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NATURE AND EVOLUTION OF THE NORUMBEGA FAULT SYSTEM IN THE GREAT POND-GRAND LAKE STREAM AREA, EASTERN MAINE

by

CHUNZENG WANG

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

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9/10/01

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Abstract

NATURE AND EVOLUTION OF THE NORUMBEGA FAULT SYSTEM IN THE GREAT POND-GRAND LAKE STREAM AREA, EASTERN MAINE

by

Chunzeng Wang

Advisor: Professor Allan Ludman

The early ductile shearing in the Norumbega fault system in eastern Maine occurred within an environment of oblique convergence as the result of adjustments following Acadian plate collision during middle to late Paleozoic times. Metasedimentary rocks were ductilely sheared into phyllonite and granite into mylonite. It took place at conditions of the lower greenschist facies, at confining pressures of 2-2.5 kbars and peak temperatures on the order of 300-350° based on comparison of quartz and feldspar microstructures and analysis of their different deformation mechanisms. Kinematical indicators at different scales confirm the dextral strike-slip movement. A regional ductile shear model is proposed based on the study of shear zone geometry and identification of three granite slivers (Amazon Mountain, Third Lake Ridge, and Morrison Ridge granites) and synthetic shear bands existing between the Kellyland and Waite zones. Shear strain was initially partitioned into the Kellyland, Waite, and Codyville zones. Extended dextral shearing and displacement between the Kellyland and Waite zones were concentrated in the synthetic shear bands representing megascopic c′-bands, displacing the Morrison Ridge and Third Lake Ridge slivers farther from their original positions. Restoration of the Morrison Ridge and Third Lake Ridge slivers to their presumed original positions yields approximately 25 km of dextral strike-slip offset along the Kellyland and synthetic ductile shear zones.

The Waite ductile fault zone was reactivated brittlely by three compressional tectonic events identified by studies of minor conjugate faults: an early WNW-ESE compression, followed by a NE-SW-directed compression, and by a drastic change in stress orientation to a N-S-oriented compression observed only in Pennsylvanian (?) redbeds. Brittle Episode 1 was a dextral-oblique-reverse faulting event that superimposed a wide and continuous cataclasite and breccia zone on the pre-existing Waite ductile shear zone. Episode 2 brittle faulting was dextral strike-slip and probably responsible for the formation of a series of narrow pull-apart redbed basins that apparently nucleated at releasing bends.

Post-Carboniferous sinistral-strike-slip brittle faulting (Episode 3) tilted the Carboniferous redbeds and juxtaposed them with older metamorphic rocks of the Fredericton belt. Episode 3 faulting is apparently the only product of Alleghanian deformation in the study area.

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This dissertation is dedicated to my parents and my two lovely baby daughters, Niuniu and Jiajia (Dora). I left Niuniu with my parents and came to New York City to work this project and the degree four years ago. I have not seen her since then. I miss her so much. Jiajia (Dora), a millennium baby, came to this world before I finished this work. She didn't help much with my thesis research, but does bring so much joyfulness to the family and me.

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CHAPTER 1

INTRODUCTION

The Norumbega fault system (NFS) is the most prominent structural feature on the state bedrock geologic map in eastern and coastal Maine (Osberg et al., 1985). Previous mapping unequivocally demonstrates the continuity of the Norumbega system for nearly 450 km, from Casco Bay in southwestern Maine to central New Brunswick (Hussey, 1988; Swanson, 1992, 1994; West, 1993; Ludman, 1991; Hubbard et al, 1996). Geophysical evidence and recent mapping (Durling and Marillier, 1990; Goldstein and Hepburn, 1999) suggest an even greater extent-- southward to Connecticut and northward to the Gulf of St. Lawrence -- a total length of almost 1,200 km. This fault system is recognized today as one of the largest transcurrent fault systems in the Northern Appalachians (Figure 1; Ludman and West, 1999). Previous studies have shown that NFS shearing began with dextral transcurrent motion around 380 Ma and continued sporadically into the Mesozoic (West and Lux, 1993; West, 1999; Doll et al., 1996; Idleman and Ludman, 1998a, 1998b; Ludman et al., 1999, 2000).

1.1. Previous Works

Most previous work along the NFS focused on the segment in southwestern and south-central Maine, where spectacular features characteristic of ductile shear are ubiquitous (Hussey, 1988; Swanson, 1992, 1993, 1999a, 1999b; West, 1993; West and Lux, 1993; Bothner et al., 1999). In eastern Maine, most geological mapping studies before Ludman's reconnaissance and detailed work were by Larrabee (1964, 1965) and

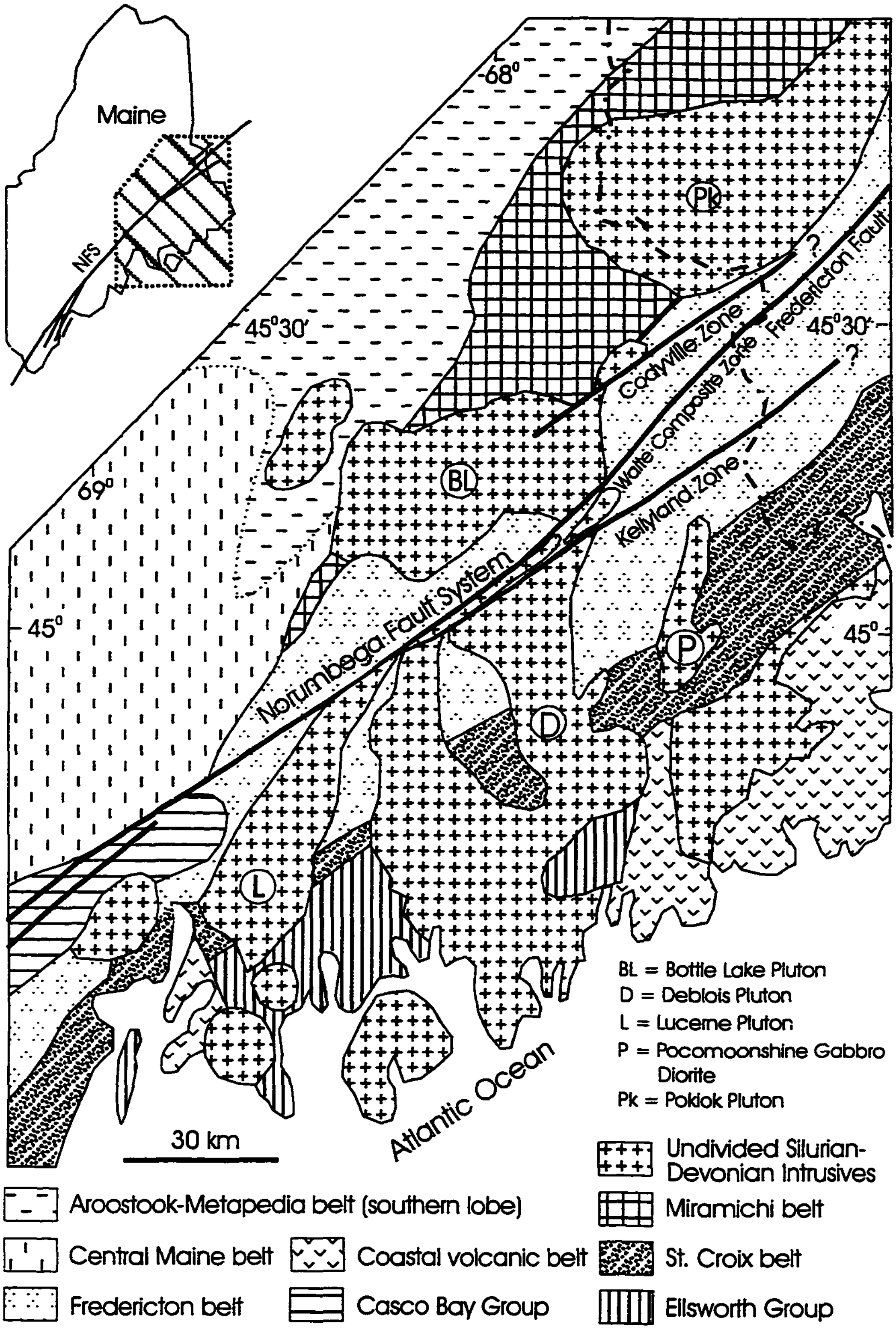


Figure 1. Schematic tectonostratigraphic and regional geologic map of central -eastern Maine and the Norumbega fault system. (After Osberg et al., 1985.)

Larrabee et al. (1967). Larrabee identified major metasedimentary rock units and intrusive bodies and recognized through-going northeast-trending faults, but did not recognize the regional significance of these structures. The most recent state bedrock geologic map (Osberg et al., 1985) considered these faults to be extensions of the Norumbega fault zone first mapped by Hussey (1972) and named by Stewart and Wones (1974) north of Penobscot Bay in the south-central part of the state. Ludman's reconnaissance in eastern Maine starting in the early 1990's revealed three major strands of the Norumbega fault system: the Waite, Kellyland, and Codyville fault zones (Figure 1). Although they are clearly separate strands of the NFS in easternmost Maine, the Waite and Kellyland fault zones converge toward the southwest and appear to merge in the Great Pond area. There, they appear to be the northeastward continuation of the Norumbega fault as defined by Stewart and Wones (1974) and Osberg et al. (1985). The Codyville fault zone is poorly exposed and will not be treated further in this study.

Ludman (1994, 1995, 1998), Ludman and Gibbons (1999), and Ludman et al. (1999) recently compared the eastern Maine and southwestern Maine segments of the NFS, and proposed that the differences are due primarily to the fact that deformation in the two areas took place at disparate crustal levels. It is suggested that differential exhumation of the ancient fault system exposes progressively shallower crustal levels from southwestern Maine, where amphibolite-facies mylonites and extensive ductile shear fabrics indicate mid-crustal faulting, to eastern Maine where lower-greenschist facies of faulted rocks and more brittle features suggest faulting at shallow crustal levels (see Figure 3; Hubbard et al., 1995; Ludman, 1998; Ludman et al., 1999a, 1999b).

Almost all previous studies of Norumbega ductile deformation were of the deeper segment in southwestern and south-central Maine, where ductile shear fabrics and ductile shear zones are extensively developed and exposed (Wones et al., 1979; Swanson, 1992, 1995, 1999a, 1999b; West, 1999; West et al., 1993,1997; Hubbard et al., 1995, 1999). Recent reconnaissance mapping in and around the Fletcher Peak area in eastern Maine, however, revealed that significant ductile shearing had also occurred in eastern Maine and that shear strain had been partitioned into the three fault zones mentioned above (Ludman, 1994; Ludman et al., 1999). Subsequent multiple brittle reactivation of these faults was localized in relatively narrow fault domains.

1.2. Purposes of This Study

These revelations about the geometric complexity and multi-stage tectonic history of the NFS suggested that more detailed mapping and petrographic research were needed to elucidate the evolution of the epizonal NFS in eastern Maine. Accordingly, the aim of this study was to decipher the mechanics and evolution of Norumbega faulting in eastern Maine, including the changing nature of fault geometry, kinematics, and dynamics with time. Specific goals were to:

- unravel the complex geometry of the NFS ductile shear system in eastern Maine and interpret the mechanism or cause of ductile deformation partitioning;

- compare ductile deformation mechanisms in the variety of metasedimentary, granitic, and dioritic rocks that were involved in the shallow-crustal ductile deformation;
- define the geographic and geologic relationships of granite fault slivers between the Waite and Kellyland fault zones (Osberg et al., 1985; Ludman, 1994, 1998) and show how these slivers were related to the evolution of ductile shearing in eastern Maine. Previous studies have shown several granite fault slivers within the fault system in the area between Amazon Mountain and Great Pond, but did not provide accurate evidence about the geometries of these slivers and their genetic relationships to the fault system.
- refine previous interpretations of the multiple brittle faulting history in metasedimentary (Ludman, 1998) and granitic rocks (Ludman and Gibbons, 1999), and analyze the changing dynamics and stress fields associated with these late reactivation events.

This study focused on the area between Great Pond and Grand Lake Stream, where the fault system is more complicated than anywhere else in eastern Maine. Significant progress has been made toward attaining these goals. The results reported here significantly refine the multiple fault stage model proposed by Ludman (1998) and Ludman and Gibbons (1999) for NFS deformation in the metasedimentary and plutonic rocks of eastern Maine, and place it in a broader regional context. Improved knowledge of the nature and sequence of deformation events provided by this research, coupled with ongoing thermochronologic studies, provides a more precise picture of NFS history in eastern Maine than that interpreted by previous workers anywhere else along the system. The new information will hopefully be a valuable contribution toward deciphering the role of the NFS in the evolution of the Northern Appalachians.

1.3. Methods of Study

This study combined detailed field mapping with petrographic and petrofabric analyses of oriented specimens. Global Positioning System (GPS) technology was used to locate bedrock exposures and facilitate navigation, and CARIS Geographic Information System software was used to analyze the data and compile the final geologic map. Mapping was carried out over a 20-week period during the summers of 1998 and 1999. Detailed fieldwork in the 1998 field season focused on the Fletcher Peak 7.5' quadrangle because previous mapping suggested (correctly, as it turned out) that this quadrangle might provide an excellent transect through the fault system and could facilitate detailed exploration of the geometry, extent, spatial shear strain variations, deformation mechanisms, displacement, and temporal evolution of the Norumbega fault system. During the 1999 field season, a combination of reconnaissance and detailed reconnaissance mapping was extended along strike northeastward to the Maine/New Brunswick border and southwestward to the Great Pond area, in order to improve understanding of the geometry and internal structures of the fault system in eastern Maine.

In all, approximately 610 outcrops were visited, assigned station numbers, and described in field notes. Nearly 220 samples and oriented samples representing typical lithologies and structures were collected, and 101 thin sections and oriented thin sections were obtained from these samples. Plate I shows locations of outcrops, most of which had not been visited by previous workers, and locations of photographs and photomicrographs contained in this dissertation.

CHAPTER 2

TECTONIC AND REGIONAL GEOLOGICAL SETTINGS OF THE NORUMBEGA FAULT SYSTEM

2.1. Lithotectonic Setting of the Norumbega Fault System in Eastern Maine

Reconnaissance and some detailed mapping of the area by Larrabee (1963, 1964a, 1964b, 1965) helped delineate boundaries between major rock units, but the stratigraphies and deformational histories of the individual lithotectonic belts have only been established in the past fifteen years (Fyffe, 1982; Ludman, 1986a, 1986b, 1987, 1991a, 1991b; Hopeck, 1988, 1989; Hopeck et al., 1988, 1989; Sayres and Ludman, 1985; Berry and Osberg, 1989; Osberg et al., 1985). The eastern Maine study area is underlain by northeast-trending lithotectonic belts composed largely of Cambrian through early Devonian strata intruded by bimodal Silurian through Devonian plutons (Figure 1). Ludman (1990) and Ludman et al. (1993) identified six major belts--from east to west, the Coastal Volcanic, St. Croix, Fredericton, Miramichi, Aroostook-Matapedia, and Kearsarge-Central Maine belts.

The Miramichi and St. Croix belts are pre-Silurian in age and experienced complex polydeformation. Evidence has been reported in the Miramichi terrane for at least three penetrative folding events corresponding to the Penobscottian (late Cambrian-early Ordovician), Taconian (middle Ordovician), and Acadian (late Silurian-middle Devonian) orogenies, and for the latter two in the St. Croix. Strata of the post-late

Ordovician Fredericton, Central Maine, Aroostook-Matapedia, and Coastal Volcanic belts had a much simpler deformation history, apparently only being affected by Acadian folding prior to the onset of Norumbega faulting. Metamorphic grade throughout eastern Maine is limited to low-greenschist-facies except in contact aureoles regardless of the age of the stratified rocks or their degree of deformation. Most of the lithotectonic belts shown in Figure 1 are known to be fault bounded (Ludman and Hopeck, 1988). Evidence for the timing of juxtaposition of these belts demonstrates that geographic relationships comparable to those of today had been achieved by the end of the Acadian orogeny (Ludman, 1981, 1986b).

Table 1 summarizes the stratigraphy of the six major belts and correlates the rocks in the six belts to one another based on previous studies (e.g., Ludman et al., 1993). A brief description of the regional geology and stratigraphy and tectonic background for each belt is provided here in order to provide full context for the discussion of the Norumbega fault system.

Coastal volcanic belt

The Coastal volcanic belt can be traced from New Brunswick through Eastport in easternmost Maine and into Massachusetts as the Newbury volcanic suite. The belt is composed largely of lava flows, ashfalls, and ashflows of mostly bimodal (rhyolite and basalt) composition intercalated with shallow-water sandstones, siltstones, mudstones, and volcanogenic breccia. The rocks range in age from earliest Silurian (Quoddy Formation) through the early Devonian (Eastport Formation), and record the Silurian-early Devonian history of the Avalonian continental margin prior to accretion to

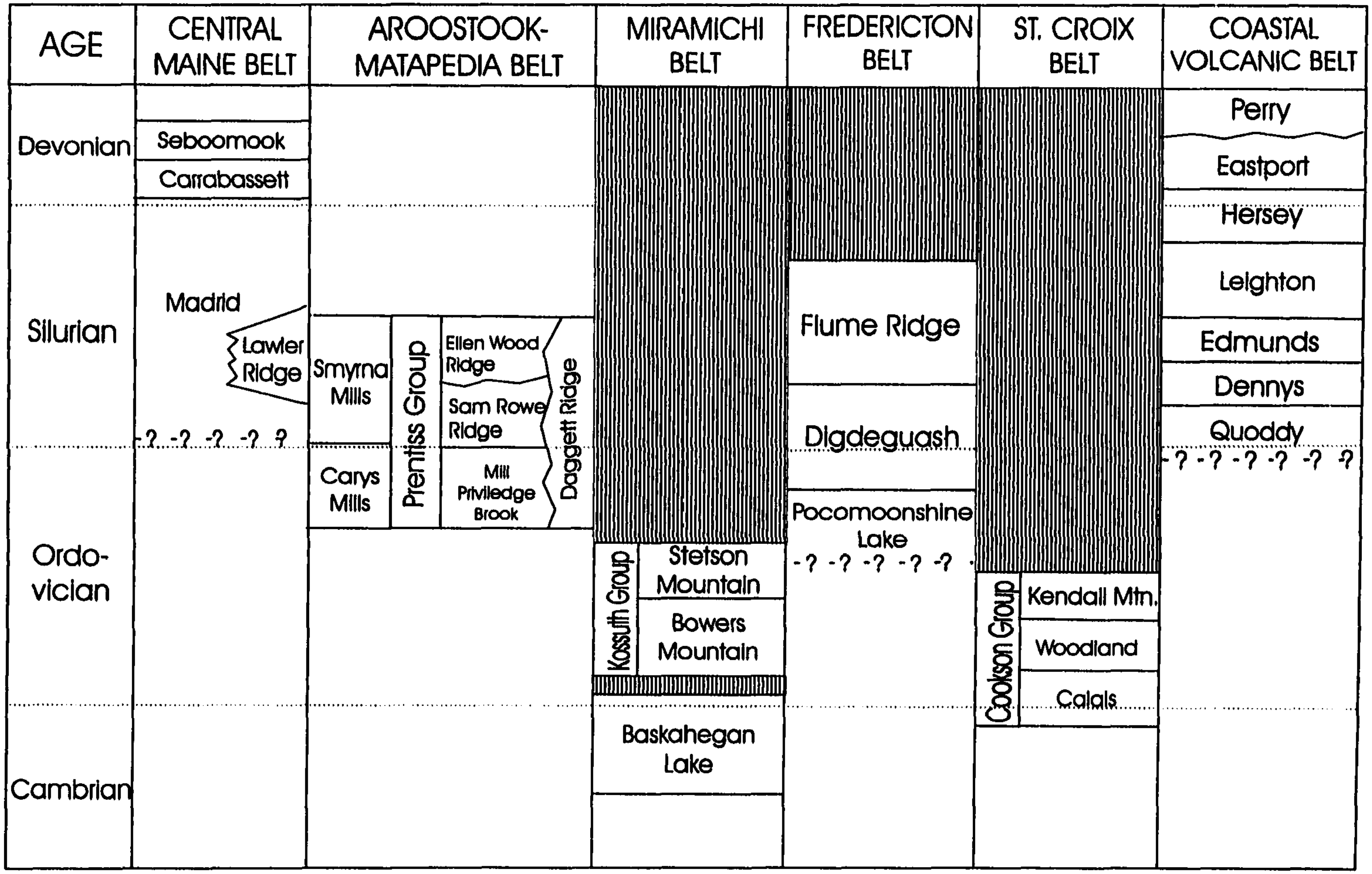


Table 1. Simplified stratigraphy and correlation of lithotectonic belts of eastern Maine. (From Ludman et al., 1993)

ancestral North America. The Eastport Formation is locally overlain unconformably by red conglomerates and fossiliferous sandstones of the Upper Devonian Perry Formation. These relationships define the classic Acadian unconformity in eastern Maine and prove that middle Devonian folding has occurred in the region.

