffaceous rocks and pillow basalts. Apparently conformably overlying this section are gray, non-carbonaceous and non-sulfidic slate and phyllite, with lesser amounts of gray quartzofeldspathic siltstone, graywacke, and minor conglomerate, including clasts of cryptocrystalline volcanic rocks, manganeseiferous siltstones, and intraformational(?) slate chips (Ludman, 1990).

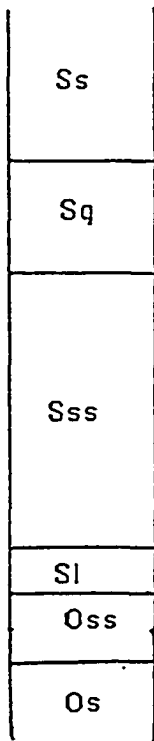
Figure 2: Evolution of models of the stratigraphy of the study area. Thickness of column sections does not correlate to presumed thickness of the units.

Key to Larrabee and Spencer (1963): Oss: black slate and siltstone; Os: black slate and siltstone with chert and light gray rhyolitic tuff; Sl: fossiliferous conglomerate of limestone and siltstone pebbles and cobbles; Sss: gray and black thin-bedded slate and siltstone; Sq: quartzite, conglomerate, gray and green slate and siltstone; Ss: gray slate, siltstone, and argillaceous quartzite and sandstone.

Key to Ludman (1985): Ss: massive, non-calcareous quartz arenite; Sls: highly calcareous shale and argillaceous limestone; Sp: siltstone and pelite (Smyrna Mills Formation); Dsm: Madrid Formation; ODg: lithic arenite and sulfidic, carbonaceous pelite; ODc: variably sulfidic and carbonaceous conglomerates; ODp: non-calcareous gray slate and minor gray siltstone; ODv: mafic and felsic volcanic rock with minor manganeseiferous siltstone; ODt: maroon and gray slates with local lithic sandstones and conglomerates. See text for description of members of Ovf/Stetson Mountain Formation. No stratigraphic order is implied for the sequence of ODp, ODv, ODt, and ODc.

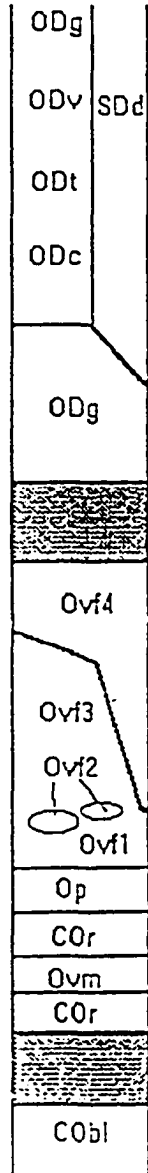
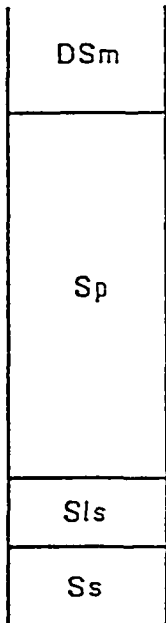
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Larrabee and Spencer (1963)

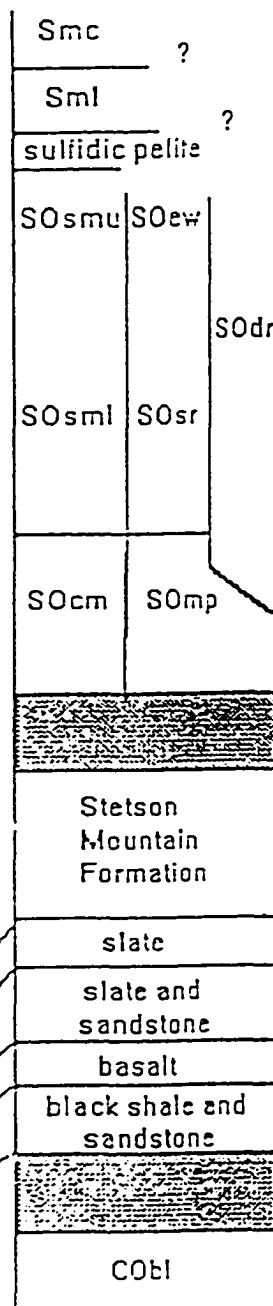


Ludman (1985)

NY of Miramichi      Miramichi



This Study and Ludman (1991)



Bowers Mountain Formation

These rocks pass conformably upward into a volcanic unit, denoted as Ovf by Sayres (1985), and the Stetson Mountain Formation by Ludman (1991). The basal member (Ovf1 of Sayres, 1985, and Tolman Hill Member of Ludman, 1991) is dominated by massive felsic (ashfall?) volcanic rocks, with lesser amounts of ashflow tuffs and lavas, the latter often bearing small gray pelite clasts. Thin arenite beds and carbonaceous pelite are sometimes interstratified with these rocks. This unit is conformably overlain by a thin, manganiferous, locally magnetite-bearing, member (Sayres' Ovf2, and Ironstone Member of Ludman, 1991) of thinly bedded or thickly laminated pelite and siltstone with occasional felsic ashflow tuffs. Conformably above these rocks is a thick, diverse section (Ovf3 of Sayres (1986), and Public Lot Ridge Member of Ludman (1991)) of ashfall and ashflow tuffs, rhyolitic quartz and feldspar porphyries, and clast-supported conglomerates. Clasts in these conglomerates include felsic volcanic rocks and manganiferous rocks resembling the Ovf2/Ironstone Member. Caradocian graptolites were found within one of the volcanic units (Larrabee and Spencer, 1963), and a brachiopod found in the uppermost part of the section is reported to be Ordovician (Ludman, 1985).

#### Ashgillian to Middle Silurian Rocks

Recognition of the Miramichi stratigraphy in this area split Larrabee's generally continuous section into two groups of rocks, roughly along the line of the Mattawamkeag River. Rocks east of the river were correlated to or derived from the Tetagouche section, while those west of the river were tentatively correlated to the Aroostook - Matapedia Belt and the Central Maine Belt. The present study, however, demonstrates that the post-Caradocian rocks of the Miramichi Anticlinorium and Aroostook - Matapedia Belt, and perhaps the Central Maine Belt as well, form a single stratigraphic package from post-Caradocian time onward.

#### "Post-Caradocian Rocks of the Miramichi Anticlinorium"

Ludman (1985) reinterpreted the rocks described by Larrabee and Spencer (1965) and Larrabee (1963) as Late Ordovician to Early Devonian “cover rocks”, unconformably overlying the Caradocian volcanic rocks. The potentially oldest unit (ODg) of this section included thinly (1 - 5 cm) interbedded, chalky weathering, pyritiferous grit and sooty carbonaceous slate in approximately equal proportions, found throughout the uplands east of the Mattawamkeag River and south of Mill Priveledge Brook. The unit was interpreted to coarsen (upward) to the east. Ludman (1985) believed these to be epiclastic rocks derived primarily from Sayres’ Ovf, and correlated them (Osberg et al., 1985) to the similar “Belle Lake Slate” of New Brunswick (Venugopal, 1978). Conglomerates with a black, pyritiferous matrix found east of Jimmey Mountain, including those within Sss of Larrabee and Spencer (1963), were included in this unit. Although Caradocian graptolites had been identified in the Belle Lake Slate, Ludman thought that the apparently conformable contact of the rocks in Maine with presumably Silurian rocks around Jimmey Mountain left their age uncertain. It was therefore unclear whether they were truly equivalent to the Caradocian Belle Lake Slate, or whether they represented post-Caradocian, post-unconformity, “Miramichi” strata.

Ludman (1985) grouped greenish clast- and matrix-supported conglomerates and intercalated green phyllite, mapped north of the ODg belt, into the Daggett Ridge Formation (SDd). Clasts are predominantly rounded pebbles and cobbles of chloritic quartzofeldspathic wacke, apparently derived from the Baskahegan Lake Formation, with lesser amounts of limonite-spotted sandstones and felsic volcanic rocks. Ludman (1985) reported Silurian brachiopods from clasts in this unit, suggesting a minimum age of Silurian for the formation as a whole. The relationship of grits, conglomerates with gray and green clasts of felsic volcanic and quartzofeldspathic rock, sandstones, slates, and mixed felsic and mafic volcanic rock (ODt, ODc, ODp, and ODv in Figure 2), identified in the area north of Bog Brook, to SDd and ODg was uncertain.

### “Rocks Northwest of the Miramichi Anticlinorium”

Ludman (1985) divided the “rocks northwest of the Miramichi Anticlinorium” into three units: a calcareous shale and argillaceous limestone (Sls) found closest to Miramichi rocks; a gray slate and siltstone, found west of Sls, and tentatively identified as the Smyrna Mills Formation of the Aroostook - Matapedia Belt, and; in the northwestern part of the Wytovitlock quadrangle, a section of medium-bedded, calcareous and micaceous sandstone identified as the Madrid Formation of the Central Maine Belt. Comparison of the type sections of the Aroostook - Matapedia units with the rocks of the study area, and reconnaissance of the intervening territory during this study and by others (Morisi, unpub. data; Ludman 1989, 1990), has shown that the Aroostook - Matapedia lithologies continue along strike into the study area.

Pavlidis (1962, 1969, 1971, 1972) and Pavlidis et al. (1964) provided a comprehensive description of Aroostook - Matapedia stratigraphy in the Houlton, Smyrna Mills, and Bridgewater quadrangles, north of the study area (See Figure 3). This stratigraphy included the Middle-to-Late Ordovician Carys Mills Formation, composed of pyritiferous and calcareous slate and graywacke overlain by argillaceous limestone and calcareous pelite, and the Smyrna Mills Formation, a unit of gray and gray-green wacke and pelite, with some beds of conglomerate and, less commonly, argillaceous carbonate (Pavlidis, 1971, 1972). Thin layers of fine-grained feldspathic rock (ash-fall tuffs?), were found at a few localities. Roy (1980, 1987) also described an Ashgillian basal slate and graywacke member of the Carys Mills Formation, north of the Houlton area, but found that younger strata of the formation could be as young as mid-Llandovery.

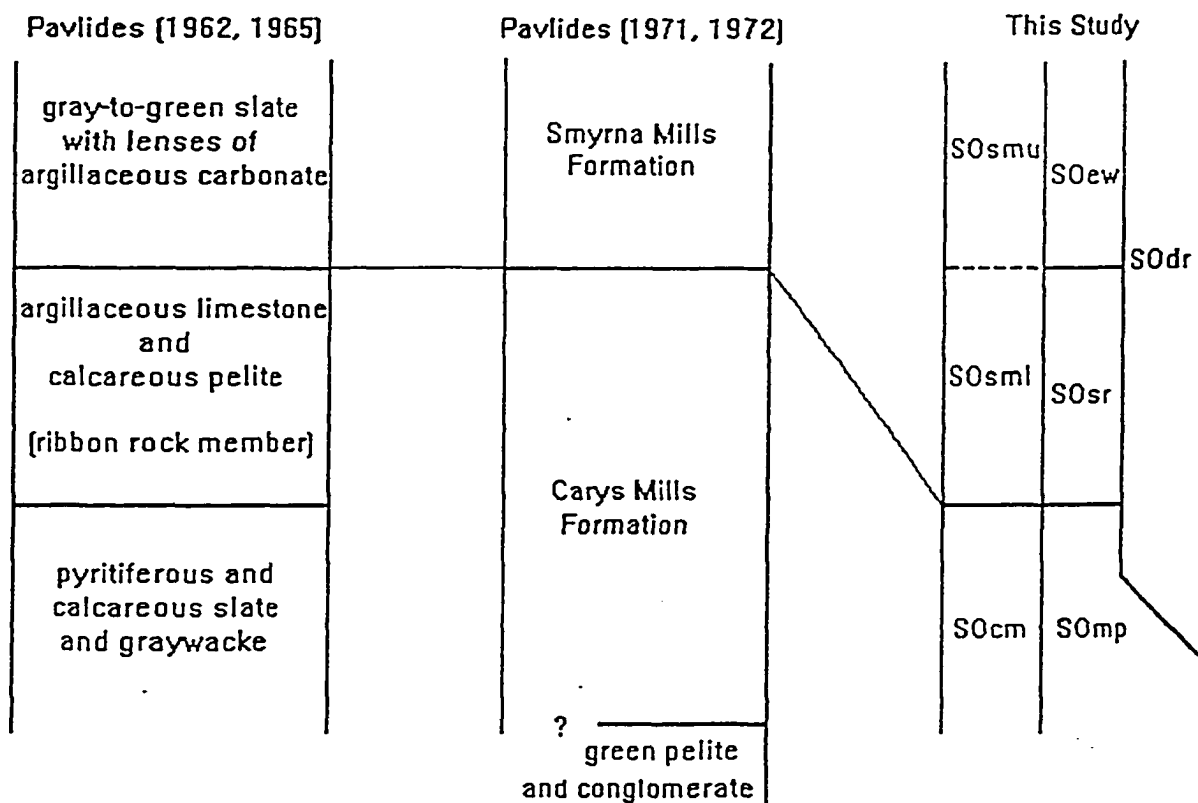


Figure 3: Evolution of models of the stratigraphy of the Aroostook - Matapedia belt. Unit abbreviations as in Figure 2. It may be debated whether the Mill Priveledge Brook, Sam Rowe Ridge, and Ellen Wood Ridge formations belong more properly in the stratigraphy of the Aroostook - Matapedia or the Miramichi tract. It has been decided in this report to place them in the Miramichi, in order to emphasize the analogy with the established stratigraphies of the Weeksboro - Lunksoos Lake and Munsungun - Winterville Anticlinoria. Note, however, that Ludman et al. (1993) place the SOmp-SOsr-SOew sequence in the Aroostook - Matapedia.

The Madrid Formation was identified to the west and northwest of the study area by Roy (1981), although he denoted these massive, variably feldspathic and calcareous, medium-to-thick bedded, quartz-rich graywackes and interbedded thin gray slate or phyllite beds as the Lawler Ridge Formation; it was assigned an age of Late Llandovery or younger based on Late Llandovery to Early Ludlovian fossils from the underlying Allsbury Formation. Roy placed the Lawler Ridge Formation conformably above the Allsbury Formation, and believed it to be laterally equivalent to upper parts of the Smyrna Mills Formation. Ludman (1985) and Osberg et al. (1985) related the Lawler Ridge Formation to the Madrid Formation of the Central Maine Belt, on the basis of their lithologic similarity, and placed it stratigraphically above the Smyrna Mills Formation.

## INTERPRETATION IN THE PRESENT STUDY

This study confirms Ludman's (1985) hypothesis that the post-Caradocian rocks derived from the Miramichi Anticlinorium form an internally conformable sequence, and also demonstrates that the units derived from Miramichi rocks (Prentiss Group of Ludman, 1991) and those "northeast of the Miramichi", (Aroostook - Matapedia and Central Maine Belts) form a single, internally conformable sequence equivalent to similar facies of the same age flanking the Weeksboro - Lunksoos Lake and Munsungun - Winterville Anticlinoria. This new interpretation of the post-Caradocian stratigraphy places constraints on the nature and dimensions of the Aroostook - Matapedia and Central Maine basins, described below.

### Prentiss Group

#### Introduction

The Prentiss Group is divided into four stratigraphic units, one composed primarily of conglomerate and the others of interbedded pelite and wacke with varying amounts of

conglomerate, calcareous wackes and pelites, and volcanic rocks. The conglomeratic unit is interpreted to be generally time-equivalent to the other three; the units appear to interfinger, and the sequence probably does not represent a simple proximal - distal relationship. In the absence of any fossils from these rocks, the post-Caradocian age of the Prentiss Group is based on: (1) rounded clasts of the Baskahegan Lake and Ovf/Stetson Mountain Formation rocks found in all units; (2) structural distinction between these rocks and the pre-Ashgillian section, and; (3) correlation between this section and the (elsewhere) fossiliferous Aroostook - Matapedia Belt.

#### Daggett Ridge Formation (SOdr)

The generally conglomeratic rocks, including massive conglomerates exposed primarily on Sherwood Mountain, in the northeast corner of the Wytopitlock quadrangle, and Jimmey Mountain, in the northwest corner of the Danforth quadrangle, as well as at the type localities along Daggett Ridge, are grouped as the Daggett Ridge Formation, after Ludman (1985). The unit outcrops at several localities between the two mountains, and appears to be continuous between them. It is certainly found as far south as Potter Hill in the Wytopitlock quadrangle, and outliers may occur farther south, in massive conglomerates on ridgetops in the southeast corner of Drew Plantation, although those particular rocks are currently mapped within the Mill Priveledge Brook Formation. Comparable conglomerates have not been found south of Drew Plantation. Ludman (1985) assigned a Siluro-Devonian age to this unit; the Ordovician - Silurian age is based on the apparent interfingering of this section with the remainder of the presumably post-Caradocian Prentiss Group.

Exposures of the Daggett Ridge Formation commonly show little or no distinct bedding (Figure 4); massive or graded conglomerate and interbedded grit and pelite are rare. Clast sizes range from cobbles to pebbles in most of the Wytopitlock quadrangle, but



Figure 4: Outcrop photograph of the Daggett Ridge Formation, showing common depositional texture.

large boulders two-to-three meters across are found in exposures on Jimmey Mountain and Hardwood Ridge in the Danforth quadrangle. Clast shapes range from roughly equidimensional to strongly elongate. Slabbed samples often show imbrication of more elongate clasts, implying their placement as debris flows (Staley, 1988; Friedman and Sanders, 1978). No facing data are available from the imbricated beds, and the clast orientations are not clear in outcrop; the general trend suggests transport along a roughly east - west line. Exaggeration of the imbrication through loss of pelitic matrix during deformation cannot be ruled out, but there is generally no evidence of rotation of the clasts. No clear map pattern distinguishes imbricated from non-imbricated conglomerate, although the imbricated subfacies appears more common in the Wytovitlock quadrangle than in the Danforth quadrangle; it may be more difficult to recognize imbrication in outcrops with larger clasts, as it is only apparent in slabbed samples.

The clast population is dominated by subrounded pebbles and cobbles of quartzofeldspathic wacke, although clasts of felsic volcanic rocks dominate some outcrops. Thin quartz veins are common in the sandstone clasts, some probably related to strain imposed after lithification of the conglomerate (see below), but many thicker veins in the clasts are apparently randomly oriented with regard to tectonic fabrics of the matrix, and so are interpreted as indicating pre- Ashgillian deformation of the source rock. The clasts are fine-to-medium grained, and frequently show variably developed cleavage or other strain fabrics in thin section, including strain-shadowed grains, granoblastic textures, and sutured grain boundaries not found in the matrix or the wackes that interfinger with the conglomerate. Their textures and composition appear identical to those of the Baskahegan Lake Formation. Lithologies of the felsic volcanic clasts resemble those of Ovf; these lithologies include: grits with subhedral-to-euhedral feldspars in a feldspathic matrix; fine-grained to aphanitic rhyolites, some slightly porphyritic with euhedral feldspars and/or subhedral quartz, and occasional felted texture in the matrix; coarse lithic

debris; mafic volcanic rocks; chert; ironstone; vein quartz; manganeseiferous pelite, and; spotted slate. The last four have thus far been found only as pebbles to coarse grit; other lithologies occur over the grit-to-boulder range.

Crinoid columnals and subrounded coral fragments are common at a few localities, but are very rare in the unit as a whole. Fossil debris, including crinoid, brachiopod, and coral fragments, forms a large fraction of the matrix in some exposures in the northwest corner of the Danforth quadrangle, north of the Canadian Pacific tracks and south of Baskahegan Stream. Pebble-sized, subrounded chunks of rugose (?) coral occur as clasts at this locality and a few others. Ludman (1988, pers. comm.) reports localities where intact rugose corals were found in the matrix, implying either very short transport distances or deposition in relatively shallow water.

The matrix (exclusive of visible biogenic debris) tends to be calcareous at all fossiliferous localities, but is also calcareous at several exposures that have proven unfossiliferous to date. There are two types of matrix, one greenish-gray, and the second gray and arguably more mud-rich; both are very poorly sorted and show chalky weathering. Pyrite and ankerite are rare-to-absent from both, and the greenish matrix is more commonly calcareous than the gray. Fragments of all clast lithologies are found as grit-size and finer grains in the matrix. No obvious lamination is found in the matrix, nor are there dewatering structures, reverse grading, or other evidence supporting emplacement of these deposits as fluidized sediment rather than debris flows, although the imbrication noted above suggests some mobility of grains within the slumping mass.

Thin-bedded wackes and pelites are locally intercalated with the conglomerate; these resemble similar rocks of the Sam Rowe Ridge or Ellen Wood Ridge Formations, described below. Some beds contain coarse tuffaceous debris resembling reworked tuffs

found in the Ellen Wood Ridge Formation, and in the Smyrna Mills Formation in the Houlton area. No clasts of clearly undeformed sedimentary rocks, coarse volcanoclastic rocks comparable to the pumiceous rhyolite in the Ellen Wood Ridge Formation, or rhythmically bedded sections or matrix-rich wackes comparable to the other Prentiss Group units, have been found in the Daggett Ridge Formation. Limited exposures make it impossible to determine whether or not the bedded sections found within SOdr are themselves large olistoliths.

#### Mill Priveledge Brook Formation (SOmp)

The Mill Priveledge Brook Formation generally underlies the area previously mapped as Belle Lake Slate (see Osberg et al., 1985), and consists largely of the gritty, pyritiferous grits, wackes, and pelites which resemble the Belle Lake Slate. The unit is named for exposures of regularly bedded pyritiferous wackes and pelites along the west side of Mill Priveledge Brook in Drew Plantation; the contact between the Mill Priveledge Brook and Daggett Ridge Formations can be located to within fifty meters along the brook on the northeast side of Potter Hill. Fossils from the Belle Lake Slate indicate a Middle-to-Late Ordovician age (Venugopal, 1978, 1979).

Mill Priveledge Brook Formation rocks are locally carbonaceous and occasionally somewhat manganiferous, and are almost uniformly sulfidic to some degree. Pyrite is ubiquitous, with euhedral cubes up to one-half centimeter across common in some beds. Ankerite and pyrite sometimes occur together in calcareous wackes with interstratified pyritiferous pelites. The abundance of easily-weathered sulfides leads to a distinctive brown-to-orange-brown rind on exposed surfaces in better-drained localities (Figure 5).

Outcrops typically show rhythmically bedded sections of wacke and pelite, with beds typically two-to-one-half centimeters in thickness, although thicker beds are

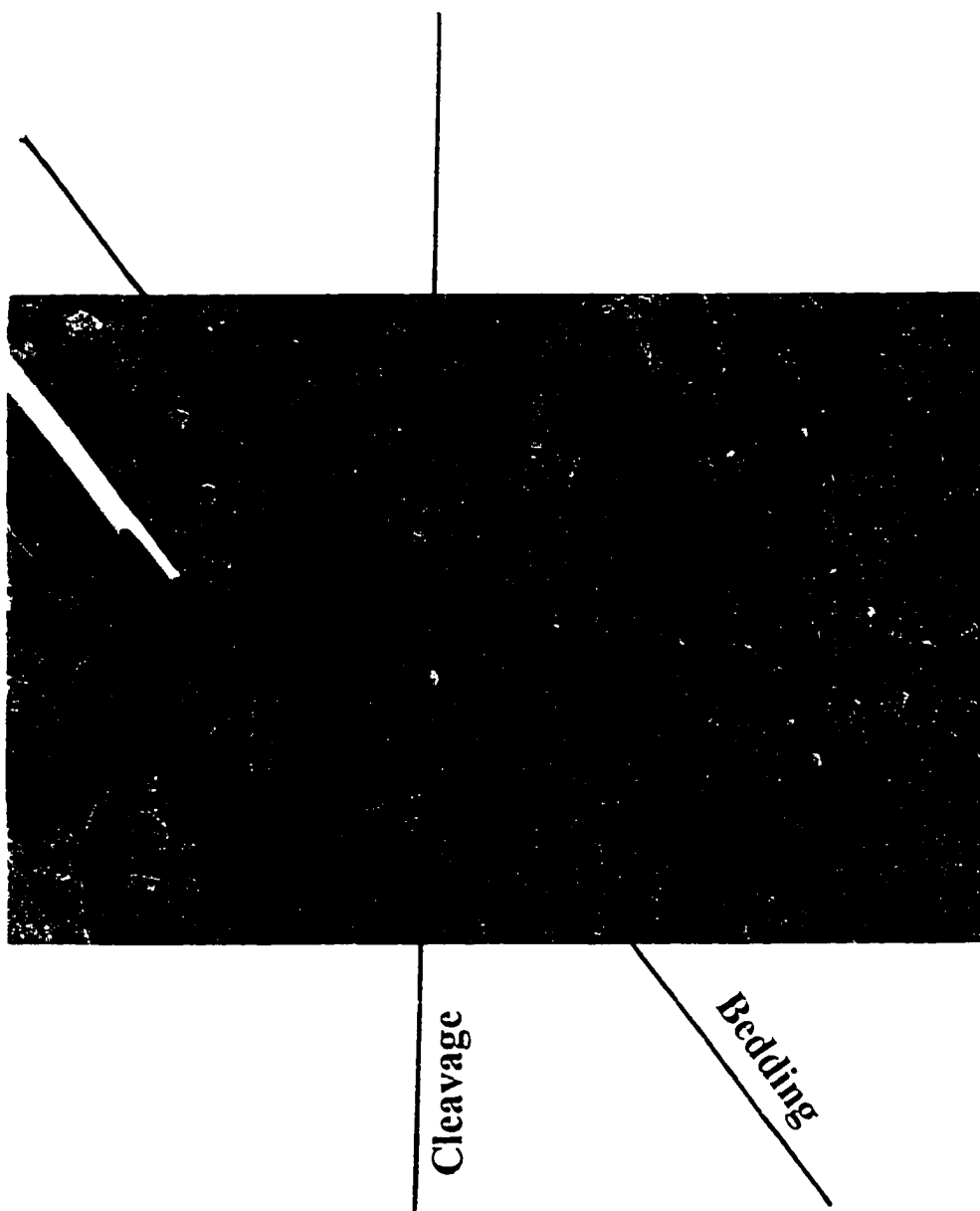


Figure 5: Outcrop photograph of Mill Priveledge Brook Formation. Pen lies in plane of primary layering, which is nearly perpendicular to the page. Note brownish weathering rind on section of exposure in center of picture.

common. Beds are usually continuous on the scale of the outcrop, but some exposures are dominated by thin discontinuous siltstone and pelite beds. Many finer-grained sections show thin silty laminae and isolated silty ripple trains. Lateral truncation by scours or other nonconformable surfaces is rare. Bases of wacke beds are sharp, and evidence of dewatering structures in the underlying pelites is extremely rare, even below wacke beds thirty centimeters or more in thickness. The wackes are typically massive or show slight coarse-tail grading, with occasional parallel laminae found near the tops of some graded beds; no beds with convolute laminae have been found. Thicker wacke beds frequently have gritty Bouma A sections; most of the thicker coarse beds show AB sections, and much of the unit could be considered as composed of ABE sequences; some ABDE turbidites occur as well. Complete Bouma sequences have not yet been observed in any of the post-Caradocian rocks, except perhaps in the Madrid Formation.

Minor lithologies within the Mill Priveledge Brook Formation include calcareous wackes and pelites, ashfall(?) tuffs, and variably carbonaceous conglomerates. Together, these comprise perhaps five-to-ten percent of the SOmp outcrops observed to date, with calcareous rocks the most common and tuffaceous rocks the most rare. Calcareous sections of the Mill Priveledge Brook Formation are thus far known only from the more regularly bedded and locally ankeritic sand/silt - pelite couplets which resemble bedding in the overlying Sam Rowe Ridge Formation. Both ankerite and pyrite may be present in the wackes. Calcareous rocks are a minor component of SOmp in the Wytopitlock quadrangle, but become increasingly common in the Springfield quadrangle, to the point where the Mill Priveledge Brook and Carys Mills Formations are not readily distinguished. At any isolated outcrop, the field distinction is based on the degree of calcareousness of the pelitic interbeds, with more calcareous units placed in the Carys Mills Formation. The more calcareous pelites tend to weather to a bluish gray, unlike the dark gray associated with SOmp pelites. Pelite-dominated sections of SOmp also tend to be much richer in

pyrite than otherwise similar sections in the Carys Mills Formation. Calcareous and noncalcareous wackes of the Mill Priveledge Brook Formation often show abundant ankerite spotting, particularly in the Springfield quadrangle south of Route 6; ankerite is typically absent from the Carys Mills Formation in this area.

Tuffaceous rocks are known only from two localities with episodic exposures along road shoulders and in drainage ditches along Route 171 between Prentiss Plantation and Reed Plantation (see Plate I). These rocks are light gray to pale gray-green and highly feldspathic, with bed thicknesses ranging from one-half centimeter to at least thirty centimeters. They are uniformly very fine grained and essentially featureless, with no internal grading, lamination, or any other primary texture apparent in outcrop. The outcrops, if they are, in fact, outcrops, are very poor and deeply weathered. The thinly bedded tuffs are clearly interbedded with the Mill Priveledge Brook Formation; the other tuff outcrop is not bounded on top or bottom, but is in an area mapped as Mill Priveledge Brook Formation, and SOmp float is common in the immediate vicinity.

Mill Priveledge Brook Formation conglomerates are generally clast-supported and dominated by rounded-to-subrounded clasts of quartzofeldspathic wacke; similar conglomerates in the Daggett Ridge Formation appear to have a more chalky-weathering matrix. Common clast microtextures include sutured boundaries, solution cleavage folia, and variably granoblastic textures; many are weakly cleaved or include white quartz veins. Most of the clasts appear to be derived from the Baskahegan Lake Formation, but some similarly rounded clasts of fine-to-medium grained felsic volcanic rocks resemble lithologies of the Middle Ordovician Miramichi volcanic section (Ovf/Stetson Mountain Formation). In general, the clast population appears very similar to that of SOdr, except that: (1) no sections have yet been found that are dominated by the volcanic clasts, and, (2) some potentially intraformational(?) clasts occur. These intraformational(?) clasts are

more elongate and often show distortion of primary laminae, and are either rare-to-absent or almost exclusively dominate the clast population in any given bed. Beds dominated by intraformational clasts often show characteristics that suggest that the clasts originated by disruption of a regularly bedded section; details of this texture and potential disruption mechanisms are discussed in the following chapter.

Conglomeratic sections range in thickness from graded beds of thirty centimeters or less to massive beds over thirteen meters thick, exposed on ridge tops in the southeast corner of Drew Plantation in the Wytopitlock quadrangle. Conglomerates are more rare in the Springfield quadrangle, in the Mill Priveledge Brook Formation, and all other post-Caradocian units. The matrix of all these conglomerates is generally similar in composition to the wackes, but SOmp(?) conglomerates with a fine-grained chloritic matrix are known from two locations on Potter Hill in the Wytopitlock quadrangle, and Ludman (1985) reports conglomerates with a sooty, carbonaceous matrix along Hot Brook Stream, in an area on strike with mapped SOmp exposures.

Cleavage is commonly at a high angle to bedding in thinly bedded sections of the Mill Priveledge Brook Formation, although it tends to lie at a relatively shallow angle to bedding in thicker-bedded sections of this unit and in the Sam Rowe Ridge and Ellen Wood Ridge Formations in general. It is unclear whether this represents a happenstance of the exposures found to date or is a result of the behavior of the less competent, pelite-rich rocks during buckling. Thus far, all exposures have proven unfossiliferous; the highly pelitic and pyritiferous rocks most promising for graptolites are also the most strongly cleaved and almost never part along bedding surfaces.

#### Sam Rowe Ridge Formation (SOsr)

The Sam Rowe Ridge Formation is named for numerous large pavement exposures of interbedded gray pelite and feldspathic wacke found in roadbeds and clearcuts in the

vicinity of Sam Rowe Ridge in Prentiss Plantation. The unit appears to be thickest in this area, either thinning to the north and south or eroded there to expose the underlying Mill Priveledge Brook Formation. Rocks of SOsr are distinguished from those of SOmp by several criteria: pelitic beds are a lighter medium gray or bluish gray rather than dark gray or black; wackes weather to light gray, buff, or white, presumably reflecting a greater proportion of both twinned and untwinned feldspar in the matrix (see Table I); and pyrite is significantly less common, found only as occasional large (up to one-centimeter) euhedra, with ankerite more common. Sandstone beds are more common than in the Mill Priveledge Brook Formation, tend to be regular and continuous, and generally appear thicker than in SOmp. Continuous beds show parallel laminae or tend to be massive; cross-laminae generally occur only in the rare discontinuous beds, isolated ripples or ripple chains, and pinch-and-swell beds (See Figure 6). Pinch-and-swell layering occurs but is rare. Wacke beds show coarse-tail grading, and bases and tops of beds are generally sharp. ABC Bouma sequences have been found only in a few rare sandstone beds over 15 centimeters thick. Single or branching burrows up to one-half centimeter in width are found in bedding planes at some localities; burrows have thus far shown no relation to bed thickness or bedding style, but they are very rare.

Conglomerates form a relatively minor portion of the Sam Rowe Ridge Formation, perhaps no more than five percent of the total exposures. The clast population is similar to that of the Mill Priveledge Brook Formation conglomerates, dominated by quartzofeldspathic wackes with a smaller portion of generally fine-grained rhyolitic rocks and lesser amounts of chert, white quartz, and pelitic fragments. Conglomerate beds dominated by intraformational clasts, commonly matrix-supported, and showing strong evidence of formation through disruption of bedding (Figure 6c) are found in several localities east of Sam Rowe Ridge, in the Springfield quadrangle. Many of these

Figure 6: Sam Rowe Ridge Formation.



Figure 6a: Interbedded pelite and wacke; note pinch and swell structure and lamination at the tops of some beds. Light speckling in pelite and some wacke beds is ankerite.

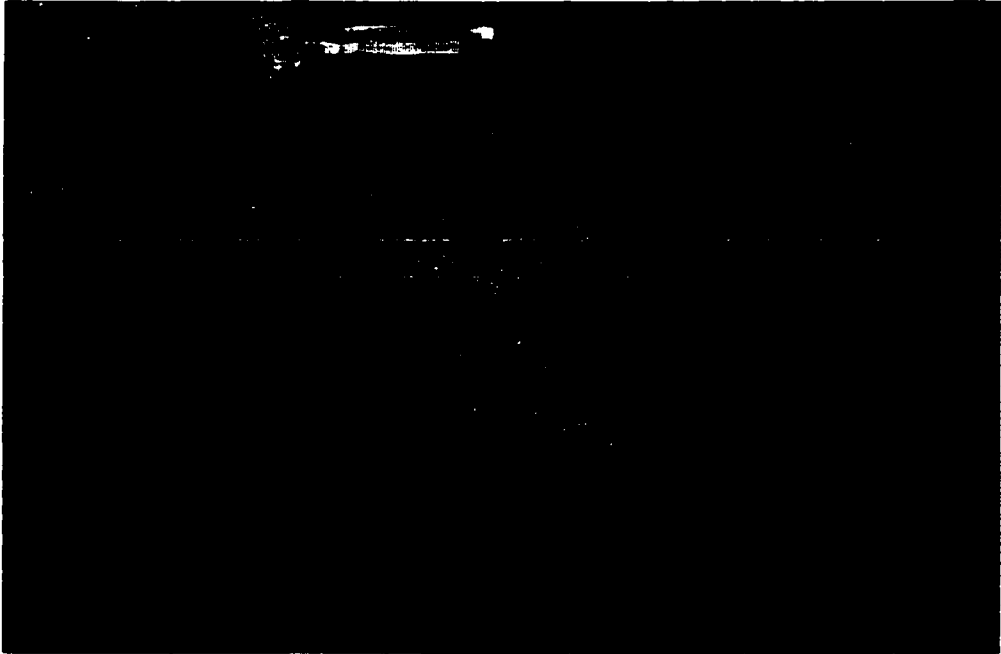


Figure 6b: Thick-bedded wacke with gritty and pebbly base. Note thin-bedded section of pelite and wacke beneath coarser bed.