St. Croix belt

The St. Croix belt extends northeastward to the longitude of Saint John and southwestward to the western shore of Penobscot Bay (Osberg et al., 1985). In the Calais-St. Stephen area, the belt is in tectonic contact with Fredericton belt (see below) to the west. The eastern contact is more complex with distal components of the Coastal volcanic belt lying unconformably upon St. Croix strata at Cookson Island (Cumming, 1965). The contact, however, appears to be a fault at Calais, just a few miles to the southwest (Ludman, 1991c).

The rocks of the St. Croix belt were assigned to the Cookson Group by Ludman (1991c), and originally included the Calais, Woodland, and Kendall Mountain formations, ranging in age from Cambro-Ordovician to middle Ordovician (Caradocian; Cumming, 1965; Fyffe and Riva, 1990). Ludman (personal communication, 2000) now recognizes the presence of a fourth unit beneath the Cookson Group, comprising rocks correlated with the Cambrian Megunticook Formation of the Penobscot Bay area (Table-1; Berry and Osberg, 1989). The coticule rocks of the Megunticook, pillow basalts and black shales of the Calais, anoxic turbidites of the Woodland, and anoxic quartz, quartzofeldspathic, and lithic arenites intercalated with black shales of the Kendall Mountain trace the early Paleozoic evolution of what is interpreted as a continental slope environment on the western (modern direction) margin of Avalon (Ludman, 1987, 1990). An alternate view interprets the Cookson Group as flanking a separate plate that collided with Avalon prior to eventual amalgamation with North America (Fyffe et al., 1988).

Fredericton belt (trough)

The Fredericton belt is a nearly 50 km wide tract in eastern Maine consisting of clastic sedimentary rocks deposited in a basin called the Fredericton trough by McKerrow and Ziegler (1971). It is separated from the Miramichi terrane to the northwest by a thrust fault, and from the St. Croix belt to the southeast by the Princeton-Crawford fault zone. The Fredericton rocks are divided into three formations (Ludman, 1990, 1991a): from oldest to youngest, the Pocomoonshine Lake, Digdeguash, and Flume Ridge formations.

These three units record the evolution of what appears to have been an ocean basin separating an early Paleozoic composite plate from a comparably complex Avalonian continent (Ludman, 1990). Intercalated carbonaceous and non-carbonaceous slates (Pocomoonshine Lake Formation) were followed by an influx of non-calcareous turbidites (Digdeguash Formation lithic wackes and slates), and then by a massive amount of variably calcareous quartzofeldspathic turbidites (Flume Ridge Formation). The Flume Ridge is by far the dominant unit in the Fredericton belt and hosts the Kellyland and Waite fault zones of the Norumbega fault system. Graptolites discovered recently in the Digdeguash Formation yielded Llandovery (earliest Silurian) ages (Fyffe and Riva, in press). Coupled with previous dating of the post-folding Pocomoonshine Lake gabbro-diorite, these new data constrain deposition of the Fredericton suite to late Ordovician through middle Silurian times.

Unnamed, unmetamorphosed red conglomerates, sandstones, and mudstones occur within the Fredericton belt as slivers in the Waite fault zone adjacent to strongly sheared Flume Ridge metasandstones. In some localities, gray or green varieties are also present. These rocks clearly post-date the penetrative Acadian folding and low-grade regional metamorphism experienced by the Fredericton strata, and provide important information about the evolution of the Norumbega fault system.

Miramichi belt

The Miramichi terrane in Maine consists of two stratigraphic packages, the Baskahegan Lake Formation and Kossuth Group (Ludman, 1988, 1993; Hopeck, 1990). The Baskahegan Lake Formation underlies most of the Miramichi terrane in Maine and has recently been shown to be of late Cambrian through earliest Ordovician age (Fyffe and Pickerill, 1993). It comprises a thick sequence of quartzofeldspathic and quartzose turbiditic wackes, with subordinate interbedded pelites and rare granule conglomerates. The lower part of the Kossuth Group contains black shales, thin-bedded turbidites, and mafic volcanic rocks assigned to the early Ordovician (?) Bowers Mountain Formation (Ludman, 1990). The upper part consists of dominantly felsic volcanic rocks of the Caradocian Stetson Mountain Formation (Larrabee and others, 1965; Ludman, 1990).

Geochemical data suggest that Miramichi volcanism was associated with an island arc developed off the eastern margin of early Paleozoic North America (Sayres, 1986; Ludman, 1999), perhaps during coalescence of microplates whose eventual collision with the ancestral continent caused the Taconian orogeny (Ludman et al., 1993).

Southern lobe of the Aroostook-Matapedia belt

Hopeck (2000, 1990) and Hopeck et al. (1989) showed that coarse to medium-grained clastic rocks west of the Miramichi terrane interfinger westward with mudstones, siltstones, and micritic limestones and dolostones, that can be traced continuously northward into rocks of the Aroostook-Matapedia belt described in the Houlton area by Pavlides (1971). Boulder through pebble conglomerates of the Daggett Ridge Formation represent a proximal facies immediately adjacent to the Miramichi source region. The other three units shown in Table 1, the Mill Privilege Brook, Sam Rowe Ridge, and Ellen Wood Ridge formations, represent an intermediate sequence. Clasts readily identified as having been eroded from the adjacent Miramichi terrane confirm the eastern source for these rocks following middle Ordovician orogeny. The Carys Mills and Smyrna Mills formations represent the distal facies deposited in a basin that separated the Miramichi and Kearsarge-Central Maine terranes.

Central Maine belt (Kearsarge-Central Maine belt of Ludman, 1993)

The Central Maine belt has well-defined stratigraphic sections on its west limb and axial region that demonstrate continuous deposition from late Ordovician through early Devonian times (Osberg et al., 1985). Western and axial deposits were derived from a western highland source, coinciding with the Bronson Hill-Boundary Mountains anticlinorium, until late Silurian time (Bradley and Hanson, 1989). All formations in the belt were tightly folded in early to early middle Devonian times during the Acadian orogeny.

The southeastern margin of the Central Maine belt is more complex structurally but far less well studied. Central Maine strata are truncated by strands of the Norumbega fault system southeast of Bangor (see Osberg et al., 1985), and are juxtaposed locally against Fredericton belt rocks without the intervening Aroostook-Matapedia and Miramichi strata.

2.2. Appalachian Orogen-parallel Fault Systems

Hubbard (1999) put the NFS in context among other faults such as the Baie Verte-Brompton, Lubec-Belle Isle, and Cobequid-Chadabucto zones in the Northern Appalachians, showing that it is one of several large dextral strike-slip faults in Maine, Quebec, New Brunswick, and Nova Scotia. The presence of such faults has been increasingly recognized throughout the Northern, Central, and Southern Appalachians (Figure 2), and their existence along the length of the entire Appalachian Mountain system indicated that forces on the scale of the entire orogen were responsible for their activity. Activity on many of these faults has been dated as late- to post-Acadian, sometimes Alleghanian, roughly spanning the times that previous workers have inferred for Norumbega deformation.

Figure 2 shows the distribution of major orogen-parallel faults that are potentially related temporally and genetically to those of the Norumbega fault system, including the Brevard zone, Brookneal zone, Ocmulgee fault, and Pleasant Grove-Huntingdon Valley fault of the southern and central Appalachians (Gates et al., 1986, 1988; Vauchez, 1987; Vauchez et al., 1993; Valentino et al., 1994; Krol et al., 1999).

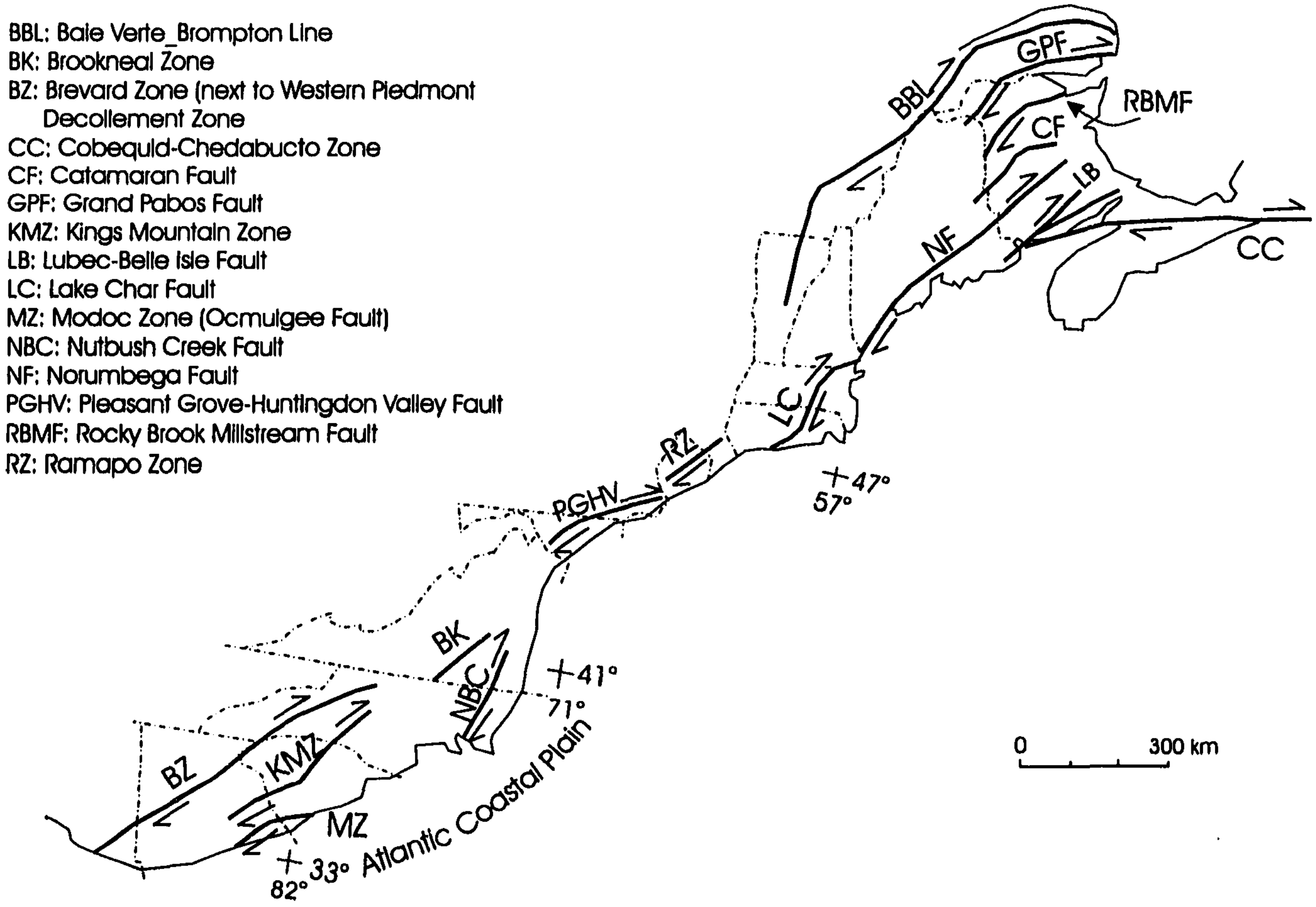


Figure 2. Generalized map showing the locations of major dextral transcurrent faults along the Appalachians.(After Bradley, 1982; Gates et al., 1986)

The temporal and genetic relationship of the Norumbega fault system to these other structures has until now been poorly understood, but it is clear that Norumbega-like activity is not restricted to eastern Maine or the Northern Appalachians. Only detailed understanding of the timing and relationship of Norumbega shearing in its local context can permit the larger picture to be understood.

2.3. Rocks That Host the Norumbega Fault System in Eastern Maine

a) Stratified Rocks

Flume Ridge Formation

The Norumbega fault system in eastern Maine is contained almost entirely within the Fredericton belt (Figure 1). The Fredericton belt rocks were tightly folded and regionally metamorphosed to the lower greenschist facies during the initial mid-late Silurian phase of the Acadian orogeny (Figure 3). The Flume Ridge Formation dominates in the belt, accounting for approximately 75% of its total area, and extending more than 40 km across strike from its contact with the Digdeguash Formation to its fault contact with pre-Silurian rocks of the Miramichi terrane (Figure 1).

The Flume Ridge Formation consists for the most part of variably but generally at least slightly calcareous quartzofeldspathic wacke interbedded with calcareous and non-calcareous siltstones and non-calcareous slates. The wackes are typically finer grained and better sorted than those of the Digdeguash Formation (Ludman, 1991a), consisting of fine sand-sized grains of quartz and feldspar in a finer grained quartz-feldspar-muscovite-

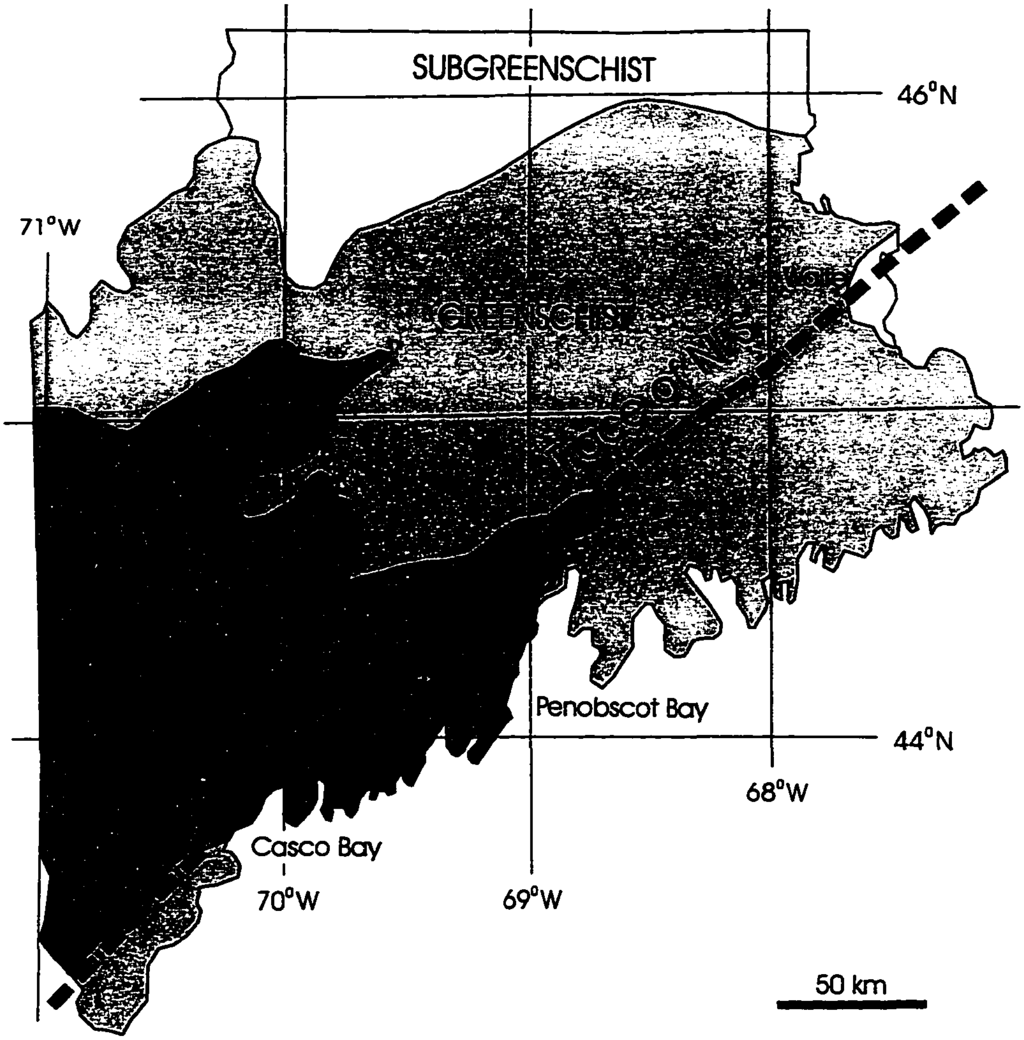


Figure 3. Regional metamorphic setting of rocks affected by the Norumbega fault system in Maine. Modified from Guidotti et al. (1985) and Ludman (1998).

chlorite-calcite matrix. Beds range from 1.5 m thick to thinly interbedded couplets only a few centimeters thick; from massive, featureless layers to well graded and laminated strata. Subordinate amounts of medium gray slate are locally interbedded with the wacke, commonly in well-graded beds, and these pelitic layers accommodated much of the shear strain to which the Flume Ridge Formation was subjected during Norumbega shearing. Wacke:siltstone:pelite proportions vary widely but unsystematically throughout the formation. Regional metamorphic grade is lower greenschist facies (chlorite and subchlorite zones) and original clastic textures are well preserved in most exposures (Figure 3). Primary sedimentary features, such as bedding (S_0), graded bedding, cross-lamination, and scour-and-fill features are well preserved as well, as is the foliation (S_1) caused by Acadian deformation.

Contact metamorphism in the Flume Ridge Formation was generated by intrusions of several batholithic scale granitic, intermediate, and mafic plutons, and by a few smaller stocks (Ludman, 2001). The apparent widths of the aureoles in map view vary with the size of plutons, the dip of the contact, and types of rocks hornfelsed, ranging from a few hundred meters near the Berry Brook pluton and unnamed granitic stocks to well over three kilometers adjacent to the Pocomoonshine gabbro-diorite and Deblois plutons. In general, aureoles are more extensive in slate and metasiltstone than in wacke. Contact metamorphism converted the wackes to dense hornfelses marked by the appearance of biotite and locally cordierite, andalusite, and sillimanite in pelitic rocks, and actinolite and diopside in calcareous horizons of the Flume Ridge Formation. Layers that were originally highly calcareous are recrystallized to white or greenish calc-silicate granofels, which alternates with the purplish quartzofeldspathic granofels in a distinctive "zebra-striped" compositional layering.