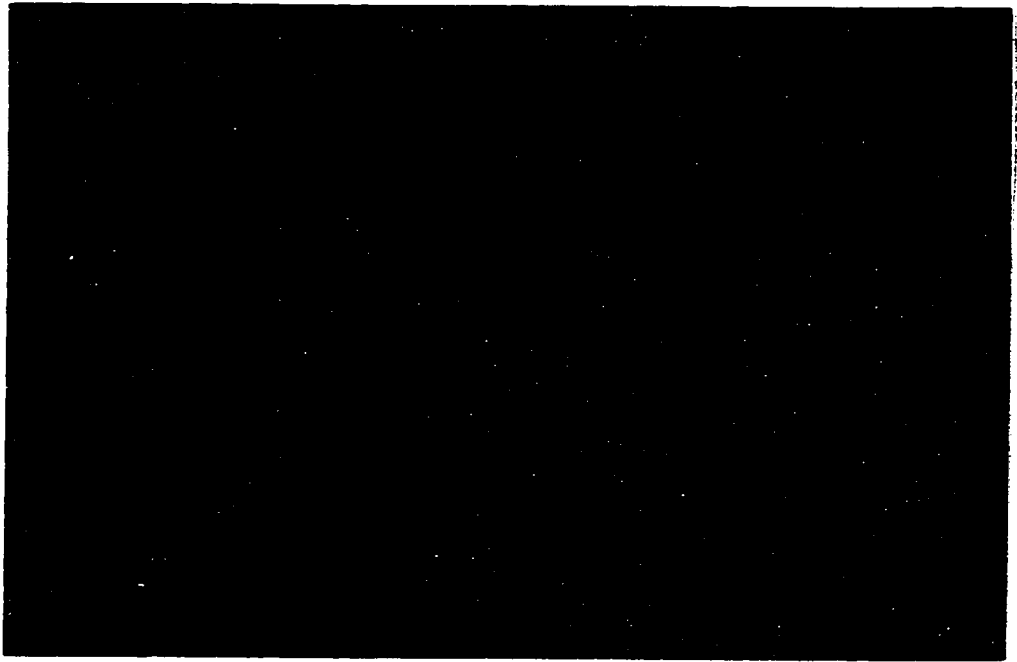


Figure 6c: Disrupted section of Sam Rowe Ridge Formation; note variety of bed thicknesses (inferred from clast dimensions) incorporated into disrupted unit. Diagonal lines across exposure are glacial fabric.

Table 1 Compositional data for wackes from the Carys Mills, Mill Priveledge Brook, Sam Rowe Ridge, and Ellen Wood Ridge Formations. Asterisks denote samples for which compositions have been recalculated without carbonate, for comparison to noncalcareous sandstones of the same and other units. Note that, although the Sam Rowe Ridge and Ellen Wood Ridge Formations are chalky weathering, in contrast to the Mill Priveledge Brook Formation, the difference in feldspar content is small, at least at the size fraction countable.

Sample no.	Carys Mills Formation				Mill Priveledge Brook Formation			
	86A98	86A98*	88A56	88A56*	87A97	87B1	87B29	
quartz	27.1	34.8	18.6	23.6	36.6	17.1	30.3	
polycrystalline qtz.	2.6	3.3	5.9	7.6	5.9	2.8	3.1	
twinned fsp.	0	0	0.9	1.2	0	0	0.2	
untwinned fsp.	7.7	9.9	5.9	7.6	10.7	11.6	15.4	
chlorite	0.2	0.2	0	0	0	0.8	0	
white mica	1.1	1.4	0	0	0.5	0.5	0.5	
pelitic rock frag.	3.8	4.9	0	0	6.9	6.3	2.7	
psammitic rock frag.	0.9	1.2	4.6	5.8	0.5	1.4	1.2	
granoblastic rock frag.	4.3	5.5	7.6	9.6	4.3	9.9	8.3	
other rock frag.	0.5	0.6	2.9	3.8	0.2	0	0	
matrix	27.8	35.8	25.5	32.4	26.8	43.9	32.3	
opaque	1.8	2.4	5.9	7.6	7.9	5.5	5.9	
carbonate	22.3	n/a	21.1	n/a	0	0.1	0	
TOTAL	100.1	100	98.9	99.2	100.3	99.9	99.9	
	n=382	n=297	n=435	n=343	n=391	n=638	n=557	

Sample no.	Sam Rowe Ridge Formation						Ellen Wood Ridge Formation		
	87B65	87A98	87A98*	87B48	87B3	87B11	87A87	87B14	87B25
quartz	10.5	28.6	34.8	36.7	35.8	20.9	7.4	22.1	22.8
polycrystalline qtz.	4.1	1.8	2.2	3.2	2.3	6.3	1.9	2.4	1.1
twinned fsp.	0	0	0	0	0	0	0	0	0.4
untwinned fsp.	4.1	10.7	13.1	11.6	12.8	4.4	5.6	4.9	6.3
chlorite	0.1	0	0	0.6	0.3	0	0.5	1.7	0.7
white mica	0.3	1.8	2.2	0.6	0.6	0.1	0	0.4	0.7
pelitic rock frag.	14.5	2.7	3.3	4.4	12.1	2.9	2.3	2.9	0.4
psammitic rock frag.	7.1	0	0	1.1	5.9	1.7	1.9	1.6	0.9
granoblastic rock frag.	16.6	6.2	7.6	2.1	8.1	7.4	5.4	5.4	5.2
other rock frag.	0.4	0	0	2.4	0	0	0.6	0	0
matrix	35.9	27.6	33.7	29.9	19.1	53.1	73.8	55.7	53.3
opaque	6.3	1.8	2.2	7.9	2.9	3.2	0.9	2.8	8.1
carbonate	0	17.9	n/a	0	0	0	0	0	0
TOTAL	99.8	99.1	99.1	100.5	99.9	100	100.3	99.9	99.9
	n = 619	n = 651	n = 506	n = 501	n = 687	n = 720	n = 660	n = 706	n = 456

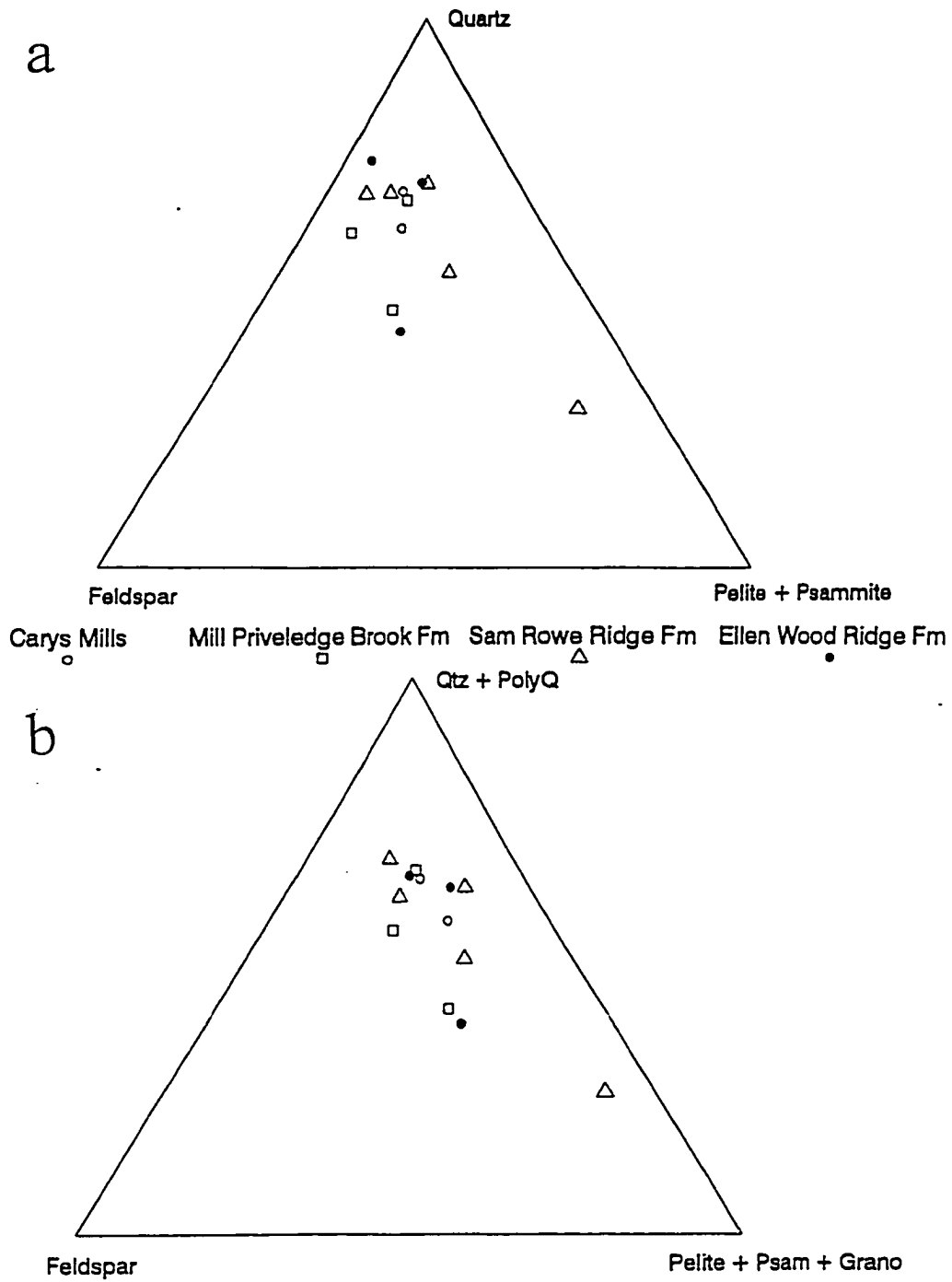


Figure 7: Quartz - Feldspar - Rock Fragment sandstone composition diagrams for data from Table I. note that Figure 7b includes both monocrystalline and polycrystalline quartz in the quartz fraction, and granoblastic rock fragments as well as pelites and psammites in the rock-fragment fraction.

conglomeratic sections appear to be over thirty meters thick. Comparable thick disrupted sections are unknown from other localities underlain by this unit.

A massive section of feldspathic and locally calcareous conglomerate is exposed in ridges immediately south of Meadow Brook in Drew Plantation; these rocks have a gritty matrix, in contrast to the sandy/silty matrix which dominates other conglomerates in the Sam Rowe Ridge Formation. The clast population appears generally similar, but includes pumiceous and vesicular felsic debris, ranging from cobbles to grit-size. This section is at least one hundred meters thick, but its top and bottom are not exposed, and repetition by folding or faulting can neither be proven nor disproven, although graded beds indicate younging to the east throughout the exposure. Swales between the thick conglomerate beds may reflect interstratified pelite or pelite - wacke sections. Many beds show cobble or pebble-sized pits which suggest weathered-out calcareous clasts; the matrix is locally calcareous, but no identifiable fossils have been extracted from this section as yet. Michel-Lévy and Carlsbad – Albite twin tests (Kerr, 1977) of twinned plagioclase euhedra in the matrix indicate a felsic-to-intermediate composition.

Volcanic or volcanoclastic/epiclastic rocks in the Sam Rowe Ridge Formation include the feldspathic-matrix conglomerate described above and thin-bedded layers of fine-to-coarse grained felsic tuff. These tuff beds are found within epiclastic-dominated exposures and are parallel to primary layering, have the same thickness as the epiclastic beds, and therefore may represent deposition of debris from a slightly different provenance, although through the same processes as the “true” epiclastic sediment. No beds consisting of mixed coarse tuff and epiclastic grains have been recognized thus far. Grains generally appear fresh, and twinned plagioclase euhedra and subhedra do not show extensive alteration or sericitization. In contrast, rare twinned feldspars in the Mill Priveledge Brook Formation, and a small fraction of the twinned feldspars in the Sam

Rowe Ridge and Ellen Wood Ridge Formations, are rounded to subrounded and highly weathered; these weathered plagioclase grains tend to be optically positive, while the fresher grains are more commonly optically negative. Coarser tuffs are greenish gray, gritty, and locally calcareous; a brachiopod fragment, which has resisted further identification, was found at one exposure.

An eight-meter-thick section of massive, fine-grained chloritic rock exposed in Little Meadow Brook in Drew Plantation contains abundant plagioclase euhedra up to one centimeter in length. No flow structures have been identified in the unit, and lath orientation is apparently random. This lithology may be associated with conglomerates having a similar greenish, chloritic matrix found approximately a kilometer to the north, although feldspar laths are not found in those rocks. This bed is assumed to represent a massive ashfall or debris flow rather than a submarine extrusive flow. Upper and lower contacts are apparently parallel to primary layering, and no alteration is observed at the exposed basal contact. Michel-Lévy and Carlsbad – Albite twin tests (Kerr, 1977) again show plagioclase Na - Ca proportions in the felsic-to-intermediate range.

Variably argillaceous limestones and massive pelites are relatively minor components of the Sam Rowe Ridge Formation, perhaps no more than five percent of the exposures observed to date. The limestones are thin beds of argillaceous micrite interstratified with fine-grained calcareous wackes. Siltstone stringers and laminae within the micrite are typically discontinuous and lenticular, often with shallow internal cross-laminae. Massive or normally graded calcareous wackes are present but less common than in SOmp. Presumably these limestones represent a local clastic-starved phase during which calcareous sediment accumulated while minor amounts of silt were reworked to form lenticular, discontinuous laminae. Massive, neutral gray pelites, up to three meters in thickness, are known from a few localities in Prentiss Plantation; these also may reflect

starvation of coarser debris. Primary lamination is absent or only faintly present in these pelites; where present, it is typically seen as thin silt laminae between thicker sections of massive pelite.

#### Ellen Wood Ridge Formation (SOew)

The Ellen Wood Ridge Formation includes green and greenish-gray feldspathic wackes, pelites, and feldspathic volcanic and volcanoclastic rocks, and is named for green wackes and pelites found on Ellen Wood Ridge in Prentiss Plantation. The name was first applied to distinguish these regularly bedded green wackes and pelites from the underlying gray rocks of the Sam Rowe Ridge Formation; volcanic rocks were not known from SOew at that time, and have not been identified thus far at the “type locality”. As is the case with SOsr, SOew is variably ankeritic, but pyrite is rare-to-absent. Further mapping may require redefinition of the type locality or division of SOew into two members, one containing only wackes and pelites and a second, apparently younger, including the volcanic rocks. The abundance of volcanic rocks appears to increase upward in this unit, but the upper contact is apparently absent throughout the study area.

The contact between the Sam Rowe Ridge Formation and the overlying Ellen Wood Ridge Formation is transitional through a thick section of regularly bedded wackes and pelites, and may be observed at several localities in the study area, although with continuous exposure only along Baskahegan Stream in the northwest quadrant of the Danforth 15- minute quadrangle. The upper part of SOsr passes to a section within which the wackes and pelites weather to green and greenish gray, but are gray on fresh surfaces; possible ashfall tuffs and coarser resedimented tuffs sometimes occur in both the gray and the green-weathering sections of SOsr. One field criterion for identification of SOew rocks is that pelites and wackes are green on fresh surfaces; many SOew feldspathic wackes weather to a light gray or white, but all are green on fresh faces. The greenish

color is apparently due to coarse-to-fine grains of strongly pleochroic chlorite, which are very different from the small, sparse grains of weakly pleochroic yellowish-green chlorite found in all formations of the Prentiss Group. The green color locally varies to grayish maroon, but the mineralogic change associated with this variation is so far unknown. Some exposures, of either maroon or green lithologies, show traces of manganese hydroxides, and manganiferous wackes and pelites found in a presumably Silurian section by Ludman (1991) may be associated with this unit. Euhedral and subhedral grains of twinned plagioclase seem to be more common in the Ellen Wood Ridge Formation wackes and grits, than either the Mill Priveledge Brook or the Sam Rowe Ridge Formations, although this distinction is not apparent in Table I. Michel-Lévy and Carlsbad – Albite twin tests (Kerr, 1977) show a felsic-to-intermediate composition for the euhedral feldspars. Rounded grains of weathered, twinned, optically positive plagioclase are a relatively rare component of SOew, as in the other units.

The thin, discontinuous beds and isolated ripples known from some exposures of the Sam Rowe Ridge Formation have not been found in the Ellen Wood Ridge Formation. Strata-bound conglomerates show clast populations apparently identical to those seen in the other post-Caradocian units. Horizontal burrows have not been found, although one outcrop may show burrows at a high angle to bedding. Most characteristic of SOew, however, is the abundance of volcanic rock and fresh volcanoclastic debris. A thick section of massive felsic volcanic rocks, including thick, highly feldspathic and rhyolitic debris flows and breccias interbedded with regularly stratified, feldspathic wackes and pelites (See Figure 8), occupies the core of a major syncline in the Wytovitlock quadrangle (see Plate I), the trace of which follows a weakly positive aeromagnetic anomaly identified by Griscom and Larrabee (1963). Clasts in the breccias include angular and subangular cobbles and pebbles of intraformational (?) greenish pelites and wackes, fine-grained felsic volcanic rocks seen, in thin section, to be composed of felted plagioclase laths in an



Figure 8: Coarse volcanic breccia of Ellen Wood Ridge Formation, with highly vesicular clasts.

aphanitic matrix, and cobbles and pebbles of pumiceous debris. Clasts of the Baskahegan Lake Formation are rare. Most of the volcanic rocks are coarser-grained than those of the Stetson Mountain Formation; from the textural difference and the angularity of the clasts, it is assumed that the majority of the volcanic clasts are of the same approximate age as the breccia. The matrix is composed of fragments of similar debris with grains of quartz and twinned and untwinned feldspar in a chloritic groundmass. Wackes interbedded with these volcanic rocks are bright white on weathered surfaces, but a deep forest-green on fresh surfaces. Similar coarse volcanic rocks in the Springfield quadrangle are more matrix-rich and include rounded clasts of fine-grained vesicular greenish rock.

A coarse, calcareous, feldspathic, mafic tuff is exposed at several localities on Sam Rowe Ridge and in the area south of Mud Brook, just south of Sam Rowe Ridge. Thin sections show this rock to contain crinoid columnal fragments, abundant intragranular calcite, and peculiar dark bluish-green vermicular chlorite. Massive fine-grained calcareous felsic tuffs are found in the Springfield quadrangle south of Route 6.

#### Aroostook - Matapedia Belt

##### Carys Mills Formation (SOcm)

Three distinct lithologies are distinguished in the Carys Mills Formation in this area: thinly bedded argillaceous micrite in layers two-to-twenty centimeters thick; alternating beds of calcareous graywacke or siltstone and pelite; and massive calcareous conglomerate. Thinly bedded green-gray noncalcareous wacke and pelite occur within the SOcm outcrop belt; these may be equivalent to the basal lithology noted to the north (see Figure 4), may be internal to SOcm, or may be interstratified tongues or fault-bounded slivers of the Smyrna Mills Formation, which they also resemble.

The argillaceous micrite typically occurs as massive layers, with primary layering (?) recognized by preferential weathering of presumably more calcareous strata (Figure 9); argillaceous beds usually weather to a buff color, in contrast to the blue-gray micrite. Primary layering is often obscured or obliterated by tectonic fabrics. Thin sections reveal silt-size and finer dolomite rhombs in varying amounts in most samples. Some pelitic beds are manganeseiferous and, more rarely, slightly carbonaceous.

Interbedded calcareous wacke or siltstone and argillaceous micrite are common south of the Mattawamkeag River, and form most of SOcm in the Springfield quadrangle. The bedding style resembles that of the Sam Rowe Ridge and Mill Priveledge Brook Formations - regularly bedded sequences of massive wackes and siltstones, sometimes showing fine subhorizontal lamination, and generally having sharp bases and tops, with bed thicknesses ranging from slightly less than one centimeter to greater than thirty centimeters, although two-to-five centimeters is most common. Fine cross lamination is found at the tops of some wacke and siltstone beds, and in occasional isolated ripple trains. Load casts, injection features, and convolute lamination are extremely rare, even in the thicker bedded sections. Some exposures show disruption of primary layering into subangular to subrounded sandstone bed fragments chaotically distributed in a pelitic matrix. This fabric resembles disruption found in the Mill Priveledge Brook and Sam Rowe Ridge Formations, and is described more fully in the following chapter.

The wackes do not show chalky weathering, and are composed primarily of quartz, untwinned feldspar, and subrounded grains of granoblastic quartzofeldspathic rocks (see Table I) with rare detrital chlorite, zircon, and small, weathered grains of optically positive, twinned feldspar. The carbonate fraction is intergranular calcite with minor but ubiquitous dolomite. Crinoid columnal fragments are present in a few samples.

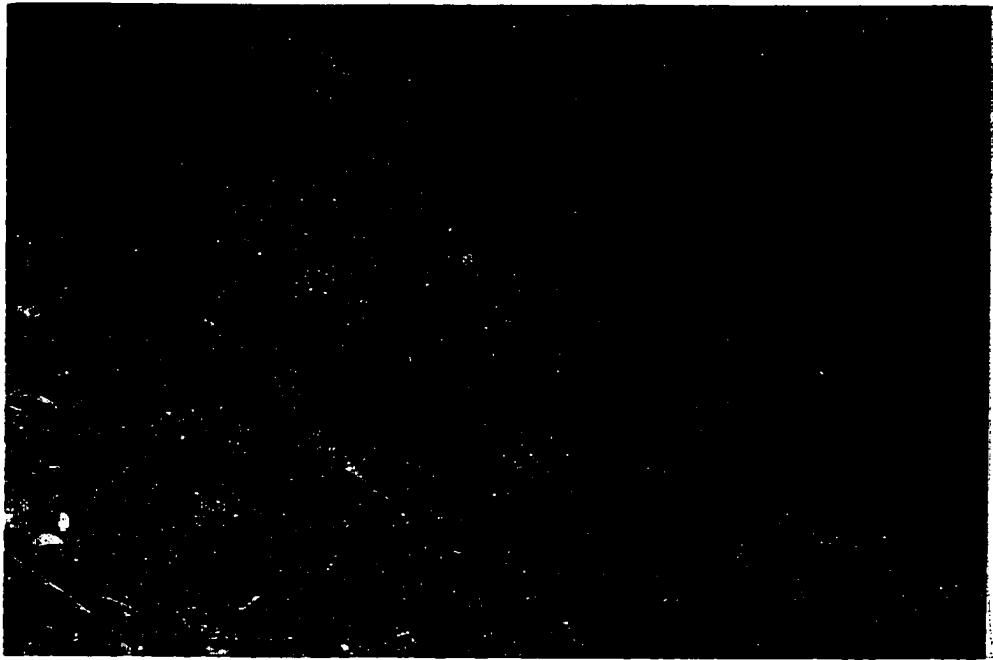


Figure 9: Outcrop of Carys Mills Formation. This exposure is unusual for the study area in that the primary layering is well-preserved, and evidence of transposition is largely absent. The calcareous layers show somewhat more resistance to weathering than the pelitic layers in this and several other exposures.

Massive calcareous conglomerate outcrops at only one locality, around a transformer substation near Thompson Corners in Prentiss Plantation, although strata-bound granule conglomerates are found at several localities. Clasts are typically well rounded, with a maximum size of seven-to-ten centimeters in diameter. Most clasts are of fine-grained, gray-to-greenish-gray quartzofeldspathic wackes, resembling the rocks of the Baskahegan Lake Formation. A lesser proportion of the clast population is composed of cleaved (?) greenish pelite, white quartz, and gray chert or siliceous pelite; unambiguously volcanic clasts have not been recognized.

#### Smyrna Mills Formation (SOsm)

The Smyrna Mills Formation consists almost entirely of thinly interbedded pelites and siltstones (Figure 10). Most siltstone beds are thinner than two centimeters, and pelitic beds tend to be only slightly thicker. Siltstone beds generally have sharp upper and lower contacts, are massive or normally graded, often discontinuous, and locally show pinch-and-swell structures. Internal lamination is generally rare. Some exposures contain minor amounts of ankerite, while pyrite is very rare. Pavlides (1971) located a transitional contact between the Smyrna Mills and Carys Mills formations units in the Houlton area, and they are presumed to be in conformable contact in the study area. This study divides the Smyrna Mills Formation into two members, based on differences in color and apparent relative feldspar (ash?) content. As with the Carys Mills Formation, primary layering is often obscured by one or more generations of structural fabric. Early disruption of primary layering, present but rare in SOcm, is extremely common in SOsm; the character of this disruption is discussed more fully in the following chapter.

#### *Smyrna Mills Formation: Lower Member (SOsml)*

The lower part of the Smyrna Mills Formation is composed of pale gray,



Figure 10: Exposure of Smyrna Mills Formation. Orange-brown layers are siltstone and fine-grained sandstone; greenish gray is pelite with thin silt laminae. Note dextral shear folding and dextral slip along cleavage planes.

occasionally calcareous siltstone and medium gray pelite. Deeply weathered exposures of the Carys Mills Formation are often indistinguishable from SOsml. Lenses of blue-gray calcareous siltstone and argillaceous limestone, apparently identical to the similar lithology in SOcm, are found only in the lower member of the Smyrna Mills Formation. The best exposures suggest that these lenses are at least eight-to-ten meters thick. Exposures of relatively undeformed pelite and siltstone in the vicinity of some of these calcareous rocks suggest primary rather than structural interfingering of the lithologies.

*Smyrna Mills Formation: Upper Member (SOsmu)*

Bedding in the upper member of the Smyrna Mills Formation resembles that in the lower member, but the siltstone and pelite are, respectively, light and medium green in color, and chalky weathering is common. In the southwest corner of the Wytovitlock quadrangle, bedding is thicker and the exposures resemble the less feldspathic strata of the Ellen Wood Ridge Formation. Thin sections of both wackes and pelites from this upper member indicate that the green color is due to strongly pleochroic, dark green chlorite comparable to that in SOew. The green color may vary greatly in both chroma and hue over a single outcrop, particularly where transpositional layering is strongly developed. Sections showing multiple well-developed transpositional fabrics tend to be lighter in hue than those showing less penetrative tectonic alteration. Lincoln and Lincoln (1991) suggest that transposed zones may be depleted in iron, magnesium, aluminum, and potassium, so that solution of phyllosilicates and at least some feldspars may be involved in the development of both the transposition and the color variability. Orange or orange-brown staining of siltstones and wackes is common.

The uppermost section of this member varies from grayish-red to maroon, with bedding characteristics similar to those in the underlying sections, although few good exposures (indeed, few exposures at all) have been found; these rocks are generally

sheared and phyllitized. Green and red wackes and pelites are characteristic of the upper member of the Smyrna Mills Formation and its lateral equivalents (Ludman, pers. comm., 1986). Roy (1981) describes red and green slate and phyllite within the upper member of the Allsbury Formation in the eastern part of the Medway - Millinocket area, which is closest to the exposures of the overlying Madrid Formation, and therefore closest to the Central Maine Boundary Fault.

### Central Maine Belt

#### Madrid Formation: General

The Madrid Formation is divided into two members in this area. The presumably younger member (Smc) is composed of fine-to-medium grained, greenish-gray, generally calcareous, massive turbidite sandstones, interstratified with thin greenish-gray pelites, and bearing minor amounts of detrital (?) muscovite. The apparently older member (Smf) is generally similar in bedding style, but is composed of noncalcareous, moderately to highly feldspathic sandstones, which are apparently poorer in muscovite. The map pattern (Plate I) suggests that the calcareous rocks are generally younger, but the relation between the two members may be complex, and interfingering of calcareous and noncalcareous lithologies is probable. In western Maine, the lower Madrid Formation is calcareous, and the upper Madrid Formation feldspathic (Hanson and Bradley, 1988); if the apparent reversal of the sequence in the present study area is not due to an error in the interpretation, it may reflect diachroneity or differences in provenance between the two regions. There are no obvious microtextures or other evidence which would suggest that either the calcareous or the feldspathic character is diagenetic.

#### Lower (Feldspathic) Member (Smf)

This unit consists of massive, thick-bedded, medium-to-fine grained feldspathic wackes, separated by thin beds of greenish-gray pelite. Most beds are structureless, but some show normal grading and faint parallel or subparallel lamination. Primary layering is not apparent in many outcrops, which fracture preferentially along cleavage surfaces due to the poor grading and massive bedding style. Beds, where recognizable, vary from over one meter to less than two centimeters in thickness, with ten-to-fifteen centimeters perhaps most common. Bases are sharp, and the tops often sharp as well, so that facing direction is not often apparent. Flame structures and load casts are rare.

Near the Central Maine Boundary Fault, thin beds of feldspathic wacke, resembling the thicker-bedded sections of the upper Smyrna Mills Formation, occur both as isolated outcrops and interbedded with thicker-bedded feldspathic wackes. While these may represent rocks of SOsm found within the Madrid outcrop belt due to complex folding and faulting, I interpret them to indicate that the contact between the Smyrna Mills and Madrid Formations is conformable, and transitional over a limited range.

The red uppermost section of the Smyrna Mills Formation and equivalent units is generally found east of the faulted contact with Madrid or Madrid-like rocks (see summary in Hanson, 1988). A distinctive section of dark gray, variably feldspathic wackes and gray-to-black, sulfidic, locally carbonaceous pelites is found immediately west or northwest of the boundary fault in the present study area. These rocks are presumably equivalent to a black shale (Roy, 1981) at the top of the Allsbury Formation, conformably below the Lawler Ridge Formation. These rocks are placed within the Madrid Formation in this study, as they are thought (see below) to signal the onset of depositional conditions appropriate to the Madrid lithology. Their bedding style varies from thinly interbedded wackes and pelites, resembling the bedding style of SOsm, to thicker wackes with only thin pelitic interbeds, more typical of the Madrid Formation. Hypothetically, the red upper

section of SOsmu and the black basal section of the Madrid Formation together reflect a period during which iron-rich sediment was transported into the area; the specific color reflecting the availability of oxygen at different times or at different places within the depositional basin.

#### Upper (Calcareous) Member (Smc)

The calcareous Madrid Formation is a monotonous sequence of fine-to-medium grained calcareous sandstones with thin pelitic interbeds. Most sandstone beds are massive, but some show a basal grit or sand, or have fine parallel lamination or shallow cross lamination throughout. These rocks commonly develop a distinctive “orange-rust” (Roy, 1981) or “punky orange” (Ludman, 1990) weathering rind, apparently from weathering of tiny pyrite euhedra found throughout the rock. Fresh surfaces are greenish-gray. Carbonate occurs as densely twinned intergranular calcite; crinoid columnals have been found in coarser beds. Detrital (?) muscovite flakes, oriented subparallel to bedding, comprise a few percent of the rock and are conspicuous on fresh surfaces parallel to primary layering. The flakes show little or no alteration and have sharp, well-defined boundaries; warping of flakes around other, more rigid, grains is rare. Orientation of muscovite flakes subparallel to primary layering, and absence of evidence of alteration around the edges of the flakes, are taken as evidence for detrital origin of the muscovite.

## DISCUSSION

### Possible Correlation to Other Tracts

#### Pre-Ashgillian Rocks

The pre-Ashgillian rocks of the study area are comparable to Cambro-Ordovician strata of other anticlinorial belts in northern Maine (Figure 11). The basal unit in the

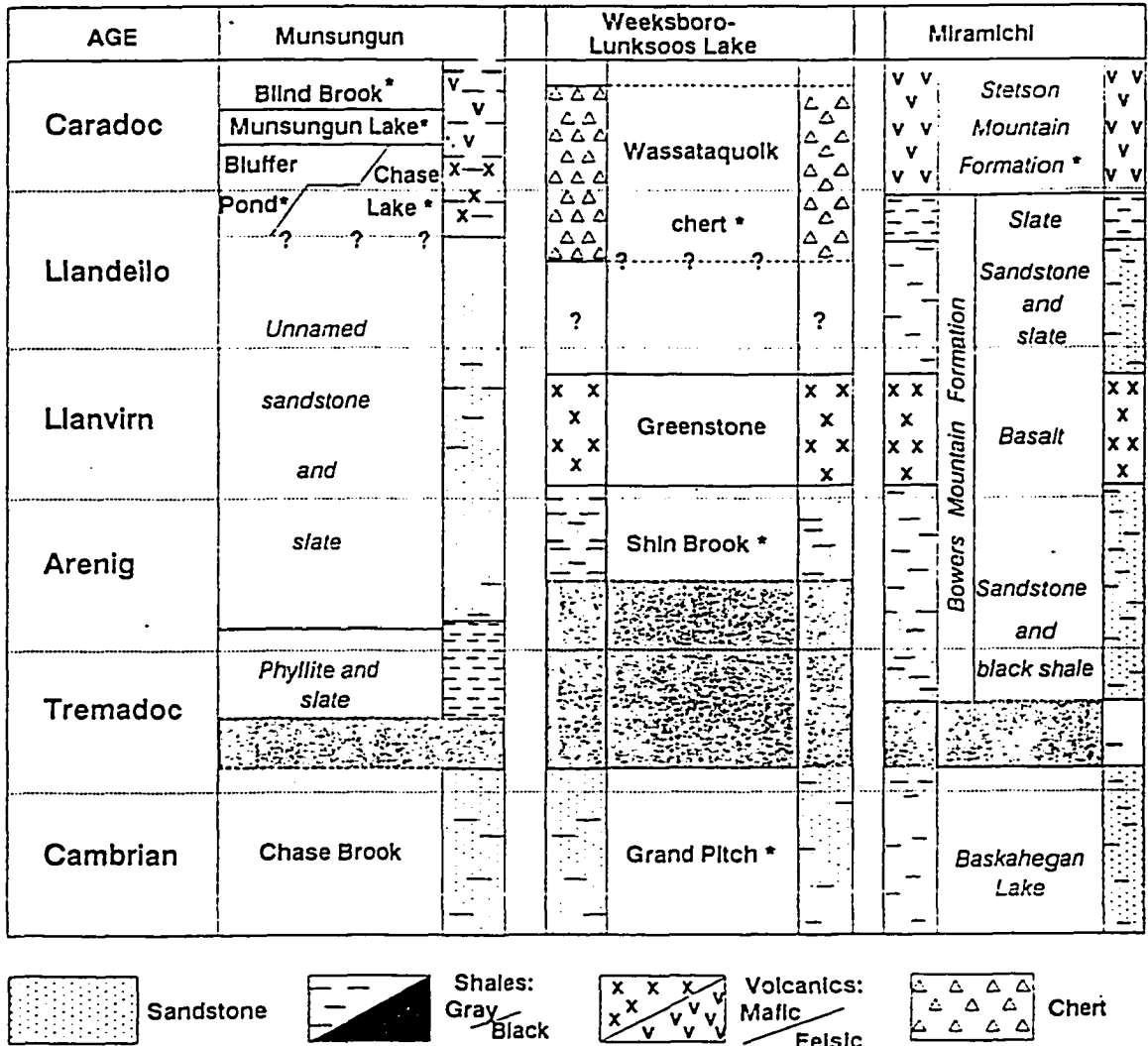


Figure 11: Correlation of Cambrian through Caradocian rocks of the Munsungun - Winterville, Weeksboro - Lunksoos Lake, and Miramichi Anticlinoria (adapted from Ludman et al., 1993). Asterisks indicate fossil age control on the marked units.