Redbeds distributed along the Norumbega fault system

Nine narrow slivers of unmetamorphosed redbeds have been identified and mapped along the Norumbega fault system in the area between Chemo Pond and the New Brunswick border (Larrabee, 1964; Wones, 1980; Osberg et al., 1985; Ludman, 1994; and this study. Figure 4). These small slivers contain granule, pebble, and cobble conglomerate, massive and cross-bedded arkosic and lithic sandstones, and smaller amounts of finer grained rocks typically consisting of homogenous mudstone and finely laminated mudstone/siltstone packages. Most of these rocks are red in color due to a hematite-rich matrix; mudstones and fine-grained sandstones are deep red, whereas the coarser conglomerates are much paler (pink in a few instances). Some green or dark-green conglomerate was found in the middle-Nicatous Lake redbed sliver, and is composed mostly of clasts derived from the Flume Ridge Formation. All conglomerate is very poorly sorted with well rounded to partially rounded clasts of slightly metamorphosed quartzite, fine-grained granite, and green wacke, suggesting multiple sediment sources. In addition, the conglomerates locally contain abundant fragments of unmetamorphosed, presumably post-Acadian, red sandstone and mudstone and white to gray arkosic sandstone. These coarse-grained rocks generally occur in very thick beds, implying short-distance transportation with rapid deposition.

Since neither macro- nor microfossils have been found in the redbeds, their age must be inferred by structural position and regional correlation. The lack of regional

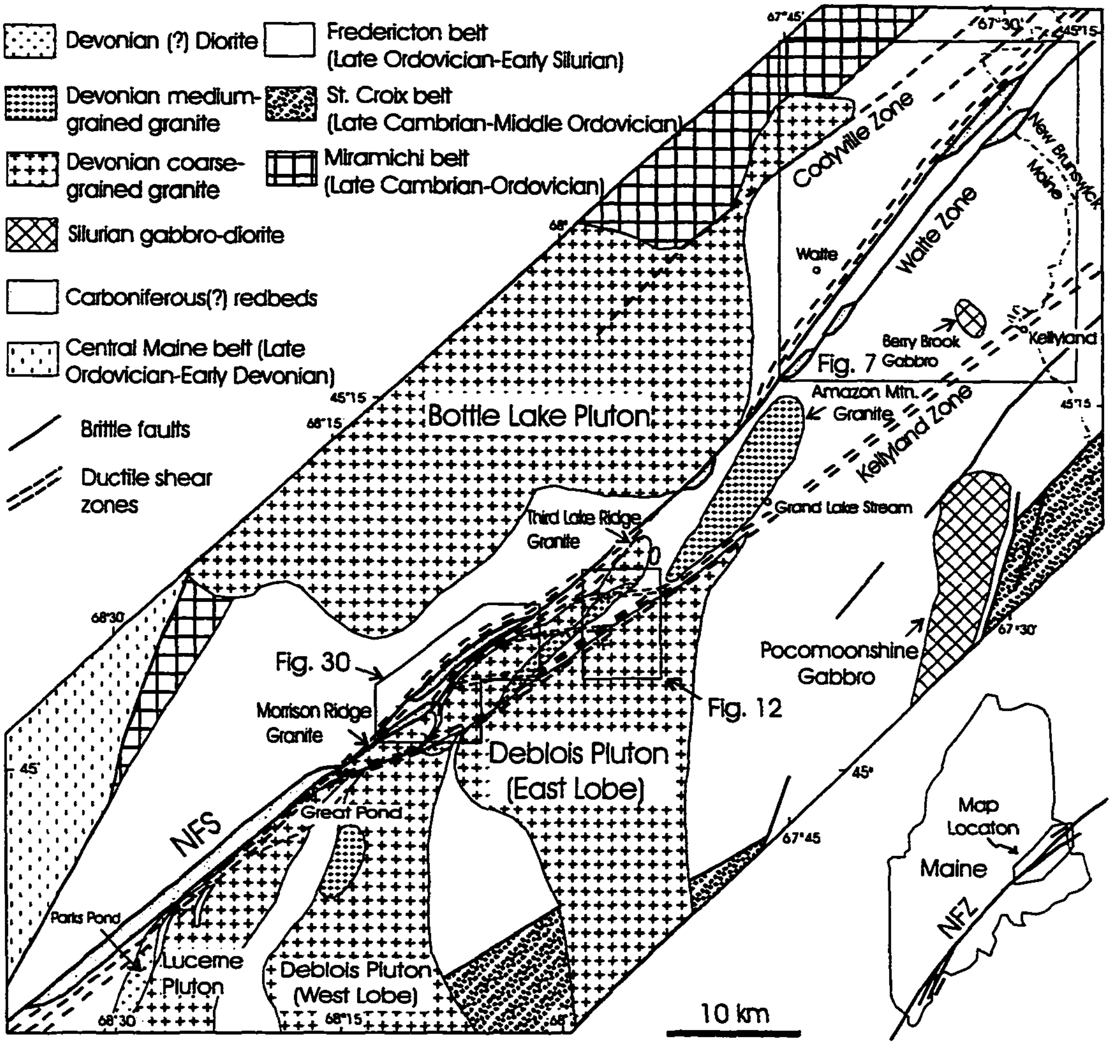


Figure 4. Regional geologic map showing the Norumbega fault system in eastern Maine. Mapped and modified based on Osberg et al., (1985).

metamorphism and penetrative cleavage indicate a post-Acadian age, most probably post-early Devonian. The occurrence in the conglomerates of clasts that are themselves of very likely post-Acadian age, and analogy with the redbeds in the New Brunswick Carboniferous basin where the Norumbega fault system continues to the northeast as the Fredericton fault, suggest that the redbeds are most probably Carboniferous and probably as young as Pennsylvanian. It is conceivable, however, that these rocks could be slightly older (Late Devonian), and correlative with the post-Acadian Perry Formation of southeasternmost Maine. The age and origin of these rocks will be addressed in more detail later.

b) Intrusive Rocks

Eastern and coastal Maine, from west of Penobscot Bay northeast to Passamaquoddy Bay, has been pervasively intruded by over one hundred mafic and felsic plutons, whose ages span Silurian to Early Devonian times (Osberg et al., 1985). The area between the Norumbega fault system and the Maine coast has been called the Coastal Maine Magmatic Province by Hogan and Sinha (1989). Plutons in the Coastal Maine Magmatic Province range in map area from less than 1 km^2 to the 1670 km^2 Deblois granite batholith in the study area. According to Hogan (1989), felsic granitoids, predominantly granite with some quartz monzonite and minor granodiorite, represent 37% of the total 14,694 km^2 of the province. Mafic rocks, such as gabbro, diorite, quartz-gabbro, and anorthosite, account for approximately 8%. The following is a brief introduction to the major plutons that are affected by the Norumbega fault system in eastern Maine (Figures 1 and 4).

Deblois pluton

The Deblois pluton is the largest pluton in the Coastal Maine Magmatic Province. It extends north from the Sullivan granite in south-central Maine to the Grand Lake Stream 7.5' quadrangle, adjacent to the Fletcher Peak quadrangle on the northeast. The batholith has intruded several lithotectonic belts including the St. Croix, Coastal Volcanic, and Fredericton belts, proving that they had been juxtaposed prior to intrusion. A well-developed contact aureole is present in Fredericton belt strata around the batholith everywhere except along its northwestern contact (the Kellyland ductile shear zone). Roof pendants are present in the pluton (Wones, 1980).

The Deblois pluton has two large north-trending lobes, termed the western and eastern lobes in this discussion, that engulf a large roof pendant (?) composed mostly of Fredericton belt strata (Riley and Barton, 2000). The northern part of the eastern lobe underlies a large part of the study area. It was first mapped as the "Wabassus Lake pluton" by Larrabee (1965) and then remapped and modified by Ludman (1988, 1996). This part of the Deblois pluton is characteristically extremely coarse-grained, with distinctive pink potassium feldspar megacrysts up to 7.5 cm in diameter set in a coarse-grained matrix of subhedral albite and anhedral quartz, biotite, and hornblende. Rapakivi albite rims are also common on alkali feldspar megacrysts. Few pegmatites and aplites are associated with the eastern lobe, suggesting a low volatile content for the melt. Minor textural variations were observed in the study area, with slightly fine-grained granite concentrated near the eastern margin.

Granite in the western lobe of the pluton was dated at 393±17 Ma by Rb/Sr whole-rock methods (Loiselle et al. 1984), but a more precise age of 384±5 Ma was determined recently by Ludman et al. (1999; U/Pb methods on zircon) for granite at Wabassus Mountain. The large-scale ductile deformation along the Norumbega fault system took place along the northwestern margin of the pluton (Figure 4).

Bottle Lake pluton

The Bottle Lake pluton is located on the northwestern side of the Norumbega fault zone in the study area, intruded into the Aroostook-Matapedia, Miramichi, and Fredericton belts. Its shape is irregular with its southeastern (faulted) contact very close to the northern margin of the Deblois pluton. The Bottle Lake body was named the "Bottle Lake Complex" by Ayuso (1984) who divided it into two major components, the Whitney Cove and Passadumkeag River plutons. Several phases have been classified in terms of geochemical variation and texture (e.g. Osberg et al., 1985). Mineralogically and geochemically there is little difference from the Deblois pluton. The batholith is cut and offset by the Codyville and Waite fault zones of the Norumbega fault system in its northeastern and southeastern portions, respectively. Isotopic dating of the pluton shows that it was emplaced around 380 Ma (middle Devonian) (Ayuso et al., 1984), just a few million years after the Deblois.

Lucerne pluton

The Lucerne pluton, about 625 km^2 in area, intruded several lithotectonic terranes including the Fredericton belt, St. Croix belt, and Coastal Volcanic terrane. It is located east of the Penobscot River, and elongated in the direction of 030°. It narrows drastically toward the northeast, particularly in the vicinity of Great Pond. The Lucerne pluton is a coarse-grained metaluminous biotite granite, typically containing megacrystic alkali-feldspar phenocrysts. Local variations include seriate to porphyritic textures. Like the Deblois and Bottle Lake plutons, aplites and pegmatites are rare and roof pendants are locally present (Wones, 1980). The Norumbega fault system forms the northern boundary of the pluton, and it is suggested by this study (see Chapter 5) that the elongate shape is the result of ductile Norumbega shear. The Lucerne pluton is also Devonian, with a reported $^{207}Pb/^{206}Pb$ age of 380±4 Ma (Wones and Ayuso, 1993).

Dioritic intrusions

Several small dioritic and quartz diorite intrusions have been found along the NFS between Great Pond and the New Brunswick border, and were subjected to varying degrees of shear strain in the Norumbega fault system. Examples are the Fletcher Peak Cliff quartz-diorite and the Parks Pond pluton on the northwest side of the Lucerne pluton (Griffin, 1976; Wones, 1977, 1980) that were sheared in the Kellyland ductile shear zone. Detailed descriptions of these dioritic intrusions are included in Chapter 4.

2.4. Metamorphism

Regional metamorphism

The regional metamorphic grade in Maine decreases systematically northeastward from amphibolite facies in southwestern and mid-coastal Maine to the study area in eastern Maine (Figure 3), where lower greenschist facies regional metamorphic intensity (chlorite zone) is pervasive regardless of the age or structural complexity of the rocks (Ludman, 1990). Neither pre-Silurian orogeny in the Miramichi belt nor Acadian deformation in the Coastal Volcanic and Central Maine belts were accompanied by metamorphic conditions more intense than those of the chlorite zone (Figure 3). Thus, the rocks in eastern Maine preserve only the shallowest crustal history of orogenic events. According to Ludman (1990), the mineral assemblages of the Flume Ridge metasedimentary rocks in the chlorite zone include: muscovite-quartz-plagioclase; muscovite-chlorite-quartz-plagioclase-graphite-pyrite±ankerite. Muscovite is the dominant metamorphic mineral, occurring in the Acadian cleavage (S_1).

Contact Metamorphism

Well-developed contact aureoles surround the plutons in eastern Maine, particularly large mafic intrusions such as the Pocomoonshine gabbro-diorite (Ludman, 1989, 1990). The metamorphic effects range from a slight increase in the size of muscovite grains and appearance of biotite to partial melting of the Digdeguash Formation at the contact with the Pocomoonshine pluton (Ludman, 1989). Most of the contact-metamorphosed wall rocks display either an equi-dimensional granoblastic texture or a porphyroblastic texture. Around the Pocomoonshine gabbro-diorite, the metamorphic minerals are cordierite, andalusite, garnet, staurolite, and sillimanite in pelitic rocks, clinozoisite, actinolite, diopside, garnet, and wollastonite in calcareous rocks, and chlorite and actinolite in mafic metavolcanic rocks. In general, the aureoles were typically metamorphosed to the albite-epidote hornfels and hornblende hornfels facies (Ludman, 1989).

Contact metamorphism around granitic intrusions such as the Deblois pluton and the Bottle Lake pluton is limited in most places to an aureole less than 500 m wide and varies with the dip of contact, strike of rocks at the contact, and types of rocks affected (Larrabee, 1965). In general, aureoles are more extensive in slates and metasiltstones than in the metawackes. The aureoles are marked by an appearance and increase in magnetite and biotite, as well as by the presence of traces of chalcopyrite and pyrrhotite.

CHAPTER 3

THE NORUMBEGA FAULT SYSTEM IN MAINE

3.1. General Introduction

Stewart and Wones (1974) and Wones (1978) first named and described the Norumbega fault in mid-coastal Maine and traced it northeastward to faults mapped by Larrabee et al. (1965) at the Maine-New Brunswick border. The Norumbega fault, now called the Norumbega Fault System by workers such as Hubbard et al. (1995) and Ludman et al. (1999) due to its multiple-high-strain-zone character, has been recognized recently as one of the most extensive and longest lived structural features of the entire Appalachian orogenic belt (Ludman, 1995). This study follows this terminology; the high-strain zones caused by strain partitioning during one single faulting (including ductile shearing) event, are defined as "zones" such as the Kellyland and Waite ductile shear zones; these zones occur within one "fault system". The Norumbega fault system extends across the state of Maine with numerous anastomosing branch faults or high-strain zones and has been estimated to be at least 30 km wide in southwestern Maine (Swanson, 1992, 1994), 25 km wide in south-central Maine (Newberg, 1986; Hussey et al., 1986; West, 1993), and 35-40 km wide in easternmost Maine (Ludman, 1995, 1998). Detailed mapping unequivocally demonstrates the continuity of the Norumbega fault system for nearly 450 km, from Casco Bay in southwestern Maine to central New Brunswick (Hussey, 1988; Swanson, 1992, 1994; West, 1993; Ludman, 1991; Hubbard et al, 1996). Geophysical evidence and recent mapping suggest its extension southward to

Connecticut and northward to the Gulf of St. Lawrence -- a distance of almost 1,200 km. Seismic studies also reveal the vertical extent of one fault in central Maine to middle and lower crustal levels before becoming listric and flattening (Unger et al., 1987). A seismic image from recent work in east-central Maine by Doll et al. (1996) shows that at least one Norumbega fault strand, the Waite fault zone, penetrates the entire crust steeply and extends at least into the uppermost mantle, suggesting that at least some Norumbega faulting postdated the formation of the Moho in eastern Maine.

Hubbard et al. (1995) suggested that the mineral assemblages now exposed along the NFS indicate that the southwestern section experienced a greater amount of exhumation than the northeastern section. As a result, if this is true, the current exposures would present a profile from mid-crustal (southwestern Maine) to shallow-crustal (eastern Maine) levels, providing a window into the evolution of a major transcurrent fault system within nearly half of the crust. Early studies of the Norumbega fault zone were restricted to the deeper segment in southwestern and south central Maine, where amphibolite facies assemblages and ductile shear fabrics indicate mid-crustal faulting immediately after early Devonian peak regional metamorphism. More recent detailed studies of the NFS in the southwestern section show that it is characterized by a wide zone of distributed dextral ductile shear with localized very high strain zones such as the Sandhill Corner fault (Pankiwskyj, 1976; West, 1993) and Flying Point fault zone (Swanson, 1989, 1992,1993, 1994, 1999a, 1999b; West, 1993, 1995, 1999; West and Lux, 1993; West and Hubbard, 1997). The northeastern segment consists of the three discrete fault zones shown in Figure 1separated by broad areas that exhibit little strain. In addition, these three zones record episodic brittle reactivation of early ductile shear zones (Ludman et al., 1999, 2000).

Microscopic, mesoscopic, and megascopic structural features, and kinematic indicators such as asymmetric porphyroclasts and porphyroblasts, s-c and/or s-c' fabrics, drag folds, mica fish, and feldspar domino structures demonstrate pervasive dextral shear from the Portland area to western New Brunswick. Swanson (1993, 1999) has proposed that the regional dextral shearing and accompanying upright folding, granitic intrusion, and metamorphism in coastal Maine can be linked to a restraining-bend geometry along the Norumbega fault system in the Casco Bay area.

The lack of cross-cutting markers along the Norumbega fault is problematic for an accurate determination of displacement across the fault system, but estimates have been made by some workers. In south-central Maine, Johnson and Wones (1984) inferred 35 km of dextral displacement by matching offset segments of the Lucerne pluton and Turner Mountain syenite, but this measurement was along what is now recognized as only one of three Norumbega high-strain zones in eastern Maine. Swanson (1992, 1994) estimated 150-300 km of dextral displacement by extrapolating from outcrop-scale ductile shear zones to the entire 30-35 km wide Norumbega system in southwestern Maine, although he later suggested that this estimate seems unlikely (Swanson, 1999). In the shallow northeastern section of the Norumbega fault system, Ludman (1995, 1998) estimated ~125 km of displacement from presumably offset plutonic bodies.

Detailed mapping of cross-cutting relationships and thermochronological investigations have recently helped constrain the onset of Norumbega faulting activity to

Middle Devonian times (West, 1993; Ludman, 1998; Ludman et al., 1999, 2000; Idleman and Ludman, 1998a, 1998b). A complex displacement history, possibly continuous for almost 100 million years, has been inferred for the deeper NFS segment in southwestern Maine by West and Hubbard (1997) although some other workers believe that some asymmetric fabrics that are thought to have been produced by the Norumbega deformation (West and Hubbard, 1997) are the products of regional deformation (Berry, personal communication). Multiple faulting events have been described over that same time span in eastern Maine (Ludman, 1994, 1995, 1998). Early motion followed emplacement of the Deblois pluton (384 Ma; Ludman et al., 1999) and Bottle Lake pluton at about 380 Ma (Ayuso, 1984). Later reactivation involved rocks as young as the red Carboniferous (?) moles in eastern Maine and New Brunswick (Ludman, 1991).

The tectonic significance of the Norumbega fault system is not yet fully understood. In southern and south-central Maine, the fault system juxtaposes several contrasting lithotectonic belts, whereas in easternmost Maine, the fault system is contained almost entirely within the Flume Ridge Formation in the Fredericton belt (Figures 1 and 4; Osberg et al., 1985; Ludman, 1991). Some early tectonic models viewed the fault system as a major transcurrent (sinistral) suture between ancestral North America to the west and exotic terranes to the east (e. g. Kent and Opdyke, 1978; Zen, 1983; Keppie, 1989). Ludman (1980), however, demonstrated that the fault system is dextral, largely intraformational, and is not a suture zone involving long-distance transport in its present context. Subsequent detailed paleomagnetic analyses also refuted it as a potential suture (Kent et al., 1984). Others have suggested that the fault system represents an important dextral break without significant offset (Rankin, 1994; Zen, 1983; Williams and Hatcher, 1983). Significant basement discontinuities across the system were identified by gravity and magnetic modeling (Coblentz, 1988) and plutonic geochemistry (Andrew et al., 1983; Ludman et al., 1990), suggesting that the NFS was a significant structure at an early stage in its evolution, but not after emplacement of the Devonian plutons. For example, it has been proposed that this major zone of crustal weakness was perhaps inherited from pre-Devonian tectonism (Ludman et al., 1999).

3.2. The Norumbega Fault System in Eastern Maine

Detailed studies of the Norumbega fault system in eastern Maine began only in the early 1990's (Ludman, 1993, 1994, 1995, 1996, 1997, 1998; Ludman and Gibbons, 1999; Ludman et al., 1999). Reconnaissance mapping has shown that strain was strongly partitioned into three 2-5 km wide strands, the Waite, Kellyland, and Codyville fault zones, which are separated by broad areas of much lower, inhomogeneously distributed strain (Figure 4; Ludman, 1994, 1995, 1998). This study shows that the Waite and Kellyland fault zones merge in the Great Pond area and are the northeastward continuation of the classical Norumbega fault zone in south-central Maine (Figures 1 and 4). They also appear to have accommodated most of the strain within the system. Therefore this study will focus on the Waite and Kellyland fault zones. Each of these high-strain zones contains subordinate-order anastomosing faults. Detailed mapping and reconnaissance-level mapping in the area between Great Pond and Grand Lake Stream in eastern Maine reveal new details of the geometry and internal structures of the fault system (Figure 4) and significantly improved the previous image of the fault system shown on the state map (Figure 5).

Physiographic expression of the Norumbega fault system in eastern Maine

Despite extensive glacial cover mostly in the study area, the Norumbega fault system has a pronounced physiographic signature throughout most of its length, particularly in eastern Maine. Figure 6 is a digital elevation model (DEM) for the NFS in eastern Maine created with the CARIS geographic information system software. It is based on USGS 30-m-resolution radar elevation data for seventy-six 7.5' quadrangles and, because it is a regional composite of 1:24,000 scale data, is the most detailed terrain model ever constructed for the area. In this version, sun azimuth is 345° and sun elevation is 45° above the horizon.

Some of the major things one can learn from the model (Figure 6) are:

(1) In general, the area is characterized by low rolling hills, but prominent ridges held up by contact aureoles surround major plutons. The plutons themselves may underlie lowlands (e.g., Pocomoonshine gabbro-diorite, or the main portion of the Bottle Lake), but most stand higher than metasedimentary rocks in elevation.

(2) A prominent NW-SE-trending glacial fabric orientation is clearly shown in the model; drumlin fields near New Brunswick border and N-S trending eskers in the western part of the DEM are also clearly visible.

(3) There are several prominent lineaments visible on the DEM, and nearly all of these correspond to mapped faults. The three Norumbega high-strain zones stand out sharply, but there are also smaller, less continuous lineament segments. The model shows

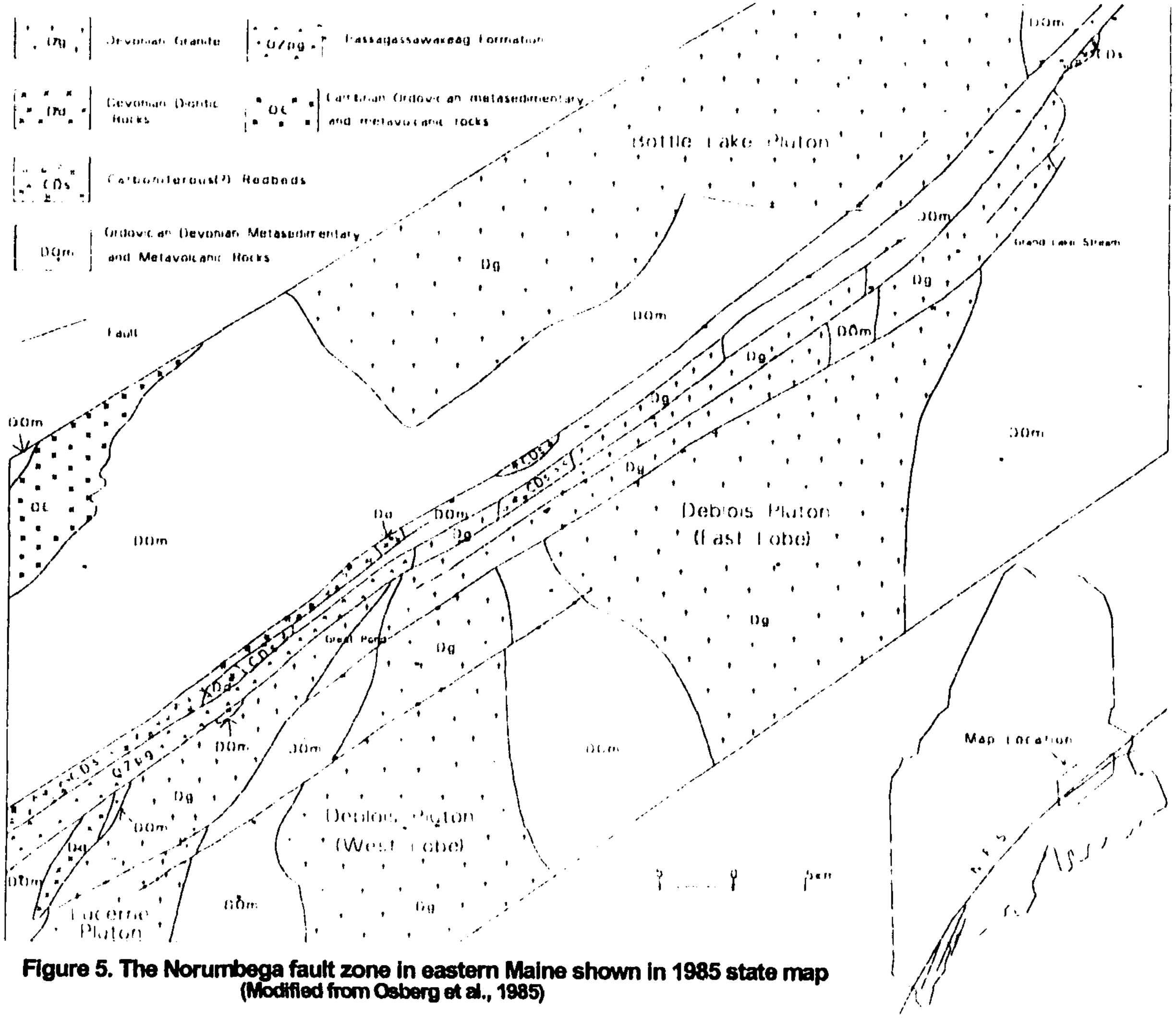


Figure 5. The Norumbega fault zone in eastern Maine shown in 1985 state map
(Modified from Osberg et al., 1985)

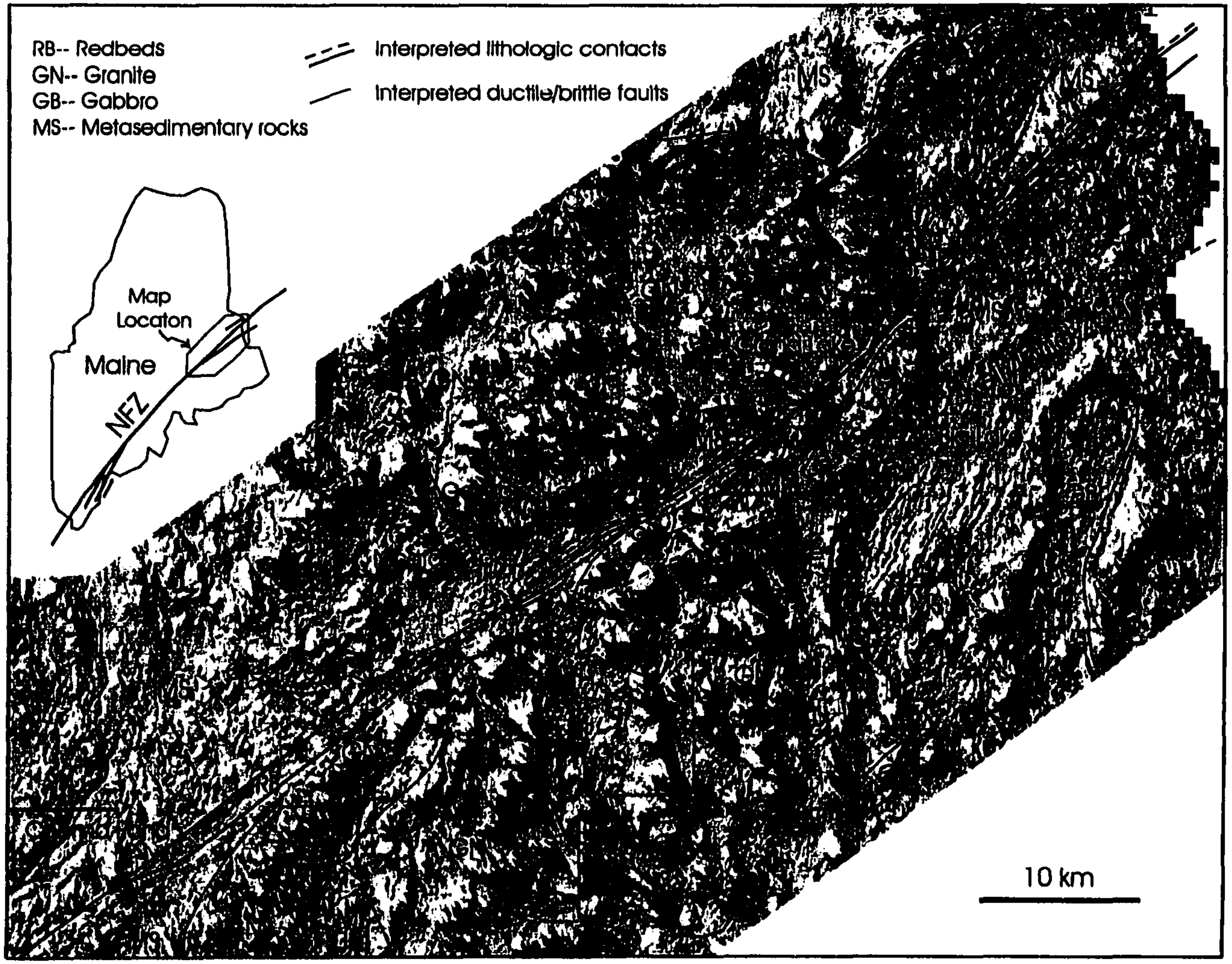


Figure 6. DEM (digital elevation model) image and geologic interpretation in eastern Maine. (Source data is from USGS website. Processed with MICRODEM and CARIS.)

that the Waite and Kellyland fault zones converge toward the SW, in the area between Nicatous Lake and Great Pond, a relationship confirmed on the ground during this study.

The linear features are caused by differential erodability of the local rocks, but in ways that were unexpected. For example, the Kellyland ductile shear zone is outlined by a pronounced lineament along the NW slopes of Washington Bald and Wabassus mountains, where the ductilely faulted granitic rock is _**more**_ resistant than the unsheared lithologies due to significant grain-size reduction caused by ductile shearing. Near the New Brunswick border, the lineament follows a flooded drainage system (Big Lake Flowage) in which the faulted Flume Ridge metasedimentary rock is _less_ resistant than the unsheared material.

The Waite composite fault zone

The Waite zone is a complex composite structure in which a band of (early stage) high-strain ductilely sheared rocks is cut into slivers by anastomosing brittle fractures (Figure 7; Ludman, 1998). The ductile component of the fault zone ranges from a maximum width of 5 km in the northeast part of the study area to 300-400 m in its narrowest regions. The variation in width along strike is the result of the brittle faulting. Because of its complex mixture of brittle features overprinting ductile structures, it is here called the Waite composite fault zone. Slices of redbeds in eastern Maine have been found only along the Waite zone.

The Waite composite fault zone extends continuously for 85 km from Great Pond to the Canadian border and continues at least 100 km farther into central New Brunswick as the Fredericton fault (McLeod et al., 1994). It cuts the southeastern end of the Bottle

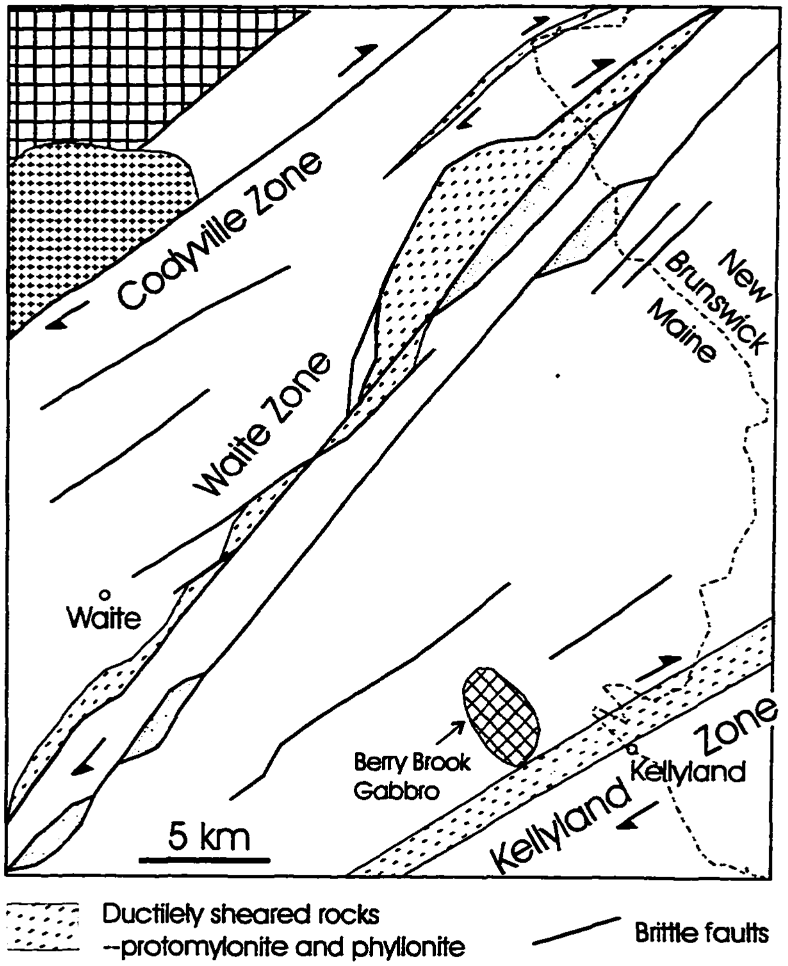


Figure 7. Internal structure and distribution of sheared rocks in the Waite composite fault zone in easternmost Maine. (Modified from Ludman (1998). See Figure 4 for location and legend.

Lake pluton, and separates the Bottle Lake and Deblois plutons in the area northwest of Grand Lake Stream.

The northwest margin of the Waite composite fault zone is typically a gradational contact between unsheared Fredericton belt metasedimentary protoliths and their ductilely deformed products. Thick-bedded, variably calcareous wackes in the transition zone are converted to a protomylonite with a closely-spaced (1-2 mm) penetrative foliation and a strong mineral elongation lineation, and subordinate fine-grained pelitic horizons are changed to coarser phyllonite. Foliation is expressed by coarsened muscovite and newly developed chlorite flakes. With increasing strain, biotite replaces chlorite in both deformed psammite and pelite, and aligned actinolite porphyroblasts develop in calcareous protoliths. The occurrence of these minerals in the zone of highest ductile strain for the entire length of the Waite fault zone has been interpreted as the result of early-stage strain heating (Ludman, 1998; Ludman et al, 2000). This study, however, prefers the elevated heat flow mechanism—heat was flowing up from deeper levels through the penetrative shear zones. The heat flow could have driven the circulation of hydrothermal fluids, resulting in abundant quartzofeldspathic veins filling in the phyllonite. The heat flow and the hydrothermal fluids could also have facilitated the formation of the spangle-muscovite-quartz-schist in some segments of the high-strain zones in the Waite zone discussed in the following chapter.

Brittle effects are generally concentrated along the southeast margin of the Waite composite fault zone in the area between Waite and the Maine/New Brunswick border and in the Nicatous Lake area, where the early phyllonite is juxtaposed against

Carboniferous (?) redbeds or metasedimentary rocks of the Fredericton belt that exhibit little evidence of ductile strain (Figure 7). Anastomosing brittle fault strands carve the mylonite into lenses, convert the mylonites to cataclasite, and retrograde the biotite and actinolite to chlorite. Relict mylonitic foliation in adjacent lenses is typically discordant, suggesting that they have rotated with respect to one another, and the originally near-vertical foliation is locally folded and flattened to sub-horizontal attitudes. The lenses of Carboniferous redbeds generally lie at the southeastern margin of this *brittle* zone. In the area between Nicatous Lake and Grand Lake, brittle effects are concentrated along the northwest margin of the pre-existing ductile Waite zone and intense brecciation is present.

The Kellyland ductile shear zone

The Kellyland ductile shear zone is the southernmost strand of the NFS in eastern Maine. Initially named the "Wabassus Mountain fault zone" from its exposure along that mountain (Ludman, 1994), it was later renamed as Kellyland zone for its exposure at the northeastern terminus of the Big Lake Flowage at Kellyland (Ludman, 1998). Extended mapping toward the southwest has revealed more and much better exposures along Washington Bald Mountain, Fifth Lake Mountain, and Sabao Mountain where there is a clear northeast-trending topographic lineament as far southwest as the southern Nicatous Lake area (Figure 6). Ductile deformation was predominant in the Kellyland zone, with very limited brittle deformation only in small-scale conjugate faults. The Kellyland ductile shear zone followed the northwest contact between the Deblois pluton and Flume Ridge Formation in the area between south Nicatous Lake area and Grand Lake Stream

(Figure 4). The contact is well exposed at Fletcher Peak Cliff in the Fletcher Peak quadrangle.

The Codyville fault zone

The Codyville zone, the northernmost high-strain zone of the Norumbega system in eastern Maine suggested by Ludman et al. (1999), truncates the northeasternmost extension of the Bottle Lake pluton (Figures 1 and 4). Ductile and brittle deformation effects have been reported along the zone (Ludman, 1999, personal communication). Because it is much less exposed than both the Waite and Kellyland zones and outside of the present study area, it will not be treated further in this study.

CHAPTER 4

DUCTILE SHEARING: DEFORMATION MECHANISMS AND CONDITIONS

4.1. Introduction

Metasedimentary rocks, granites, and dioritic rocks have been involved in the early ductile shearing in the Norumbega fault system in eastern Maine. This provides an excellent opportunity to study the nature of the ductile deformation mechanisms in these different rocks sheared under possibly similar conditions. Interpretation of the deformation mechanisms and physical conditions associated with the ductile phase of Norumbega activity is based on deformation fabrics and structures found within sheared rocks and individual mineral crystals and comparison of these features with results from deformation experiments.

4.2. Ductile Shearing and Deformation Mechanisms in Metasedimentary Rocks

The Waite ductile shear zone and part of the Kellyland ductile shear zone are hosted in part by metasedimentary rocks of the Flume Ridge Formation, generally variably calcareous quartzofeldspathic wackes interbedded with siltstone and slate. Effects of ductile shearing in these rocks vary considerably, depending on strain intensity and location within the Kellyland and Waite zones. Temperature appears to increase along the fault system from northeast, the area between Waite and New Brunswick border, to southwest, the area between Amazon Mountain and Great Pond, perhaps because of the effects of pluton emplacement and elevated heat flow. Shear strain intensity ranges from relatively low in small individual strands of the Kellyland and

Waite zones to very high at the contact between the Deblois pluton and Flume Ridge Formation in the Fletcher Peak area (see Figures 12 and 13).