Weeksboro - Lunksoos Lake Anticlinorium is the Grand Pitch Formation (Neuman, 1967), a quartzofeldspathic wacke composed of approximately equal amounts of vitreous quartzite and slate and siltstone, and lesser amounts of graywacke and tuff; it is not said to be feldspathic. Neuman did not establish a distinct stratigraphy within this unit, but described a pelite-rich section of interbedded red slate and quartzite which may be comparable to the lower member of the Baskahegan Lake Formation (Ludman, 1988). The Cambrian age is based on occurrence of the Late Precambrian to Early Cambrian trace fossil Oldhamia, (Neuman, 1967). In the Munsungun - Winterville Anticlinorium, Hall (1970) described gray or black to greenish-gray slate, calcareous siltstone, and non-calcareous graywacke (Chase Brook Formation) and an unnamed unit of green, gray, and reddish-gray phyllite. A Cambrian age for these units is based on lithologic similarity to the Grand Pitch Formation and other dated units in New England.

Both Neuman (1967) and Hall (1970) characterize the structural style of the Cambrian rocks as significantly different from those of the overlying units. Osberg et al. (1985) show the Chase Brook Formation, but not the Grand Pitch Formation, as melange; the Hurricane Mountain Formation, a section of similar age and composition northwest of the Munsungun - Winterville Anticlinorium, is also shown as melange. The Baskahegan Lake Formation and equivalent rocks in New Brunswick do not contain the melange found in western and west-central Maine.

Felsic and mafic volcanic rocks and associated sedimentary rocks, divided into the Shin Brook Formation, an unnamed greenstone unit, and the Wassataquoik Chert (Neuman, 1967) unconformably overlie the Grand Pitch Formation. The Shin Brook Formation contains tuffs, lava flows, slate, siltstone, sandstone, and polymict breccia and conglomerate, containing clasts of other felsic volcanic rocks and quartzite. The most common clast lithology is an andesitic - dacitic porphyry with an aphanitic felsic

groundmass. Early-to-Middle Ordovician brachiopods and trilobites are found in fossiliferous sandstones. The greenstone is composed primarily of basaltic-to-andesitic volcanic rocks, including pillow basalts and volcanic breccias; felsic volcanic rocks are rare. These rocks are overlain by the thinly layered gray, greenish-gray, and red chert, sulfidic pelite, and felsic tuffs and tuff breccias of the Wassataquoik Chert; Middle Ordovician graptolites are found in the sulfidic pelite.

A similar volcanic section in the Munsungun - Winterville Anticlinorium (Hall, 1970) is divided into the temporally equivalent Chase Lake and Bluffer Pond Formations, and the overlying Munsungun Lake and Blind Brook Formations. The Chase Lake Formation is a sequence of interbedded conglomerate and graywacke grading upward into a slate and graywacke section. The Bluffer Pond Formation interfingers with the Chase Lake Formation and is composed of basalt, diabase, porphyritic rhyolite, rhyolitic and mafic tuffs, carbonaceous shale, chert, and gray tuffaceous siltstone. The Munsungun Lake Formation is dominated by felsic pyroclastic rocks and diabase, with lesser amounts of slate, mafic volcanic breccia, and red and black chert and is conformably overlain by the Blind Brook Formation, a unit of medium-to-dark gray, laminated or thin bedded, pyritiferous slate and sandy slate, with rare tuffaceous layers. Graptolites from the slate indicate an upper Middle Ordovician age, but Hall (1970) suggests that the unit may be as young as Ashgillian.

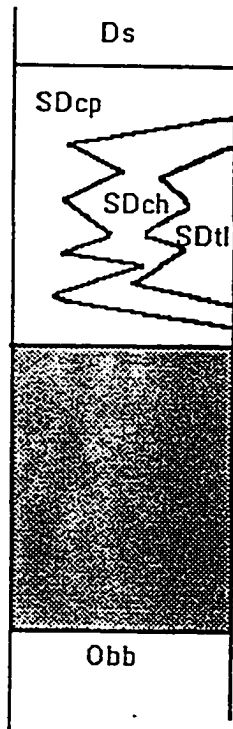
In all three tracts Cambrian(?) quartzose-to-quartzofeldspathic rocks form a basal unit with a more complex structural history than the overlying strata. These rocks are unconformably overlain, locally, by gray pelite and siltstone, and everywhere by Middle Ordovician, sulfide-bearing, bimodal volcanic rocks, and chert and ironstone. Mafic-to-intermediate extrusive rocks precede intermediate-to-felsic extrusive rocks, although mafic rocks occur throughout; this section is terminated by an angular unconformity.

### Post-Caradocian Rocks

Neuman (1967) reports massive, fossiliferous, post-Caradocian conglomerates of local provenance in the Weeksboro - Lunksoos Lake belt (See Figure 12). Well-rounded clasts of quartzitic and pelitic rocks from the Grand Pitch Formation are most common, although clasts of felsic volcanic rocks, chert, and siliceous siltstone also occur. The matrix consists of fragments of felsitic and quartzitic rocks, graywackes, and sericitized slate. Clasts of quartz diorite, apparently derived from Late Ordovician - Early Silurian intrusive rocks in the Shin Pond (Neuman, 1967) and Island Falls (Ekren and Frischknecht, 1967) quadrangles, suggest local provenance. Thinner conglomerate beds are interstratified with regularly bedded sandstone and siltstone. The conglomerate also includes Late Silurian bioherms, consisting primarily of stromatoporoids with interstitial pelmatozoan debris. Fragments of stromatoporoids, rugose corals, and brachiopods occur in bioclastic beds interlayered with siltstone.

A similar pattern is described by Hall (1970) in post-Caradocian rocks of the Munsungun - Winterville Anticlinorium. Poorly sorted, generally massive conglomerate of the Chandler Pond Formation, or other, unnamed, conglomerates, unconformably overlie the volcanic and clastic rocks of the Munsungun Lake Formation. The most common clasts are chert and siliceous volcanic rocks derived from the Munsungun Lake Formation, although Chase Brook Formation quartz graywacke clasts dominate locally. The section becomes internally conformable with distance from the exposed Cambrian- through- Middle-Ordovician rocks (Hall, 1970), but local disconformities are common near the core of the anticlinorium, where it is dominated by the massive conglomerate.

## Munsungun-Winterville



## Weeksboro-Lunksoos Lake

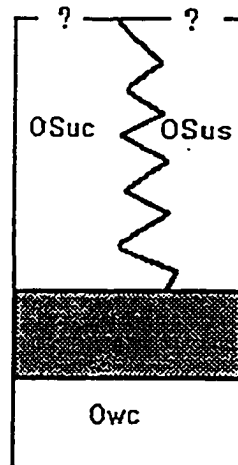
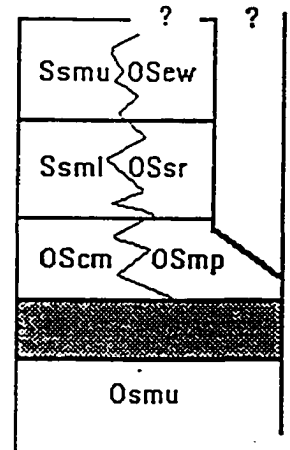
Aroostook-Matapedia/  
Miramichi  
[western margin]

Figure 12a: Comparison of post-Caradocian stratigraphy in Munsungun - Winterville, Weeksboro - Lunksoos Lake, and combined Aroostook - Matapedia and Miramichi tracts.

Key to units: Munsungun - Winterville: Obb = Blind Brook Formation; DScp = Carpenter Pond Formation; Dsch = Chandler Pond Formation; Dstl = Third Lake Formation; Ds = Seboomook Formation. Weeksboro - Lunksoos Lake: Owc = Wassataquiok Chert; OSuc = Unnamed Conglomerates; OSus = Unnamed Sandstones. Miramichi: Osmu = Stetson Mountain Formation, undivided; other units as defined in Figure 2.

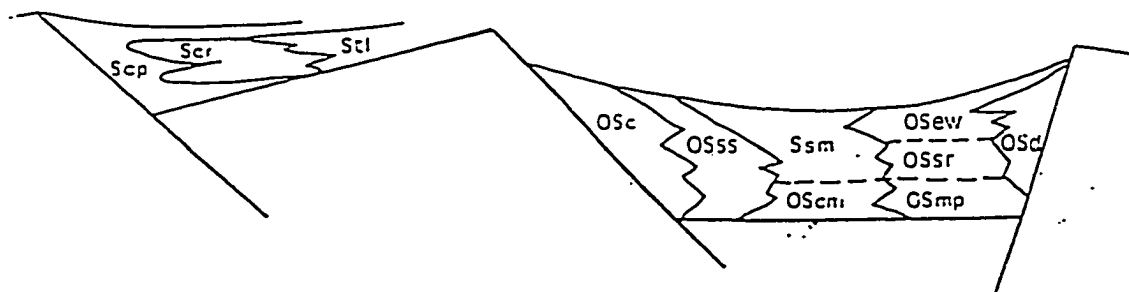


Figure 12b: Cartoon showing general depositional relationships hypothesized for post-Caradocian rocks of the Munsungun - Winterville, Weeksboro - Lunksoos Lake, and Aroostook - Matapedia/Miramichi tracts. The pre-Ashgillian rocks exposed during the Late Ordovician or Silurian do not necessarily correspond to the currently exposed pre-Ashgillian cores of the anticlinorial belts.

Key to stratigraphic units: Scp = Chandler Pond Formation; Scr = Carpenter Pond Formation; Stl = Third Lake Formation; OSc = unnamed conglomerate; OSss = unnamed sandstone and shale; OSsm = Smyrna Mills Formation; OScm = Carys Mills Formation; OSew = Ellen Wood Ridge Formation; OSsr = Sam Rowe Ridge Formation; OSmp = Mill Priveledge Brook Formation; OSd = Daggett Ridge Formation.

The more distal parts of the Munsungun - Winterville belt are composed of the Carpenter Pond Formation, Third Lake Formation, and Spider Lake Formation. The Carpenter Pond Formation consists of aphanitic to fine-grained mafic and felsic volcanic rocks, which vary in hue from greenish-gray to grayish-red, locally showing pillows and brecciated textures. The Third Lake Formation consists of calcareous siltstone and argillaceous limestone, with lesser amounts of tuffaceous, medium-grained sandstone. Fossil debris, including crinoid columnals, corals, and brachiopods, dates the unit to Ludlow or Pridoli. The Spider Lake Formation consists of andesitic and dacitic volcanic rocks, calcareous siltstone, feldspathic wackes, and massive conglomerate with clasts again apparently derived from the underlying pre-Silurian rocks.

All three Cambro-Ordovician tracts are therefore flanked along at least one margin by similar Late Ordovician - Early Silurian clastic-dominated facies. Massive conglomerates proximal to the older rocks grade into regularly bedded feldspathic wackes, siltstones, and pelites, with variable amounts of felsic-to-intermediate volcanic rocks, and, less frequently, mafic tuffs and flows. All conglomeratic facies are locally fossiliferous, and contain at least fragments of hermatypic fauna, suggesting that some sections of each tract were emergent or in shallow water. Conglomerates and interstratified finer-grained clastic rocks are restricted to the vicinity of the older source rocks, as at least the Prentiss Group and the post-Caradocian Weeksboro - Lunksoos Lake are separated by time-equivalent Aroostook - Matapedia strata. These sections cannot, therefore, represent parts of a continuous belt, as the pre-Ashgillian rocks appear to. Consequently, limits are placed on the width of the Aroostook - Matapedia basin and on the nature of the depositional basin for longitudinally equivalent rocks in Central Maine.

#### An Alternative Hypothesis

The stratigraphic correlations developed above assume that the Prentiss Group is presented in the correct stratigraphic order. In the absence of fossil ages for these rocks, however, inversion of the Prentiss Group is not impossible. The felsic volcanic rocks of the Ovf/Stetson Mountain Formation section could pass upward into those of the Ellen Wood Ridge Formation; volcanic deposits could become less abundant toward the Ashgillian, and water depth could increase, so that fewer fresh feldspars and chlorites are generated, and the pyrite content of the sediment would increase. The Mill Priveledge Brook Formation would be equivalent to the Caradocian Belle Lake Slate, and also equivalent, or transitional upward to, the graywacke - slate member of the Carys Mills Formation, so that the larger picture of linkage of the Aroostook - Matapedia and Prentiss Group rocks remains intact. The clastic rocks of the Ellen Wood Ridge and Sam Rowe Ridge Formations would then be equivalent to the green and gray pelitic rocks of the Pyle Mountain Argillite (Roy, 1976; also see Figure 3). Rounded clasts of Tetagouche-equivalent lithologies could still be derived from emergent shorelines, and transported in channels or canyons to deeper water. The Daggett Ridge Formation could still represent a debris flow deposit, or series of such deposits.

Work in northern New Brunswick and southeastern Quebec by Malo (1987) indicates continuous sedimentation from Caradocian through Llandovery time at many localities. Malo describes greenish-gray lithic wackes with clay slate interbeds above a tuffaceous sequence; these green rocks are then overlain by a unit of terrigenous mudstone, sandstone, and conglomerate, which pass upward into argillaceous carbonates. While not explicitly stated, it appears from Malo's discussion that these rocks are equivalent in age to other strata known to be deformed in Taconian-age events in easternmost Quebec.

Ultimately, however, I prefer the interpretation of the stratigraphic succession presented previously, for several reasons. First, an upward transition from the Sam Rowe Ridge Formation to the Ellen Wood Ridge Formation can be inferred at three separate localities. Facing reversals over short distances sometimes occur, presumably due to local, tight, short-wavelength folds, but at least the section along Baskahegan Stream is relatively continuous. Second, the chloritic sediments and massive flows of coarse volcanic debris which comprise much of the volcanic component of SOew are apparently absent from the Ovf/Stetson Mountain Formation section, and particularly from the younger rocks of that sequence (see Sayres, 1986). Third, Sayres' (1986) work in the Danforth area showed that both recumbent folding and faulting with a strong vertical component were associated with development of this unconformity. Evidence of a significant angular unconformity at the top of the Caradocian volcanic section is present in the other tracts as well. Fourth, although there are problems in the relation of the Mill Priveledge Brook Formation to the Belle Lake Slate, the lithologic similarities among the various post-Caradocian conglomerates, identical reworked tuff beds in the Sam Rowe Ridge, Ellen Wood Ridge, and Smyrna Mills Formations, and the analogy to the flanks of other anticlinorial tracts in which the unconformity is clearly present, strongly support equivalence of the Aroostook - Matapedia and Prentiss Group strata.

#### Basin Margin and Slope-Apron Environments

The relation of the massive Daggett Ridge Formation conglomerates to the sandstone - pelite sequence is of major importance. It is suggested here that the Daggett Ridge Formation interfingers with at least the Sam Rowe Ridge and Ellen Wood Ridge Formations (it may be largely progradational above the Mill Priveledge Brook Formation). Ludman (1990), however, considers that the Daggett Ridge Formation might lie unconformably above the more regularly bedded pelites and wackes, potentially reflecting

the mid-Silurian Salinic Disturbance, and perhaps analogous to a prograding (?) conglomerate underlying the Seboomook Formation (Hall, 1970). This would eliminate the need for a very rapid transition from a “proximal” Daggett Ridge Formation to more “distal” sandstones and pelites and address the near absence of conglomerate in the Aroostook - Matapedia rocks. (Tectonic effects could also remove an intermediate section.) The outcrop pattern of the Daggett Ridge Formation, and the similar tectonic fabrics found in both conglomerate and wacke - pelite sections, require at most that any unconformity not have been related to major tectonic deformation of the stratified sequence; a shallow regional angular unconformity cannot be ruled out on the basis of the present structural evidence alone.

If, however, the Smyrna Mills Formation passes conformably upward into the Madrid Formation, which in turn is conformably overlain to the west and southwest by Siluro - Devonian and Devonian strata, there is no time available to develop a regional unconformity between the Ashgill and the Early Devonian. Deposition of the conglomerate may have eroded previously deposited wacke - pelite sections, and stratabound conglomerates within the wacke - pelite units could be derived from cannibalization of the massive debris flows, so that the contact between the Daggett Ridge Formation and other Prentiss Group units could be generally nonconformable.

Rapid transitions from coarse-grained to fine-grained facies are not uncommon in certain tectonostratigraphic environments. Fault-controlled margins may show proximal (near-fault) facies including rockfalls, debris flows, gravel-rich turbidites, and associated relatively coarse-grained deposits, that grade rapidly into and interfinger with sandy and muddy facies both with distance from the fault, and laterally along the fault, reflecting discontinuous fault activity and the presence of channels across the scarp (Stow, 1986). In Jamaica (Burke, 1967), conglomeratic clastic wedges pass directly into deep water

submarine fan and slope facies over a span of ten-to-fifteen kilometers. In eastern Greenland, Surlyk (1978) found Jurassic normal faults associated with a sequence in which rockfall breccias proximal to the fault graded rapidly into resedimented conglomerates and sandstones, and then into siltstones and mudstones, within thirty-to-forty kilometers of the apparent fault scarp.

Stanley (1988) describes Cretaceous wacke - pelite sequences from the Virgin Islands in which the coarse beds are predominantly BCE and CE incomplete turbidites. These rocks are interpreted to be deposits at the base of a debris apron, with a slope of perhaps as much as ten degrees, based on interfingering of thin-bedded sections (formerly thought to be distal turbidites) with polymict debrites (including shallow-water faunal debris) and other gravity-driven mass flow deposits. Stanley found that the majority of the thin-bedded rocks probably formed by reworking of thicker turbidite beds by traction currents; in many cases, the original turbidite sand is almost entirely eroded. The resulting layers show sharp bases and tops, with some development of pinch-and-swell structures and shallow-angle cross-lamination, and closely resemble the wacke - pelite sections of the Prentiss Group and equivalent Aroostook - Matapedia rocks. Calcareous sandstones interbedded with argillaceous carbonates in the Sam Rowe Ridge Formation are typically lenticular on the scale of a few inches, and well-laminated throughout, and so suggest operation of bottom currents reworking previously deposited sands.

Finally, Moench and Pankiwskyj (1988) in a review of research on the rocks of northwestern Maine, show a transition from shelf facies to deep-water deposits over a span of perhaps fifty kilometers in rocks temporally equivalent to those of the study area. These rocks are blanketed by the monotonous deep-water facies of the Lower Devonian Carrabasset Formation.

Transitions from coarse proximal deposits to thin-bedded, presumably distal deposits may therefore occur over distances comparable to those separating the eastern and western sides of the study area - presently some fifteen-to-twenty kilometers - prior to shortening through folding and faulting. This does not rule out the possibility that the Daggett Ridge Formation may be a single coarse debris flow derived from shallower water, and deposited onto or within a channel of a deep-water "distal" fan. There is no reason to assume that the depositional process would homogeneously mix the contents of the flow. If SOdr represents deposits which are channelized and/or which lie at or near the mouth of a point source of coarse debris (e. g., a channel in the debris apron), lateral variation, as well as proximal - distal relations, would play a very substantial role in the facies patterns preserved. Significant sections of "proximal" debris may have been cut out by thrusting of the debris apron facies southeastward over the Miramichi along early low-angle faults, such as the Class III Faults discussed in the following chapter.

#### Regional Correlation and Interpretation

Linkage of the stratigraphies of northeastern Maine with those of central and southern Maine has been problematic. Doyle et al. (1967) were unable to clearly resolve this problem and so left a large area of east-central Maine blank on their preliminary state geologic map. Osberg et al. (1985) linked the two areas by extending the area mapped as Madrid Formation as far north as the present study area, but did not correlate it to Silurian calcareous sandstones found farther to the north. Neither did they directly link the stratigraphy of the Aroostook - Matapedia block with that to the south, showing instead, unnamed Silurian pelite (Spu) and limestone (Sul) units passing into the Waterville and Vassalboro Formations of south-central Maine in the general area between Lincoln and Greenbush, southwest of the study area. This study suggests that the Aroostook - Matapedia section continues southwestward through the study area into the

Central Maine Synclinorium (Figure 13), with the Smyrna Mills Formation equivalent to the Waterville and upper Sangerville Formations of Osberg (1988), and the Carys Mills Formation transitional into the Vassalboro Formation of Osberg et al. (1985), now the Hutchins Corner and lower Sangerville Formations of Osberg (1988).

The Hutchins Corner Formation, which is composed of slightly rusty, gray to dark gray, variably bedded calcareous and noncalcareous wackes interbedded with lesser amounts of thin-bedded phyllite and quartzite, lies unconformably on pre-Ashgillian rocks (Osberg, 1988). A thin, continuous, marble unit is found near the base of the formation. Distinct marbles or limestones also form mappable marker beds in both the Sangerville and Waterville Formations (Osberg, 1968; Ludman, 1977), laterally equivalent units which conformably overlie the Hutchins Corner Formation.

The Waterville Formation is composed primarily of interbedded quartz - mica phyllite and quartzite. At the stratigraphic middle of the Waterville Formation is a distinctive unit of interbedded limestone and phyllite; a similar unit is found in the Sangerville Formation. The lower member of the Sangerville Formation is composed of rusty-weathering, black, sulfidic quartz-mica slate, white or light gray weathering, sometimes slightly calcareous, wacke, and gray or light green phyllite or slate, occasionally containing rhombs of ferroan carbonate. Other sulfidic horizons are found within both the Sangerville and Waterville Formations, but only that of the basal Sangerville Formation is thick and continuous. Polymict conglomerate occurs both as massive lenses and one-to-two-meter thick layers interbedded with the wacke - phyllite section. Clasts range from pebble to grit sizes, and clast lithologies include quartz, feldspar, wacke, chert, slate, felsic and mafic volcanic rocks, and plutonic rocks.

NW

SE

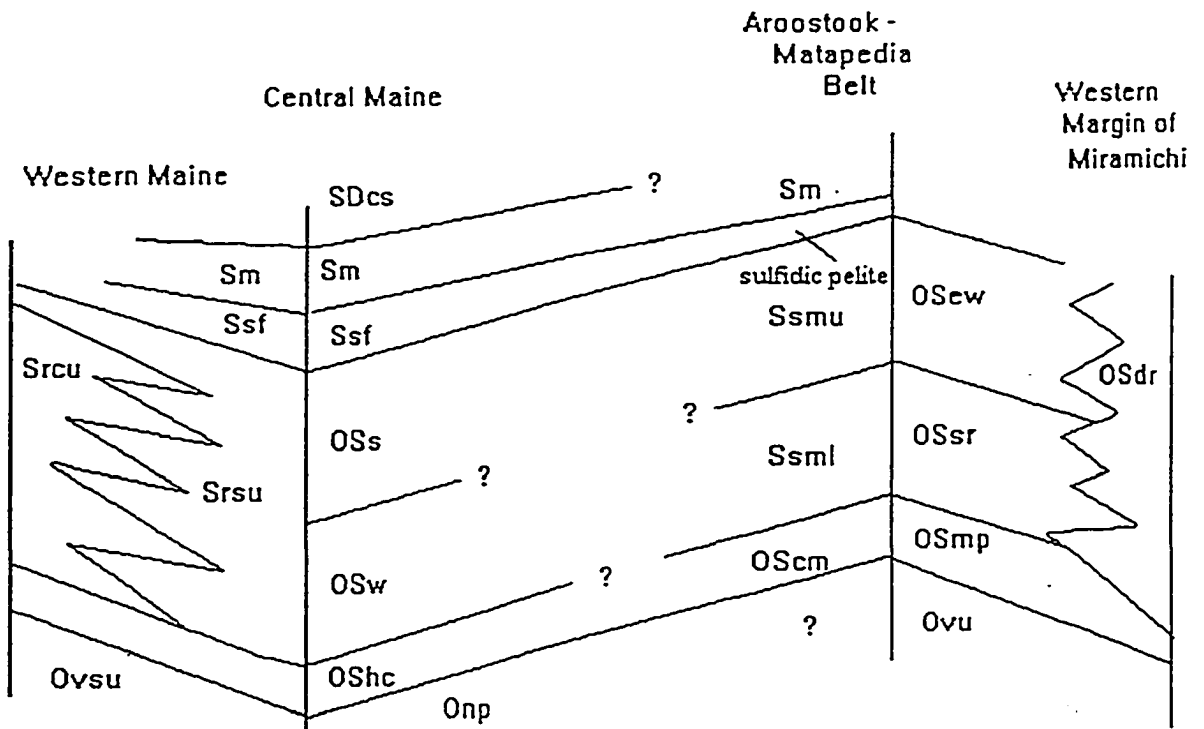


Figure 13: Schematic fence diagram (not to scale) showing hypothesized relationships between combined Aroostook - Matapedia/Miramichi belt, Central Maine Belt (Osberg, 1988), and "tectonic hinge" area of northwestern Maine (Moench and Pankiwskyj, 1988).

Key to Abbreviations: Ovsu and Ovu = Pre-Ashgillian volcanic and sedimentary rocks, undivided; Onp = Nehumkeag Pond member of Cushing Formation; Oq = Quimby Formation; SOhc = Hutchins Corner Formation; Srcu = Conglomeratic Rangeley Formation, undivided; Srsu = Sandy and silty units of Rangeley Formation, undivided; OSw = Waterville Formation; OSs = Sangerville Formation; Ssf = Smalls Falls Formation; Sm = Madrid Formation; DScs = Carabassett and Seboomook Formations; other units as defined in Figure 12.

The Waterville and Sangerville Formations therefore show lithologies and bedding styles similar to those of the Prentiss Group. The Hutchins Corner and lower Sangerville Formations span Ashgillian to Llandoveryan time (Osberg, 1988), and could reflect conditions comparable to the oxygen-poor depositional environment of the Mill Priveledge Brook and Carys Mills Formations. The Central Maine rocks do show classical turbidite features, such as load casts, convolute bedding, and climbing ripples, to a much greater extent than the Prentiss Group and Aroostook – Matapedia Belt, which also show no distinct calcareous unit (other than the thin calcareous siltstones and pelites within SOsm and SOsr) above the upper contact of the Carys Mills Formation. Massive conglomerates comparable in extent to the Daggett Ridge Formation are not found in the Waterville and Sangerville Formations, consistent with an interpretation that the rocks represent more truly distal deposits than the debris-apron facies of the Aroostook - Matapedia and Prentiss Group.

Many workers in central Maine, most recently Hanson (1988), have noted a distinct change in sediment type and sedimentary facies associated with the onset of deposition of the Madrid Formation. Both these rocks and the overlying Seboomook Group show lithologies and paleocurrents indicative of an eastern provenance, in contrast with the western provenance indicated for most of the older clastic rocks (Due to local conditions the Prentiss Group provenance is to the east of the basin; the carbonate component of the Carys Mills Formation is presumably derived from shelf or ramp environments to the northeast (Roy, 1980)). Together with the progressive westward younging of the Seboomook Group (Boucot and Heath, 1969), this facies change led Hanson (1988) to infer that the lithologic changes reflected “diachronous northwesterly subsidence throughout central and western and Maine.”

This transition from westerly derived, frequently coarse debris, to easterly derived submarine fan deposits in western and central Maine is generally associated with the Smalls Falls Formation (see Moench and Pankiwskyj, 1988), a unit of sulfidic shales and sandstones overlain by a thin calcareous upper member containing minor ironstone and “other probable chemical sediments”, which passes conformably upward into the basal Madrid Formation. Hanson (1988) interpreted the sulfidic Smalls Falls Formation to have been deposited in the sediment-starved, poorly oxygenated environment of the crest of the flexural bulge advancing before the Avalonian continent. In this model, the Madrid Formation is deposited above the sulfidic rocks after the bulge has passed and the area has settled into deeper, better oxygenated waters of the foredeep. Either model may be acceptable for the transition between the Smyrna Mills Formation and the Madrid Formation in the study area, although the association of SOsm with conglomerates bearing in-place (?) shallow-water fauna suggests that subsidence may be more likely. In the sulfidic basal Madrid Formation of this study, and in equivalent rocks of the Frenchville Formation (Roy, 1980), the character of the bedding remains generally the same as in the underlying rocks. Sulfidic phyllites in the Waterville and Sangerville Formations may indicate that oxygen-poor conditions were occasionally found in deeper waters throughout the deposition of the Smyrna Mills Formation. Perhaps only during regionally extensive subsidence in advance of the Avalonian continent and clastic wedge did the study area see oxygen-poor water for any length of time after the Ashgillian.

In the preferred stratigraphic model for the post-Caradocian evolution of the study area, several distinct depositional basins developed across northeastern Maine during Ashgillian time. These may have developed through block faulting of the volcanic and clastic basement rocks underlying all tracts. Models of apparently similar depositional environments include relatively steep slopes in the area of the proximal deposits. Distinct basins in the northern part of the state were linked to a single, presumably wider and

deeper, basin in south-central Maine. Initially, the waters of this basin were anoxic, perhaps reflecting depth or relative isolation from better circulated ocean waters. Coarse debris shed from the flanks of the basins graded rapidly into argillaceous micrite transported along the basin axis from carbonate environments to the north (Roy, 1981), presumably by density-driven bottom currents.

As circulation in the basin improved, the volume of carbonate declined, perhaps as a result of increasing relief and consequent increased supply of terrigenous sediment smothering large areas of the shelf. In the area of this study, the increasing relief inland of the basin margin may be reflected by the thicker and more regularly bedded sands of the Sam Rowe Ridge Formation, and the increase in the volume of coarse debris above the Mill Priveledge Brook Formation. Increasing feldspar content of the wackes and the occurrence of fresh volcanic or volcanoclastic rocks in the section suggest that some of the change in relief may be associated with increasing volcanism. This volcanism is not evident along strike to the southwest, except perhaps by the feldspathic nature of the wackes in that area; flows and ashfalls comparable to those in the study area are not noted in the Hutchins Corner - Waterville - Sangerville sequence. The increase in iron content of sediment suggested by the red rocks at the top of the Smyrna Mills Formation may also relate to an increase in the influx of weathered terrigenous material. As the equivalent section in the Ellen Wood Ridge Formation is apparently absent, there is no change in coloration to any change in the more "proximal" rocks.

In the middle Silurian, although perhaps diachronously over that interval, bottom waters became anoxic across the entire basin, from south-central Maine to as far northeast as the Presque Isle area. This anoxic event concluded prior to deposition of submarine fan facies across apparently all of central and northern Maine. These two widespread events may reflect deepening of waters across the entire area in advance of a prograding

submarine clastic wedge, which progressively buried the entire state from southeast to northwest. The diachroneity inherent in this progradation, together with variation in the activity of local volcanic centers, may be reflected in local variability in the succession of calcareous and feldspathic sandstones in the wedge. This model for the evolution of the regional stratigraphy will be related to tectonic events in the New England - New Brunswick area in the final chapter.

## STRUCTURAL GEOLOGY

### INTRODUCTION

The lithotectonic belts of the study area had been nominated as “terranes” as early as 1983 (Williams and Hatcher, 1983; Zen, 1983). However, stratigraphic evidence discussed in the previous chapter and elsewhere (Hopeck, 1988, 1989; Hopeck et al., 1989; Ludman 1988, 1989, 1990) demonstrates a common stratigraphy for the Prentiss Group and Aroostook - Matapedia rocks from at least the latest Ordovician, and suggests conformable deposition of the Central Maine Belt rocks above these belts. This chapter presents evidence for a common structural history among all three tracts.

#### Previous Work

Early work (Doyle et al., 1961; Larrabee et al., 1965; Griscom and Larrabee, 1963; Larrabee and Spencer, 1963) showed that the gross distribution of lithologies reflected symmetric, northeast-trending folds; this generalization remains accurate. The role of faulting was not clearly recognized, although disrupted zones were identified along the trends of the present Norumbega Fault Zone (Larrabee et al., 1965) and Stetson Mountain Fault (Doyle et al., 1961). Dextral-slip faults were mapped in the Danforth quadrangle by Larrabee and Spencer (1963), but evidence of these structures was not discussed. Pre-lithification disruption was not described.

Ludman (1981) and Mangini (1983) distinguished the Tetagouche-equivalent and younger stratigraphic sections in the area, and identified an early recumbent folding event in the pre-Ashgillian rocks. An unconformity between the Tetagouche section and at least part of the present Prentiss Group was hypothesized from clasts of well-cleaved Caradocian phyllite within the current Daggett Ridge Formation. Mangini hypothesized

northwest-trending, post-Acadian dextral faults and late normal faulting to juxtapose post-Caradocian conglomerates and older Tetagouche rocks.

Finer subdivision of the stratigraphy by Sayres (1986) and Sayres and Ludman (1985) led to a more detailed structural model. Early, west-vergent recumbent folds associated with a weak, presumably axial-planar, subhorizontal cleavage were observed in outcrop and inferred from an asymmetric distribution of poles to primary layering and the mapped outcrop pattern. Sayres found that the strong regional cleavage that cross-cuts the sub-horizontal fabric was associated with open, upright folding, and related that cleavage to Acadian events and the recumbent folding to pre-Acadian tectonics. Sayres concluded that the Acadian-era folds plunged to the north-northeast and, more gently, to the south-southwest, and also distinguished a northwest-trending fabric, hypothetically related to steeply plunging minor folds observed in outcrop.

#### Outline of Regional Structural Evolution

The present study is concerned with rocks no older than latest Ordovician, so that the effects of any mid-Ordovician recumbent folding were not directly observed. The earliest structural events recorded in these rocks are syn- or immediately post-sedimentation disruptions of primary layering. This event is termed D<sub>0</sub>, and the associated zones of disruption denoted as Class I Faults (see Table II).

Northwest-vergent low-angle faults (Class II faults), associated with the approximately mid-Silurian juxtaposition of the St. Croix Belt and Fredericton Trough, preceded east-vergent thrusting (Class III Faults/D<sub>1</sub>). The traces of Class III faults show the effects of the upright folds, (see Plates I and II) that dominate the regional map pattern and are associated with a north-northeast trending axial planar cleavage. This folding event, D<sub>2</sub>, is thought to represent a continuation of the compressional phase

<b>FAULT CLASS/EVENT</b>	<b>STRUCTURE</b>	<b>FABRIC</b>
Class VI/D6	Sinistral strike-slip faults; steeply plunging kink folds	Regional slip cleavage and transposition
Class V/D5	Dextral oblique-slip faults (not in area)	
Class IVb/D4a, D4b	Dextral oblique-slip faults; steeply plunging folds	Regional slip cleavage and transposition
Class IVa/D3	Reverse faults; shallowly plunging folds	Localized slip cleavage and transposition
D2	Upright folds	Regional axial-planar cleavage and transposition
Class III /D1	Thrust faults	local shear structures
Class II	Thrust faults (not in area)	
Class I/D0	Normal faulting and slumping	Disruption of primary layering

Table II: This table summarizes the fault classes discussed in this chapter, and relates them to observed structures and fabrics. Note that only the upright “Acadian” folds are unrelated to a fault type; these folds may, however, be considered as genetically related to the Class III thrust faults.

first signaled by the Class III faults. Continued compression led to reverse faulting (Class IVa/D3) along north-northeast trends subparallel to the axial-planar cleavage. The sense of motion on these faults is apparently west-side-up, with vertical offsets of perhaps a few hundred meters at most. A localized slip cleavage and transposition, axial-planar to relatively rare minor asymmetric drag folds, is found parallel to shear planes in less competent rocks close to the fault trace.

These same faults were subsequently reactivated as dextral strike-slip faults (Class IVb/D4), which are associated with a strong regional slip cleavage and minor dextral shear folds with subvertically plunging axes. The D4 event is divided into two subphases, one (D4a) occurring along faults trending north-northeast, and related to a north-trending slip cleavage and local transposition, and a second (D4b), immediately subsequent or slightly overlapping, along similar structures trending northeasterly, and related to similar cleavage and transposition fabrics.

Sinistral strike-slip (D5) along northwest-trending, near-vertical Class VI faults produced fractures and slip cleavage, and vertically plunging kink folds. This fabric crosscuts all other regional fabrics, indicating that it is very late, perhaps post-Acadian.

## D0: PRE-OROGENIC (CLASS I) FAULTS

### Nature of Class I Faulting

Class I Faults are zones of complex disruption of unlithified sediment that range in width from less than thirty centimeters to hundreds of meters, and separate zones in which primary layering is continuous or nearly so. These structures are characterized by discontinuous and dismembered beds and beheaded tight-to-isoclinal folds. A typical exposure is shown in Figure 14. Identical fabrics are found in both wide zones of disruption and narrow zones which are strata-bound on the scale of an outcrop. These

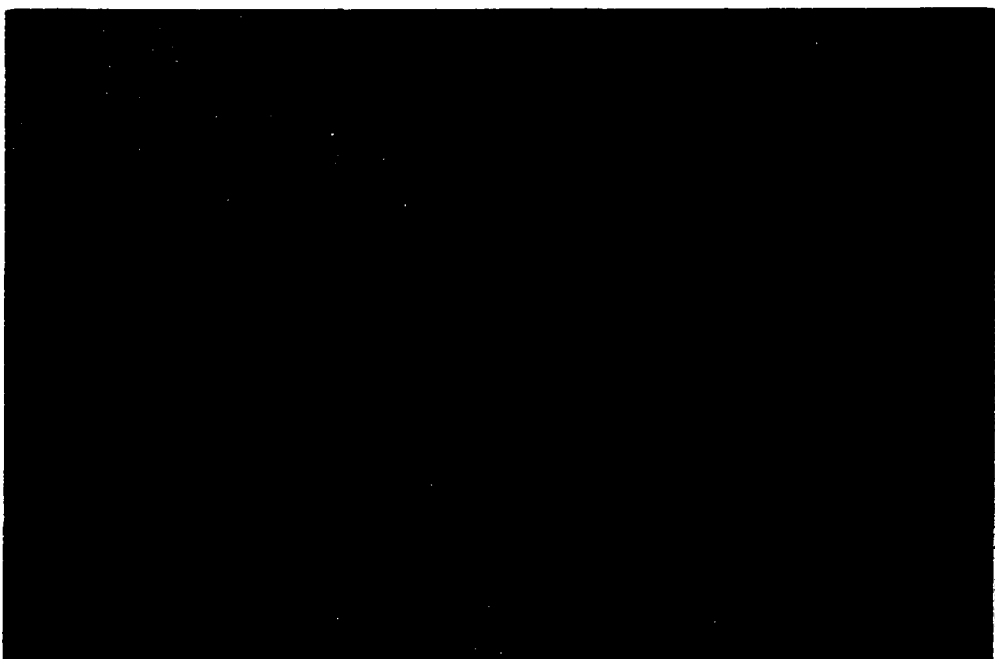


Figure 14a: Disrupted bedding in Mill Priveledge Brook Formation, possibly related to emplacement of Daggett Ridge Formation debris flow. Note primary layering in many clasts. Diagonal lines are glacial striae.

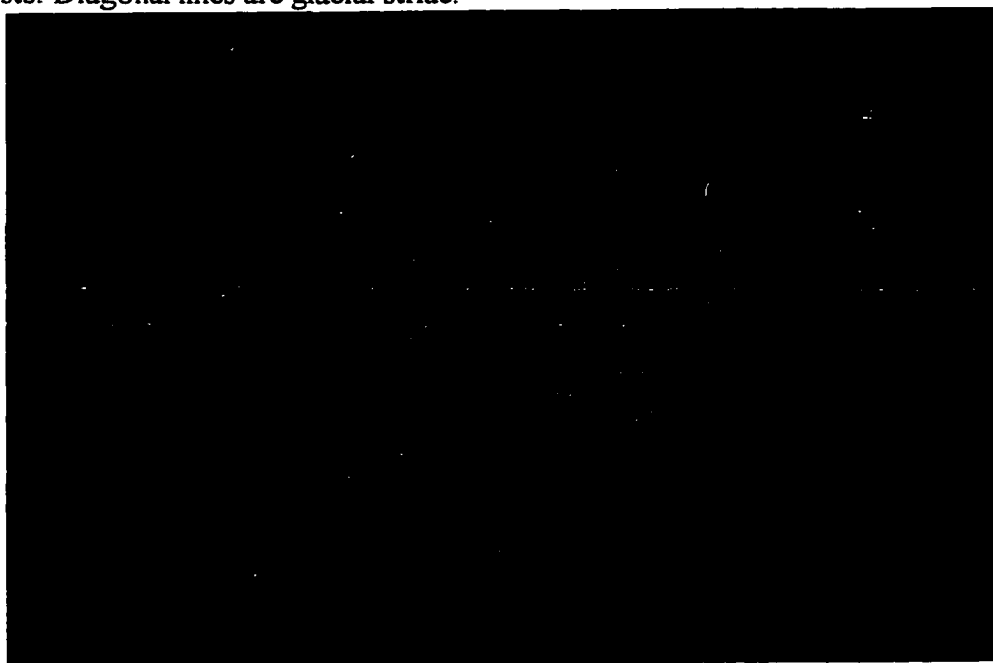


Figure 14b: Disrupted bedding in Smyrna Mills Formation. Fracturing and folding is more apparent than in Figure 14a, suggesting that this unit was more rigid during Class I deformation. See also Figure 6c.

structures are most common in units composed primarily of interbedded pelite and varying amounts of siltstone or fine-to-medium grained sandstone or wacke: the Smyrna Mills Formation of the Aroostook - Matapedia Belt and the Mill Priveledge Brook and Sam Rowe Ridge Formations of the Prentiss Group. Textural evidence indicating that this deformation was either syndepositional or immediately post-depositional (pre-lithification but possibly post-consolidation) includes:

- (1) mixing of sand or silt and pelite in adjacent beds or bed fragments;
- (2) along-strike transition from disrupted into continuously bedded sections;
- (3) chaotic orientation of folds and bed fragments with respect to cleavage and transposition; and,
- (4) absence of mineralized tension gashes, shear fractures, and other kinematic fabrics characteristic of tectonic disruption of lithified multilayered sequences.

Scaly fabrics typically associated with tectonic melanges from compressional environments (Moore et al., 1986, for example) are not found in these disrupted zones. Brittle fabrics and transposed layering are sometimes found, but are not clearly related to or concentrated along these zones, with the possible exception of the Kingman Fault Zone, discussed below. The strata-bound nature of many Class I features and their possible association with olistostromal(?) debris suggest that these fabrics are related to slumping and liquefied sediment flow. Some disrupted zones apparently underlie thick, areally extensive bodies of massive conglomerate, including some blocks several meters in diameter. No evidence of upper flow regimes or inverse grading, which might be associated with grain-flow conditions, has been noted in Class I structures thus far.

#### Kingman Fault Zone

The Kingman Fault Zone of Morisi (1984) and Morisi and Ludman (1985) is the best-studied example of a Class I structure. This northeast-trending zone extends at least

from the town of Kingman to the confluence of the Mattawamkeag and Penobscot rivers (Osberg et al., 1985). Morisi (1984) proposed four models for this zone:

- 1) a major strike-slip fault separating two different lithologic suites;
- 2) a relatively unimportant strike-slip fault without significant offset;
- 3) a package of relatively incompetent rocks bounded by the more competent sections of the Miramichi and Central Maine Belt;
- 4) the tightly folded nose, toe, or plane of a regional soft-sediment slump.

The first hypothesis is inconsistent with the present stratigraphic model, which shows the zone to lie entirely within the Smyrna Mills Formation, and the third is to some extent contraindicated, at least with regard to the pre-transposition fabrics, by the recognition of similar disruption on smaller scales in more competent sequences (See Figures 14a and b). Morisi (pers. comm., 1991) now regards the complex fabrics of the Kingman Fault Zone as the result of early, soft-sediment disruption overprinted by several generations of brittle and ductile fabrics, a model which combines elements of the second and fourth hypotheses from her previous work.

Unlithified-disruption fabrics similar to those at Kingman are now known from several localities in the Aroostook - Matapedia Belt and Prentiss Group, and the Central Maine Belt as well (Hanson, 1988; Hanson and Bradley, 1989). The younger ductile and brittle fabrics also displayed at Kingman are common throughout the study area, although best developed in more pelitic units, and are not associated exclusively with rocks showing well-developed transpositional layering. The linear zone mapped by Morisi (1984) and shown on the current state geologic map (Osberg et al., 1985) may represent a fault of a later class, perhaps Class IV, and the trace of the Kingman fault, as defined by the well-developed transposition fabrics, may be coincident with one or more zones of Class I disruption. Extensive premetamorphic faulting has been documented in many areas of

northwestern and central Maine (Boone et al., 1988; Boone and Boudette, 1988; Hanson, 1988; Moench and Pankiwskyj, 1988a; Hanson and Bradley, 1989). In northwestern Maine (Boone et al., 1988), this faulting is related to abrupt changes in stratigraphic thickness; such changes are not noted in the study area. Rocks displaying disrupted fabrics comparable to those of Class I zones have been termed Type I melange by Cowan (1983), who indicates that presumably olistostromal melange of this sort may develop during extensional or transtensional tectonic phases, so that the presence of non-scaly Type I melange need not imply the location of a terrane boundary.

In the absence of much more continuous exposure, the primary geometry of any extensive Class I zone is impossible to determine, although smaller zones are strata-bound and subparallel to bedding. The stratigraphic model discussed above suggests that some Class I zones can be interpreted as mass-flow deposits. They are considered as “faults”, in a loose sense, as a result of the precedent of Morisi’s work on the Kingman Fault Zone, evidence of shear in the distorted beds and laminae, and the possibility that some zones may be layer-parallel detachment surfaces. The tectonic model proposed in the following chapter does not require that these zones represent shallow-angle faults within an unconsolidated accretionary prism; structures similar to Class I Faults are likely to develop in any dynamic depositional environment.

#### Age of Class I Faulting

Class I zones reflect the oldest post-Caradocian deformation in the study area and affect rocks known (Smyrna Mills Formation) or thought to be (Mill Priveledge Brook and Sam Rowe Ridge Formations) of latest Ordovician to Early Silurian age. They are deformed by subsequent folding and faulting, and crosscut by transpositional fabrics, most constrained to be no younger than Early Devonian. For example, Class I disruption along

the Kingman trend apparently truncates against the Central Maine Boundary Fault, a Class III structure juxtaposing the Central Maine and Aroostook - Matapedia belts. This latter structure must be older than the 385 Ma age of the Bottle Lake Complex (Ayuso, 1982; Ayuso and Arth, 1983) which intrudes both belts. Class I zones therefore began forming by at least the late Ordovician - Early Silurian. It is probable that comparable structures developed at various locations and times throughout the evolution of the basin.

## CLASS II FAULTS

### Nature of Class II Faulting

Class II faults do not occur in the study area, but have been identified in southeastern Maine, particularly in the St. Croix Belt, and are discussed here to provide background for the tectonic model developed in the following chapter. These faults are most prominent near the contact of the St. Croix Belt and the Fredericton Trough, and may have comprised that contact prior to deformation related to faults of Classes IV and V. Class II faults are associated with outcrop-scale and map-scale drag folds in the Woodland and Kendall Mountain Formations. Axes of these folds trend northeast to east-northeast; the folds are asymmetric, northwest-vergent, and strongly reclined or recumbent with axial surfaces dipping 5 to 40 degrees to the southeast and horizontal or shallowly plunging, northeast-trending axes (Ludman and Hill, 1989). The inferred southeast-over-northwest thrusting is also supported by minor thrusts observed at the type locality of the Woodland Formation and elsewhere in the Calais quadrangle.

### Age of Class II Faulting

Class II Faults thrust the Late Cambrian - middle Caradocian St. Croix Belt over mid-Silurian (?) and older rocks of the Fredericton Trough, and so must be later than mid-Silurian. An age of 420 Ma has been obtained from the Pocomoonshine Gabbro-Diorite

(West et al., 1992), which seals the contact of the St. Croix Belt and the Fredericton Trough. All features attributed to Class II faulting are cut by plutons in the Calais - Woodland area, but the minimum age of displacement is uncertain due to uncertainties regarding the ages of the plutons. This problem is discussed by Ludman and Hill (1989), and centers on the question of whether the cross-cutting intrusive rocks are Late Silurian, (Jurinski et al., 1988) or Early Devonian (Ludman and Hill, 1989). If the former age is correct, the faults are restricted to a post-Caradocian, pre-Late Silurian age. If the latter age is appropriate, Class II thrusting may be a late, post-accretionary phase of the Acadian; the tectonic model developed below assumes the faulting to be early Acadian.

#### D1: CLASS III FAULTS

##### Nature of Class III Faulting

In the field, Class III Faults are narrow zones within which float blocks of massive white quartz and phyllonitized pelite are common; shear structures are common in quartz or calcite veins within the phyllite blocks. Slabbed float blocks of phyllonitized Smyrna Mills Formation show sheared veins and strongly disrupted primary layering, although some of the latter may be a relict Class I fabric. The more competent rocks of the Madrid Formation show mineralized brittle fractures at both microscopic and macroscopic scales; thin sections of samples from outcrops near these fault zones show strain-shadowed quartz grains and sutured grain boundaries.

The Central Maine Boundary Fault is the only Class III fault well supported by field evidence. The Stetson Mountain Fault has been variously interpreted as either a Class III structure comparable to the Central Maine Boundary Fault, or a Class IV structure comparable to the North Bancroft Fault; Ludman (1990, 1991) reports rocks east of this fault, formerly mapped as Caradocian volcanic rocks, which may in fact belong in the Late Ordovician - Silurian section. It is not yet clear whether these are klippen of younger

rocks, emplaced on a Class III fault, or whether much of the presumed Ordovician section may, in fact, be Silurian. These post-Caradocian strata may also have been deposited directly onto the Caradocian rocks.

Eastward vergence of Class III faults is supported by truncation of the Aroostook - Matapedia stratigraphy against the Central Maine Boundary Fault, and by seismic evidence revealing shallow-angle, westward-dipping reflectors beneath the study area. The Central Maine Boundary Fault appears to truncate the folded contact between the two members of the Smyrna Mills Formation. North of the study area, in the Mattawamkeag Lake and Amity quadrangles, SOsm has been faulted out or completely overridden by the eastward thrusting of the Central Maine Belt (Osberg et al., 1985, and unpub. reconnaissance mapping by Ludman); rocks of the Carys Mills Formation are adjacent to the Central Maine Boundary Fault, in contact with the Madrid Formation, and show fabrics indicative of fault-related deformation (Ludman, pers. comm., 1987). The Central Maine Boundary Fault thus may form the western boundary of the Aroostook - Matapedia Belt throughout much of eastern Maine. Hanson's (1988) discussion of the contact of the Madrid Formation with the Allsbury Formation indicates that the Central Maine Boundary Fault follows the pelitic and pyritiferous rocks of this contact from the study area at least as far to the west as Medway and Millinocket.

#### Age of Class III Faulting

Class III Faults juxtapose rocks of equivalent ages or rocks of Silurian age with Ordovician - Silurian or Cambro - Ordovician rocks. The Central Maine Boundary Fault is folded in the same F1 structures as latest Ordovician - early Devonian rocks (see Plate I). These folds and the associated axial-planar cleavage are in turn truncated by Early Devonian (385 Ma) intrusive rocks of the Bottle Lake Complex (Ayuso and Arth, 1985). The age of Class III faulting is thus narrowly constrained between Middle-to-Early

Silurian (younger than the Smyrna Mills and Madrid Formations) and Early Devonian. Recent work by Ludman (1996, pers. comm.), however, suggests that the Central Maine Boudary Fault may not be folded, and may be a much younger structure. This would not rule out very early faulting at the Allsbury/Smyrna Mills - Madrid contact.

## D2: UPRIGHT FOLDING

Early workers (Larrabee, 1963; Larrabee et al., 1965) recognized that the map-scale outcrop pattern reflected open, upright folding of the stratified rocks, and that the effects of subsequent deformation on the gross lithologic distribution were relatively minor. This early model is supported by the present mapping as well. Stereographic projections of poles to bedding show patterns indicative of upright folds (Figure 15) with nearly vertical axial surfaces and fold axes plunging from zero to ten degrees to the north-northeast or south-southwest. The steep dips of most beds shown on this figure and observed in the field may result from minor, small-wavelength parasitic folds (see Osberg et al. 1985), generally not seen in outcrop, but inferred from closely spaced reversals of facing direction in some units. Only a few exposures show a section through any minor folds at a high angle to the fold axis; complete crest-to-crest sections have not been observed, and the folds are apparently disharmonic. The minor folds seen vary from relatively open structures to tight, nearly isoclinal folds.

The axial-planar cleavage and transposition form a regionally penetrative fabric. Figures 16a and b show that this fabric is subparallel to primary layering. Intersection of bedding with this fabric produces strong, shallowly plunging intersection lineations, stereoplots of which (Figure 17) show the shallow plunge of the map-scale folds.

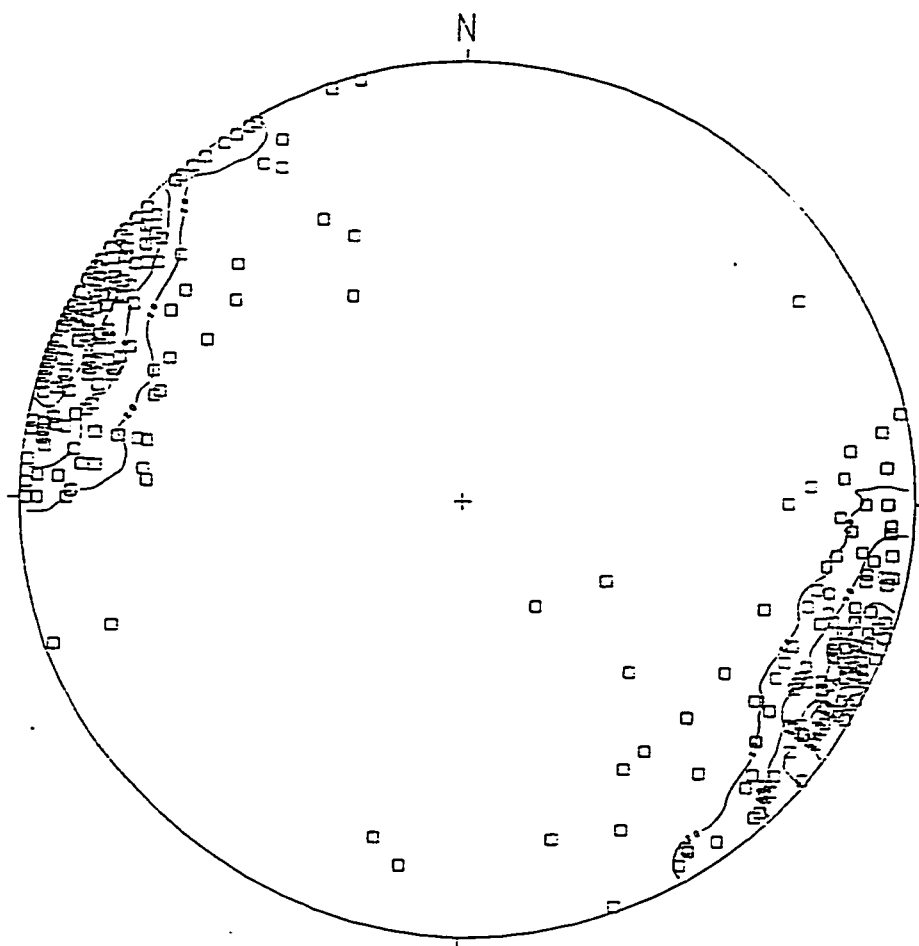


Figure 15: Equal-area lower hemisphere projection of poles to all bedding planes ( $n = 340$ ) in the study area. The asymmetry noted by Mangini (1981) and Sayres (1986) in plots of poles to bedding surfaces is apparently absent from this figure. This may be due to the earlier deformation present only in the Caradocian-and-older rocks mapped by Mangini and Sayres, or may indicate a subsequent deformation more pronounced in the Danforth Quadrangle than farther west. The former interpretation is preferred, due to the apparent refolding of fabrics axial planar to the presumed recumbent folds (see text and Sayres, 1986).

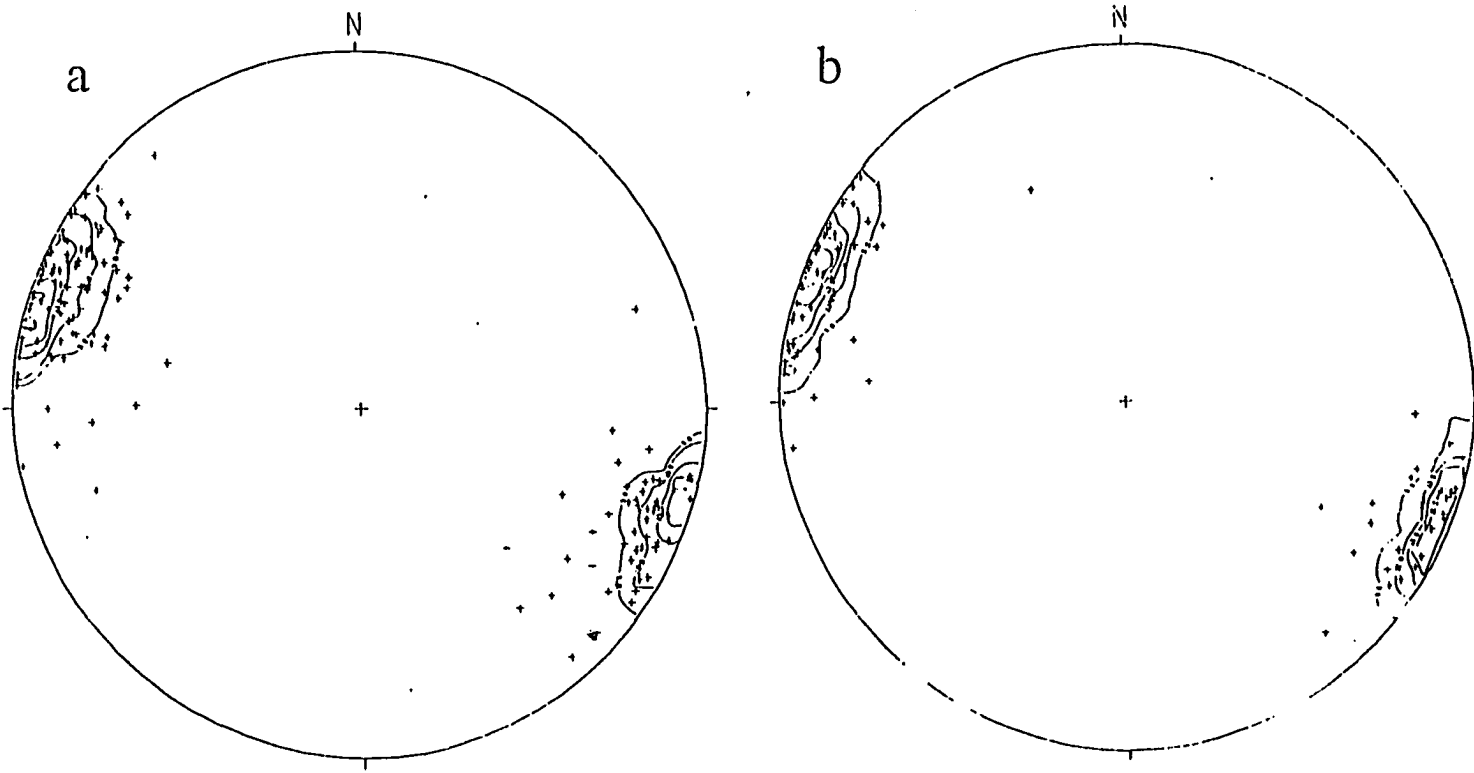


Figure 16: Equal-area lower hemisphere projections of poles to axial-planar cleavage ( $n = 190$ ) (Figure 16a) and transposition ( $n = 82$ ) (Figure 16b). Note similarity to poles to bedding (Figure 15).

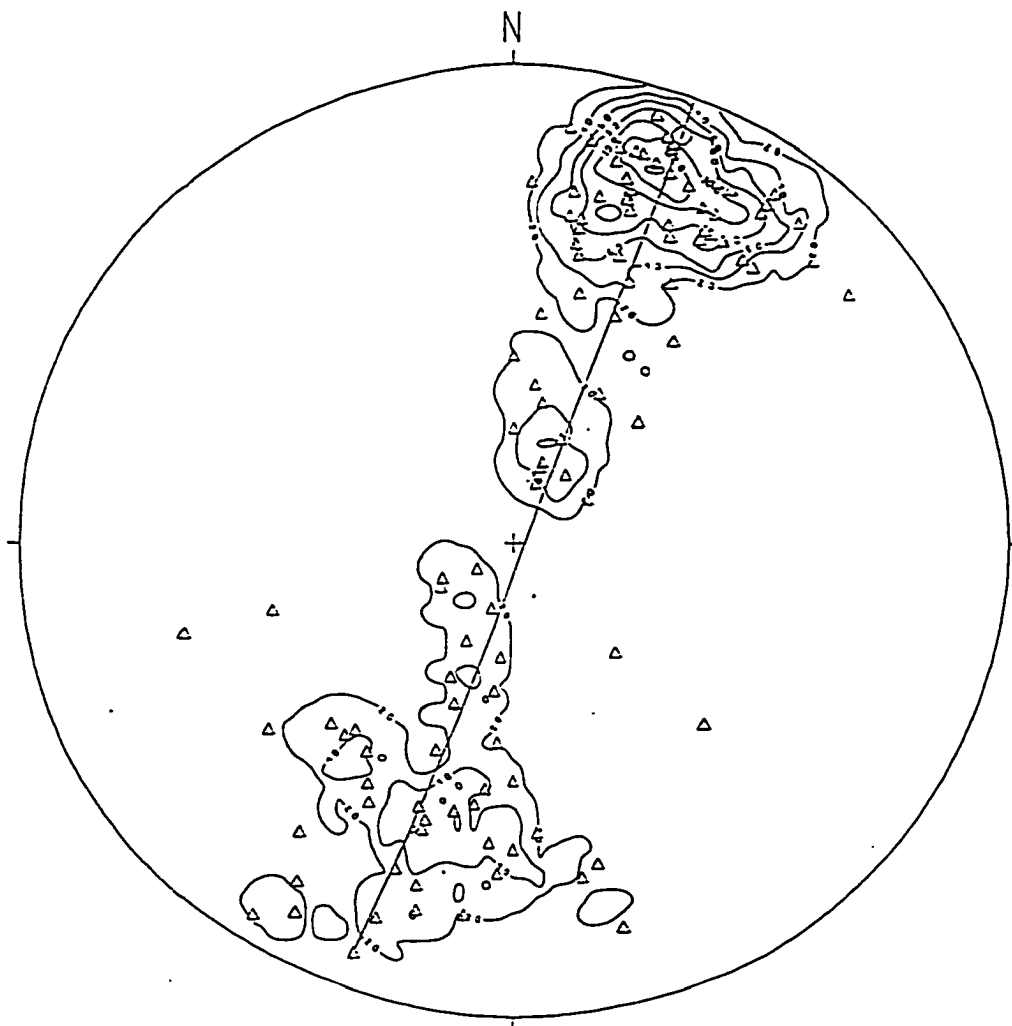


Figure 17: Equal-area lower hemisphere projections showing lineation formed by intersection of bedding and axial planar fabric. Extensions of points clockwise from each cluster may reflect reorientation of an initial distribution by dextral shear (Hobbs et al., 1976), but the southerly location of most of those data points suggests that these extensions reflect the regional variation of bedding to a more northeasterly trend in the southern part of the study area, perhaps because of development in originally (?) more northeasterly trending surfaces.

Clustering of data around the northeasterly plunge direction may reflect a northeastward plunge for the entire lithologic package within the study area (see Plates I and II).

Figure 18 shows axes of minor folds (excluding kink folds) in bedding, including vertically plunging folds; it was decided to include these, since, other than the steeper plunge, the morphology of many shallowly plunging D3 folds is not strikingly different from the F2 folds associated with D4.

### D3, D4a, AND D4b: CLASS IV FAULTS

#### Nature of Class IV Faulting

Class IV Faults are narrow, vertical or steeply dipping zones of intense brittle and ductile deformation trending either within a few degrees of north (000) or northeast (040). Class IV Faults and/or potentially associated fabrics are now mapped throughout southeastern and east-central Maine, and have been identified in all lithotectonic tracts. These faults show complex, multi-stage deformation histories, extending perhaps from Late Ordovician - Early Silurian time through emplacement of granitic plutons after the peak of Acadian metamorphism. Evidence discussed below indicates that these faults extend into basement structures, and that Late Ordovician - Silurian activity on some of these deeper structures may have formed the Aroostook - Matapedia basin.

Class IV Faults show an early phase of primarily west-side-up reverse motion (D3/Class IVa Faults), followed, in an apparently distinct later episode, by dextral oblique slip (D4/Class IVb Faults). In much of the southern two thirds of the study area, this dextral phase evinces two distinct subphases, discussed further below: the first (D4a) occurs along faults trending approximately north or north-northeast; the second (D4b),

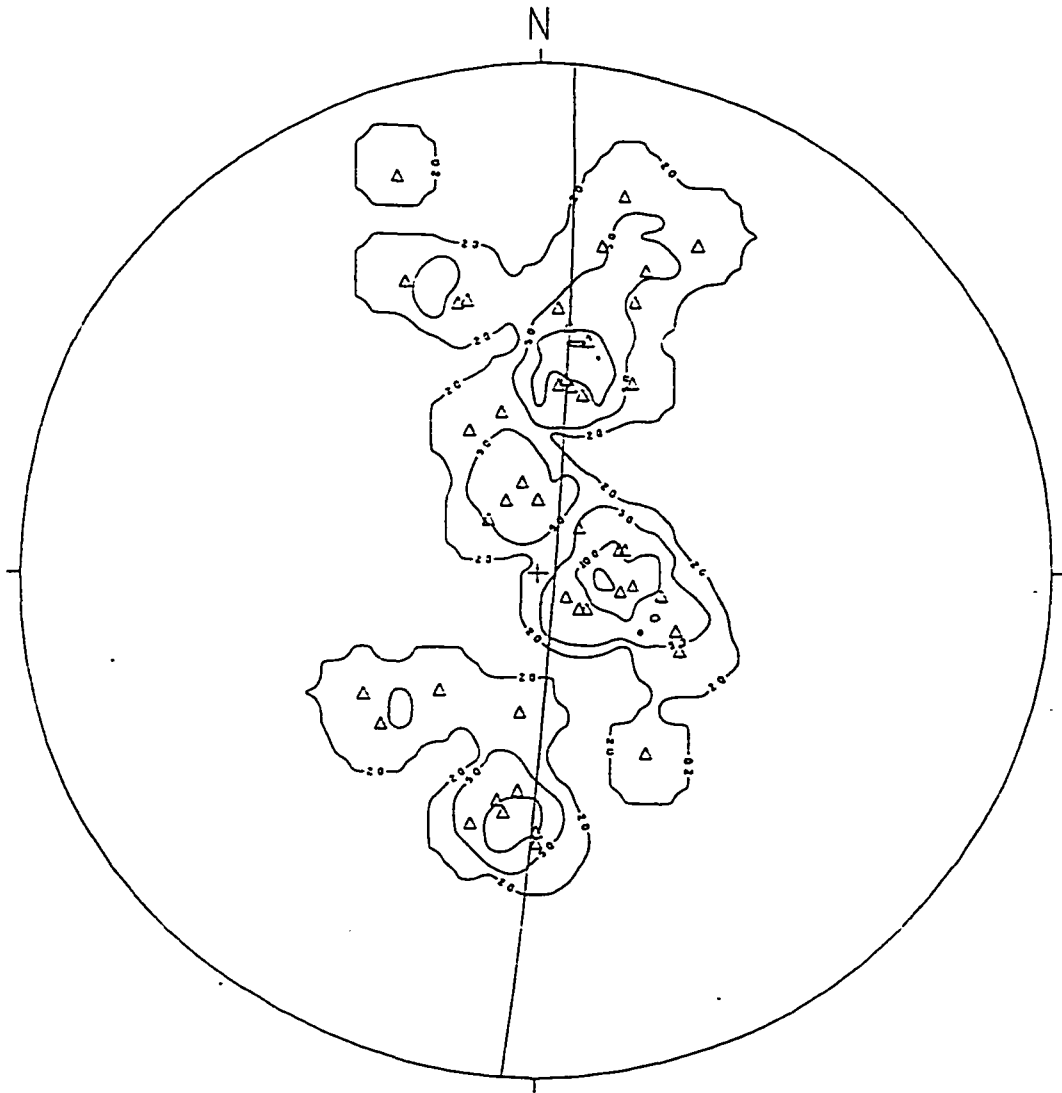


Figure 18: Equal-area, lower hemisphere projection showing axes to all folds in primary layering ( $n = 45$ ). The steep plunges of most outcrop-scale folds suggest that they are related to D4 rather than D2.

generating identical fabrics and structures, follows northeast-trending faults. No such distinction has thus far been noted for the earlier, reverse phase of Class IV faulting.