Deformation in the environment of lowest temperature and strain has been discussed by Ludman (1998) in the Kellyland area at the New Brunswick border, where ductile strain is concentrated in pelitic horizons and was controlled largely by the behavior of the phyllosilicate minerals. Shearing occurred mostly by intercrystalline glide with a small component of intracrystalline slip in matrix muscovite and chlorite (Ludman, 1998). Ductile shearing penetrated only a few centimeters into adjacent wacke beds, where the dominant deformation mechanism was pressure solution mass transfer that resulted in a closely spaced anastomosing cleavage (Ludman, 1998). Similar low temperature is found along the easternmost segment of the Waite zone east of Waite, where a continuously mappable zone of biotite-rich protomylonite defines the highest strain portion of the Waite zone.

To the southwest, in the area between Amazon Mountain and Great Pond, phyllonites and coarser-grained schistose rocks characterize the high-strain portions of the Waite and Kellyland ductile shear zones adjacent to the Bottle Lake, Deblois, and Lucerne plutons. Although phyllonites dominate ductile shear zones developed in metasedimentary rocks in this area, a belt of coarse-grained spangled muscovite-quartz schistose mylonite was discovered in the highest strain zone of the Waite zone in the area between the southwest side of Gassabias Lake and southeast side of Fourth Machias Lake (see Figures 12 and 30). The ductile shear zone on the northwestern side of the Lucerne pluton has been also investigated by this study, and the strongly sheared non-granitic rocks proved to be spangled muscovite-quartz-schist as well.

Phyllonite

The presence of phyllonite characterizes the zones of highest ductile shear strain in the Flume Ridge Formation in both the Waite and Kellyland ductile shear zones. Primary sedimentary features are very poorly preserved in phyllonite zones, generally having been obliterated by penetrative mylonitic foliation (S_2) caused by the intense ductile shearing. Relatively shallow crustal conditions are implied by the greenschist facies assemblage that characterizes these pelitic fault rocks. Phyllonitic foliation defined by mostly muscovite flakes and some biotite typically anastomoses in areas exhibiting the highest shear strain (Figures 8a and 8b). Detrital quartz grains in the more quartzose rocks are plastically deformed and flattened or elongated to develop grain-shape-preferred fabrics (Figure 9a), and some core-and-mantle structures are present. Sub-grain rotation recrystallization of quartz is only common in areas of high strain bands. Quartz and feldspar (albite) occur as larger individual porphyroclasts in highly micaceous phyllonite, and numerous σ-type porphyroclasts have been observed that uniformly indicate dextral strike-slip shearing (Figure 8b). Grain-size reduction due to dynamic recrystallization and sub-grain development are common, producing a remarkably fine-grained texture typically around 0.2 μm or less. Microscopic s-c or s-c′ structures are developed in the sheared metasiltstones.

Synkinematic quartz veins are well developed in the phyllonites in the Waite zone in the area between Third Machias and Gassabias lakes, implying the involvement of fluids during deformation. The lobe-shaped subgrains of quartz in these veins are aligned to define a continuous foliation parallel to the dominant phyllonitic foliation. The veins

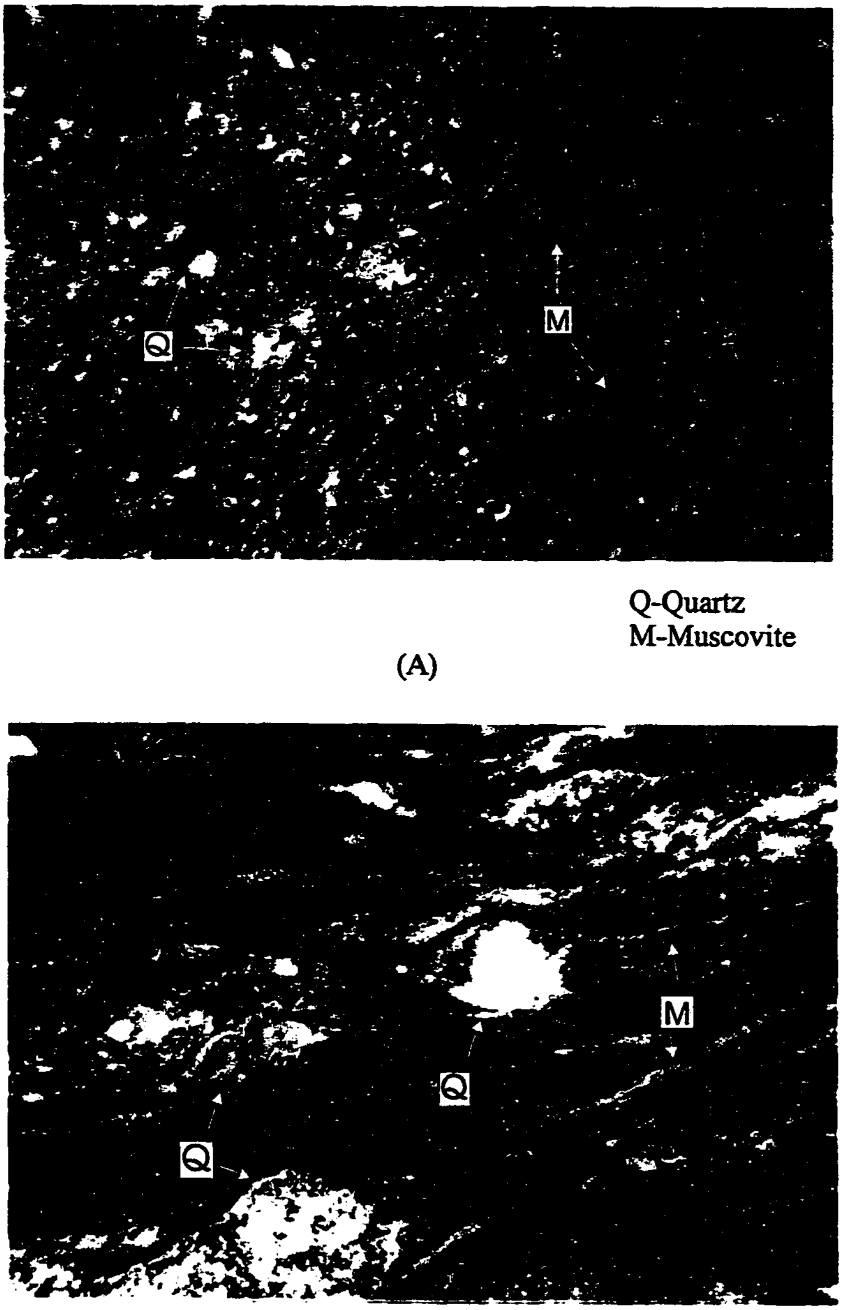


Figure 8. Ductilely sheared Flume Ridge metasedimentary rocks. (A) Photomicrograph of phyllonite. Width of view is 3.5 mm. (B) Photomicrograph of phyllonite with σ-type quartz porphyroclasts. Width of view is 0.9 mm. Cross-polarized light for both.

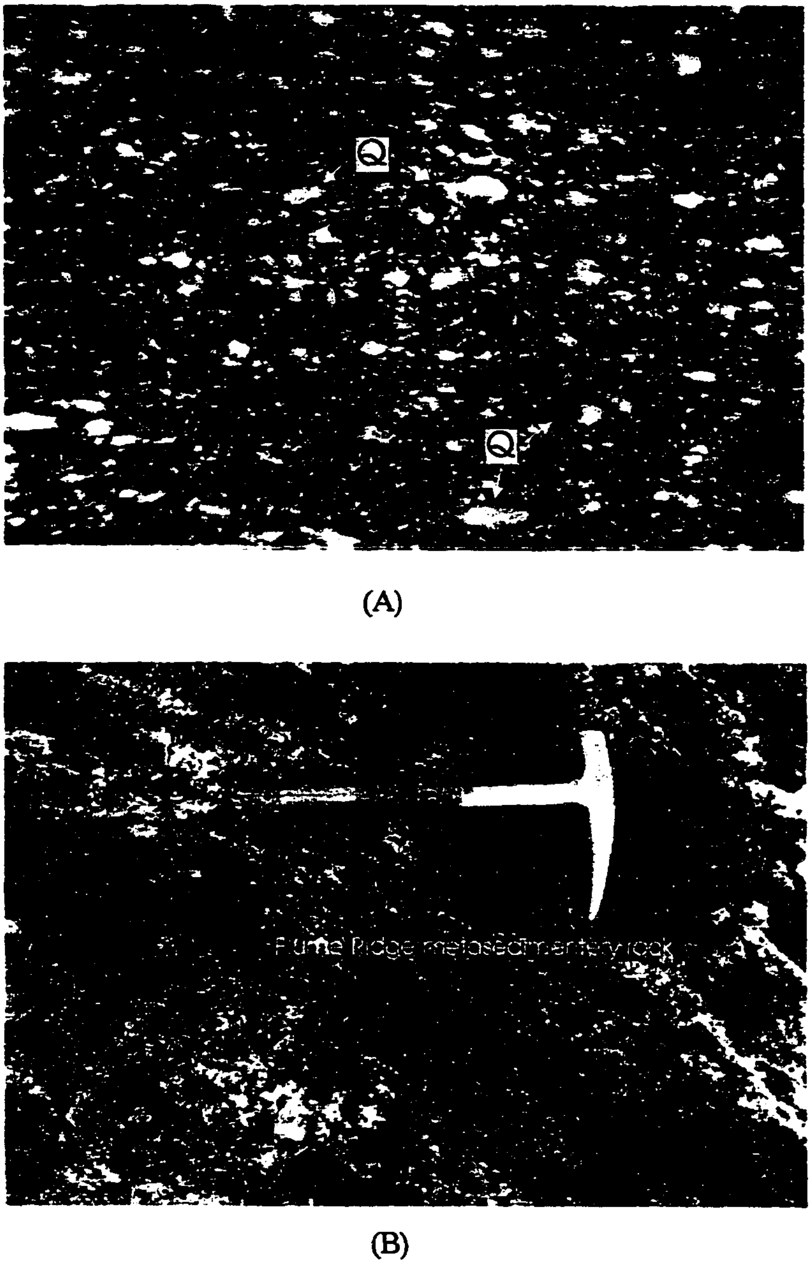
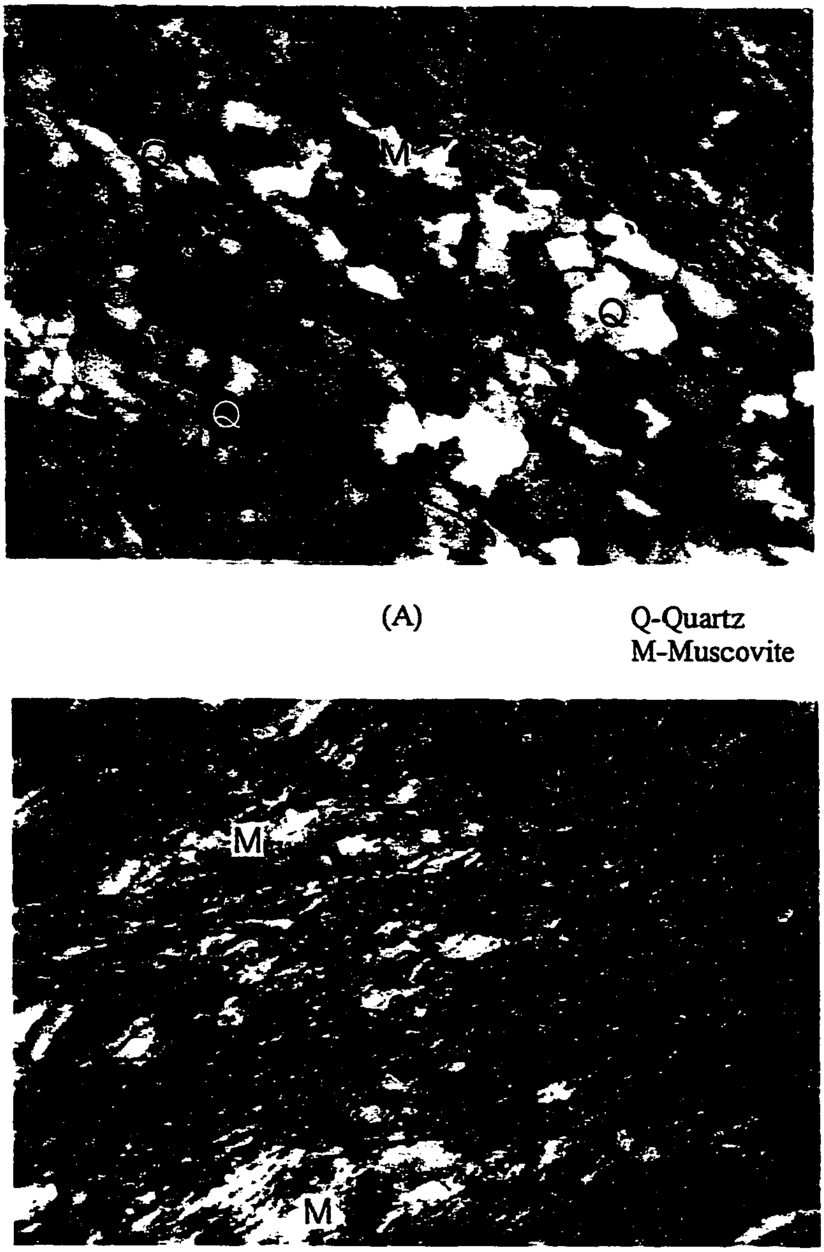


Figure 9. (A) Photomicrograph of sheared quartzofeldsparthic wacke and grain-shape-preferred fabrics. Width of view is 3.5 mm. Cross-polarized. (B) Boudinaged pre- or syn-kinematic quartz veins (appear as holes due to erosion and resolution) with near vertical neck lines in the Waite fault, interpreted to indicate horizontal movement. Plan view. Hammer points north. Fourth Machias Lake.

are generally boudinaged to form foliation-parallel boudin strings and isolated asymmetric boudin lenses that are, in turn, converted to quartzose mylonite in the zones of most intense shearing. The boudin necklines are nearly vertical and almost perpendicular to near-horizontal stretching lineations, consistent with horizontal simple shear (Figure 9b). Some 10 cm - 1 m thick aplite dikes found within both the Waite and Kellyland zones in the same area are also strongly sheared to form quartzofeldspathic mylonite and ultramylonite. Small-scale asymmetric folds are common. Some appear to be synkinematic with the ductile shearing and may have been formed by flow perturbations during progressive ductile shearing because their hinge lines are near vertical, whereas some have very gently plunging hinge lines and probably have been formed during later stage brittle reverse faulting discussed in Chapter 6.

Spangled muscovite-quartz-schist

The central, highest-strain portion of the Waite ductile shear zone is exposed in the area between the southwest side of Gassabias Lake and the southeast side of Fourth Machias Lake (see Figures 12 and 30). It is characterized by a belt of strongly sheared and mylonitized rock (see Figures 12 and 30) which differs from the phyllonite described above in that it is more schistose and has larger recrystallized grains than are found anywhere else in the sheared Flume Ridge Formation (Figures 10 a and 10b). The width of this schistose belt is estimated to be at least 500 m and the boundary with the adjacent phyllonite zones is gradational. Its protolith is determined as metasedimentary rocks based on some relict sedimentary features and quartzite beds. Texturally and petrographically it resembles the Cape Elizabeth Formation of southwestern Maine. However, because there appears to be a gradational relationship with the Flume Ridge



(A)

(B)

Figure 10. (A) Photomicrograph of spangled muscovite-quartz-schist with triple-junction and rectangular strain-free quartz grains. (B) Photomicrograph of muscovite-quartz-schist with s-c structure and mica-fish, showing dextral shear sense. Both have width of view 3.5 mm.

phyllonite on both sides of the spangled schistose mylonite and because there is no additional evidence for possible affiliation with the Cape Elizabeth Formation, this belt of sheared metasedimentary rocks is mapped as part of the Flume Ridge Formation. Fabrics indicative of dextral shearing are abundant, including features such as σ- and δ-type porphyroclasts, shear bands, mica-fish, etc. (e. g. Figure 10b). Therefore, this belt is determined as a high-strain ductile shear zone generated by ductile shearing instead of the regional metamorphism that accompanied the earlier Acadian orogenesis, in the Flume Ridge.

This spangled muscovite-quartz schist zone is characterized by the presence of voluminous (>15%) light-color (pale white to white) and fine quartz veins, about 1 mm to 2 cm thick, besides the interbeded thin (0.5-5 cm thick) and grey quartzite layers. These are evenly distributed throughout the schistose mylonite zone but are sheared and boudinaged, implying significant fluid involvement before and/or during ductile shearing. The flux of silica-rich fluids made pre-existing metasedimentary rocks much more quartzose. Original detrital quartz and feldspar grains in graywacke and quartzite and quartz grains within quartz veins are completely recrystallized, and coarse to very coarse muscovite and biotite flakes define a penetrative foliation. Strain recovery is locally incomplete, so that a slightly earlier dynamic recrystallization event comparable to that recorded in the phyllonite is locally preserved. Triple junction boundaries between strain-free quartz grains and the predominant rectangular strain-free quartz grains (Figure 10a) suggest that grain size enlargement was due to significant post-kinematic static recrystallization. The static recrystallization may have been caused by elevated heat flow from deeper crustal levels toward the end of ductile shearing, possibly related to fluid migration in the fault zone. Strain recovery and strain-free quartz grains with 120° triple junctions suggest that the temperature reached as high as 450-500°C based on work by Srivastava and Mitra (1996) and Hirth and Tullis (1992).

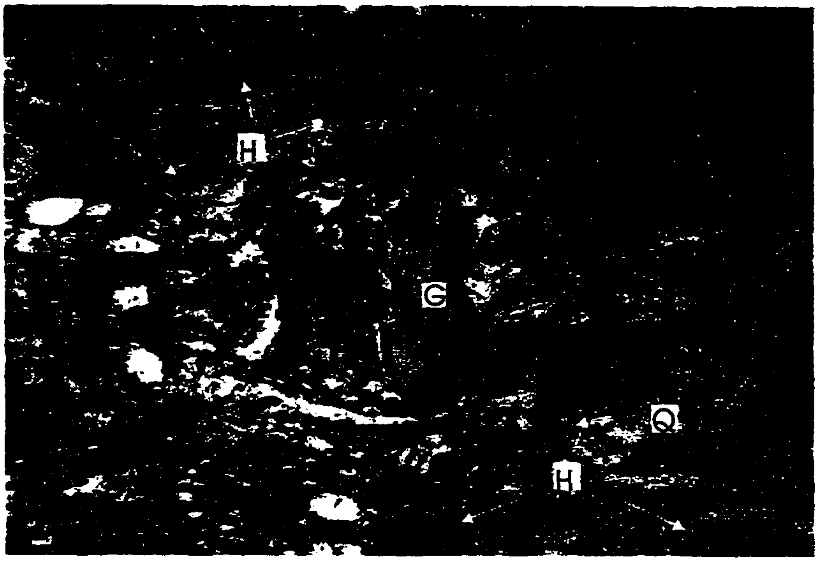
It is suggested that the elevated heat flow from deeper levels through the high-strain segments along the Waite ductile shear zone drove the circulation of the silica-rich fluids and raised the temperature of the high-strain segments during and after the ductile shearing.