The principal Class IV Fault in the study area is the North Bancroft Fault, the trace of which follows the Mattawamkeag River (see Plate I) through the northern two-thirds of the Wytopitlock quadrangle, and the valley of Mattagodus Stream toward Granite Ridge in the Springfield quadrangle. In the Wytopitlock quadrangle the fault is also marked by the topographic change from uplands underlain by wackes, conglomerates, and pelites east of the fault to flat, poorly drained areas underlain by the Carys Mills Formation to the west. Thin sections from wackes near the east side of the fault show ubiquitous strain-shadowed quartz and sutured grain boundaries.

### D3: Class IVa Reverse Faults

Fabrics unambiguously related to Class IVa have been recognized only in the vicinity of the North Bancroft Fault, although comparable fabrics may occur at a few localities in the Springfield quadrangle. Shear fabrics in slabbed samples of the Carys Mills Formation from the west side of the fault indicate a west-side-up sense of shear and show development of slip cleavage and asymmetric shear of the axial-planar transposition, with variably developed transposition along the slip-cleavage plane (Figure 19). East of the North Bancroft Fault, the Daggett Ridge Formation also shows well-developed cleavage, although again only close to the fault. A clear transition from intensely cleaved to massive conglomerate occurs over a span of a hundred meters normal to the fault trace, south of the railroad bridge in Bancroft (Hopeck, 1991b), with intensely deformed rocks near the Mattawamkeag River, and progressively less cleaved conglomerate to the east, away from the fault. Fresh surfaces of the cleaved rock show strong phyllitic sheens, and many clasts

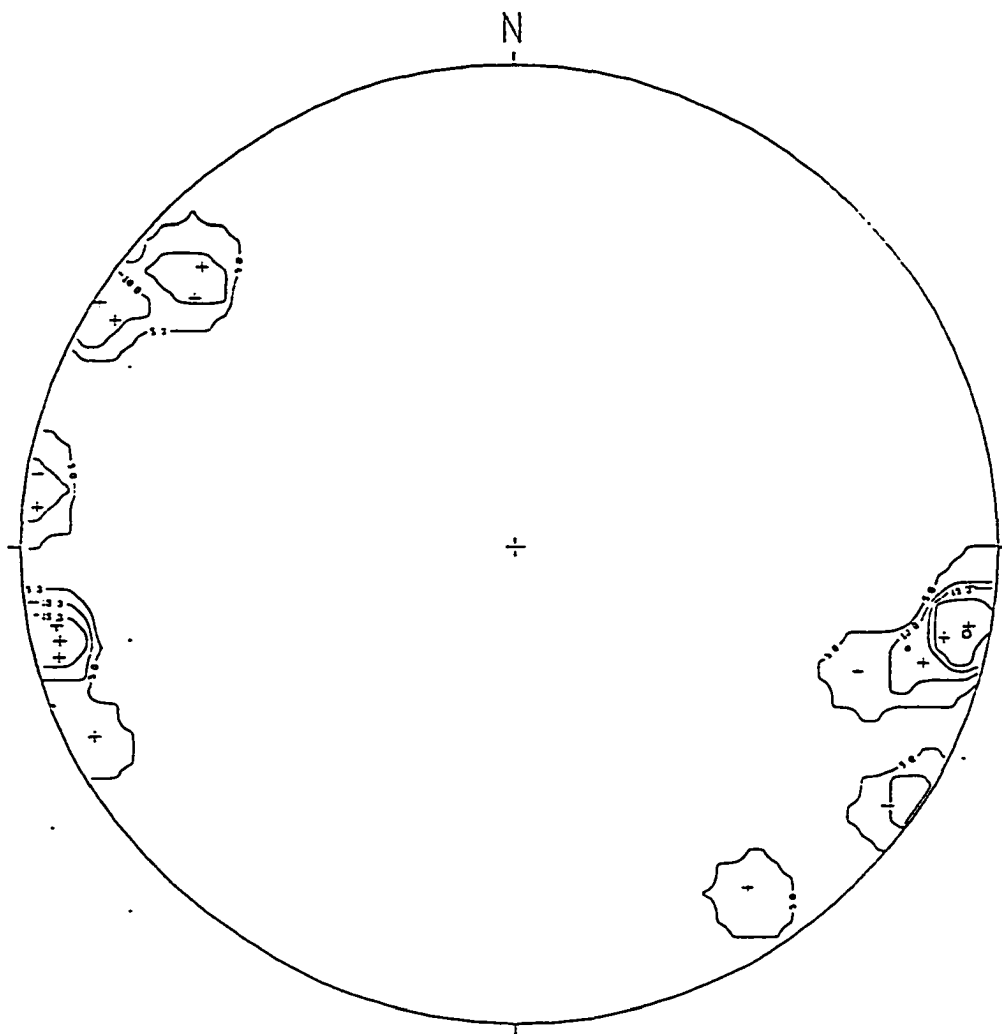


Figure 19: Equal-area, lower hemisphere projection showing poles to transposition and slip cleavage associated with D3 reverse faulting (Class IVa Faults). These data were obtained primarily from exposures of the Carys Mills and Daggett Ridge Formations in the vicinity of the Bancroft railroad bridge, and so may not be strictly representative of these fabrics. Given the limited areal extent of these fabrics, however, and their association with Class IVa Faults, discussed in the text, the overall population would probably not show a substantially different orientation.

within the sheared conglomerate contain paper-thin, subhorizontal, quartz-filled tension fractures. Clasts broken out of the exposure sometimes show irregular, elongate bodies of matrix adhering to their bottoms or tops. This “pseudo-beard” texture suggests high shear strains in the matrix outside the pressure shadows of the more rigid clasts. Clast long axes are subvertical (subparallel to bedding?). Clast orientation is believed to be a primary fabric because: (1) no textural or kinematic evidence of rotation of clasts is observed, and, (2) microstructures of pebbles in thin section show no evidence of ductile deformation and recrystallization. Clasts along the fault trace show similar internal structures and lithologies to those observed in relatively undeformed conglomerate, which often shows similar “imbricate” primary fabrics where clasts are elongate. It is unlikely that the relative dimensions of the clasts and associated matrix fringes provide a realistic measure of the finite strain, since the conglomerate is generally clast-supported in both highly strained and relatively unstrained exposures.

The magnitude of Class IVa displacement on the North Bancroft Fault is unknown, but cannot be more than a kilometer, at most, as the Carys Mills Formation has been shown, in the previous chapter, to be equivalent to rocks that directly underlie the Daggett Ridge Formation. At most localities along the fault trace in the Springfield quadrangle and the southern third of the Wytovitlock quadrangle, evidence of significant offset across the fault trace is lacking, as the calcareous wackes and pelites of SOcm are not readily distinguished from the variably calcareous, identically bedded rocks of the Mill Priveledge Brook Formation, and both units occur on either side of the fault trace. If the Daggett Ridge Formation were deposited directly onto the calcareous rocks, as the stratigraphic model would allow, throw could be less than the maximum estimate here.

#### Distinction between Class III and Class IVa Faults

Given both the very limited number of exposures displaying Class IVa fabrics and that the style of folding is such that originally subhorizontal fabrics are almost always subvertical in outcrop, it is necessary to consider whether or not Class IVa, as described here, is equivalent to Class III; both would appear in outcrop as subvertical shear zones. First, the tectonic fabric offset by Class IVa shear is axial planar to D2 folds. Second, the contact of the Smyrna Mills and Madrid formations may show the effects of D2 upright folding, while the North Bancroft Fault runs essentially straight from the Bancroft railroad bridge to Granite Ridge in the Springfield quadrangle (see Plates I and II, and Figure 24, below). Third, the North Bancroft Fault shows evidence of reactivation as a strike-slip fault during D4. If Class IV structures were initially subhorizontal, they would have been effectively locked by D2 folding; if they were initially subvertical, reaching to basement, their reactivation to develop younger fabrics is more easily accomplished.

#### D4: Class IVb Faults

Subsequent reactivation of Class IVa faults as dextral oblique shears is related to development of a regionally penetrative subvertical slip cleavage and local transposition. Steep or vertically plunging folds in older fabrics are common (Figures 20a - c); stereographic analysis of intersection lineations formed by the D4 fabric and prior fabrics is shown in Figure 21. D4 fabrics show two distinct maxima (Figure 22), indicative of two subsets of Class IVb structures, one striking approximately due north, and the second due northeast. In general, the northeast trend is present throughout the Springfield quadrangle and in the southern quarter of the Wytopitlock quadrangle, except in the vicinity of the North Bancroft Fault, where the northerly trend remains common; the macroscopic appearance of these two fabrics is identical. Figure 22 shows no transitional zone between the maxima, suggesting that the pattern does not represent map-scale warping of a single cleavage. Moreover, where both cleavages are observed (Figure 23), the north-trending

Figure 20: Vertically plunging D4 folds in prior fabrics.

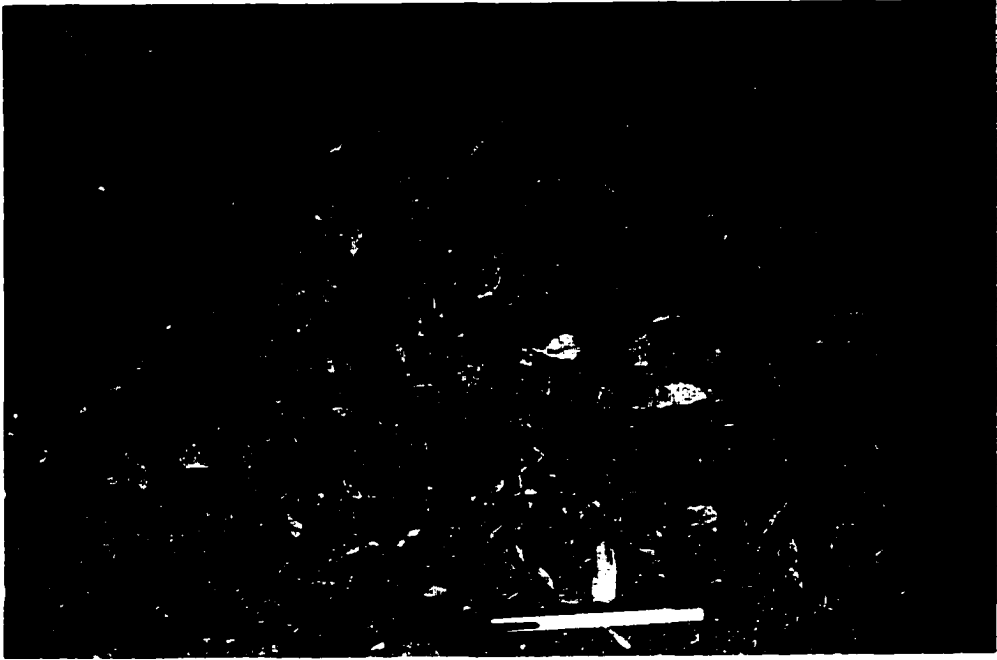


Figure 20a: Fold in wacke and pelite of Mill Priveledge Brook Formation.

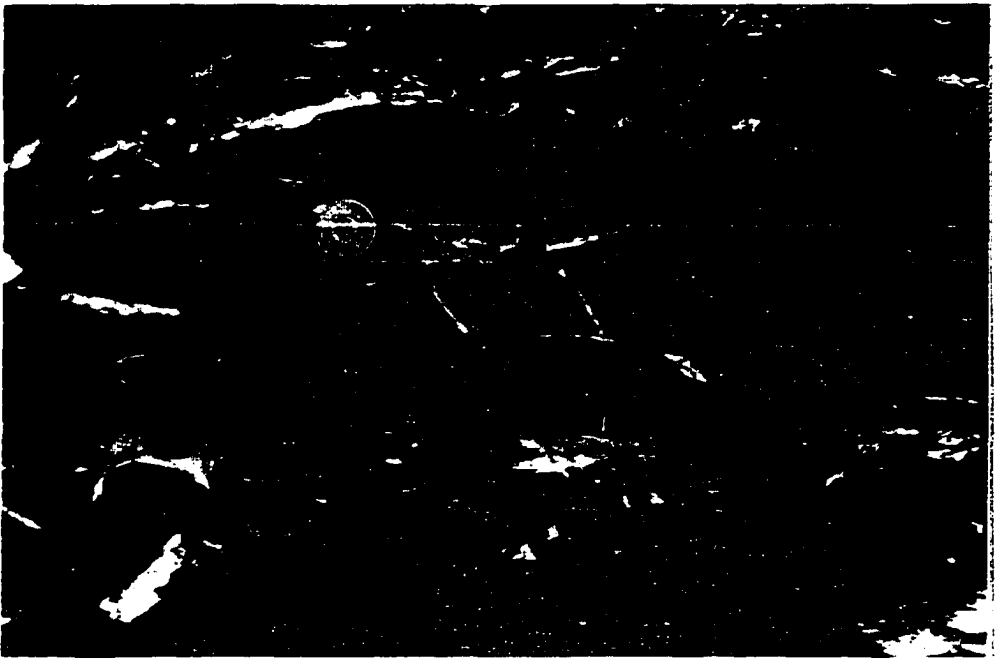


Figure 20b: Fold in axial planar transposition in Carys Mills Formation; note transposition axial planar to this fold, and several dextral shear planes in the photograph.



Figure 20c: Fold in D3 cleavage in Daggett Ridge Formation.

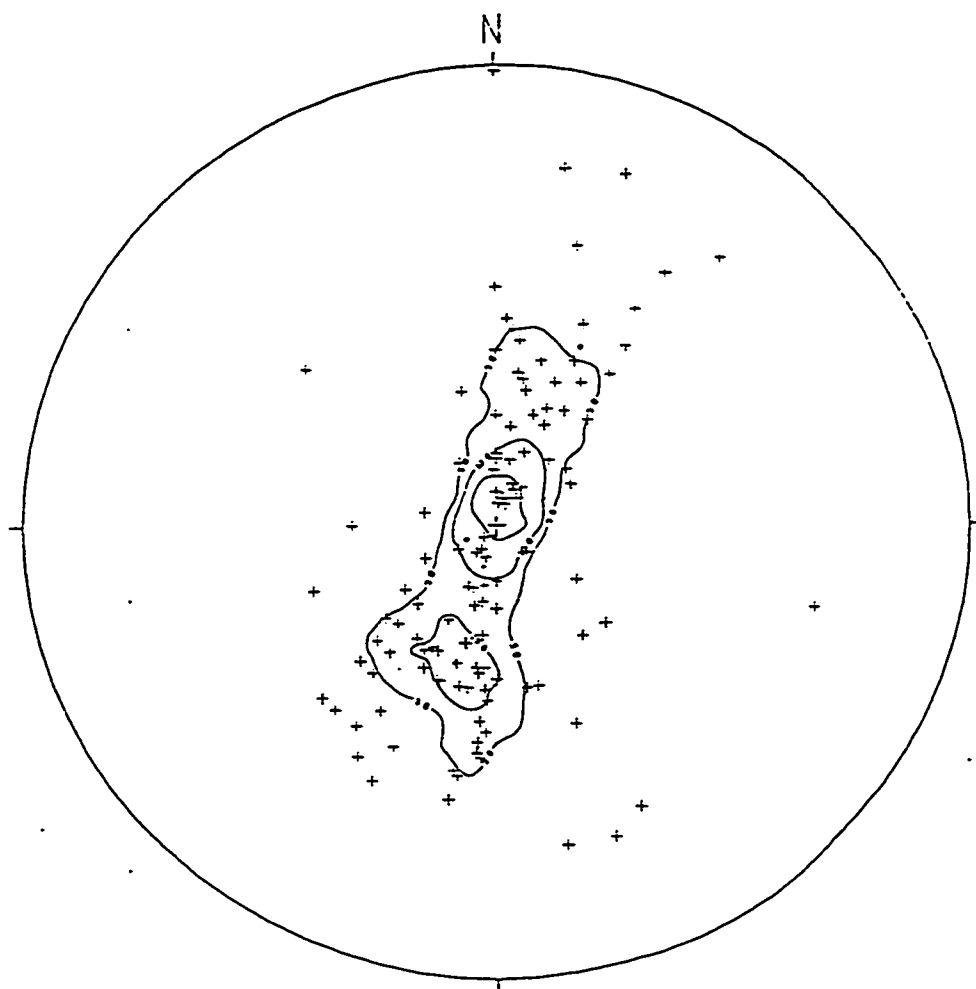


Figure 21: Equal-area lower hemisphere projection of intersection lineations ( $n = 130$ ) formed by intersection of D4 dextral slip cleavage with either primary layering or D2 axial-planar cleavage or transposition.

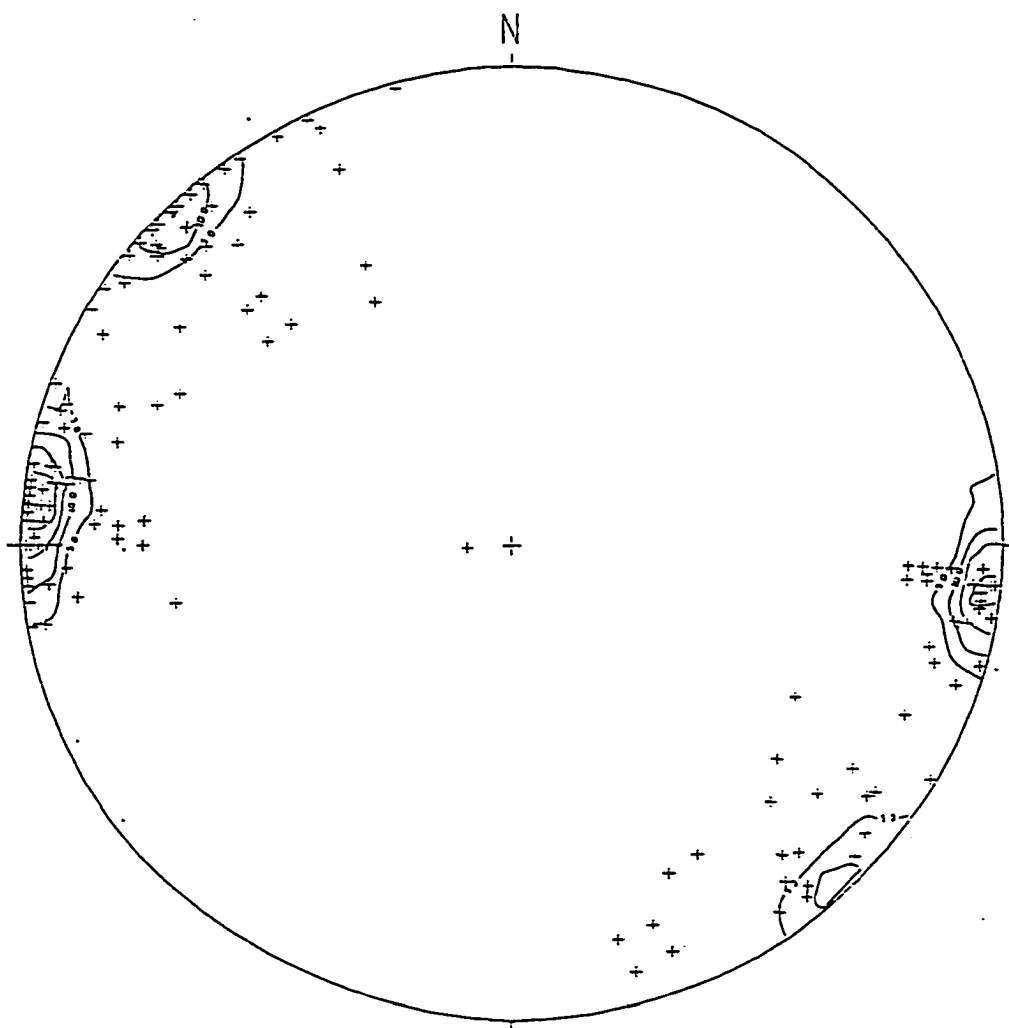


Figure 22: Equal-area lower hemisphere projection of poles to D4 dextral slip cleavage or parallel transposition fabric ( $n = 196$ ). Note two distinct maxima; these correspond to the two stages of Class IVb dextral slip faulting, discussed in text.

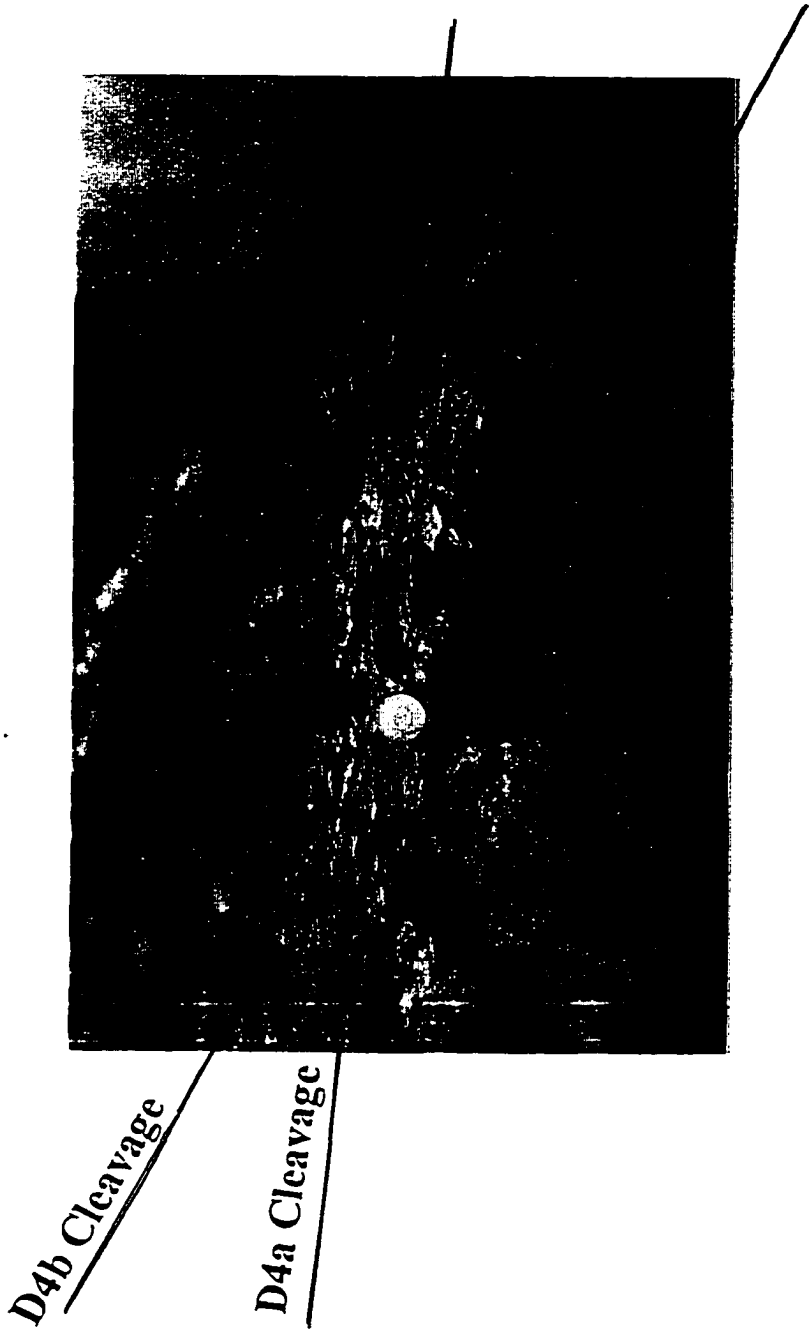


Figure 23: Smyrna Mills Formation showing two generations of D4 slip cleavage. Northerly-trending cleavage (approximately vertical in photograph) is cut by and sheared in a dextral sense along northeast-trending (distinct diagonals in photograph) cleavage.

cleavage is offset by dextral slip along the northeast-trending fabric, and the reverse relationship is never observed, implying two distinct subphases of Class IVb slip, D4a and D4b.

Several lines of evidence support lower confining pressures during D4, when compared to D2 and D3. Thin sections showing both D2 and D4 fabrics reveal that the axial-planar cleavage is often defined by thin folia of tiny, subparallel chlorite microlites, while the D4 slip cleavage is defined exclusively by dark or opaque pressure-solution residues along the cleavage folia. Wide brittle fractures, filled with calcite and quartz, occur in the Carys Mills Formation along the North Bancroft Fault; the sense of dextral shear shown by these fabrics suggests that they developed during D4. In contrast, only very minor hairline fractures in the rigid quartzite clasts of the Daggett Ridge Formation are associated with D3. Pyrite euhedra occasionally show quartz-fiber pressure fringes; these fringes show subhorizontal extension in the plane of the D4 slip cleavage, and frequently indicate dextral shear as well. This contrasts with the near-vertical extension direction of Class IVa, indicated by the fractured clasts and “pressure shadows” in conglomerate along the North Bancroft Fault.

#### Age of Class IV Faulting

The linear fault traces of Class IV Faults and the shear folding of the axial planar foliation into vertically plunging folds indicate that Class IV faulting post-dates the upright folding. D4 dextral slip affects both D2 axial planar foliation and D3 slip cleavage and transposition. North-striking D4 cleavage fabrics are offset, as shown in Figure 23, along northeast-striking dextral-slip surfaces, distinguishing D4a and D4b.

The North Bancroft Fault may be traced (Figure 24a), by direct observation of strained rocks and linear streams and breaks in ridgelines, from the Bancroft railroad

bridge into the biotite-facies rocks of the pluton's aureole. The last of the ridgeline breaks is at Granite Ridge, at the pluton - country rock contact. Granite exposures at the gap are crossed by closely spaced, north-trending quartz pegmatite dikes, up to ten centimeters in width (Figure 24b). Some of these pegmatites (Figure 24c) show evidence of having undergone dextral slip while in a plastic state, or, perhaps more likely, of the pegmatite magma having flowed from one north-trending fracture to another across a synthetic tensional fracture. Thin sections of these pegmatites reveal north - south trending zones of weak cataclasis, strain-shadowed quartz, and, rarely, dextrally kinked biotite. The age of D4a dextral slip on the north-trending Class IVb faults is therefore inferred to be approximately coincident with intrusion and cooling of the older rim facies (see Ayuso, 1982) of the Passadumkeag River Pluton. The possibility that the minor brittle structures within the dikes reflect very late, minor amounts of slip, rather than the final fraction of north-trending D4, cannot be ruled out at this time.

North-trending D4a fabrics are largely absent from the younger core facies of the pluton, as shown in Figure 25, which is, however, based on data from only the Springfield and Scraggly Lake quadrangles (Hopeck, 1991c). In the core facies, D4b fabrics, parallel to the northeast-trending Class IVb structures, are ubiquitous in both outcrop and thin section. Oriented thin sections, even from apparently massive samples of core-facies granite, reveal penetrative, northeast-trending cataclastic zones. Exposures of pink granite dikes parallel to the northeast trend, most only a few centimeters wide, but some several meters in width, are common. One such dike is exposed on Rand Hill in the western portion of Lakeville Township (Figure 26). Fractures up to one centimeter in width are filled with cataclasite, recognizable in thin section as quartz, potassium feldspar, and corroded plagioclase, with common dark or opaque material and rare fragments of epidote. The dike lies within a zone of extensive hydrothermal alteration, approximately twenty-five meters in width. Plagioclase within the zone is deeply

Figure 24: Granite Ridge pegmatites.

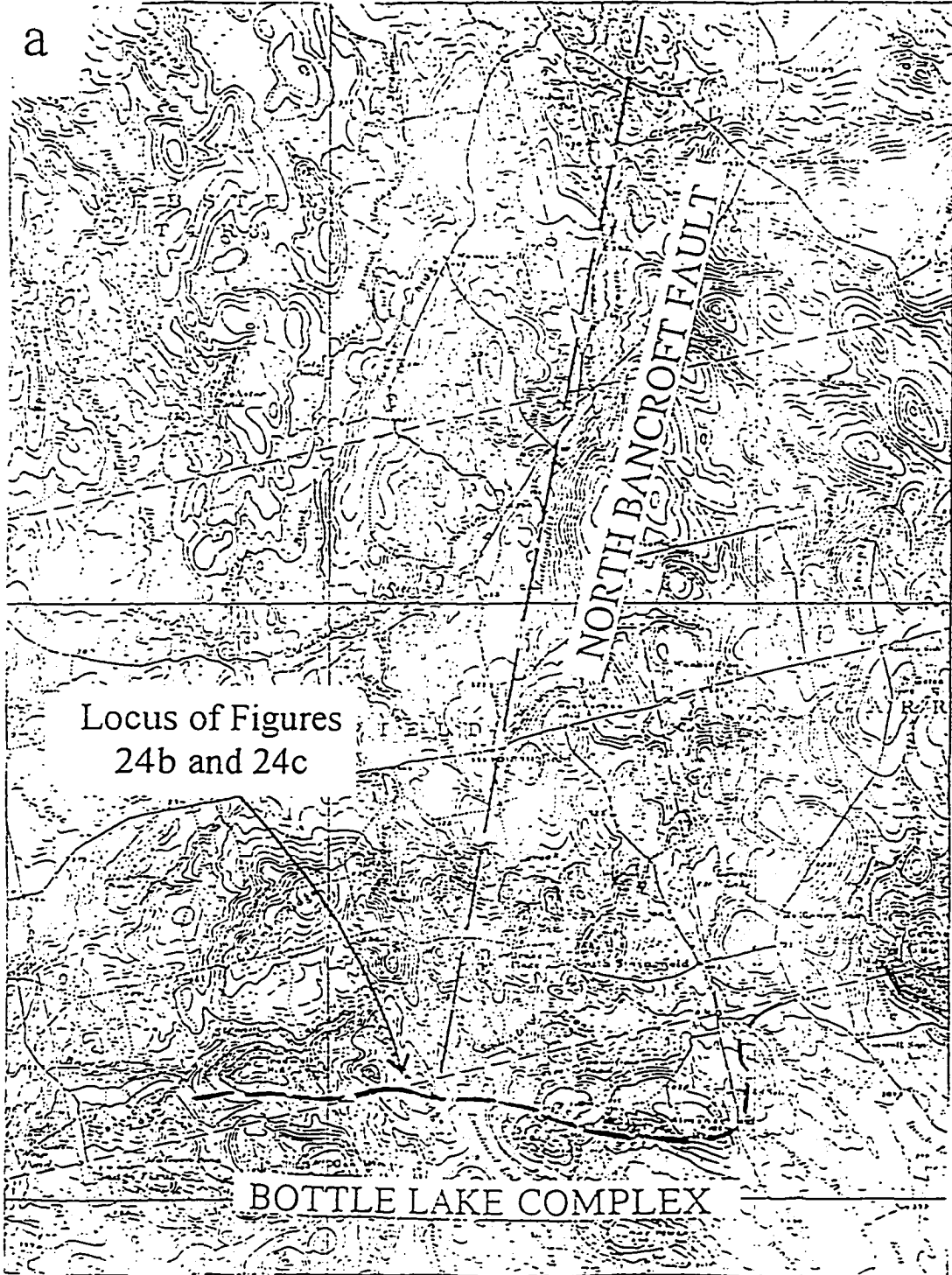


Figure 24a. Section of Springfield 15-minute quadrangle showing locations of Granite Ridge near terminus of mapped North Bancroft Fault:



Figure 24b: Quartz pegmatite and alteration zone. Discontinuous nature of pegmatite may be a primary fabric or indicate deformation while in liquid or plastic state.

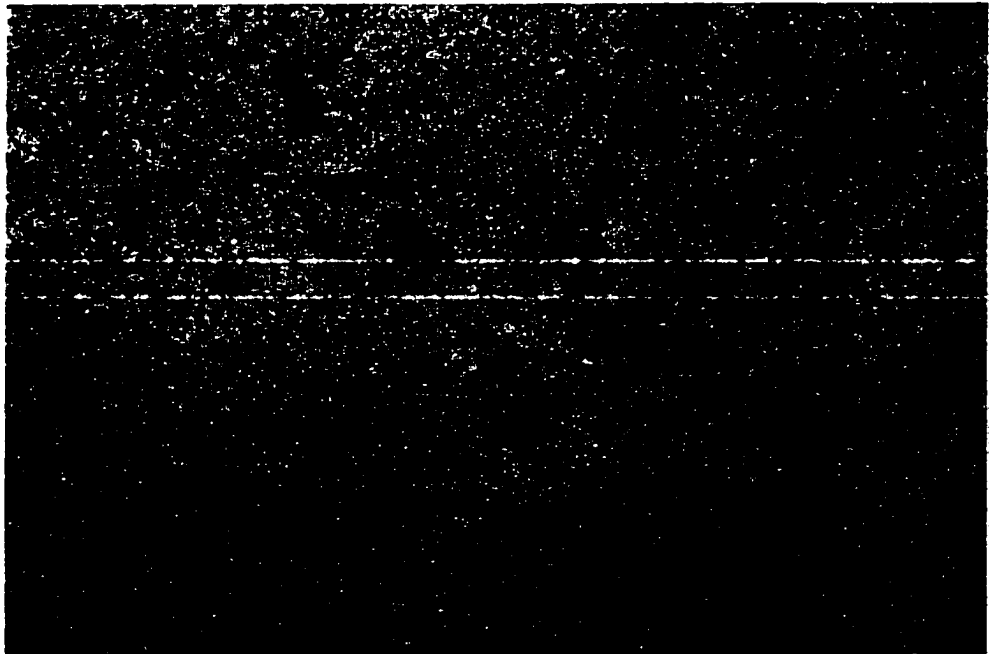


Figure 24c: Quartz pegmatite showing “dextral shear” or injection through a pull-apart between two slip planes; note greater thickness of quartz in potential pull-apart. Alteration zone around quartz suggests emplacement during original pegmatite injection.

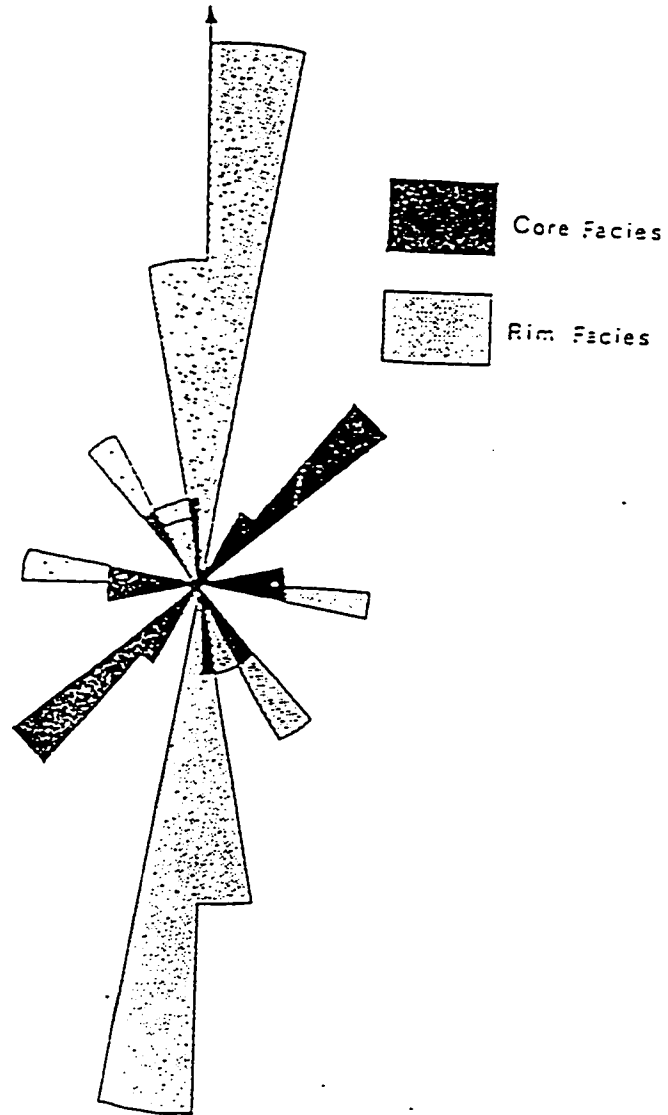


Figure 25: Orientations of dikes in Bottle Lake Complex within the study area. Note absence of northeast-trending dikes in the older rim facies of the pluton, and corresponding near absence of north-trending dikes in younger core facies. This is interpreted as reflecting influence of north-trending Class IVb Faults on emplacement of rim facies dikes, while the stress field associated with northeast-trending Class IVb Faults controlled the orientation of the slightly younger core facies dikes (modified from Hopeck, 1991c).

Figure 26: Rand Hill Locality.



Figure 26a: Photograph showing quarry in which dike is located; the dike is the vertical red-brown zone at the approximate center of the photograph.

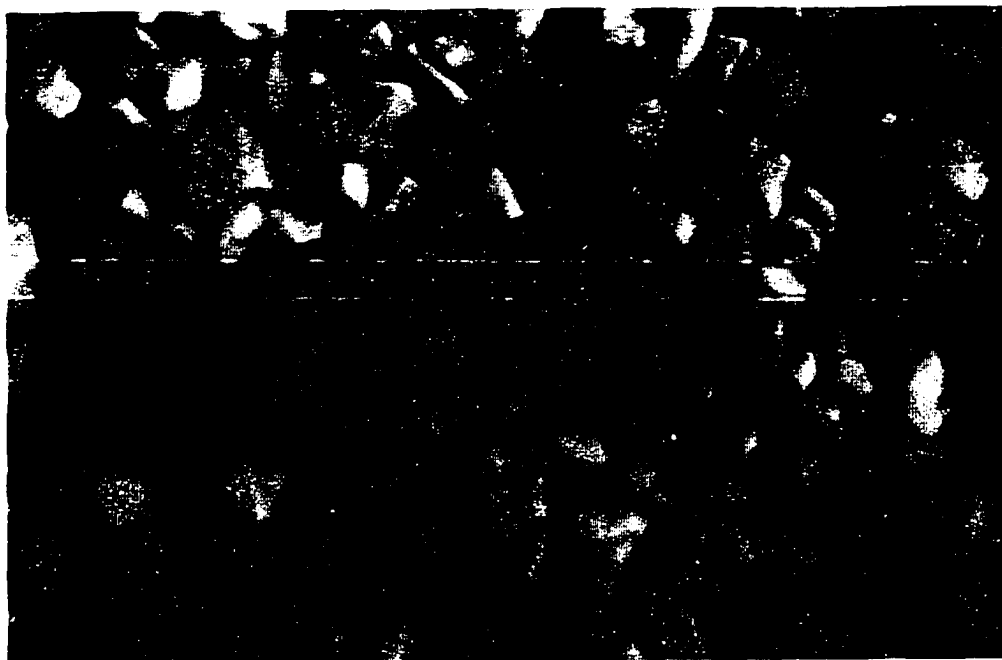


Figure 26b: Photograph of slabbed sample of the dike rock. Note epidote-bearing fractures throughout sample.



Figure 26c: Photograph of slabbed sample of altered granite around dike. Red areas are hematite-bearing clay minerals, pink areas are potassium feldspar, white areas are altered plagioclase, and gray areas are quartz.

corroded and has a very chalky luster, suggesting alteration to clay minerals, possibly kaolinite. Fractures within this zone comprise up to 15 percent of the rock by volume and are partly or wholly filled by hematite or a hematite - clay mixture (Figure 26b). These fracture fills have also undergone extensive cataclasis, with debris of similar composition to that described above accompanying the hematite in the fractures. Comparable lithologies are known from poor exposures at two other localities in the Springfield quadrangle, northeast of Rand Hill in a small excavation near the south shore of Upper Sysladobsis Lake, and in a gravel pit in the southwest corner of Lakeville Township.

Remnants of cordierite, now largely retrograded to micaceous minerals, are found within rusty pelites of the Mill Priveledge Brook Formation northeast of Granite Ridge. The northeast-trending D4b cleavage is deflected around these remnants, some of which show asymmetric pressure shadows indicating dextral shear rotation of the metamorphic grains. Clearly the peak of contact metamorphism predated D4b at at least this locality.

The final phase of D4b continued after the intrusion and cooling of the granite, with some faults and tension fractures serving as conduits for residual magmas and late magmatic fluids. Slip continued after cooling of these hydrothermal zones was complete. The total offset on these faults after emplacement of the pluton was apparently minor, as the pluton contact and metamorphic isograds are not obviously offset along the fault traces. The amount of dextral slip which may have occurred prior to and during emplacement of the pluton also does not appear to be significant.

The North Bancroft Fault is apparently sealed by a diabase dike which crosses it immediately south of the town of Bancroft and is exposed in the Mattawamkeag River and on the north side of Sherwood Mountain. It appears as a very strong, continuous, east - west linear anomaly on the aeromagnetic survey of Griscom and Larrabee (1973). The

anomaly shows no evidence of offset where it crosses the fault, and diabase outcrops on either side of the fault apparently lie along a single line. This dike may be related to the Triassic - Jurassic Caraquet dike of New Brunswick (Greenough and Papezik, 1986).

## D5: CLASS V FAULTS (NORUMBEGA FAULT ZONE)

### Nature of Class V Faulting

Evidence of Class V Faults in the study area is ambiguous; they are discussed here because of their significance to the regional geology and tectonic models of Acadian and post-Acadian events. Class V consists of northeast to east-northeast trending faults, including the Norumbega Fault Zone (Wones and Stewart, 1974); these faults show dextral oblique-slip displacement, followed in some places by high-angle reverse slip. In south-central Maine, the Norumbega separates high-grade metamorphic rocks of the Coastal Lithotectonic Belt from chlorite-grade rocks of the Central Maine Belt (Osberg et al., 1985), but south of the study area, faults of the Norumbega zone are intraformational within chlorite and biotite-grade rocks of the Flume Ridge Formation (Ludman, 1991).

Class V Faults in the Flume Ridge Formation and Bottle Lake Complex are associated with both brittle and ductile fabrics; a brittle strike-slip fault offsetting the boundary of the Center Pond Pluton and a mylonite zone within the Whitney Cove Pluton both lie along the east-northeast trend of Class V Faults, although the former may be related to a shallowly dipping seismic reflector that projects to the surface at the trace of the North Bancroft Fault (Doll et al., 1993). Within the area of detailed mapping, only a few epidote-filled, east-northeast-trending brittle fractures and very minor shear zones found within the Passadumkeag River Pluton are tentatively associated with Class V Faults; none are associated with dikes or zones of hydrothermal alteration.

### Age of Class V Faulting

The mylonite zone within the Whitney Cove Pluton, truncation of the pluton boundary by other strands of the Norumbega (Osberg et al., 1985), and the pluton age of 385 Ma, suggest that Class V faulting is younger than 385 Ma. Biotite found along the trace of a strand of the Norumbega Fault within the Flume Ridge Formation, thought to have developed during the strike-slip phase by fault-related heating, has yielded a potassium - argon age of 380 Ma (Ludman, pers. comm. 1991). West and Lux (1992) have demonstrated dextral shear within the Norumbega Fault zone as late as 290 Ma. Late, high-angle motion on faults of the Norumbega Zone has affected Carboniferous molasse sediments in eastern Maine and New Brunswick. These post-Acadian rocks do not show effects of dextral slip along either the trend of Class V Faults or earlier trends.

## D6: CLASS VI FAULTS

### Nature of Class VI Faulting

The final episode of faulting recorded in the rocks of the study area involved numerous outcrop-scale sinistral strike slip faults, developing a common slip cleavage and vertically plunging sinistral kink bands. Class VI Faults and the associated cleavage trend approximately 285 - 300, and are typically expressed as vertical fractures along which all previous primary and tectonic fabrics have been offset by no more than a few centimeters. A typical example is shown in Figure 27a; a stereoplot of poles to slip cleavage is shown in Figure 27b. No map-scale features associated with this trend have been found in the study area, although Ludman (1989) mapped several northwest-trending sinistral faults in the Danforth quadrangle which offset rocks of the Tetagouche-equivalent section by a kilometer or less. In both the rim and core facies of the Passadumkeag River Pluton, brittle fractures form a penetrative fabric parallel to D6 kink bands in the country rock. No offset is apparent in outcrop, even where the fractures cross minor dikes, but thin sections show

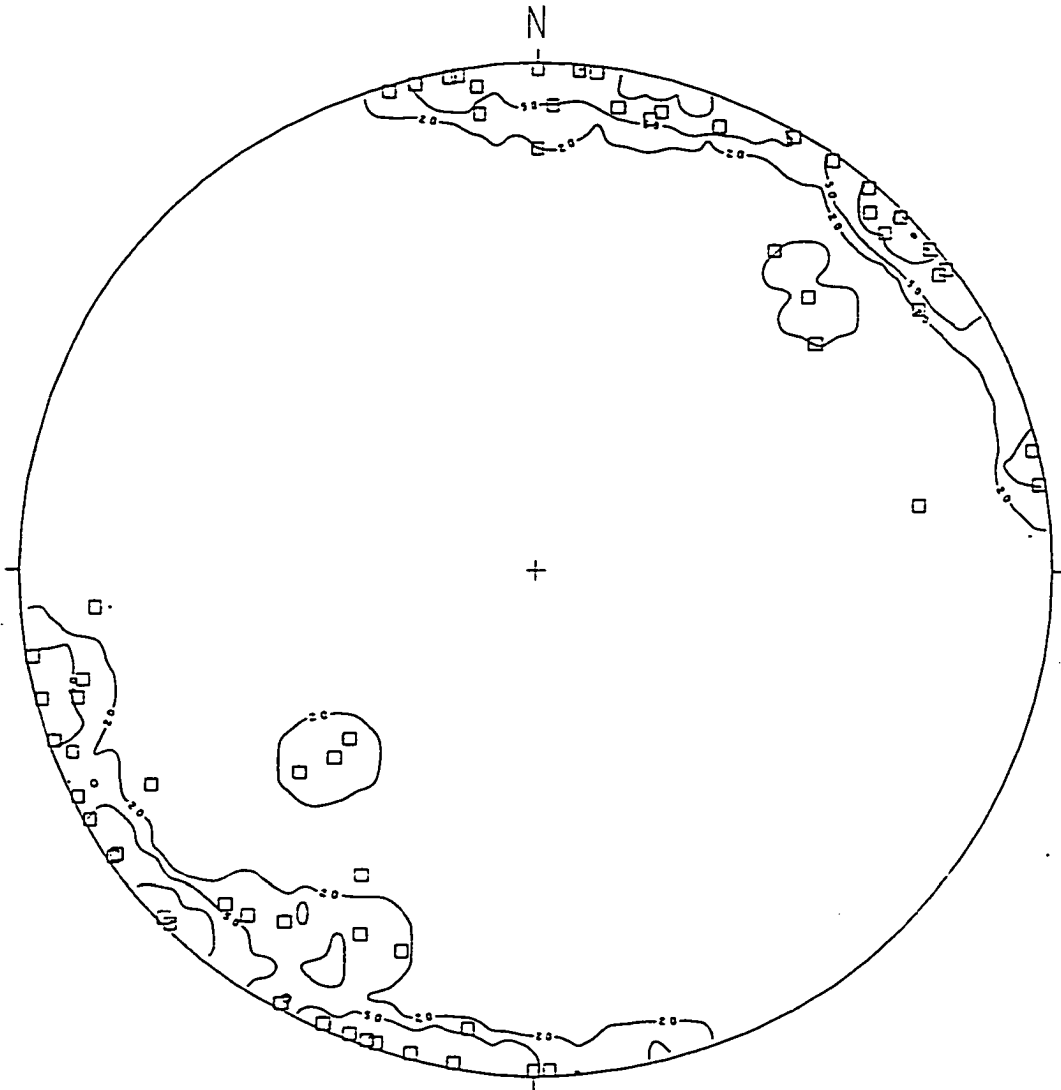


Figure 27: Equal-area, lower hemisphere projection of poles to D6 sinistral slip cleavage.

linear zones of sinistrally kinked biotite and strain-shadowed quartz and feldspar, often with minor cataclasis. No dikes or hydrothermally altered zones have been found along this trend.

#### Age of Class VI Faulting

The orientation and vergence of Class VI fabrics suggest that they could have developed as shear zones antithetic to dextral shear in the Class V Norumbega Fault Zone. In this case, the regional maximum stress would have been directed along an east-west or west-southwest - east-northeast axis, consistent with regional compression related to convergence of North America and Avalon, roughly synchronous with the major motions on the Norumbega. Textures associated with Class V Faults include both ductile and brittle shear, but Class VI Faults are, at least in the study area, associated only with brittle fabrics and kink folds in older surfaces. If Class V and Class VI were part of a wrench-tectonic environment (Harding, 1974), one might expect folds with north- or northwest-trending axes; other than F4 kink folds, however, all folds within the study area apparently predate both episodes of faulting, although low-amplitude folds might not be apparent in these strongly deformed rocks.

Class VI structures post-date the 385 Ma intrusion of the Bottle Lake Complex, but apparently pre-date development of the Carboniferous molasse basins. This could imply that Class VI faulting was synchronous with or followed the strike-slip phase of Norumbega activity, but pre-dated the Permo-Carboniferous reverse phase.

#### REVIEW AND COMPARISON WITH SURROUNDING AREAS

The post-Caradocian structural history of the study area, summarized in Table III, is thus one of sequential faulting episodes. Only the development of upright F1 folds may be unrelated to a distinct faulting event, and even that episode could be viewed as related to a regional compressive tectonic phase also displayed by faults of Classes II, III, and IVa. With the exception of Classes III and VI, all brittle or post-lithification faults show evidence of re-activation, implying direct linkage between the mapped surface traces and deeper structures. Given the stratigraphy developed in the previous chapter and the plutons which lock faults up to at least Class V, faulting subsequent to Class IV cannot have resulted in significant displacement of the juxtaposed lithotectonic belts.

The structural history developed in this chapter is comparable to that found in adjacent areas and in other parts of the state. Early disruption comparable to Class I faulting is known from several areas. Roy (1981, p. 15), described "disruption of bedding continuity [ranging] from fairly simple offsets...along faults that are quasiparallel to bedding, through mild boudinage in beds which are broken into rectilinear pieces, to whole-scale disruption of the fold pattern and the production of 'delimbed' fold hinges, lensoid bed fragments, and fault-bounded packages of coherent strata" in the Allsbury Formation, stratigraphically equivalent to the Smyrna Mills Formation. Griffin (1973) provides an extensive discussion of a stratigraphically and lithologically equivalent section in Central Maine, with "flowage bedding", sedimentary breccia, and chaotic bedding, which resemble Class I fabrics. Hanson (1988) and Hanson and Bradley (1989) have discussed a variety of strongly similar fabrics in units younger than the Smyrna Mills Formation, suggesting that this style of deformation continued from the Early Silurian through the earliest Devonian. This need not indicate any more than that deposition of sediment along unstable debris aprons and submarine fans continued throughout the period, and does not of itself exclude any tectonic model. It appears that Class I-like

disruption is a common primary fabric in the Central Maine and Aroostook - Matapedia belts. Analogous fabrics are, however, apparently absent or thus far unrecognized in the Fredericton Trough, St. Croix Belt, and Coastal Volcanic Belt.

Class III Faults, or equivalent low-angle faults, and related recumbent folds, have been proposed for telescoping sedimentary sections in most areas of the state (see Osberg et al., 1985). Roy (1987), however, has noted neither recumbent folds nor subhorizontal faults in the Ordovician - Devonian section in the Caribou - Presque Isle area, although Rast et al. (1980) report recumbent folding in the Carys Mills Formation in western New Brunswick. Muscovite-bearing, calcareous wackes sandstone adjacent to Smyrna Mills Formation rocks near Houlton (Osberg et al., 1985) may be klippen of the Madrid Formation, so that Class III Faults may extend this far north, unless those calcareous wackes are conformable above SOsm. Neither red nor the black pelite, found at the contact between these two units in the study area, has been found in the Houlton area.

Pavlidis (1971, 1972) mapped steeply dipping reverse faults, possibly related to Class III or Class IVa, in the Smyrna Mills and Houlton quadrangles. In the Bridgewater quadrangle (Pavlidis, 1965), a late N80W fracture cleavage cuts across fabrics of north-trending folds and all other fabrics, and northwest-trending faults, perhaps analogous to Class VI, are mapped in both the Bridgewater and Houlton quadrangles. Roy (1987) has mapped a variety of north-trending strike-slip and normal faults in the Presque Isle area, but shows the upthrown block of at least one fault to lie east of the fault trace. These faults show little significant offset, and apparently developed relatively late.

Roy (1981) did not map major fault structures in the Sherman - Millinocket area, but presented stereoplots of cleavage showing a bimodal distribution, trending approximately N10E and N30E, comparable to that of the D4 cleavages (see Figures 17

	FAULT CLASS/EVENT	STRUCTURE	FABRIC
D E V O N I A N	Class VI/D6	Sinistral strike-slip faults; steeply plunging kink folds	Regional slip cleavage and transposition
	Class V/D5	Dextral oblique-slip faults	Only minor cleavage and fractures in study area
		<i>shallow granitic intrusion</i>	
		<i>deep mafic intrusion</i>	
	Class IVb/D4a, D4b	Dextral oblique-slip faults; steeply plunging folds	Regional slip cleavage and transposition
		<i>Peak regional metamorphism</i>	
S I L U R	Class IVa/D3	Reverse faults; shallowly plunging folds	Localized slip cleavage and transposition
	D2	Upright folds	Regional axial-planar cleavage and transposition
	Class III /D1	East-vergent thrust faults	Local shear structures
	Class II	West-vergent Thrust faults	Not in study area
O R D	Class I/D0	Normal faulting and slumping	Disruption of primary layering
		<i>Post - Caradocian (Taconian) Unconformity</i>	

Table III: This table shows the relationships among the deformational events, fault classes, map-scale or outcrop-scale structures, and tectonic fabrics within the study area. Key regional events are also shown; possible relationships between these events and the fault classes are discussed in the text.

and 25, above). The bimodality was noted only in the Lawler Ridge Formation, in the southeast portion of Roy's (1981) study area and the area most proximal to that of the present study. Poles to cleavage and bedding elsewhere show a single maximum, about a vertical surface trending approximately N15 - 20E. Roy did not have sufficient information to define a sequence of fabrics, but did note both steeply plunging open concentric folds, apparently related to faults paralleling the dominant cleavage fabric, and possibly analogous to F3, and kink bands of unspecified orientation post-dating at least the axial planar cleavage, possibly analogous to F4.

Hibbard and Hall (1992), working in an area south of the Munsungun - Winterville Anticlinorium, defined a complex structural sequence dominated by northeast-trending cleavage and faults of unspecified sense of motion. They suggest that tectonism may have accompanied deposition of post-Caradocian sediments and that the effects of Acadian deformation were confined to a short time interval.

Osberg (1968) noted a generally similar pattern of tectonic fabrics in south-central Maine, distinguishing late, dextral asymmetric folds with north-trending axial surfaces from similar northeast-trending dextral asymmetric folds. Cross-cutting relationships among the tectonic fabrics demonstrated that the asymmetric folds developed later than the early Acadian upright northeast-trending folds. Sinistral folds with vertically plunging axes and east-west striking axial planes formed a conjugate set with northeast-trending dextral folds. Osberg also noted that the associated fabrics were offset by north-trending folds, the reverse of the relationship found in the study area.

Griffin (1973) described vertically plunging folds and a related, north-striking, vertical fracture cleavage, post-dating upright folding and peak metamorphism, and associated these with a stress field distinct from that which had produced the upright folds

and associated cleavage. He also noted that slip surfaces parallel to both the axial planar cleavage and a subsequent slip cleavage had been reactivated after peak metamorphism. Griffin also discusses “left-lateral monoclines” with vertical axial planes striking west to northwest, and dextral, vertically plunging kink folds with north - south trending axial surfaces. These kink bands offset almost all previous fabrics, the exception being minor shears which offset several kink bands; the orientations of those kink bands and the offsetting shears are not stated.

## TECTONICS

### INTRODUCTION

Modeling of the Acadian Orogeny is complicated by the general absence of Late Ordovician - Devonian ophiolites, melanges with exotic blocks, and blueschists. The absence of such indicators of subduction-related terrane assembly, and the recognition of the role of transcurrent faulting in the western North American margin have been taken to support models which invoke assembly of this portion of the eastern continental margin through transcurrent faults. Debate on the nature of the Acadian Orogeny has thus often centered on the relative roles of transcurrent accretion of unrelated terranes and subduction-related tectonism acting on terranes within a single depositional basin (compare Bradley, 1983, with Ludman, 1981, 1986). Tectonic modelers have sometimes interpreted the lithotectonic belts dominated by volcanic rocks as island arcs, and the sedimentary rocks of the intervening tracts as deposits in marginal seas or ocean basins (McKerrow and Zeigler, 1971; Bradley, 1983); alternatively, some or all of these belts have been interpreted as "exotic" terranes separated by transcurrent faults (Zen, 1983).

The stratigraphic and structural evidence presented above indicates that the present configuration of all tracts inboard of and including the Miramichi Anticlinorium had been achieved by the Late Ordovician (see also Pollock et al., 1988). This chapter describes the relation of the "inboard" blocks to those to the south, and uses data from isotope geochemistry (Brock, 1989, 1990, 1993) and seismic reflection (Ludman et al. 1990; Costain et al. 1989; Luetgert et al. 1987) to develop a comprehensive picture of the evolution of the supracrustal section on a composite basement terrane of continental or ensialic island-arc blocks, and describe the assembly of these blocks during the events which controlled the stratigraphic and structural sequence.

## SUPRACRUSTAL BELTS

Figure 28 shows a simplified version of the bedrock geology of the area discussed in this chapter, including the supracrustal belts identified by Osberg et al. (1985), and the faults which bound them. Figure 29 summarizes the stratigraphies of these belts. The discussion below emphasizes two critical aspects of the stratigraphy: 1) the similarities and differences between the Cambrian - Caradocian section and the Ashgillian-and-younger section, and; 2) the changes in lithology and, by inference, in depositional environment, apparently related to events at the Caradocian - Ashgillian boundary.

### Cambrian - Caradocian

The Caradocian-and-older strata of the Miramichi, Munsungun - Winterville, and Weeksboro - Lunksoos Lake tracts were shown above to share a common basement of Cambro-Ordovician feldspathic sandstones and pelites. In all three belts, this section is unconformably overlain by a section of black shale, thin-bedded turbidites, cherts or silicic volcanic rocks, and bimodal Tremadocian-through-Caradocian volcanic rocks.

Cambro - Ordovician rocks of the Cookson Group (Ludman, 1985) in the St. Croix Belt reflect a very different depositional environment. Strata equivalent in age to the Baskahegan Lake Formation include coticule rocks (lower Calais Formation), black shales and pillow basalts (upper Calais Formation), and wackes and pelites (Woodland Formation). Both the upper Calais Formation and the Woodland Formation include lithologies superficially similar to those of the Ovf/Bowers Mountain Formation (Ludman, 1991), but reverse the order of sulfidic clastic and volcanic rocks; silicic volcanic rocks, cherts, and conglomerates are rare to absent in the Woodland and Calais Formations. Primary layering in the Woodland Formation is thicker and turbidite features much more common than in the Stetson Mountain Formation. The Woodland Formation is overlain

Figure 28: Simplified geologic map of east central Maine, from Ludman et al. (1993), modified to show lithotectonic belts of Osberg et al. (1985). Dark pattern indicates post-Acadian redbeds; light stipple indicates plutons. DBL = Deblois Pluton; PGD = Pocomoonshine Gabbro-Diorite; MH = Moosehorn Complex.

Key to 15-minute quadrangles shown in inset: ML = Mattawamkeag Lake; A = Amity; WY = Wytopitlock; D = Danforth; F = Forest; V = Vanceboro; SP = Springfield; SL = Scraggly Lake; W = Waite; K = Kellyland; WL = Wabassus Lake; BL = Big Lake; C = Calais.

Key to stratigraphic units: CObl = Baskahegan Lake Formation; COc = Cookson Group, undivided; Oku = Kossuth Group, undivided; Opu = Prentiss Group, undivided; OSs = Sam Rowe Ridge Formation; Ovm = unnamed mafic volcanic rocks; OSc = Carys Mills Formation; OSp = Pocomoonshine Lake Formation; Sd = Daggett Ridge Formation; Sdf = Flume Ridge Formation; Sdi = Digdeguash Formation; Ssm = Smyrna Mills Formation; SDm = Madrid Formation; SDv = Coastal Volcanic Belt, undivided.

Key to faults: CMB = Central Maine Boundary Fault; NB = North Bancroft Fault; SM = Stetson Mountain Fault; C = Codyville Fault; SPC = South Princeton - Crawford Fault.

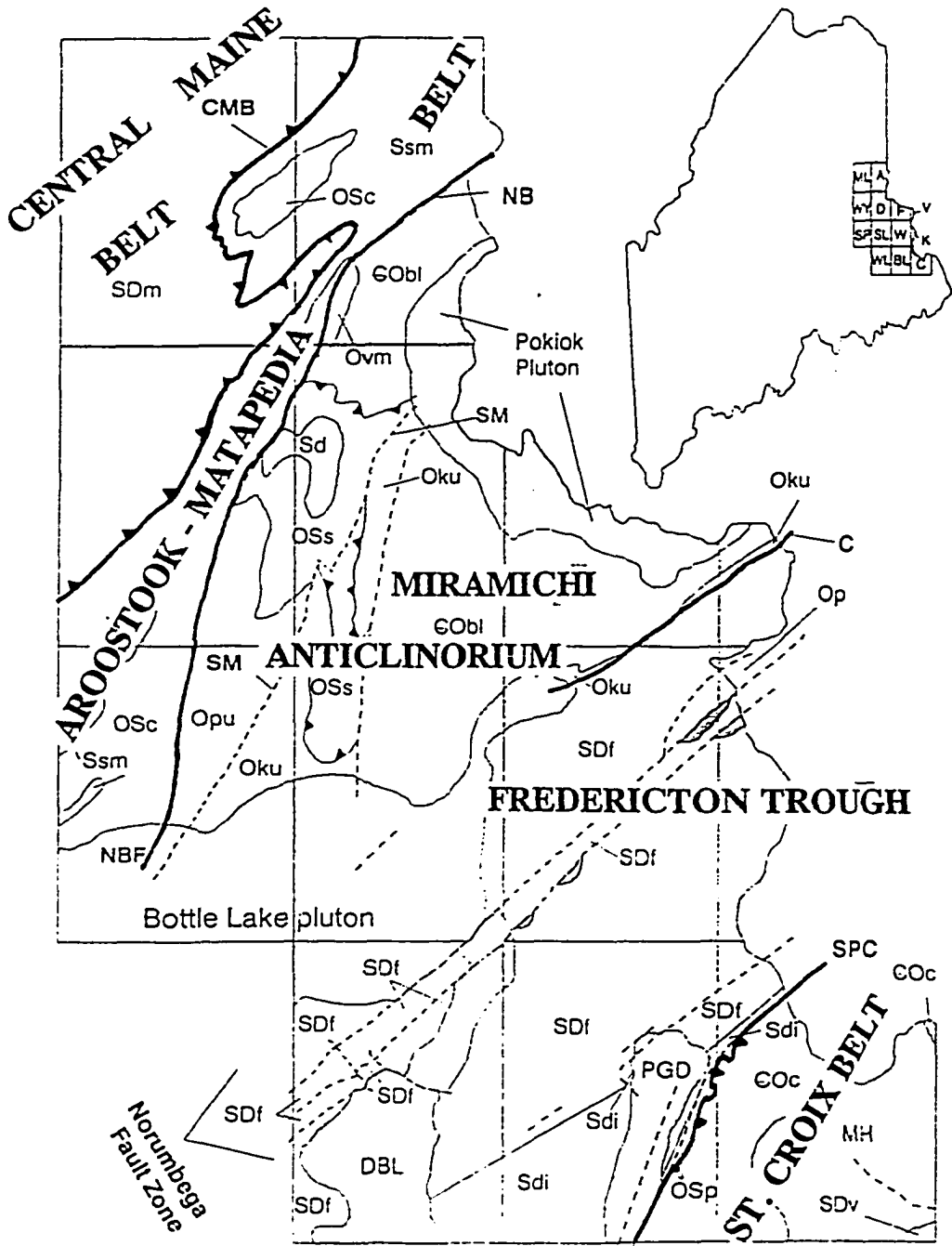


Figure 29: Stratigraphy of lithotectonic belts discussed in this report.

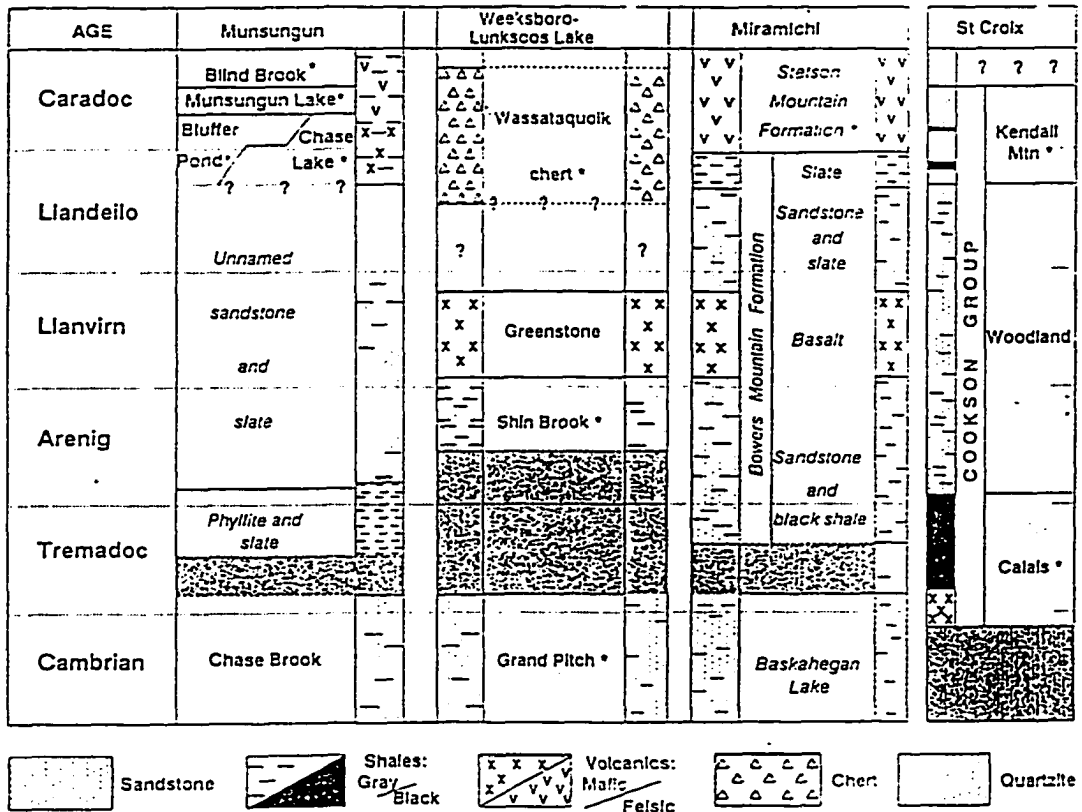


Figure 29a: Pre-Ashgillian stratigraphy of Munsungun - Winterville, Weeksboro - Lunksoos Lake, Miramichi, and St. Croix belts (from Ludman et al., 1993). Asterisks indicate faunal age control. Note marked difference between stratigraphy of the St. Croix Belt and those of the other tracts.

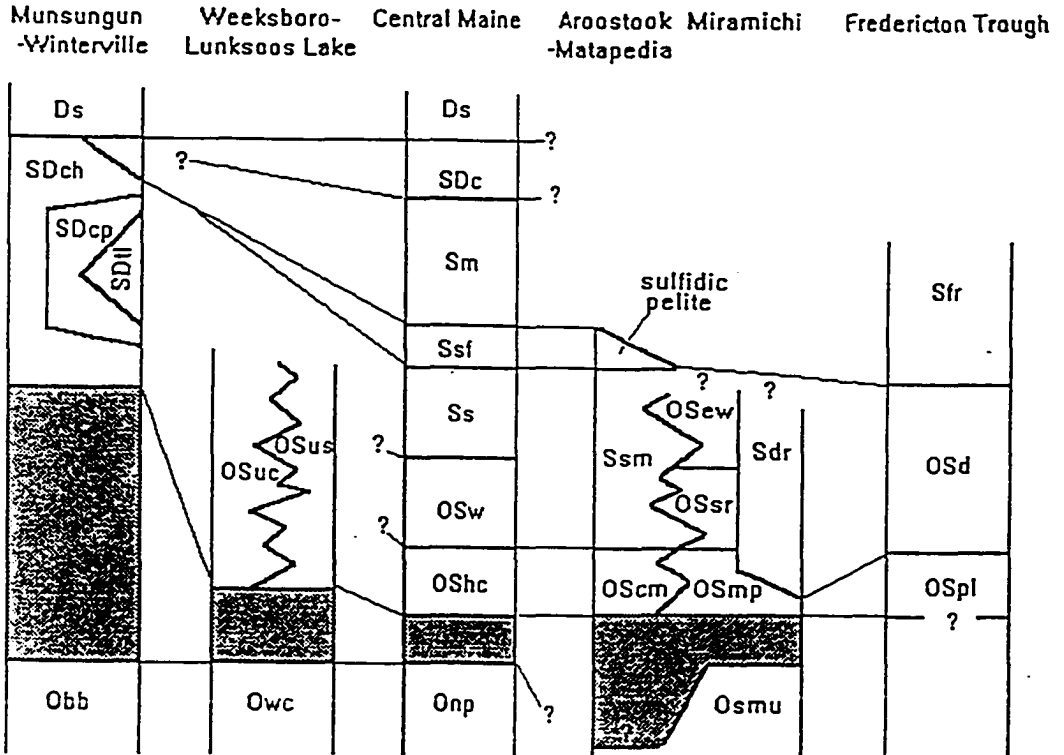


Figure 29b: Late Ordovician - Devonian stratigraphies of Munsungun - Winterville, Weeksboro - Lunksoos Lake, Central Maine, Aroostook - Matapedia/Miramichi, and Fredericton Trough tracts. Shaded area indicates post-Caradocian unconformity.

by the Kendall Mountain Formation, which is composed of massive, thick-bedded orthoquartzites with thin black shale interbeds. This unit shows no obvious relation to any rocks in the time-equivalent strata of the study area.