A belt of strongly mylonitic and schistose rocks northwest of the Lucerne pluton had been assigned previously to the Copeland Schist (Griffin, 1976) and Passagassawakeag Gneiss (Griffin, 1976; Wones, 1977, 1980; Osberg et al., 1985). However, it has been found that the northeastern segment of the belt next to the Lucerne granite is a zone of granitic mylonite and ultramylonite derived from the northern margin of the Lucerne pluton by intense Norumbega ductile shearing (see Plate I). The shearing took advantage of the contact between the Lucerne granite and the metasedimentary rocks--the Flume Ridge Formation or its equivalent in this area, the Bucksport Formation. Northward next to this granitic mylonite zone is a continuous schistose zone which is very similar to the spangled muscovite-quartz-schist discussed above in that it is much coarser than phyllonite and richer in muscovite (Figure 10b). Due to high shear strain, the primary structural and textural features are rarely preserved, and can only be seen within relict low-strain domains. In these areas, the schist's protolith is readily identifiable as fine-grained quartzofeldspathic metagraywacke with minor metapelitic layers. Detrital quartz grains and fine quartz veins are completely dynamically recrystallized and ribboned forming aggregates of sub-grains with irregular boundaries. The schistosity is defined by alignment of quartz ribbons and muscovite flakes in different sizes. Muscovite fish are well developed due to extensive development of shear bands or microscopic s-c and s-c' structures in mica-rich layers, and indicate a dextral shear sense (Figure 10b).

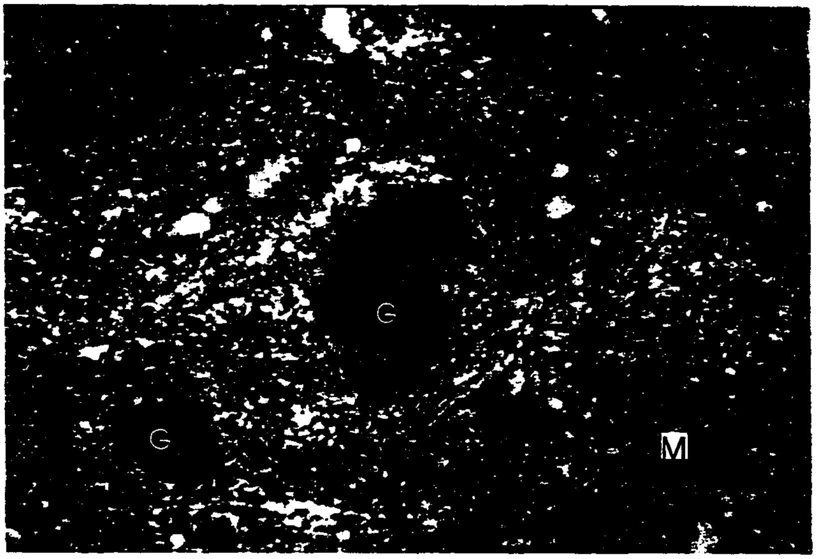
Some less-strained and originally finer-grained but phyllonitic horizons with calcic amphibole, plagioclase feldspar, and garnet occur next to this schistose zone. Both the calcic amphibole and garnet grains appear to have been pre-kinematic porphyroclasts (Figures 11a and 11b), suggesting that the pre-existing stratified rocks had been metamorphosed at upper greenschist facies (garnet-zone grade; Passagassawakeag Formation?). This is consistent with the observation that the pre-NFS regional metamorphic grade increased southwestward from eastern Maine (chlorite-zone) to southwestern Maine (garnet zone and higher) along the strike of NFS (Guidotti, 1985). The garnet and calcic amphibole porphyroblasts were deformed into porphyroclasts and the rocks were retrograded by the ductile shearing. Felsic segregation and quartz veins are common within the zone, but unlike the spangled muscovite-quartz-schist belt discovered in the area between the southwest side of Gassabias Lake and the southeast side of Fourth Machias Lake, there is neither static recrystallization nor strain recovery but only dynamic recrystallization. This zone contains some small dioritic dikes and some felsic pegmatite dikes which were sheared as well.

4.3. Ductile Shearing and Deformation Mechanisms in Granitic Rocks

Very few previous Norumbega studies dealt with the effects of ductile shear on the batholithic granites affected by the fault system (e. g., Ludman and Gibbons, 1999; Ludman et al., 2000). The effects of ductile shearing on granitic rocks are well exposed in



(A) G-Garnet
H-Calcic hornblende



(B)

Figure 11. (A) Photomicrograph of co-existing garnet and calcic hornblende porphyroclasts; and (B) photomicrography of garnet porphyroclast in sheared metasedimentary rocks northwest side of Lucerne pluton. σ-type asymmetric garnet porphyroclasts in both (A) and (B) indicate dextral shear sense. Both have width of view 9 mm. (A) is plane polarized and (B) cross-polarized.

the Kellyland ductile shear zone between Sabao Mountain and Grand Lake Stream, especially in the Fletcher Peak area where the maximum observed shear was recorded at the contact between Deblois granite and the Flume Ridge Formation (Plate II and Figure 12). Therefore, the Kellyland ductile shear zone in the Fletcher Peak quadrangle (Plate II) and adjacent areas was mapped in detail and studied petrographically. Variations due to this tectonic overprint are mapped separately, essentially as estimates of strain facies in terms of dynamic grain-size reduction, intensity of mylonitic foliation, and estimated shear strain. Three strain facies sub-zones consistent with different types of mylonite described by Sibson (1977) and Lister and Snoke (1984) are now recognized in Deblois granite deformed in the Kellyland ductile shear zone (Plate II and Figure 12). The progressive change with increasing strain from protomylonite to mylonite to ultramylonite within the Deblois granite clearly involved a reduction in the mineral grain size and an increase in the number of K-feldspar and plagioclase porphyroclasts. The zone of ductile shearing in the granite in the Fletcher Peak area is about 4 km wide (including all these sub-zones).

Undeformed Deblois granite

Undeformed granite in the eastern lobe of the Deblois pluton has a typical granitic to megacrystic texture, with only slight chilling at the eastern margin where there is a finer-grained marginal facies ranging from several meters to several tens of meters in width. The pluton is remarkably homogeneous in the study area, consisting of a K-feldspar-rich, hornblende-biotite granite. Perthitic microcline occurs as coarse to megacrystic (2.5-7 cm) subhedral crystals whereas the sodic plagioclase exhibits three different habits, all commonly visible in a single exposure: small euhedral crystals,

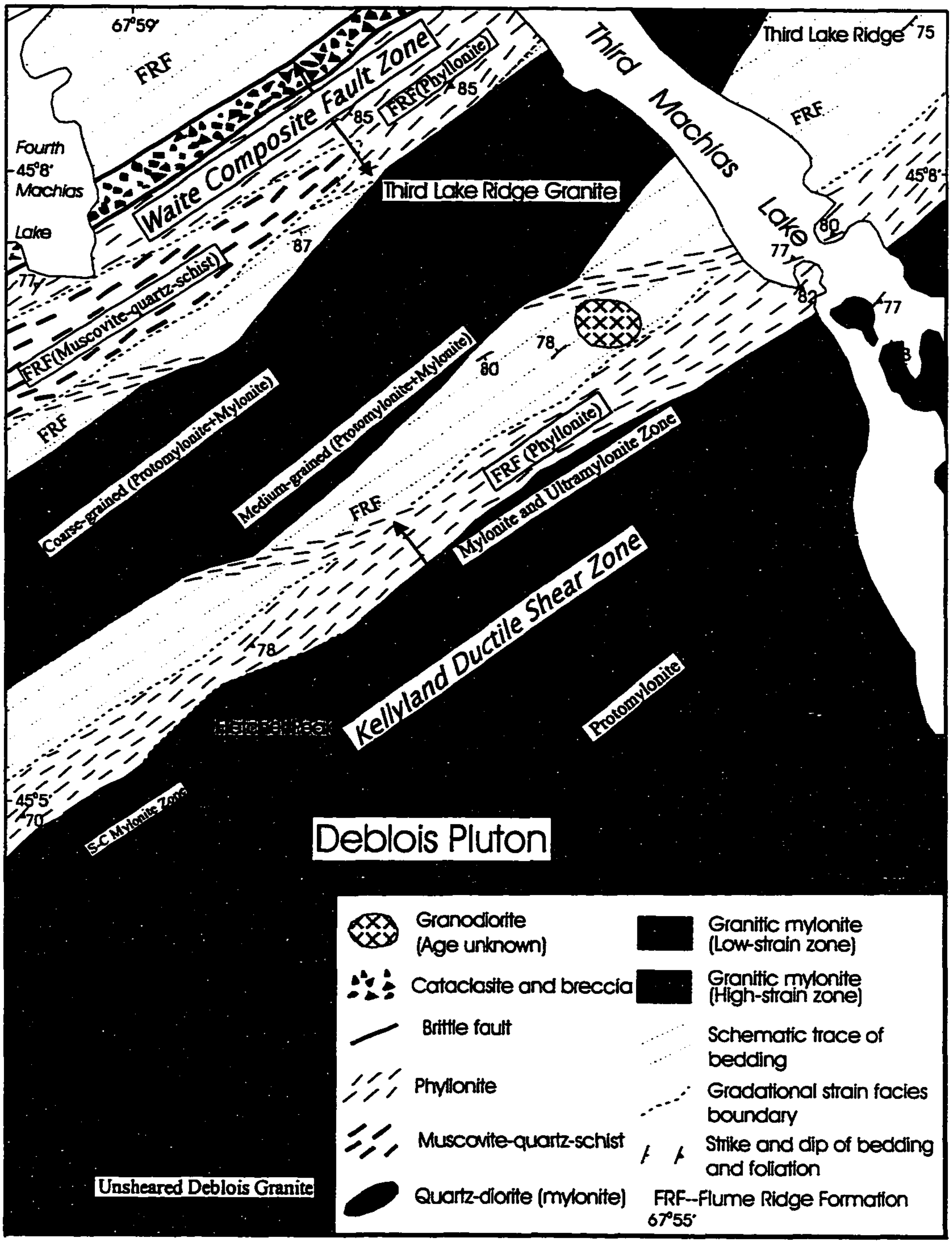


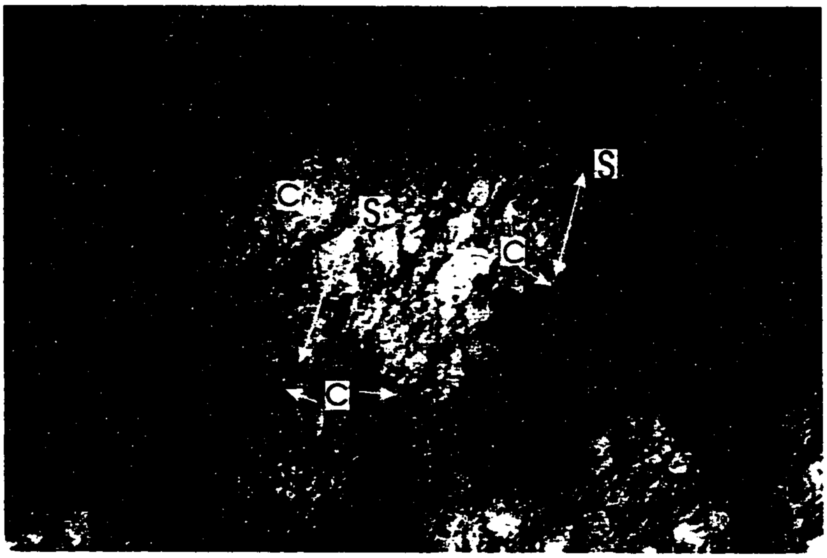
Figure 12. Schematic structural map showing geometry and internal structure of the Norumbega fault system and strain variations in sheared Deblois pluton in the Fletcher Peak area. See Figure 4 for location.

inclusions in microcline megacrysts, and mantling the microcline in rapakivi texture. Two minor variations include slightly more mafic zones found on the northeast side of Slewgundy Ridge and the southwest side of Elwell Ridge. The more mafic zones are characterized by more than twice the typical abundances of hornblende and biotite, producing a significantly darker color than is found throughout the main body of the pluton. The increased abundance of these ferromagnesian phases is largely at the expense of quartz. Since the relative ease of quartz deformation controls shearing in the granite, the more mafic granitic rocks proved to be more competent than the typical granite. They therefore accommodated little shear strain and are barely foliated. Primary flow foliation has locally developed within undeformed granite. The foliation is defined by alignment of euhedral feldspars, but no plastic deformation has been observed in the quartz grains in these rocks.

Protomylonite subzone (foliated to slightly foliated granite)

The zone of foliated Deblois granite, here termed the protomylonite subzone, is about 3.5 km wide in the Fletcher Peak quadrangle. Due to dextral simple shearing, the feldspars in this sub-zone are oriented to form shape-preferred fabrics and foliation (Figure 13a). The foliation strikes 355^0-000^0 in slightly foliated granite adjacent to undeformed Deblois rocks in the south and swings gradually to 020^0-035^0 at the contact with the s-c mylonite zone, the next higher strain zone to the northwest (Figures 12 and 18). This sigmoidal pattern is consistent with the dextral shear deduced from megascopic and microscopic shear indicators. Feldspar grains themselves are barely deformed, either plastically or brittlely. Quartz grains, however, are plastically deformed and dynamically recrystallized though not completely. Some quartz ribbons are formed around mostly

(A)



(B)

Figure13 . (A) Foliated coarse-grained granite from protomylonite sub-zone. Pen is pointing to north. (B) S-C mylonite granite from s-c mylonite sub-zone, showing dextral shear sense. Pen is pointing to north.

intact feldspar crystals. The intensity of dynamic recrystallization as estimated by amount of sub-grains increases progressively northwestward from undeformed granite toward zones of higher shear strain. With more intense foliation, weakly developed s-c structures begin to appear locally near the s-c mylonite sub-zone. Grain size reduction is not significant in the protomylonite zone compared to the next sub-zone.

S-c mylonite subzone (mylonitized granite with classic s-c structure)

Next to the granitic protomylonite subzone is a mylonite zone characterized by well-developed s-c structure (Figure 13b; Lister and Snoke, 1984) and intensified grain-size reduction. Therefore, this sub-zone is named the s-c mylonite zone. It is about 200-300 m wide, and contains lenses of lower strain indicating the heterogeneous nature of the shear strain. S-bands are typically defined by arrangement of feldspars and tails of sigmoidal quartz ribbons parallel to the foliation in the granitic protomylonite sub-zone.

The c-foliation begins to appear when the foliation in the protomylonite strikes 030°-035°, which is when the angle (θ') between this foliation and the shear zone boundary (the boundary between the unsheared granite and protomylonite sub-zones; Figure 13; or shear direction) reaches 10°-15°, or when the shear strain (γ) reaches 3.5-5.5 ($\gamma=2/\tan2\theta'$ according to Ramsay and Huber, 1983). Grain-size reduction by dynamic recrystallization and sub-grain rotation becomes significant in this zone and is also propagated from C-domains, indicating that the simple shear is more concentrated in C-domains than in S-bands. Toward the higher strain margin of the s-c mylonite zone, s-bands are systematically rotated and more closely approach orientations comparable to the dominant c-foliation. In other words, the angle between s-bands and c-foliation decreases toward the highest strain portion of the Kellyland ductile shear zone (the contact between the granite and the Flume Ridge metasedimentary rocks). It is therefore suggested that the formation of c-foliation indicates increasing shear strain.

All quartz grains in the s-c mylonite zone have been dynamically recrystallized to form quartz ribbons (Figures 14a and 14b). Abundant features of crystal-plastic deformation are present in quartz grains, including core-mantle structure, sub-grain development, and deformation bands. Plagioclase and alkali feldspars, however, are deformed almost entirely by brittle fracturing into smaller porphyroclasts sandwiched between quartz ribbons. Some plagioclase feldspars show twin-lamellae kinking and undulose extinction (Figure 14b), the only intracrystalline plastic deformation phenomena observed within feldspar grains. Cleavage planes in biotite are typically kinked and some mica fish have been observed (Figure 14a). The s-c structure and all asymmetric shear-sense indicators consistently indicate dextral simple shear.

Mylonite and ultramylonite subzone (mylonitized and ultramylonitized granite)

The highest shear strain recorded in the Deblois pluton in the Kellyland ductile shear zone is a zone of interlaminated mylonite (Figure 15a) and ultramylonite that ranges from 250-700 m wide at the fault contact with the Flume Ridge Formation in the study area (Figure 12). The s-c structure within this zone may persist locally but the angle between s-bands and c-foliation is typically so small that they are almost parallel to one another. The intensive c-foliation--the mylonitic foliation--dominates. It strikes predominantly 045°-050°, roughly parallel to the strike of the Kellyland ductile shear zone (Figure 12). Grain-size reduction is much more significant in this zone due to the extremely high strain. Quartz grains are completely dynamically recrystallized and individual quartz ribbons (Figure 15b) are stretched to as much as 10 cm long. All large

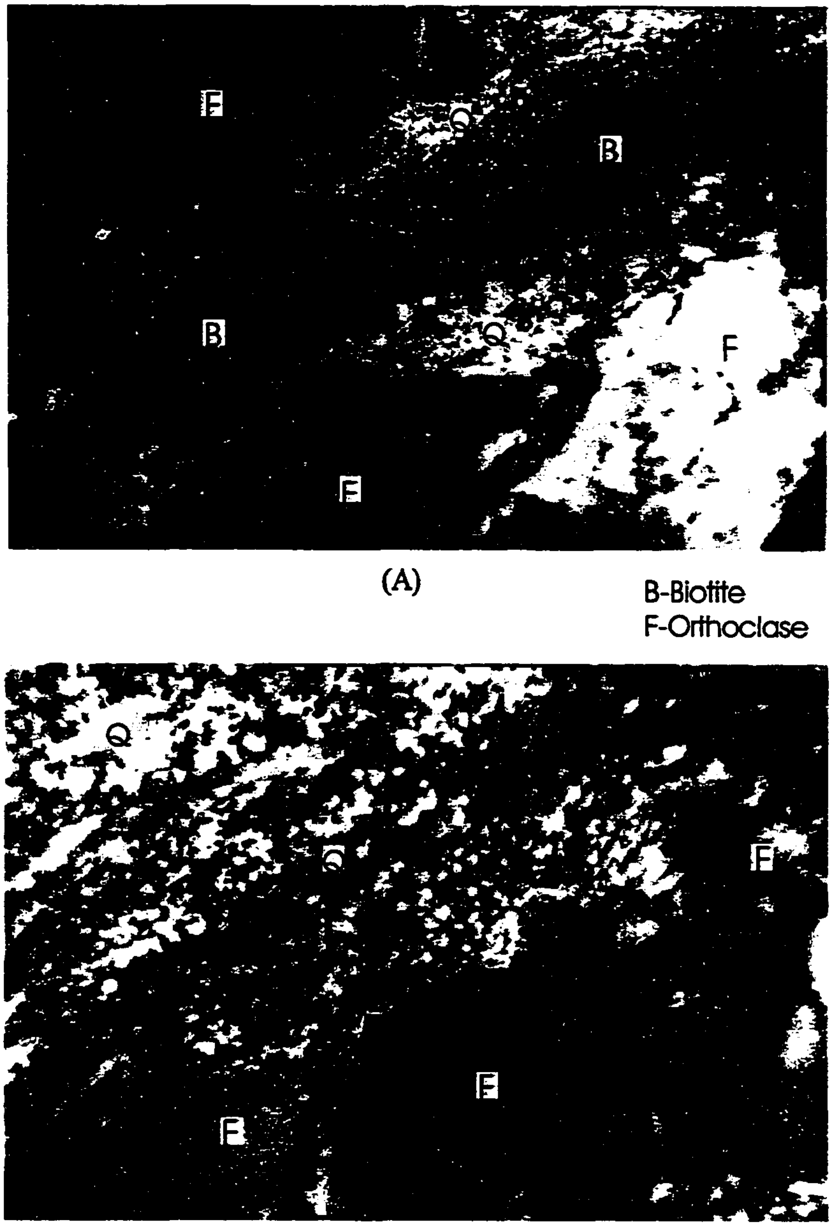


Figure 14. Photomicrographs of s-c mylonite. (A) Mica-fish, quartz sub-grain ribbons, and fractured feldspar grains. Width of view is 9 mm. (B) Residual quartz sub-grain ribbons (upper left) and kinked feldspar twins (lower right). Both have width of view 3.5 mm. Cross-polarized light.