The common structural histories of all three units of the St. Croix Belt (Ludman and Hill, 1988) argue against correlation of the turbidite-facies rocks of the Woodland Formation to those of the Baskahegan Lake Formation, since the St. Croix Belt must have distant from the event which developed the major unconformity separating the Baskahegan Lake Formation and equivalent rocks from the overlying volcanic and clastic strata. The Cookson Group rocks may be related to the Cambro-Ordovician continental shelf deposits of the St. John Group of southern New Brunswick (Pickerill and Taoli, 1985), which are generally interpreted as the edge of the Avalonian continental shelf. The coticule rocks, euxinic shales, and turbidite facies of the Cookson Group suggest a deeper water environment receiving considerable amounts of sediment (such as that which formed the orthoquartzites of the Kendall Mountain Formation) from the continental shelf. The Cookson Group may represent the northwest slope and rise of the Avalonian continent, synchronous with the St. John Group strata higher on the shelf.

Ludman et al. (1993) interpret a significant break between the pre-Ashgillian rocks of the St. Croix Belt and the rocks of equivalent age to the north and west. If the similar stratigraphies of the more northerly tracts reflect their common development, the break indicates that the Cookson Group rocks cannot have been proximal to this portion of North America during the Caradocian; the terrane on which the Ordovician volcanic tracts developed was accreted to North America during the Ordovician orogenic event, and the St. Croix Belt must have arrived at approximately its present location relative to those tracts subsequently. The potential suture between the post-Late Ordovician North

American margin and the St. Croix Belt rocks therefore lies beneath the post-Caradocian rocks of the Fredericton Trough.

#### Ashgillian - Middle Silurian

As in the Aroostook - Matapedia, the pre-Ashgillian basement of the Fredericton Trough is not exposed in the belt itself. In the Aroostook - Matapedia the basement may be inferred to be equivalent to the Cambrian - Caradocian section exposed on either side of the belt; the nature of the Fredericton Trough basement is less clear, although general inferences can be made. The post-Caradocian Fredericton Trough (Figure 29b) ranges in age from Ashgillian(?) to mid-to-late Silurian, and so is temporally equivalent to strata discussed previously. Fossils are rare-to-absent, so ages are determined by inference from tectonic fabrics, facing data at unit contacts, and presumed equivalence to strata of known or less-removed inferred ages. This discussion of the Fredericton Trough stratigraphy is drawn largely from work by Ludman (1989, 1991).

The lowermost unit, the Pocoomoonshine Lake Formation, is a sequence of dark gray to black, variably carbonaceous, pyritiferous pelites, siltstones, and wackes. Bed thickness ranges from 5 millimeters to 10 centimeters, but is typically on the order of 2 - 4 centimeters; coarser beds are typically well graded (Ludman, 1989). These rocks are distinguished from somewhat similar carbonaceous and sulfidic rocks in the Cookson Group by a distinctly less sooty character and by the absence of the deformational fabrics associated with Class II faulting. Contacts of the Pocoomoonshine Lake Formation with the Woodland and Kendall Mountain Formations occur only along known or inferred faults, while intermittently visible exposures of the Pocoomoonshine Lake Formation in the southwestern cove of Pocoomoonshine Lake show interstratification with the overlying Digdeguash Formation.

The Digdeguash Formation is a thick sequence of generally well-graded feldspathic granule conglomerates and gritty wackes which grade upward into siltstone and pelite. Turbidite features, including well-developed Bouma sequences, are common, although some sandstone beds are massive. Clasts include quartz, plagioclase, felsic and hypabyssal volcanic rocks, and polycrystalline quartz, with some muscovite + chlorite + quartz + feldspar clasts occurring within coarser grits (Ludman, 1989). Westerman (1978) describes coarse conglomerates in the Digdeguash Formation near the eastern edge of the Fredericton Trough; the entire unit may fine to the northwest.

The Digdeguash Formation is conformably overlain by the Flume Ridge Formation, which underlies most of the Fredericton Trough mapped in Maine. This unit is composed of generally fine-grained quartzofeldspathic wackes interbedded with calcareous and noncalcareous siltstone and generally noncalcareous pelite (Ludman, 1989). Wackes contain large muscovite flakes, readily visible to the unaided eye, and oriented with c-axes subnormal to the primary bedding. Chlorite-grade exposures weather to a rusty orange-brown, reflecting fine dissemination of pyrite and ankerite throughout the unweathered rock.

Ludman et al. (1993) describe the gritty wackes of the Digdeguash Formation as nearly identical to gritty wackes in the Sangerville Formation of Central Maine, which was linked, above, to the post-Caradocian rocks of the Prentiss Group and Aroostook - Matapedia Belt. In the interpretation proposed here, the thinly bedded pyritiferous rocks of the Pocomoonshine Lake Formation are equivalent to similar lithologies in the Mill Priveledge Brook Formation, and temporally equivalent to the argillaceous and sulfidic carbonates of the Carys Mills Formation, and comparable rocks reported in the Hutchins Corner Formation (Osberg, 1988). An increase in fresh volcanogenic sediment in the

Latest Ordovician (?) - Early Silurian is reflected in the generally coarser-grained and feldspathic Digdeguash, Ellen Wood Ridge, Smyrna Mills, and Sangerville Formations.

The muscovite flakes, orange weathering, and turbidite depositional fabrics of the Flume Ridge Formation suggest a correlation to the Madrid Formation. Lithologies analogous to the Smalls Falls Formation or the sulfidic units found at the base of the Madrid Formation in the study area are not known from the Fredericton Trough. Several hypotheses could explain the absence of the sulfidic unit. Anoxic water may not have been present at the time of deposition of the Flume Ridge Formation, perhaps due to a less restricted seaway at the time, if the anoxic condition is related to the closing of the North America - Avalon seaway. Alternately, the depth of deposition of the Flume Ridge Formation could have been significantly different than that of the Madrid Formation, due to a different location relative to the subsiding North American margin or the trench between North America and Avalon. The Madrid Formation may be derived largely from cannibalization of the Flume Ridge Formation, in which case it could be deposited later in time, while representing the same depositional environment.

It is suggested here and elsewhere (Ludman et al., 1993) that the Fredericton Trough rocks include the most oceanward sediments deposited offshore of North America during the Taconian - Acadian interval, and that these sediments may have been deposited on oceanic crust. Pelagic and hemipelagic equivalents of the Pocomoonshine Lake and Digdeguash Formations, if such rocks existed, have been overridden by the rocks of the St. Croix Belt. Seismic reflection studies of coastal Maine (Stewart et al., 1985; Unger et al., 1987) and east-central Maine (Costain et al., 1989; Doll et al., 1990; Ludman et al., 1990) show that no oceanic crust is present beneath the Fredericton Trough, implying that any oceanic crust on which these rocks may have been deposited has been subducted and that the Fredericton Trough rocks are largely allochthonous, thrust either southeastward,

onto Avalonian basement, or northwestward, onto the composite block. The former interpretation is preferred, due to the analogy and presumed synchronicity with the Class III faulting described above.

None of the blocks in or associated with the study area are stratigraphically linked with either the St. Croix Group or the Siluro-Devonian Coastal Volcanic Belt; the latter may represent volcanism related to southwestward subduction beneath Avalon of oceanic crust on which Fredericton Trough rocks may have been deposited. Silurian cover rocks of the Coastal Volcanic Belt link the St. Croix and Coastal Volcanic Belts (Ludman et al., 1993), so that the Avalonian block must have developed prior to the Acadian structural events described above. Several lines of evidence indicate that the Avalonian terrane was widely separated from North America prior to the Acadian Orogeny. Faunal data summarized in Berry and Osberg (1989) indicate that the Acado-Baltic fauna of the Avalonian terrane were distinct from North American fauna as late as the Early Devonian. While barriers to faunal migration are not necessarily geographically wide, paleomagnetic data suggest that the Pre-Acadian separation between Avalon and North America was at least twenty degrees of latitude in the Early Silurian (Van der Voo et al., 1988); this separation is absent by mid-Devonian time.

#### Timing of Avalon - North America Accretion

The stratigraphic and geophysical data cited above show the differences between the supracrustal sections associated with North America (Miramichi block and all terranes inboard, and perhaps including the rocks of the Fredericton Trough) and Avalon. The approach of the Avalonian block toward North America is signaled by the Middle Silurian submarine-fan sediments of the Flume Ridge and Madrid Formations. These may have

been eroded from the advancing Avalonian continent, but the provenance, and petrographic equivalence, of these units has not been determined.

The relative timing of Class II and Class III Faults is critical to determining the sequence of convergence of North America and Avalon. Intrusive rocks of the Pocomoonshine Gabbro-Diorite, the Deblois Pluton, and the Moosehorn Igneous Complex seal the Class II (?) South Princeton - Crawford Fault at the contact of the Fredericton Trough and Avalon terrane. Ages of plutons in the Moosehorn Complex (Jurinski, 1989; Jurinski and Sinha, 1989) suggest that linkage between these two blocks was complete by the Late Silurian. The 420 Ma contact metamorphism age (West et al., 1992) for biotite from the aureole of the Pocomoonshine Gabbro-Diorite is consistent with Silurian closure of these tracts. The present configuration of the Miramichi, Aroostook - Matapedia, and Central Maine tracts is fixed at 385 Ma (Ayuso, 1984) by the Bottle Lake Complex, which was emplaced well after the convergence of Avalon and North America in the general area of New Brunswick and eastern Maine. These ages imply rapid closure of a relatively narrow basin within which the Fredericton Trough rocks were deposited.

Stratigraphic, structural, paleontological, and paleomagnetic data thus lead to the conclusion that the Acadian Orogeny included juxtaposition of the North American block (all terranes inboard of the Fredericton Trough) with the Avalon composite block, including at least the St. Croix Belt and Coastal Volcanic Belt. Prior to the convergence, these terranes were separated by a belt presently concealed by the in whole or part allochthonous rocks of the Fredericton Trough. This model, however, relies entirely on data gathered from the supracrustal section, and all supracrustal sections are potentially allochthonous, not only that of the Fredericton Trough. It is necessary to define the basement blocks of the orogen, and consider their relative motions.

## DEFINITION OF BASEMENT BLOCKS

This section relies on analysis of published and unpublished isotopic data from Silurian-to-Carboniferous igneous rocks by Pamela Chase Brock (Brock 1989, 1990, 1993), which resolved five distinct basement blocks underlying New England and New Brunswick (Figure 30); Table IV summarizes the isotopic data from this study. Efforts have been made to cite this work directly at appropriate specific locations in the text, but the influence of the work is found throughout the section, and cannot be readily isolated.

Adjoining basement blocks with contrasting isotopic compositions can be distinguished if each contributed to magmas generated during any given period. Igneous rocks in three of the blocks - Grenville, Central, and Avalon - show a broad range of isotopic ratios and evidence of granitic source rocks, such as enrichment in radiogenic strontium ( $^{87}\text{Sr}/^{86}\text{Sr} > 0.703 - 0.719$ ), and  $\delta^{18}\text{O}$  values greater than 11 per mill. Some plutons presumably derived from or passing through these basement blocks contain xenocrystic zircons that yield middle Proterozoic ages, and samarium - neodymium model ages from plutons in these blocks are also Proterozoic. In contrast, the Boundary Mountain and Sebago blocks contain plutons which show very narrow ranges of isotopic compositions. Strontium isotope ratios from these blocks are generally less than 0.706, and  $\delta^{18}\text{O}$  is generally less than or equal to ten per mill; these data apparently preclude upper continental crust sources for these igneous rocks. Brock (1993) inferred that plutons in those areas did not show isotopic evidence of derivation from Middle Proterozoic source materials.

Broadly speaking, two types of crust underlie New England and the adjacent Maritimes. Three of the blocks - Grenville, Central, and Avalon - show isotopic

Figure 30: Basement blocks and supracrustal terranes in Maine (from Ludman et al., 1993).

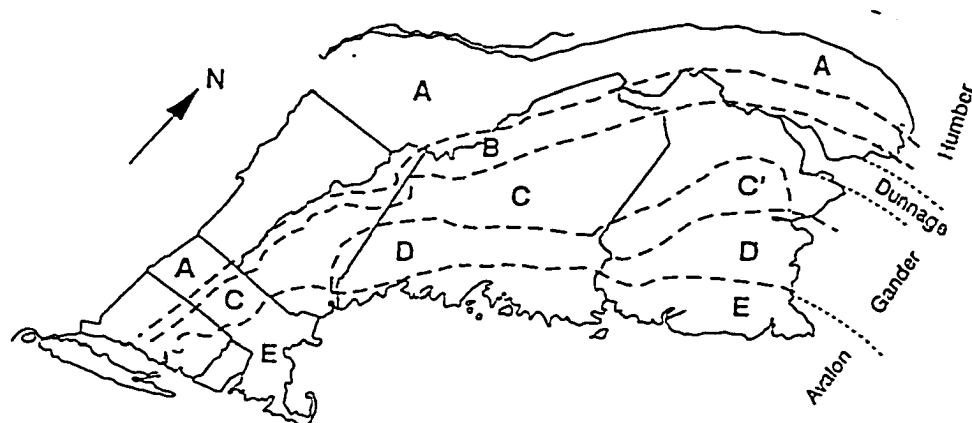


Figure 30a: Isotopically defined basement blocks in New England, New Brunswick, and adjacent Quebec.

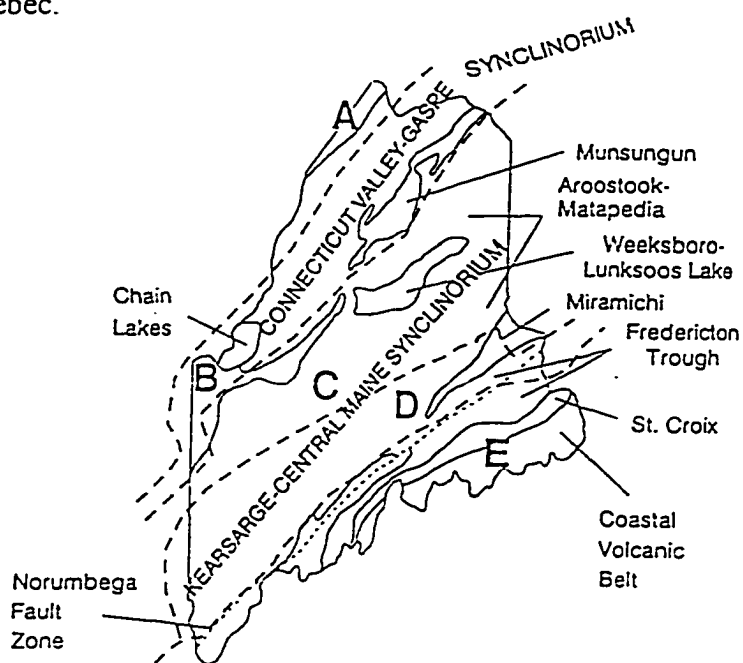


Figure 30b: Relation of isotopically defined basement blocks to supracrustal terranes in Maine. The boundaries of the supracrustal blocks do not coincide with the boundaries of the basement blocks, implying that the supracrustal blocks (particularly the Miramichi Anticlinorium) may be, in whole or part, allochthonous.

	Grenville	Boundary Mountain	Central	Sebago	Avalon
$^{87}\text{Sr}/^{88}\text{Sr}$ Initial ratio	0.704–0.7165	0.7045–0.7051 (Ordovician)	0.705–0.7161	0.7031–0.7056	0.703–0.719
$^{206}\text{Pb}/^{204}\text{Pb}$	18.02–19.04	17.96–18.44	18.21–19.13	18.25–18.44	18.00–19.21
$^{207}\text{Pb}/^{204}\text{Pb}$	15.52–15.64	15.51–15.58	15.57–15.71	15.56–15.58	15.52–15.69
$^{208}\text{Pb}/^{204}\text{Pb}$ (feldspar in Dev. plutons)	37.80–29.10	37.80–38.37	38.01–38.63	38.06–38.29	38.05–38.58
$\delta^{18}\text{O}$ (whole rock)	.....	6.8–8.2	7.2–13.3	7.4–11.1	5.8–12.6
Inferred age of basement' (b.y.)	0.9–1.4	<0.750	1.4–1.8	<0.750	>1.8

Table IV: Table showing the distinct isotopic ratios and inferred ages of basement blocks underlying New England and Maritime Canada, modified from Ludman et al. (1993).

compositions indicative of diverse, ancient, isotopically evolved sources, inferred to be Middle Proterozoic continental crust and associated cover rocks. The isotopic character of the Boundary Mountain and Sebago blocks implies a different basement composition, presumed to be Late Proterozoic to Early Paleozoic crust of island-arc origin. Figure 30 also shows that the lithotectonic belts of Osberg et al. (1985), do not coincide with the isotopically defined crustal blocks. If the basement assemblage has been correctly identified, the supracrustal "terrane" must be at least somewhat allochthonous, and at least some of the exposed Cambrian-through-Middle Ordovician rocks may be slivers of basement thrust upward into the Post-Caradocian cover sequence.

Westward thrusting of the Middle Proterozoic Chain Lakes section during the Taconian has been suggested by Boone and Boudette (1989); this is consistent with the occurrence of that block in the supracrustal section above the Late Proterozoic - Early Paleozoic basement of the Boundary Mountains basement block. The exposed "basement" of the Chain Lakes Massif may be an allochthonous sliver of the Middle Proterozoic Central basement block thrust upward and eastward into the supracrustal section. Eastward thrusting of the Miramichi block over the Fredericton Trough, and both eastward and westward thrusting involving the Fredericton Trough and St. Croix Belt have been proposed during the Acadian Orogeny by Ludman and Hopeck (1988) and Ludman (1990) to explain the sequences of tectonic fabrics observed in those belts. Seismic reflection studies by Doll et al. (1989a, b) and Ludman et al. (1990) revealed reflectors that are shallow-dipping or horizontal at depth, and which may correlate to some of the detachments between the supracrustal and basement rocks required for transport of the supracrustal section.

#### A MODEL FOR THE TECTONIC EVOLUTION OF EASTERN MAINE

The structural and stratigraphic work described in previous chapters may be combined with the basement block delineation to develop a comprehensive model addressing the evolution of the stratigraphic section and the structural history from the Cambrian(?) to an indefinite, but clearly post-Acadian, date. This model is summarized in a series of cartoons beginning with Figure 31.

The Baskahegan Lake Formation and equivalent Cambro - Ordovician units to the northwest show tectonic fabrics absent from any overlying units, and tend toward apparently intraformational melange toward the northwest, with primary layering coherent and continuous in only the Baskahegan Lake and Grand Pitch Formations. Development of this melange and of the angular unconformity may be related to formation of a composite terrane by Early Ordovician collision of the Boundary Mountain and Central basement blocks. Occurrence of melange in the area of the Boundary Mountain block, with undisrupted equivalent rocks in the supracrustal section above the Central block, suggests that subduction was to the northeast, beneath the Boundary Mountain block. The island-arc crust of the Boundary Mountain block may well have developed above this subduction zone, and suturing of these blocks would constitute the Penobscot Orogeny.

In the Middle Ordovician, this composite terrane, in this area corresponding roughly to the Dunnage and Gander terranes of Williams (1978), converged with North America. Oceanic crust separating the two sialic blocks was subducted beneath the composite terrane, and the Caradocian-and-older volcanic rocks and associated sedimentary rocks, was deposited above the regional angular unconformity. Suturing of the composite block to the Grenville block (North America) in the Middle to Late Ordovician may be equivalent to the Taconic Orogeny (see Figure 32). In Maine, this

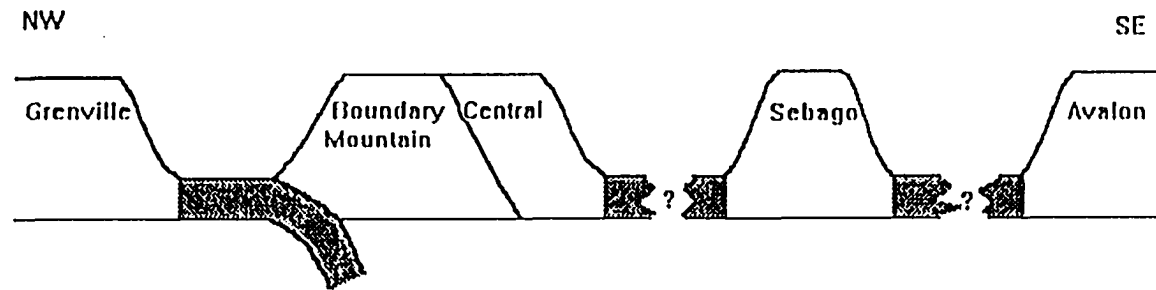


Figure 31: Hypothesized relationships among basement blocks at the close of the Penobscot Orogeny, which involved closure of an oceanic basin between the Boundary Mountain and Central blocks. Hypothesized oceanic crust is shaded.

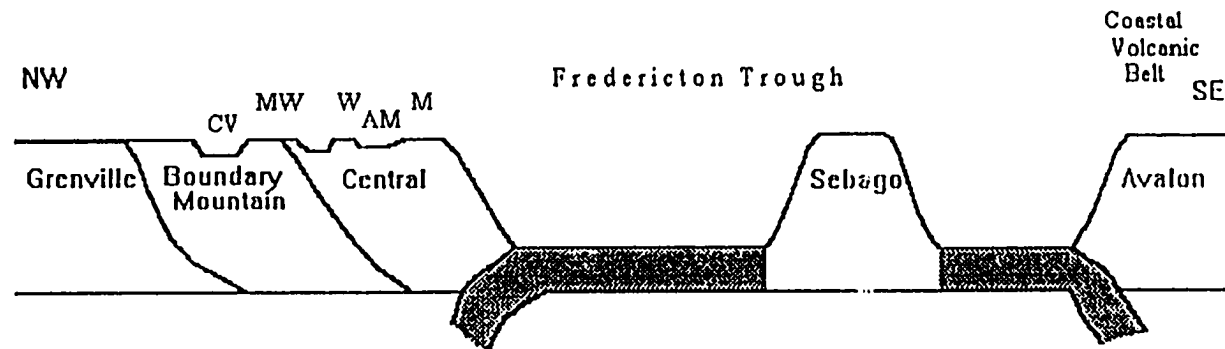


Figure 32: Hypothesized relationships among basement blocks at the close of the Taconic Orogeny, which involved accretion of the composite Boundary Mountain - Central block to the Grenville block (North America). Presumed oceanic crust is shaded. CV = Connecticut Valley Synclinorium; MW = Munsungun - Winterville Anticlinorium; W = Weeksboro - Lunksoos Lake Anticlinorium; AM = Aroostook - Matapedia basin; M = Miramichi Anticlinorium. The diagram is not to scale, and the Connecticut Valley, Aroostook - Matapedia, and other basins were presumably more significant than shown here.

event is reflected in the melange described by Pollock (1989), and the post-Caradocian unconformity described by Hall (1970), Neuman (1967), and Sayres (1986).

By the Ashgillian, the North American margin in the area of Maine and the Maritime Provinces consisted of the Grenville, Boundary Mountain, and Central blocks. The tectonic hinge of Moench and Pankiwskyj (1988) was slightly inboard of the contact between the Central and Boundary Mountain blocks. Extensional basins on the accreted composite terrane developed soon after the orogenic event. Initial restriction of these basins, or some other cause of anoxic water, is recorded by the pyritiferous facies of the Carys Mills and Mill Priveledge Brook Formations, and perhaps the Pocomoonshine Lake Formation. If the Pocomoonshine Lake Formation does represent more oceanward conditions, it is difficult to attribute the sulfidic nature of the rocks solely to restricted circulation; the gap between Avalon and North America, as noted above, is estimated to have been approximately twenty degrees of latitude (Van der Voo et al., 1988) at this time. The present borderland basins of Southern California (Gorsline, 1978; Crowell, 1974), however, have developed in an area undergoing transcurrent extension, and are accumulating sediment under anoxic conditions while bordering the open Pacific Ocean. This does not suggest a strict analogy between the two areas, but indicates that anoxic conditions can occur in more open waters under certain conditions. Alternatively, the anoxic sediments could have been deposited over the relatively flat-lying surface of the unconformity, and the basins developed subsequent to or during their deposition.

The Daggett Ridge Formation, and conglomerates of the Weeksboro - Lunksoos Lake and Munsungun - Winterville tracts indicate that bottom-water circulation improved and relief increased as time passed. These environments would perhaps have extended subparallel to the strike of the orogen into south-central Maine (Osberg, 1988) and the Connecticut Valley - Gaspé Synclinorium. Roy (1989) has suggested that extension in this

latter belt might have been contemporaneous with Late Taconian deformation. Work in Indonesia by Charlton (1991) indicates that normal-fault bounded basins may develop on island-arc terranes following their accretion to continental masses. Charlton (1991) found that extensional tectonics leading to basin development began within less than five million years after accretion of an island-arc terrane. The extension resulted (see Figure 33) from uplift of the overridden part of the continental or transitional crust after it decoupled from, and consequently was freed from the negative buoyancy of, the subducted oceanic crust. As this lithosphere rose, the base of the overriding arc lithosphere extended, leading to normal-fault bounded basins at the surface.

Throughout the deposition of the Aroostook - Matapedia section and laterally equivalent rocks, the Avalonian landmass continued to approach North America. Geochemical evidence (Ludman et al., 1993; Brock 1991, 1992, 1993) suggests that the convergence of the two continental masses occurred through subduction of oceanic crust beneath both North America and Avalon. Early Silurian volcanic rocks of "indeterminate" affinity are distributed on either side of the Sebago block (Figure 34). The Sebago block lay between the converging continents and may have formed part of the basement for the Fredericton Trough; it is not exposed at the surface. On both Avalon and North America, belts of volcanic rocks with intraplate affinities are found farther from the contact with the Sebago block; on North America, a region of transitional volcanic rocks separates these suites, while the transition is more abrupt on Avalon. These parallel trends in volcanic chemistry are interpreted (Ludman et al., 1993) as reflecting paired subduction zones of opposite vergence beneath North America and Avalon through Late Ordovician and Early Silurian time. This model is similar to that proposed by Bradley (1983), and is in accord

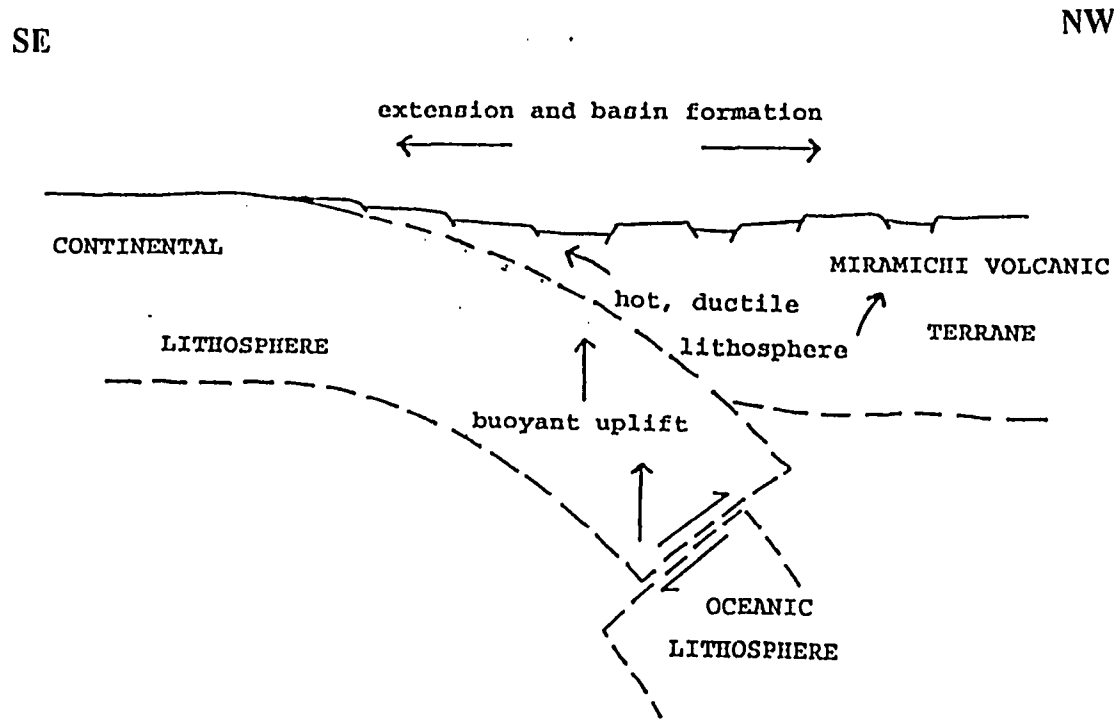


Figure 33: Cartoon showing hypothesized mode of development of extensional basins on accreted blocks after the Taconic Orogeny, modified from Charlton (1991).

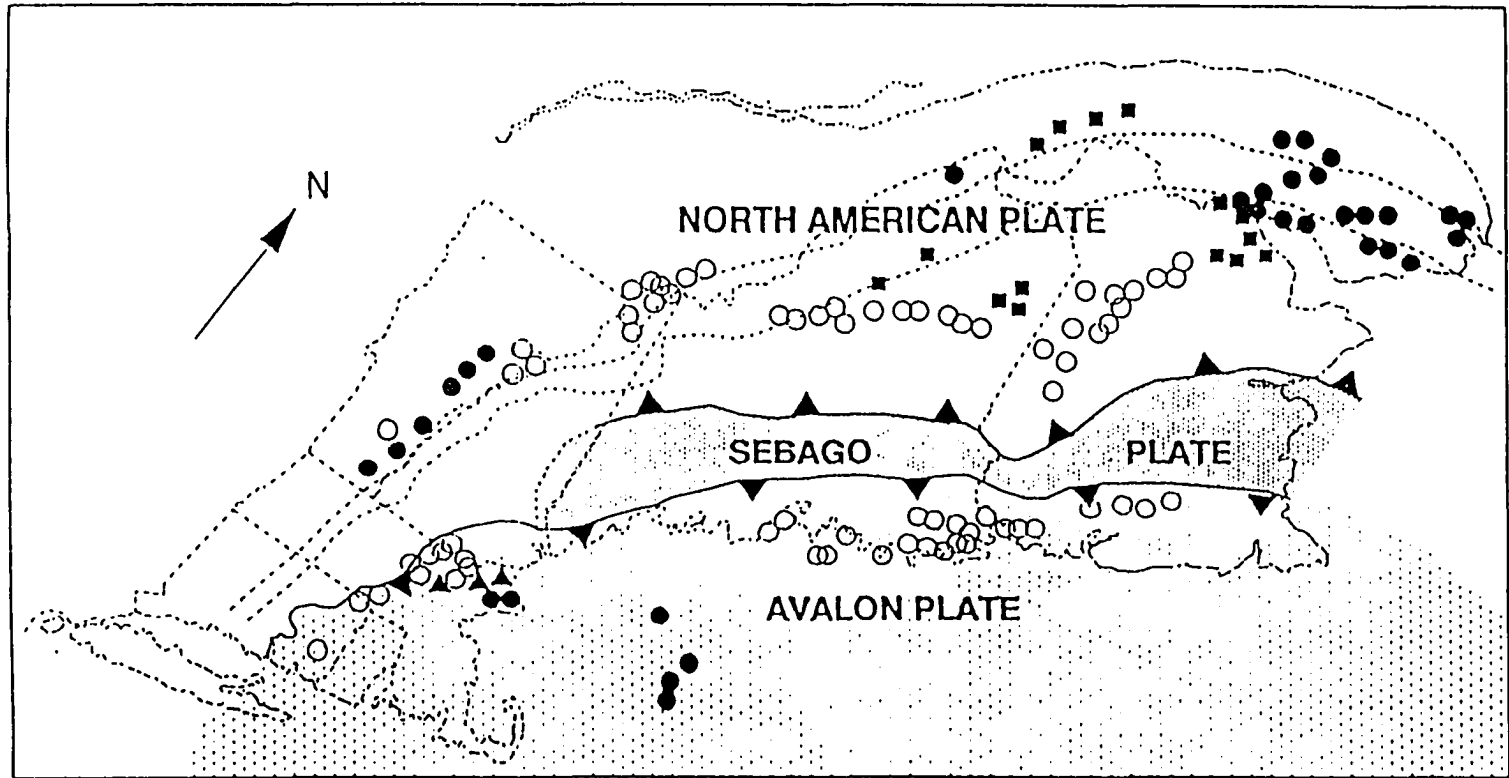


Figure 34: Distribution of post-Caradocian, pre-Acadian volcanic rock types in the Northern Appalachians (from Ludman et al., 1993, and Brock, 1993). Inferred tectonic affinities: solid circles = intraplate; open circles = indeterminate; solid squares = transitional; triangles = volcanic arc. Note distribution of volcanic rocks on either side of Sebago block.

with the vergence direction of Acadian deformation in the St. Croix Belt discussed by Ludman (1988), and attributed to Class II Faults. A westward-dipping subduction zone beneath North America also agrees with the vergence of the Class III Faults proposed above. Subduction of oceanic crust beneath North America could have begun by upward migration of a fault beginning at the plane of separation of subducted oceanic and unroofed continental crust, through the overriding oceanic plate (see Charlton, 1991). This fault would have broken through the crust seaward of the Central block.

The apparent linkage between the Pocumoonshine Lake Formation and the Mill Priveledge Brook and Carys Mills Formations implies that deposition of the Pocumoonshine Lake Formation occurred in relative proximity to North America as well. Since the Pocumoonshine Lake Formation may be in whole or part allochthonous on the Sebago block, this does not necessarily imply proximity of that block to North America during the Late Ordovician, although the inferred age of the Sebago block would allow for it to have served as a basement for the Pocumoonshine Lake Formation.

In any event, the area east-southeast of the "tectonic hinge" of Moench and Pankiwskj (1988), and comprising the basins of the Munsungun - Winterville, Weeksboro - Lunksoos Lake, and Aroostook - Matapedia/Prentiss Group as a single (forearc basin?) unit, must have been an area of relatively little subaerial exposure during the Early Silurian, and so probably did not contribute substantial quantities of sediment to any trench which may have been offshore of the Central block. The clastic wedge shed from emergent rocks of Avalon (Flume Ridge and Madrid Formations), could have provided a more substantial volume of sediment, burying the trench and overriding the subsiding North American margin, as shown in Figure 32. In this hypothesis, the sulfidic rocks of the Smalls Falls Formation and equivalent strata would lie in advance of or at the toe of this wedge, rather than in an crustal bulge advancing either before the wedge or on the

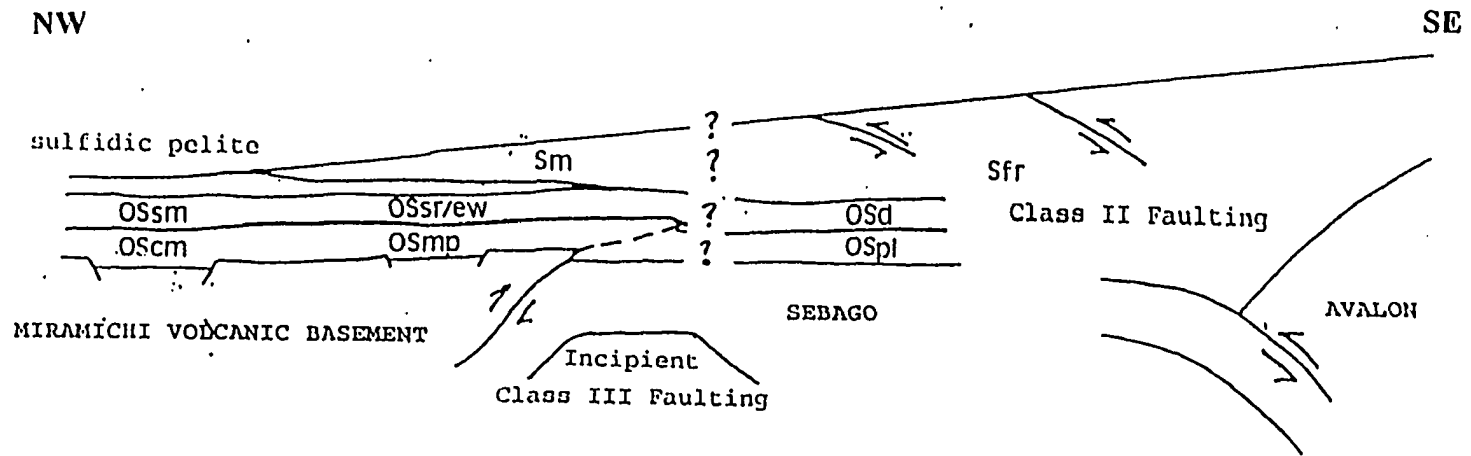


Figure 35: Cartoon showing hypothesized depositional sequence and tectonic environment during convergence of North America and Avalon. OScm: Carys Mills Formation; OSmp: Mill Priveledge Brook Formation; OSpl: Pocomoonshine Lake Formation; OSsm: Smyrna Mills Formation; OSsm/ew: Sam Rowe Ridge and Ellen Wood Ridge Formations; OSd: Digdeguash Formation; Sm: Madrid Formation; Sfr: Flume Ridge Formation.

clastic wedge itself. Class II Faults reflect convergence of Avalon with the Sebago block, or at least with the Pocomoonshine Lake Formation; Class III Faults may reflect subsequent convergence of the North American block with the Avalonian clastic wedge, or with the Sebago - Avalon composite block. If the interpreted vergence for Class III Faults is correct, they developed through backthrusting of the clastic wedge toward Avalon, synchronous with thrusting of the supracrustal Miramichi section (Figures 36 and 37) over the Fredericton Trough and Sebago block. If the vergence is opposite to that proposed here, Class III Faults could instead reflect sliding of the advancing wedge above the weak sulfidic rocks.

#### Relation of Acadian Tectonics to Tectonic Fabrics

Faults of Classes I through IVa record the development of the post-Taconian basins on the accreted arc terrane and the compressional phase of the Acadian Orogeny. Class I Faults developed on debris aprons along the faulted margins of sedimentary basins above the Caradocian arc terrane of the Boundary Mountains and Central blocks. The trigger for development of these basins could have been the detachment of oceanic lithosphere from the overridden plate (Charlton, 1991), or, if westward subduction of oceanic crust beneath the accreted block was initiated shortly after accretion, by tectonic erosion of the base of the accreted terrane (see, for example, Dickinson, 1977). Ludman et al. (1993) indicate that westward subduction may have been initiated later than eastward subduction beneath the Avalon block, which is consistent with deposition of the Pocomoonshine Lake Formation on the Sebago block, and the need, indicated by the faunal and paleomagnetic data described above, for the Avalon block to close a wide expanse of ocean during the Silurian. Fresh volcanogenic debris is rare within the basal, pyritiferous units of the Ashgillian-and-younger section, but much more common upward, suggesting that the Silurian volcanic phase lagged behind the initiation of subsidence. The

Figure 36: Hypothesized relation of crustal blocks during Acadian orogenic events. Presumed areas of oceanic crust are shaded.

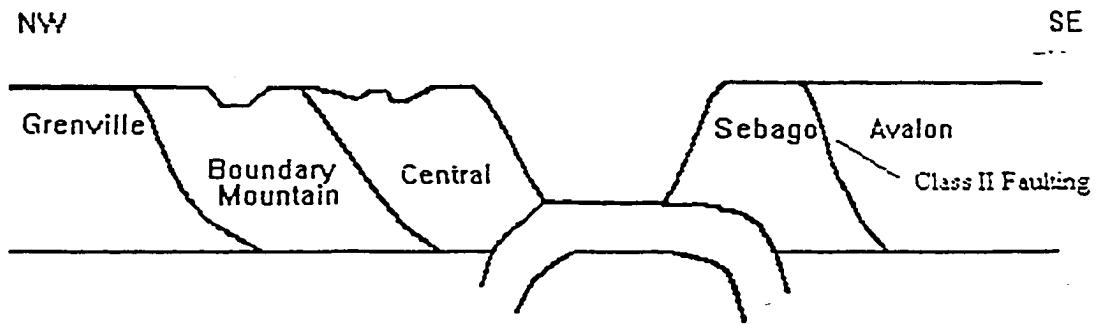


Figure 36a: Relative positions of crustal blocks during deposition of Acadian clastic wedge and development of composite Avalon terrane in the vicinity of North America; this figure depicts essentially the same events as Figure 35, with less stratigraphic detail.

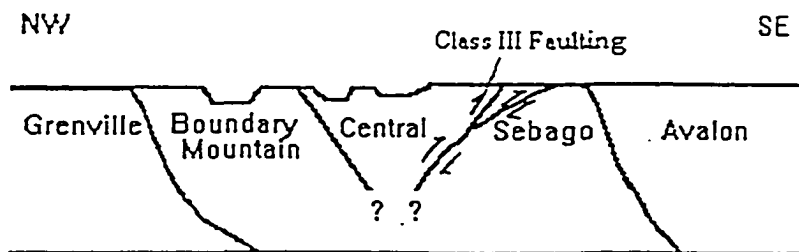


Figure 36b: Climax of Acadian orogenic phase, with suturing of Avalon composite terrane to North America.

rarity of coarse-grained beds within the pyritiferous rocks also suggests that local relief during the early phase of deposition was relatively low, assuming that the observed exposures are truly representative of the pyritiferous units.

Class II Faults and related structures, including west-vergent thrusts and recumbent folds in the Woodland Formation, and faults which thrust it above the Pocomoonshine Lake Formation, reflect closure of the subduction zone between Avalon and the Sebago block. Potassium - argon ages of approximately 420 Ma for the Pocomoonshine Gabbro - Diorite (West et al., 1992), which intrudes both the St. Croix Belt and the Fredericton Trough, suggest that convergence of the two blocks occurred by the middle Silurian. An unresolved problem, however, is the provenance of the early Silurian (?) Digdeguash Formation; a North American provenance is preferable, in that it would avoid the problem of developing a model in which volcanoclastic sediments would bypass the advancing submarine fan-delta complex of the Flume Ridge Formation, although the unit is thought to fine to the northwest. The apparent cessation of volcanic activity could then be due to a greater rate of sediment accumulation in the fan-delta section, blocking transport of the North American sediments farther to the southeast.

Class III Faults developed through the Middle-to-Late Silurian, and could be partially synchronous with latter stages of Class II faulting. If they are not east-vergent, they could be west-vergent faults at a higher level in the section than the Class II Faults, and so reflect thrusting of the Avalonian accretionary prism onto North America. Displacement of exposed Miramichi Anticlinorium rocks above the Sebago basement block, as shown in Figure 36, could be along a fault of Class III. Class IVa Faults include the reverse phase of motion on the North Bancroft Fault. The presumed eastward vergence of both Class III and Class IVa Faults is compatible with northwestward subduction of any oceanic crust remaining between the Central and Sebago blocks, (see

Figure 35). The vergence of Class II Faults is consistent with that expected in a fan shed westward from Avalon above a southeastward-dipping subduction zone (Figures 35 and 36). The timing of Class II and Class III faulting is consistent with closure of the Avalon and Sebago blocks, and the sealing of this juncture by the Pocomoonshine Gabbro-Diorite, prior to the accretion of the composite block to North America.

Fault classes from I to IVa may therefore be related to the assembly of isotopically distinct lithospheric blocks into a pattern generally similar to their present arrangement, prior to 385 Ma. Overthrusting of the St. Croix Belt and the Miramichi tract above the Fredericton Trough, together with the sealing the St. Croix Belt - Miramichi contact by 420 Ma, and the Miramichi - Fredericton Trough contact by 385 Ma, indicate that minimal lateral offset can have occurred after D4. The assemblage of blocks was, however, subjected to ongoing stresses related to the Acadian event shortly after the conclusion of the compressional phase of the orogeny in eastern Maine.

Class IVb Faults show dextral strike-slip motion along the same traces as the reverse faults of Class IVa, implying that both reflect down-to-basement fractures and stresses within the Avalon - North America terrane. Slip on north-trending Class IVb faults, specifically the North Bancroft Fault, overlapped emplacement and cooling of the rim facies of the Passadumkeag River Pluton at 385 Ma (Ayuso and Arth, 1984). North-trending fabrics are absent from the younger (Ayuso, 1983) core facies of the pluton (see discussion above and Hopeck et al., 1988; Hopeck, 1991c), although northeast-trending Class IVb faults are present within the core facies, where they appear to control the orientation of dikes and zones of late magmatic fluid migration. Brittle fabrics parallel to this northeast trend in both facies suggest that slip on this trend continued after cooling of the pluton was complete. Biotite assumed to have developed through frictional heating along strands of the Class V Norumbega Fault Zone has a K-Ar age of approximately 380

Ma (West et al., 1992). This leaves very little time between the emplacement of the Bottle Lake Complex and the onset of dextral strike slip on the Norumbega Fault Zone.

The plutons of the Bottle Lake Complex, along with the other major mid-to-late Devonian granitic bodies in Maine, fall into the category of "postmetamorphic" granites (Rast and Skehan, 1993), interpreted as reflecting the main phase of the Acadian Orogeny, although crosscutting the Acadian folds and cleavages which affect rocks as young as Lower Devonian. Of these postmetamorphic plutons, at least those of the Bottle Lake Complex show evidence of association with mafic intrusive bodies. Xenoliths of amphibolite, in various states of resorption, occur throughout the complex in varying abundance, and at least one large body of amphibolite underlies several hundred acres within the complex (Ayuso, 1982). Postmetamorphic plutons developed after the closure of any ocean basin separating North America and the Sebago block, and consequently could not represent a magmatic arc associated with the northwestward subduction. Silurian intrusive bodies are required as an ultimate source for the volcanogenic sediments described above. Many plutons in New Brunswick and eastern Maine have recently been found to have Silurian ages (Bevier et al., 1991, for example).

It is generally considered that the convergence of North America and Avalon was oblique, with "Acadian" or "Caledonian" orogenesis in Newfoundland and the area of Scandinavia and the British Islands beginning in the Silurian (Van der Pluijm, et al., 1989; Rast and Skehan, 1993), and potentially continuing into the Carboniferous in Virginia (Ettensohn, 1987). Oblique convergence implies dextral shear along the boundary of North America and Avalon; paleomagnetic data of Van der Voo (1988) and Miller and Kent (1988) also indicate dextral slip on this boundary. Consequently, the faults of Class IVa and Class IVb are thought to reflect the changing stress field during the transition from oblique convergence of the composite Avalon terrane with North America to

transcurrent motion between the two blocks (Figure 37) as convergence continued farther to the south. Intrusion of granitic bodies synchronous with these dextral faults suggests that the intrusives may reflect local extensional conditions and reduced pressures in the lower crust during the phase of dextral slip. Mafic xenoliths in the Bottle Lake Complex and the Center Pond Pluton (Loiselle and Wones, 1983) imply that extensional stress in the lower crust allowed intrusion of mafic bodies from the upper mantle. Wones (1978) indicated that the total post-early Devonian slip on the Norumbega Fault Zone was no greater than 35 kilometers; the stratigraphic continuity, and absence of offset pluton boundaries, suggests even less offset on Class IV Faults, yet the penetrative slip cleavage associated with Class IV faulting indicates distribution of the stress throughout the crust at the time of faulting. Reduction of confining pressures at the base of the crust in the transtensional regime may be a more likely cause of the intrusions than development of extensional openings in the lower crust. Evidence discussed above implies lower confining pressure, and lower temperatures, during Class IVb slip. The orientation of the north-trending Class IVb faults is compatible with their interpretation as synthetic strike-slip faults associated with compression along a southwest - northeast axis. The sense of principal stress required for this compression is clearly different from that evinced by faults of Classes II and III, and the F1 folding.

Brock (1993) suggests that the convergence of North America and the Sebago block may have been accomplished by squeezing the Sebago block into its position between the obliquely converging Avalonian and North American continents, as shown in Figure 37. Stresses related to the southeastward motion of Avalon relative to North America would be communicated into the Sebago, Central, and Boundary Mountain blocks. Initially, this stress could be reflected in the synthetic Class IVb faults; development of the Class V Norumbega Fault Zone, parallel to the plane of relative motion between Avalon and North America, would localize the strain into a narrow zone,

Figure 37: Map view showing oblique closure of composite North American and Avalonian terranes. Areas of presumed oceanic crust are shaded.

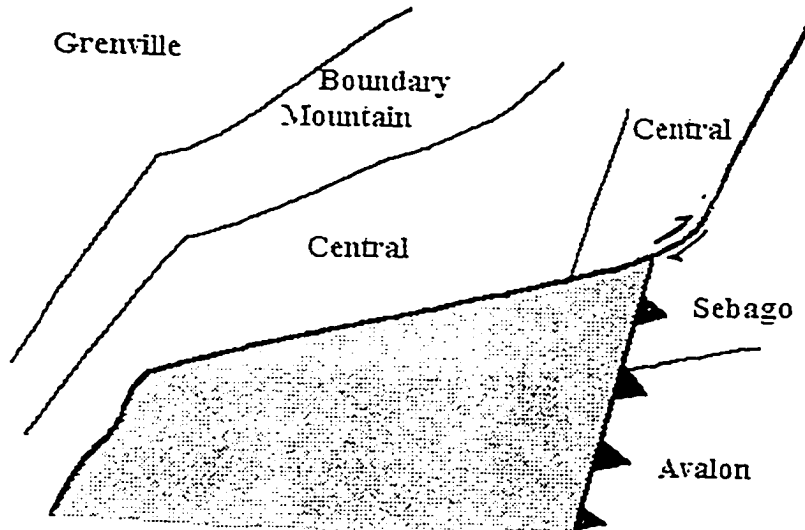


Figure 37a: Oblique closure initiates dextral slip along pre-existing north- and northeast-trending basement fractures (D3 in the present study). The delocalized transtensional regime encourages melting of deeper basement under reduced pressures.

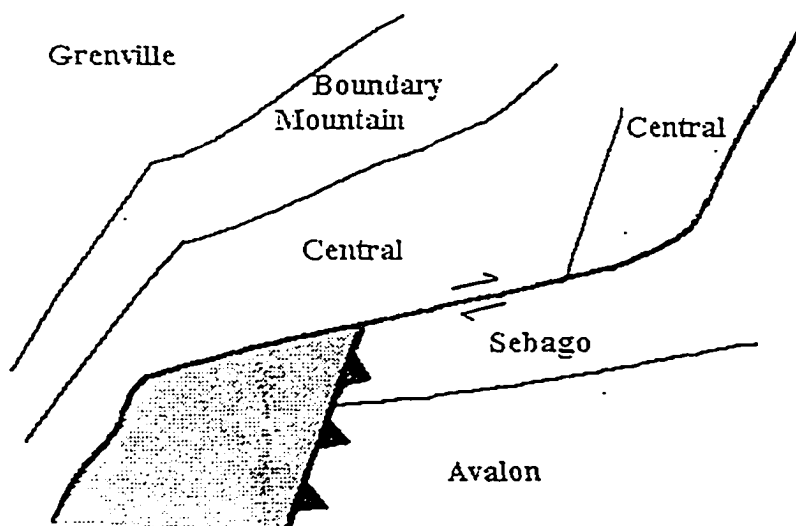


Figure 37b: Strain localizes along specific northeast- and east-northeast-trending transform structures (Class V Faults of the present study).

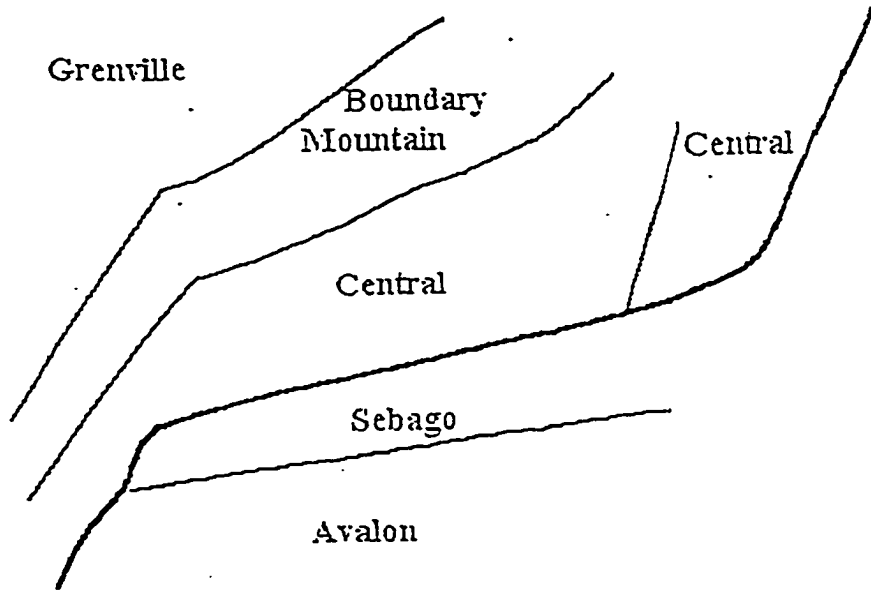


Figure 37c: Climax of Acadian orogeny in central Atlantic area. Remaining stress in Maine may appear as sinistral kink bands and minor sinistral strike-slip faults (Class VI Faults of the present study).

rather than distributing it through the crust. Intrusion of the postmetamorphic plutons could be related to more widely distributed transtensional dextral slip during D4.

The role of the north-northwest trending Class VI Faults remains uncertain. Their orientation and sinistral shear sense suggest that they could have developed as antithetic sinistral faults to a northeast - southwest directed dextral shear couple, potentially that of the Class V Faults; it seems unlikely, however, that antithetic faults would develop after slip on the synthetic faults had been completed. Tectonic fabrics associated with sinistral slip clearly crosscut all earlier fabrics, and are associated only with brittle fabrics in the Bottle Lake Complex. Where Class V and Class VI fabrics are found together south of the study area (Ludman, pers. comm. 1989), the Class VI fabrics offset those associated with the Norumbega Fault Zone. Reconnaissance of the Mississippian Sebago Pluton (Hopeck, unpub. data), and photolinear mapping of this body by Caswell et al. (1992), suggest that fabrics with the northwest-striking orientation are absent from those Carboniferous intrusive rocks, and that the Class VI Faults are more likely Late Acadian than Alleghenian.

## CONCLUSION

The model developed in this chapter proposes that the latest Ordovician - Early Silurian rocks of the Carys Mills and Mill Priveledge Brook Formations are related to the thinly bedded pyritiferous wackes of the Pocomoonshine Lake Formation, and that the feldspathic grits of the Digdeguash Formation and the massive calcareous wackes of the Flume Ridge Formation are related to similar rocks of the Ellen Wood Ridge Formation and the Madrid Formation, respectively. The Fredericton Trough, therefore, is the most outboard section that can be linked to North America during the post-Taconian, pre-Acadian interval. Paleontologic and paleomagnetic data show that the rocks of the St.

Croix Belt, to the south of the Fredericton Trough, represent the Cambro-Ordovician slope and rise of the Avalonian continent, and must have been at some distance from North America during the latest Ordovician.

Brock (1989, 1993) used isotopic indicators to divide the basement blocks underlying the supracrustal terranes of New England and the Maritime Provinces into two groups, one of continental (less-evolved) affinity and Late Proterozoic - Early Paleozoic age, and a second, inferred to be younger island-arc crust. Collision of the arc-type Boundary Mountain block and the less-evolved Central block offshore of North America in the early Ordovician, created an angular unconformity above the Baskahegan Lake Formation and equivalent strata. Melange belts (Osberg et al., 1985) mark the suture zone of this collision. Subsequent subduction of oceanic crust southwestward beneath this composite terrane led to the development of the Caradocian volcanic-dominated section described above and discussed by Sayres (1986) and Ludman (1991).

Following accretion of this composite block, the margin began almost immediately to subside. Possible causes of this subsidence include tectonic erosion of the base of the accreted block and uplift of the overridden continental or transitional crust following separation of oceanic lithosphere; either could result in extension and subsidence within the accreted block. The extension led to development of localized, fault-bounded basins in the area from the Maine - Quebec border to the southern limit of the Fredericton Trough. Late Ordovician lithologies are sulfidic and imply a low rate of clastic sedimentation; younger rocks are not sulfidic and are generally thicker bedded, coarser grained, and more feldspathic. Coarse debris accumulated along the basin edges, and graded rapidly into finer-grained sediment toward basin axes. Areas along the margins of the basins supported shallow-water fauna, including corals and stromatoporoids. Slumping and remobilization

of debris-apron sediments are reflected in soft-sediment disruption (Class I Faults), and strata-bound conglomerates.

The transition from a regime of isolated basins with rapid lateral facies changes to a laterally more homogenous section is marked almost everywhere by a thinly bedded pyritiferous unit of varying thickness. Deposition of these euxinic facies directly on top of rocks (Smyrna Mills Formation) thought to be equivalent to sections containing shallow-water fauna (Daggett Ridge Formation), is thought to indicate the relatively rapid foundering of the Central and Boundary Mountains blocks. This foundering may represent continued or renewed attenuation of the already stretched upper crust above a westward-dipping subduction zone, or general subsidence of the crust in advance of the clastic wedge (Flume Ridge and Madrid Formations) shed from the Avalonian landmass. An equivalent pyritiferous unit has not been observed between the Digdeguash and the Flume Ridge Formations, implying that this area was not subject to anoxic conditions, although, as argued above, it was probably relatively close to North America at the time.

The Avalonian clastic wedge prograded northwestward across the Sebago block, across any intervening oceanic crust, and onto the submerged Central and Boundary Mountain blocks. The turbidite sediments of the Madrid and Lawler Ridge Formations, derived from the Avalonian continent or older parts of the wedge, filled the deep (locally anoxic?) basin northwest of a trench related to southeastward subduction of oceanic crust separating the Avalon and Sebago blocks. Disrupted layers within these rocks, (see Hanson and Bradley, 1989) represent slumps, layer-parallel faults, and similar features within the clastic wedge. Convergence of the North American and Avalonian composite blocks along a northwest-dipping subduction zone led to development of east-vergent (Class III) faults as supracrustal sediments on at least the Central block were thrust eastward over the Sebago block. Maximum crustal thickening was accomplished by

development of upright folds with an axial planar transposition, and, at the climax of the compressional phase, east-vergent reverse faults (Class IVa), and localized transpositional layering, subparallel to the axial planes of the earlier folds.

The oblique convergence of North America and Avalon established a transtensional regime shortly after convergence the two composite blocks. Dextral slip associated with this regime was first apparent as reactivation of the former reverse faults as dextral strike-slip faults (Class IVb); widespread distribution of strain through the supracrustal section is shown by the development of penetrative slip cleavages, and vertically plunging folds in all earlier layering. Synchronous with this slip, and hypothetically related to it, granitic plutons were intruded into the supracrustal rocks. Emplacement of the large Devonian granitic bodies in Maine may therefore be related to extension of the lower crust rather than a magmatic arc. This regional shear was eventually localized along the Norumbega Fault Zone (Class V Faults).

Very late sinistral strike-slip faults (Class VI) and slip cleavage occurred after pluton emplacement, but do not appear to be as young as Alleghenian. These structures and fabrics could represent slip along antithetic planes at the latest stage of the Acadian farther south, but, in the area of this study, they clearly crosscut all other tectonic fabrics. Unambiguous evidence of any subsequent deformation is not known from this study area, although a few, rare, shallowly dipping planar fabrics found at a few locations may (Ludman, pers. comm., 1992) be related to Alleghenian thrusting at very shallow levels in the crust; these later faults may now be largely or entirely absent, due to erosion of the shallow crustal section.

## APPENDIX

BEDROCK GEOLOGIC MAPS OF THE WYTOPITLOCK AND SPRINGFIELD  
FIFTEEN-MINUTE QUADRANGLES

## LEGEND

## Intrusive Rocks

**JTrd** diabase

**Dbl** Bottle Lake Complex, primarily granite with minor amphibolite

## Central Maine Belt

**Smc** Calcareous Madrid Formation: Massive, thick-bedded, calcareous, muscovite-bearing sandstones

**Smf** Feldspathic Madrid Formation: Massive feldspathic sandstones and interbedded pelite

## Aroostook - Matapedia Belt

**SOsmu** Smyrna Mills Formation, Upper Member: green to greenish-gray, thinly bedded feldspathic and ankeritic siltstones, wackes and pelites

**SOsml** Smyrna Mills Formation, Lower Member: gray, thinly bedded siltstones, wackes, and pelites, minor argillaceous limestone

## Prentiss Group

**SOdr** Daggett Ridge Formation: massive conglomerates and interbedded wacke and pelite

**SOew** Ellen Wood Ridge Formation: green and greenish-gray ankeritic feldspathic sandstone and pelite; felsic breccias and tuffs occur in upper part

**SOsr** Sam Rowe Ridge Formation: gray wackes and pelites, minor conglomerate and argillaceous limestone

<b>SOcm</b>	Carys Mills Formation: pyritiferous argillaceous limestone and calcareous wacke	<b>SOmp</b>	Mill Priveledge Brook Formation: pyritiferous wackes and pelites, minor conglomerate and calcareous wacke
		<b>SOu</b>	Silurian - Ordovician rocks, undivided: Prentiss Group in Wytopitlock Quadrangle, includes Carys Mills Formation in Springfield Quadrangle

### Caradocian-and-Older Rocks

<b>Ovsu</b>	Pre-Ashgillian rocks, principally Bowers Mountain Formation and Baskahegan Lake Formation, undivided
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### Symbols

•	Outcrop, no structural information shown or available
/	Bedding, vertical
/	Bedding, inclined
/	Bedding, inclined and facing direction known
/	Bedding, overturned
/ /	D2 cleavage or unknown generation: vertical; inclined
/ /	D4 cleavage: vertical; inclined
/ /	D6 cleavage: vertical; inclined
/ /	dike in granite: vertical; inclined
/ /	joint in granite: vertical; inclined
- - - - - . . . . .	unit contact: dashed where approximate or inferred; dotted where possibly concealed
- - - - - . . . . .	fault: dashed where approximate or inferred; dotted where possibly concealed

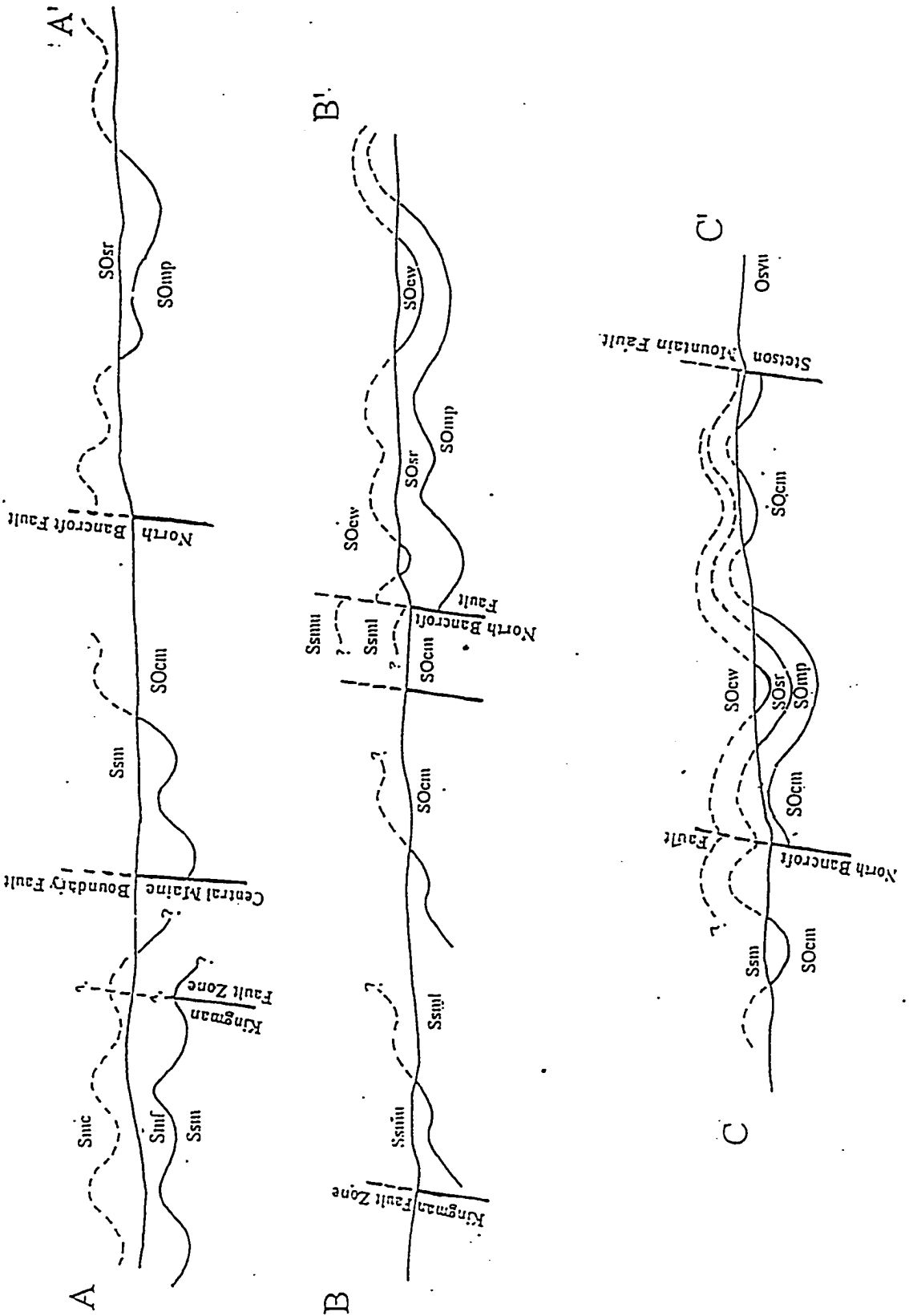
— ↕ — → axial trace of anticline; barbs show direction of plunge  
← — ↙ — axial trace of syncline; barbs show direction of plunge

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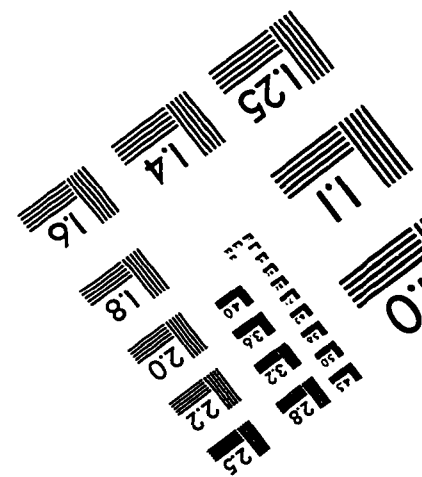
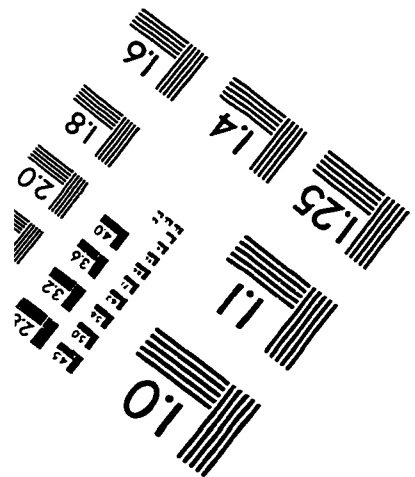
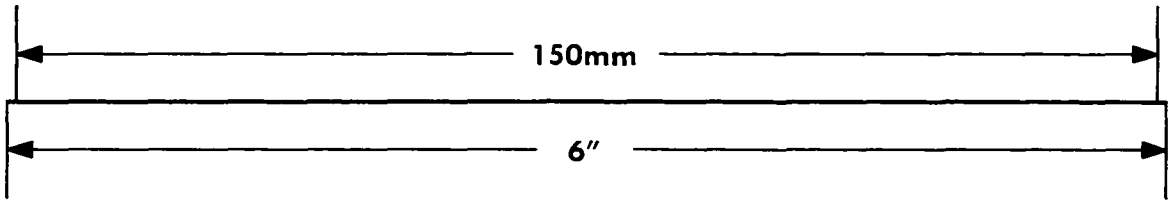
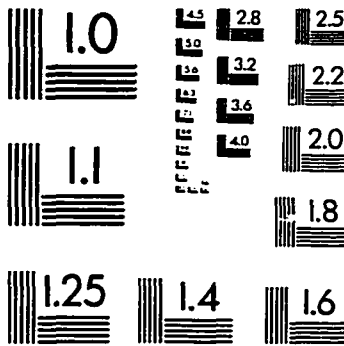
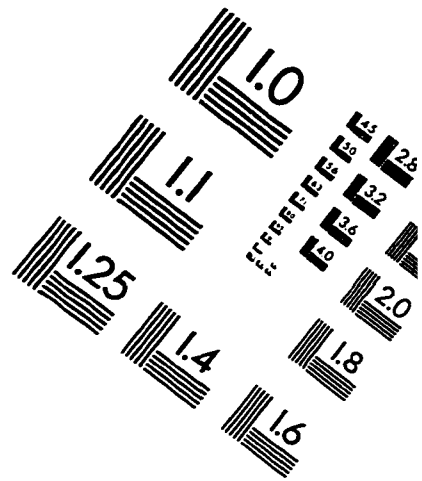
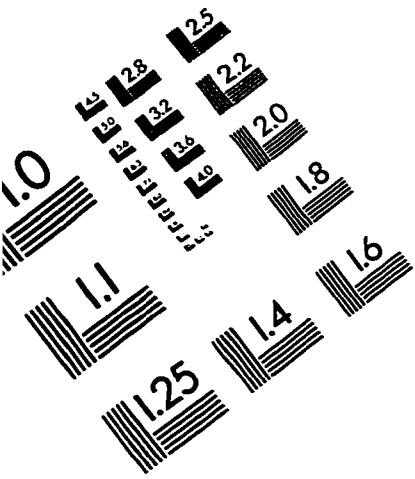
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