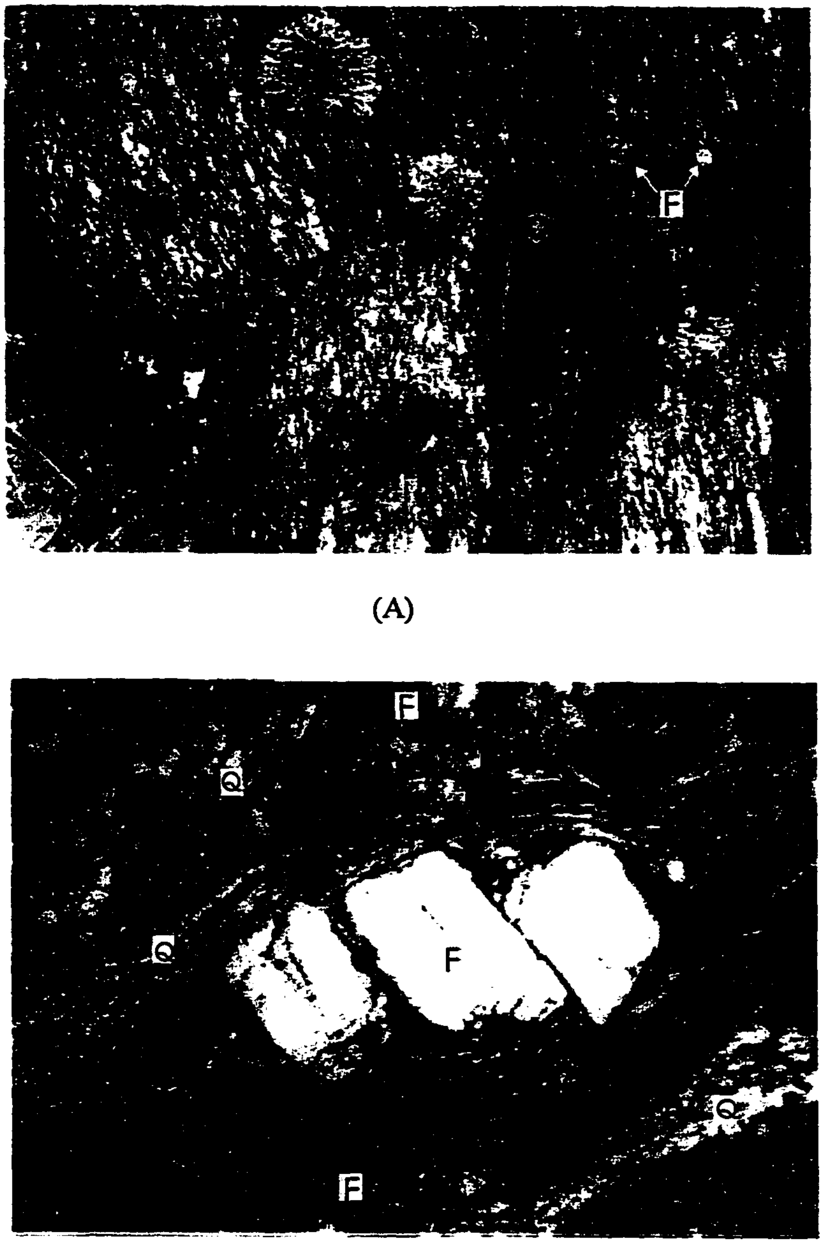
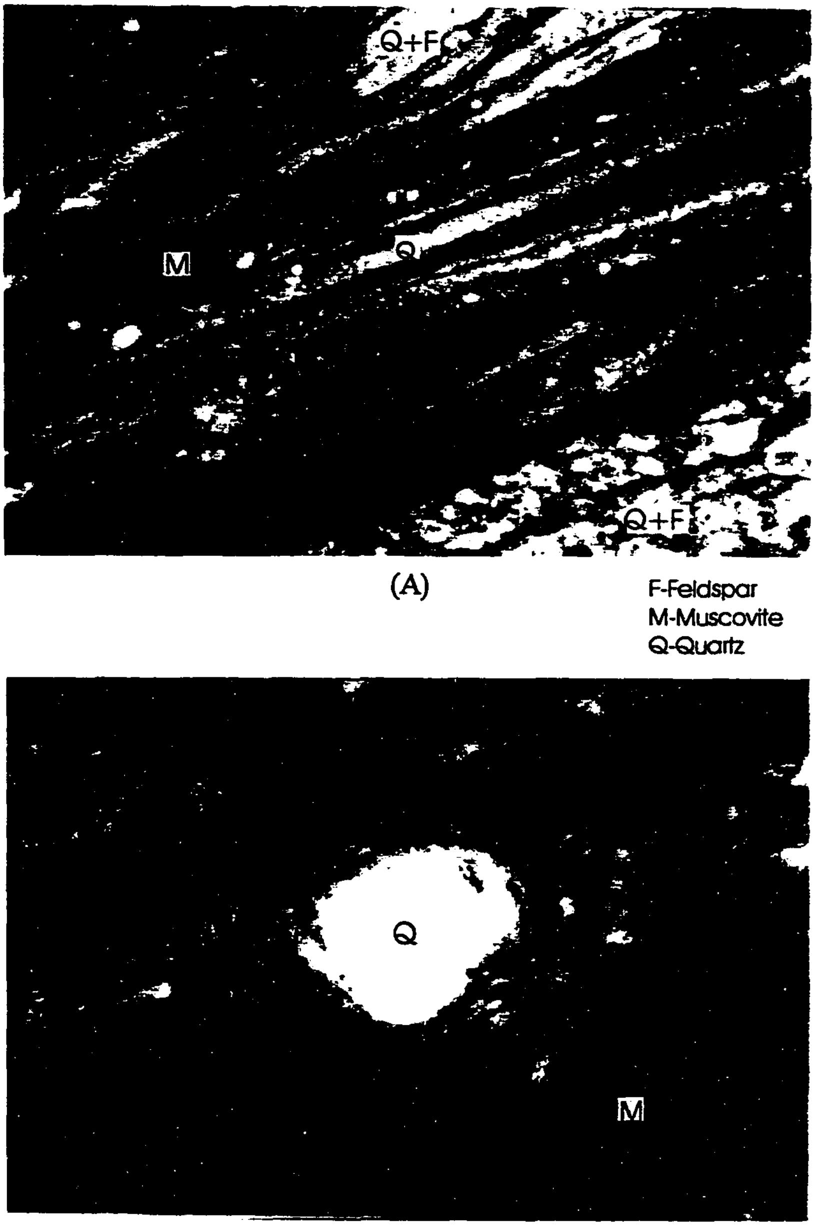


Figure15. (A) Typical granitic mylonite from mylonite and ultramylonite sub-zone. Viewer faces northwest. (B) Photomicrograph of mylonite showing brittlely-fractured feldspar grains wrapped by quartz grain ribbons, and imbricated feldspar grains that consistent withdextral shear sense. Width of view is 3.5 mm. Cross-polarized light.

quartz grains have been converted to complex sub-grain assemblages by dislocation and rotation recrystallization, and are extremely fine-grained in the ultramylonite sub-zones (Figures 16a and 16b). Porphyroclastic feldspars are fractured and broken into progressively smaller and mostly round and elliptical grains as one approaches the fault contact with the Flume Ridge Formation to the northwest. Some porphyroclastic feldspars are fractured and imbricated to form domino structures (Figure 15b) and occur as classic asymmetric sigma and delta shear indicators. Aggregates of small fragmental feldspar porphyroclasts are progressively stretched to become feldspar bands. Unlike quartz ribbons, however, these feldspar bands were not formed by plastic deformation but by cataclastic flow. The laminated structure caused by alternating quartz ribbons and feldspar bands is the dominant feature of the fine-grained mylonite and ultramylonite. Asymmetric features such as σ- and δ-type porphyroclasts (Figure 16b) are common, once again indicating dextral shear sense. Apparently because of a lack of fluids during mylonitization, the mylonite and ultramylonite are generally quite unaltered and contain mineral assemblages identical to those of their granitic protolith. Some ultramylonite, however, is rich in very fine-grained sericite most likely derived from plagioclase feldspars, and there is little alteration of the mafic minerals except for a few chlorite veins found in some thin sections.

The ultramylonite might be mistaken for mylonitized Flume Ridge Formation (phyllonite) since both are fine to very fine-grained and felsic. However, the granitic ultramylonite is tougher and harder and has potassium feldspar microporphyroclasts that are visible in thin sections. This sub-zone is adjacent to the phyllonite subzone in the Flume Ridge Formation described earlier, and together they define the highest strain



(B)

Figurel 6'. Photomicrographs of ultramylonite from mylonite and ultramylonite suzone. (A) shows asymmetric folds indicating dextral shear sense. Width of view is 3.5 mm. (B) shows a δ-type feldspar porphyroclast indicating dextral shear sense. Width of view is 0.9 mm. Both are cross-polarized light.

portion of the Kellyland ductile shear zone. The granitic mylonite and ultramylonite subzone also preserves lower-strain domains (such as coarse-grained s-c mylonite) due to the local heterogeneity of shear strain.

Aplite dikes have been found around the contact between the granite and Flume Ridge Formation at Fletcher Peak Cliff. These dikes have experienced the same shear strain as the host granite, and have also been converted to mylonite and ultramylonite.

4.4. Ductile Shearing and Deformation Mechanisms in Dioritic Rocks

Several small diorite and quartz diorite intrusions have been found within the NFS between Great Pond and the New Brunswick border. Some, such as the Berry Brook pluton (Ludman and Idleman, 1998; Figure 7) preserve most of their primary igneous texture and mineralogy, but those subjected to the ductile shear strain have been mylonitized. Examples include the Fletcher Peak cliff quartz-diorite that was completely sheared and smeared in the Kellyland ductile shear zone, and the quartz-diorite intrusion on the northwest side of the Lucerne pluton, the Parks Pond pluton (Griffin, 1976; Wones, 1977, 1980).

The Fletcher Peak Cliff quartz-diorite

A narrow slice (about 40 m) of strongly sheared medium- to fine-grained quartz diorite has been identified at Fletcher Peak cliff between the Deblois granite and Flume Ridge metasedimentary rocks in the zone of most intense ductile shear associated with the Kellyland fault zone (Figure 12). It contains several aplite dikes and the dikes are also mylonitized and ultramylonitized. The quartz-diorite is composed of hornblende, plagioclase feldspar, and quartz. In a manner comparable to that displayed by the Deblois granite, the primary igneous phases responded differently to ductile shearing. Plagioclase feldspars and some hornblende have been brittlely fractured and most have been broken into much smaller fragments, but some remain as ellipsoidal porphyroclasts or augen set in the highly comminuted matrix (Figure 17a). A large percentage of the hornblende crystals have been converted to secondary calcic amphibole; some are replaced by fine-grained biotite. In contrast, quartz grains have been dynamically recrystallized and have coalesced locally to form a ribbon texture that, along with aligned secondary amphibole and biotite, defines the mylonitic foliation (Figure 17a).

The Parks Pond quartz-diorite

Part of the Parks Pond pluton identified and mapped by previous workers (Griffin, 1976; Wones, 1977, 1980; Osberg et al., 1985) on the northwest margin of the Lucerne pluton (Figure 4) is dioritic according to this study. It has a typically fine- to medium-grained dioritic texture, and consists of mostly hornblende and plagioclase feldspar with some biotite and interstitial quartz. Minor pyroxene has also been identified. Detailed petrologic and petrogeochemical study is needed to find out details of the petrologic and petrographic variations, but for the purposes of this study the body will be described simply as a quartz diorite. Where its northernmost portion has been deformed along the Norumbega fault system, the massive quartz-diorite has been ductilely sheared and foliated to become dioritic mylonite (Figure 17b). The foliation is defined by alignment of elongated hornblende and feldspar, biotite, and quartz ribbons (Figure 17b). The amphibole is fragmented by shearing, and many grains have been partially retrograded to biotite during retrograde metamorphism apparently related to the shearing. Quartz has been dynamically recrystallized by sub-grain rotation and stretched to become quartz

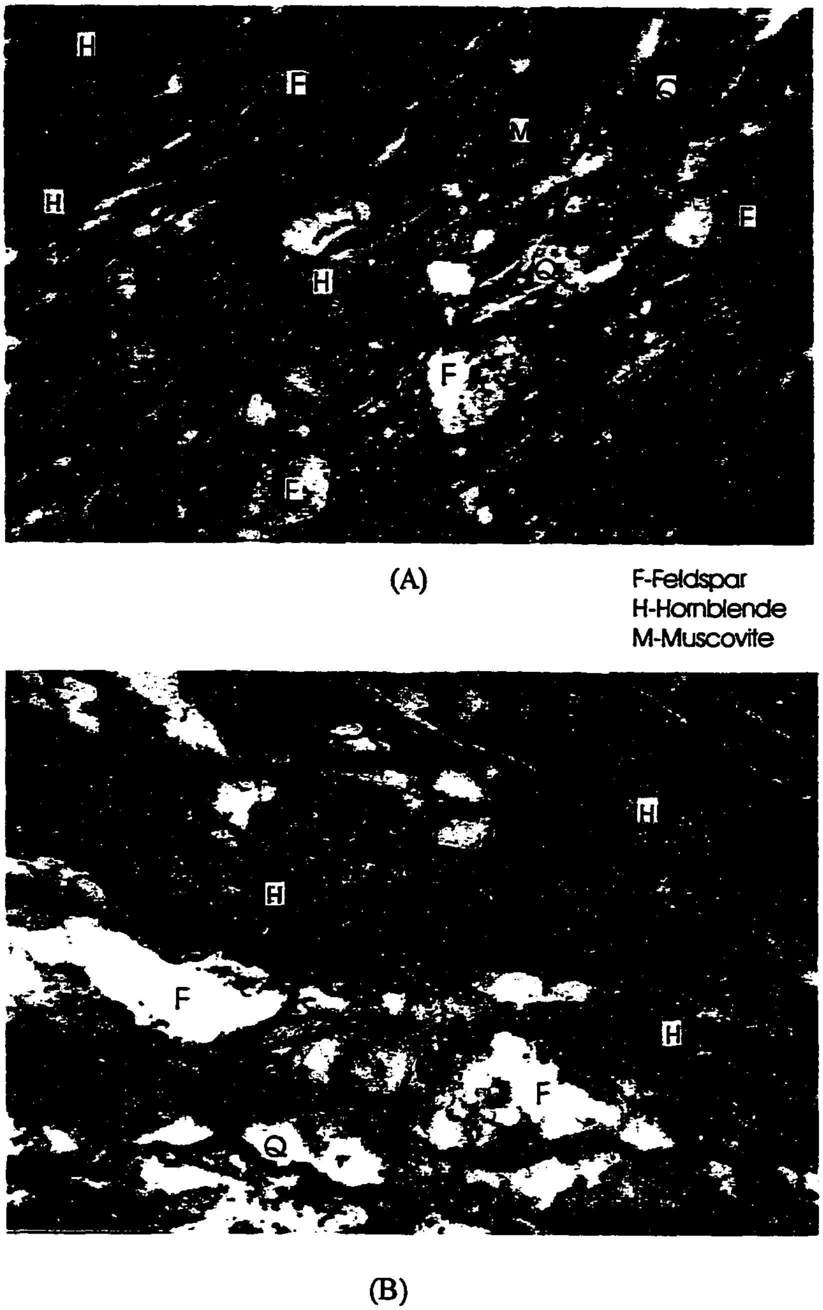


Figure 17. Photomicrographs of ductilely-sheared quartz diorite. Width of view is 3.5 mm. See text for explanation. (A) Fletcher Peak Cliff quartz diorite mylonite. Cross-polarized light. (B) Parks Pond quartz-diorite mylonite. Plane polarized light.

ribbons. Plagioclase is fractured and fragmented. The shear strain in the northern portion of the quartz-diorite is generally heterogeneous, with discrete anastomosing narrow shear zones striking mostly northeasterly, but becomes more homogeneous toward the central part of the Norumbega ductile shear zone.

4.5. Conditions of Ductile Shearing

Factors controlling the behavior of rocks during ductile shearing include temperature, confining pressure, strain rate, differential stress, lithology, and partial pressure and composition of fluids. The freshness of most feldspars and ferromagnesian minerals in even the zones of highest strain in the Deblois granite in Kellyland zone suggests that there was not much fluid-rock interaction during deformation, i.e. the granitic rocks were relatively dry, compared to the Flume Ridge metasedimentary rocks in the spangled muscovite-quartz schist zones and some quartz-vein-rich phyllonites in the Waite zone. There is no evidence concerning strain rate, but it is possible to closely constrain the temperature and ambient pressure during Norumbega ductile shearing in eastern Maine.

Temperature

Differential deformation mechanisms of specific minerals provide a key to the temperature during faulting. Studies of both experimentally and naturally deformed rocks have led to a basic understanding of the relationship of intracrystalline microstructures for quartz and feldspar and their deformation temperatures (e. g. Tullis et al., 1985; Simpson, 1985; Hirth et al., 1992; Srivastava et al., 1996). A widely-accepted threshold established by these studies is that the onset of crystal plasticity for quartz is ~300°C in naturally deformed rocks. Feldspar deforms mainly by such brittle processes as internal microfracturing, brittle cataclastic flow, kinking, and twinning at such low temperatures. Crystal plastic deformation of feldspar begins at higher temperature upper greenschist facies (400-450°C) conditions by mechanisms such as dislocation climb.

With the assumptions that (1) strain rate and differential stress were constant, and (2) the experimental results can be safely applied to the natural environment, these thresholds can be used to estimate deformation temperature and its possible variations along the strike of the NFS. All the rocks involved in the ductile shearing in eastern Maine contain quartz and feldspar. As described above, regionally consistent microstructures have been developed in quartz and feldspar grains in all these rocks, except the spangled muscovite-quartz-schist, in the area between the northwestern side of the Lucerne pluton and the New Brunswick border. Quartz has undergone extensive dynamic recrystallization to form fine, approximately equant, recrystallized grains. Relict quartz grain ribbons are very common in granite and dioritic mylonites (Figures 14a, b, 15b, and 17a), and these ribbons contain subgrains the same size as the surrounding recrystallized grains in mylonite (Figures 14a, b and 15b). The presence of ribbons and recrystallized grains at grain boundaries indicates the operation of dislocation climb. The recrystallized grains formed by subgrain rotation with minor grain-boundary migration, indicating moderate temperature conditions of "Regime 2" as proposed by Hirth and Tullis (1992). Quartz in phyllonite is mostly flattened and core-and-mantle structure is seen in some quartz grains (Figures 8a and 9a). The dominant deformation behavior in feldspars was brittle microfracturing, including antithetically imbricate fractured feldspars in all strain facies, and cataclastic flow in the zones of highest strain (Figures

14a, 14b, and 15b). Some twin-laminae kinking and undulose extinction have been observed (Figure 14b) but no other plastic deformation structures have been observed in either plagioclase or alkali feldspars.

Therefore, the contrasting behaviors of quartz and feldspars in all lithologies described above constrain the deformation temperature during ductile shearing to be on the order of 300-350°C. The presence of antithetically imbricate fracturing or "bookshelf" microfracturing (Passchier and Trouw, 1996) in feldspar (Figure 15b) in granitic mylonite also suggests a similar temperature (Pryer, 1993).

Confining pressure

Metamorphic mineral assemblages, thermochronologic studies of the Deblois pluton, and textures in several plutons indicate that the part of eastern Maine transected by the Norumbega fault system was situated at shallow crustal levels at the time that ductile shearing began. The evidence for this conclusion is presented in detail by Ludman et al. (1999, 2000) and will be summarized briefly here.

The very low intensity of regional metamorphism that characterizes all terranes in eastern Maine (lowest greenschist facies; sub-greenschist facies) indicates relatively low lithostatic pressures during the Acadian folding that preceded Norumbega activity. The absence of kyanite and presence of andalusite and sillimanite in contact aureoles surrounding post-Acadian plutons clearly defines pressures below the aluminosilicate triple point throughout the entire study area.

$^{40}Ar/^{39}Ar$ thermochronology studies of potassium feldspar from the undeformed Deblois pluton at Wabassus Mountain indicate extremely rapid cooling for the batholith (Idleman and Ludman, 1998; Ludman et al., 2000). These rates, at or exceeding

100°C/million years, are consistent with what would be expected at a very shallow position in the crust. Finally, miarolitic cavities reported in granite batholiths close to the study area have been used to infer depths shallower than 7 km.

These lines of evidence combine to indicate a crustal depth of approximately 5-7 kilometers for the rocks of the study area prior to onset of fault activity in the Waite and Kellyland fault zones of the Norumbega system. This depth corresponds to confining pressures of approximately 2-2.5 Kbars.

CHAPTER 5

EVOLUTION OF NORUMBEGA DUCTILE SHEARING IN EASTERN MAINE

Four additional pieces of information are needed in order to decipher the ductile history of the Norumbega fault system in eastern Maine: the precise timing of deformation, the internal geometry of the fault system, the kinematics associated with ductile shearing, and their changes (if any) during this early phase of Norumbega activity. New information about kinematics and geometry, particularly in the previously unstudied area between Great Pond and Fletcher Peak, has proved valuable in understanding the complex faulting between the Waite and Kellyland zones. For example, several slivers of granite have been mapped between the Waite and Kellyland zones, roughly parallel to the fault system, and were deeply involved in the ductile shearing. Understanding their spatial distribution, deformation nature, origin, and relation to the major regional granitic plutons is essential for reconstructing the regional ductile shear pattern and the evolution of the ductile shearing in eastern Maine. This chapter presents a model for the evolution of progressive Norumbega ductile deformation in eastern Maine, based largely on new information obtained during this study. New evidence for the timing of ductile shearing will be discussed later, in Chapter 7.

5.1. Shear Zone Geometry: Relationships Among Granite Slivers and Major Plutons

It has long been known that granitic rocks have been affected by Norumbega faulting and that granitic fault slivers exist between the Waite and Kellyland zones in the area between Great Pond and Amazon Mountain, but the geometry shown by previous mappers (e. g. Osberg et al., 1985; Ludman, 1994, 1998) proves to have been too simplistic. Mapping from Fletcher Peak southwestward to the Great Pond area reveals three separate granitic slivers: from northeast to southwest, they are here named the Amazon Mountain granite, the Third Lake Ridge granite, and the Morrison Ridge granite (Figure 4). In addition to the information they yield about fault geometry, the relationships of these slivers to the major batholiths of the region could provide valuable clues for measuring post-intrusion fault displacement along the NFS (Ludman, 1998).

The Amazon Mountain granite

The easternmost granite sliver, the Amazon Mountain granite, crops out between Wabassus and Amazon mountains (Figure 4). Previous workers showed the Amazon Mountain granite as being connected to the eastern lobe of the Deblois pluton, although locally cut by faults in the area between Grand Lake Stream and Wabassus Mountain (Larrabee, 1964; Ayuso, 1984; Osberg et al., 1985; Ludman, 1995, 1998, 1999b). However, at least two distinct lines of evidence indicate that it should be considered as a separate and independent intrusion.

(1) *The Deblois and Amazon Mountain granite are nowhere in direct physical contact:* Detailed mapping in the Kellyland fault zone on the northwest side of Wabassus and Little River mountains has identified a zone of phyllonite derived from the Flume Ridge Formation that separates the two granite bodies.

(2) *The two bodies are mineralogically and texturally distinct*: The Amazon Mountain granite is uniformly medium-grained and finer than any granite in the nearby eastern lobe of the Deblois granite. The medium grain size is even smaller than the slightly chilled but still coarse-grained marginal facies of the eastern part

of the Deblois pluton at its contact with the Flume Ridge Formation. Petrographically, the Amazon Mountain granite contains more quartz and less ferromagnesian minerals than the Deblois although both plutons are hornblende-biotite granites. No porphyritic granite associated with more mafic varieties--characteristic of both Deblois and Bottle Lake plutons—has been found within the Amazon Mountain granite. Rapakivi textures and microcline phenocrysts, characteristic of the east lobe of the Deblois pluton, are also absent from the Amazon Mountain body.

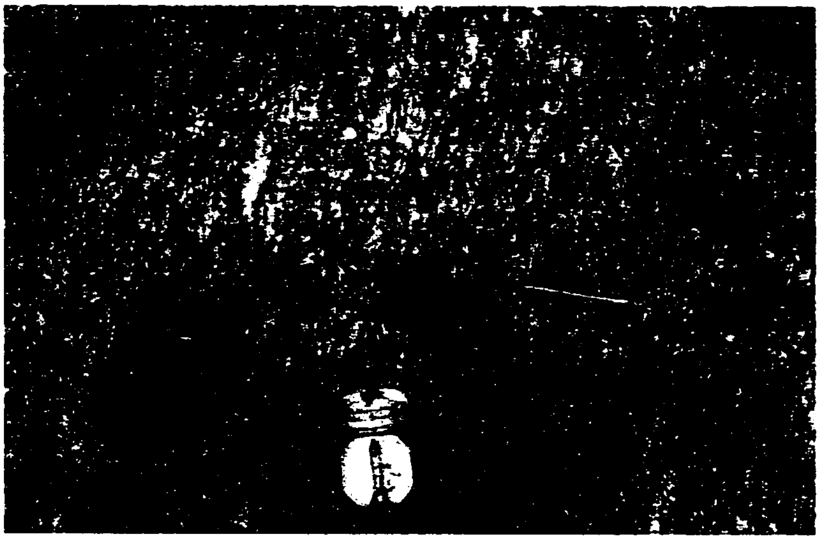
The same textural and mineralogical differences also distinguish the Amazon Mountain granite from its neighbor to the northwest, the Bottle Lake pluton, from which it is separated by the Waite composite fault zone—first by another zone of Flume Ridge Formation phyllonite and then, to the northwest, by mylonite developed in the Bottle Lake granite. The Amazon Mountain granite is therefore considered to be an independent pluton and a new member of the large granite family in eastern Maine. Additional geochemical and geochronologic data are needed to fully characterize the pluton, and the work to provide the latter is under way.

The Third Lake Ridge granite

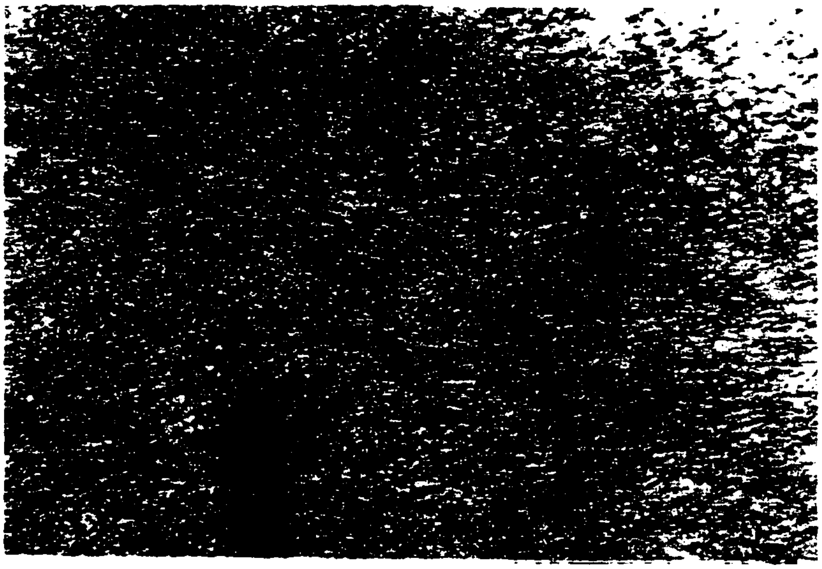
The largest and most elongate sliver, the Third Lake Ridge granite, extends southwestward from Third Lake Ridge and Wabassus Lake to the southeast side of Nicatous Lake (Figure 4). It, too, is separated by fault-bounded slivers of Flume Ridge rocks from the nearby Bottle Lake pluton to the northwest, and from the Deblois pluton in the area between Third Lake Ridge and Sabao Mountain. The Third Lake Ridge granite can be subdivided into two phases based on textural and mineralogical criteria (Figures 4, 12).

The northwestern half of the Third Lake Ridge sliver consists of coarse to megacrystic, pink microcline-rich, hornblende-biotite granite identical to the main phase of the Deblois pluton. Rapakivi texture is common throughout the Third Lake Ridge granite. It is ductilely deformed and locally mylonitized and ultramylonitized to become granitic protomylonite and mylonite (Figure 18) similar to that in the Deblois pluton in the Kellyland fault zone described above. Conditions and mechanics of its ductile deformation are also the same as in the Deblois. Typical s-c structures are common in higher strained zones. Quartz grains are plastically deformed into quartz ribbons and dynamically recrystallized, feldspars are rotated and fractured to become porphyroclasts, and several meter-wide mylonite and ultramylonite zones have been found, mostly in the northwest contact zone with the Flume Ridge Formation. Shear sense indicators such as s-c structures and asymmetric σ and δ feldspar and quartz porphyroclasts all suggest dextral shearing.

The southeastern half of the sliver is medium-grained, finer than either the coarse grained variety just described or the main body of the Deblois pluton. It is also a pink microcline-rich, hornblende-biotite granite. Most of this textural variety is also ductilely sheared and foliated (Figure 18). Quartz is smeared and dynamically recrystallized and s-c structures are also seen in zones of high strain. All shear-sense indicators (sigmoid shear patterns, s-c structures, asymmetric feldspar porphyroclasts) suggest dextral simple shearing geometrically compatible with the shearing within the coarse-grained granite.



(A)



(B)

Figure 18. Ductilely-sheared Third Lake Ridge granite sliver. (A) Mylonitic granite in the coarse-grained phase. Plan view and compass pointing to north. (B) Mylonitic granite in the medium-grained phase. Mylonitic foliation strikes 075°, showing existence of synthetic shears. In the middle is a narrow superimposed dextral shear zone with typical s-c' structure. Plan view and pen pointing to north.

Reconnaissance mapping in the area south of Nicatous Lake reveals lithologic variations in the western lobe of the Deblois pluton comparable to those observed in the Third Lake Ridge granite sliver (Figure 4). Riley and Barton (2000) also describe comparable phases farther south in the western lobe of the Deblois pluton. Therefore this study suggests that the Third Lake Ridge sliver was initially connected to the western lobe of the Deblois pluton.

The Morrison Ridge granite

The Morrison Ridge granite sliver, located between the southwest side of Nicatous Lake and Great Pond, is best exposed on and near Morrison Ridge on the southwest side of Nicatous Lake (Plate I and Figure 4). It is bounded on the north by one of the post-Acadian redbed slivers and on the south by a narrow zone of high-strain Flume Ridge phyllonite that separates it from the Third Lake Ridge granite (see Figure 30). Texturally and petrographically, it resembles the Lucerne granite (Wones, 1980) and the coarse-grained phase of the Third Lake Ridge granite sliver in that it is a coarse-grained and megacrystic leucocratic hornblende-biotite granite composed mostly of pink perthitic microcline, white sodic plagioclase, and interstitial quartz. Few textural and petrographic differences have been noted between the Lucerne and the coarse-grained phase granite of the Morrison Ridge granite. The whole Morrison Ridge sliver is uniformly sheared and foliated with the foliation generally striking at 010°-055°.

Wones (1980) reported that the northern part of the Lucerne pluton had been removed by Norumbega faulting, but wondered where the truncated part had been transported. This study suggests that the Morrison Ridge granite sliver was the removed part of the Lucerne pluton, and that it was dextrally dragged along the Kellyland ductile shear zone from its initial position near the northern boundary of the Lucerne. Their similar mineralogies and textures, the teardrop shape of the Morrison Ridge granite, and elongated gooseneck shape of the Lucerne pluton all support this suggestion.

Synthetic regional-scale shear bands within granite slivers

The Waite and Kellyland zones converge from northeast to southwest, nearly merging at the longitude of Great Pond (Figure 4). It was mentioned earlier that the Amazon Mountain granite was least affected by the ductile shearing but shear strain increases southwestward into the area of convergence. The fault-bounded Morrison Ridge and Third Lake Ridge granite slivers were almost entirely sheared and foliated into protomylonite and mylonite.

Detailed mapping in the Fletcher Peak and Gassabias Lake 7.5' quadrangles has revealed some of the geometric complexities associated with convergence of the two master ductile shear zones (Figure 4). A well-exposed high-strain zone mapped within the Third Lake Ridge granite in the northern part of the Fletcher Peak quadrangle strikes 075°, much more easterly than either the Waite or Kellyland zone (Figure 12). Foliation normally striking 015°-035° in the Third Lake Ridge granite also swings into a more easterly orientation in this high-strain zone (Figure 18). This high-strain zone extends eastward into phyllonite derived from the Flume Ridge Formation, and terminates by merging with the Kellyland ductile shear zone in Third Machias Lake. Scattered exposures of similarly oriented high-strain zones within the Third Lake Ridge granite sliver suggest that there are additional ENE-trending high-strain zones that connect the Waite and Kellyland master faults (Figure 4). Once again, all kinematic indicators such as s-c and s-c' structures (Figure 18) indicate dextral strike-slip shearing.

The geometry of these high-strain zones is interpreted as representing a set of second-order, synthetic dextral shear bands developed in the zone where the Waite and Kellyland master ductile shear zones converge. These dextral shears resemble c' bands in a typical megascopic s-c' shear system. Differential shear strain intensity in this convergent zone, these synthetic regional-scale shear bands, and the effects of deformation on the different granite slivers help decipher the progressive evolution of the region during Norumbega ductile shearing phase.

5.2. Summary of Small-scale Structures and Fault Kinematics

Structures and fabrics generated by ductile shearing in the metasedimentary rocks, granite batholiths, and igneous fault slivers provide hitherto unreported information on NFS kinematics. Coupled with the local and regional fault geometries just detailed, these permit interpretation of the kinematics associated with the early-stage ductile shearing. Features used to infer kinematics include the following:

Foliation. The foliation (S_2) generated by the ductile shearing in Flume Ridge Formation metasedimentary rocks in both the Waite and Kellyland ductile shear zones is readily distinguished from the axial-plane foliation (S_1) associated with the Acadian upright folding that preceded Norumbega ductile shearing. The S_2 foliation is typically strongly penetrative, and is characterized by strong preferred grain-shape orientation of quartz and feldspars in zones of moderate to intense strain (Figures 8a and 9a). In contrast, the early axial-plane S_1 foliation is broadly spaced, only weakly developed even in pelitic rocks, and quartz and feldspar rarely exhibit grain-shape-preferred orientation.

The fault-generated foliation is defined in the metasedimentary rocks by alignment of phyllosilicates such as muscovite, biotite, and chlorite, and in the granites by aligned and elongated feldspar porphyroclasts outlined by quartz ribbons (Figure 15b) and aligned biotite flakes. In the Fletcher Peak area where the eastern lobe of the Deblois pluton is cut by the Kellyland ductile shear zone, the shear foliation changes from a northerly (355-010°) orientation in the low-strain zone (foliated and protomylonite zone) to a northeasterly (040-050°) orientation in the highest strain zone (mylonite and ultramylonite zone; Figures 12 and 19). The steepness of the foliation and the sigmoidal pattern are consistent with dominantly dextral strike-slip fault motion (Figure 12).

Mineral elongation lineations. Mineral elongation lineations are well developed on foliation planes in both sheared granite and metasedimentary rocks throughout the study area. These are defined by elongated minerals in the granites (Figure 20), and by elongated quartz and feldspar grains in strongly sheared quartzofeldspathic wackes and pelites. Figure 19 shows the range of attitudes of the stretching lineation; nearly all are sub-horizontal or plunge very gently (10°-15°) to the southwest, supporting the interpretation of dominantly strike-slip motion.

Small-scale synkinematic folds. Three types of outcrop- to hand sample-scale folds have been observed within the ductile shear zones, each generated by a different deformation event. The earliest folds are parasitic to the Acadian upright folds in the Flume Ridge Formation. The second set was synkinematic with respect to the ductile shearing event. Most folds of this set are dextrally asymmetric, tight, and plunge very steeply to vertically. Even the pre- or syn-kinematic quartz veins and boudins in high strain metasedimentary rocks exhibit these asymmetric folds. Similar asymmetric folds

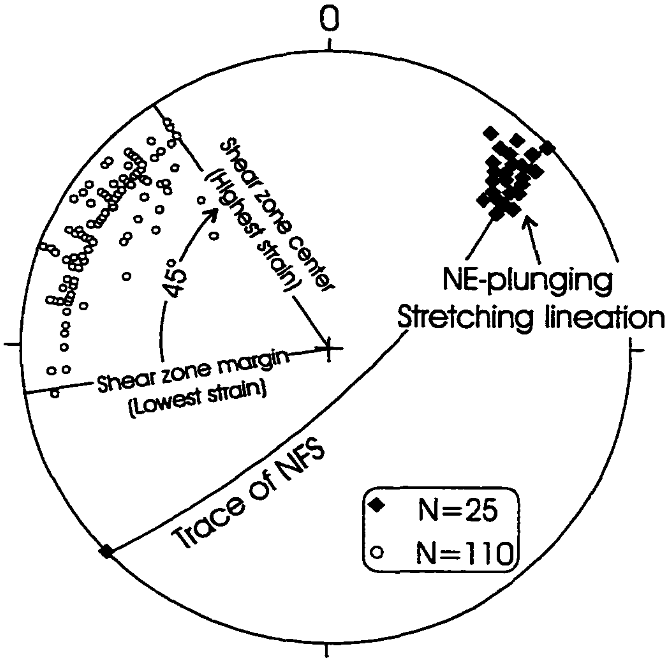


Figure 19. Equal-area stereogram of poles to mylonitic foliation (open circles) in the Deblois granite in Kellyland ductile shear zone in Fletcher Peak area and stretching lineations (diamonds) measured along the ductile shear zones.

Figure 20. Stretching lineation in granitic mylonite in Kellyland ductile shear zone. Vertical view facing southeast. Southwest side of Slewgundy Ridge.

have been seen at the thin-section scale (Figure 16a). These are interpreted as resulting from progressive deformation during the ductile shearing, and the asymmetric nature of the folds is attributed to dextral simple shearing. No sheath folds have been observed. The third set includes folded phyllonites with hinge lines that plunge gently to the southwest, and are suggested to have been generated by post-ductile stage brittle faulting discussed in Chapter 6.

Boudinage. The interbedded wacke and siltstone layers and synkinematic quartz veins in sheared metasedimentary rocks were boudinaged in the ductile shear zones (Figure 9b). The competent wacke beds and quartz veins formed foliation-parallel boudin strings and isolated boudin lenses. The neck lines of the boudin lenses (b-lineation) are near vertical (e. g. Figure 9b) and mostly perpendicular to the near-horizontal stretching lineation, also indicating a strike-slip shearing.

S-C structures. Typical s-c structures have been developed mostly in the s-c mylonite sub-zone in Deblois granite in the Kellyland ductile shear zone as discussed earlier (Figure 13b). S-C structures have been also developed in high-strain phyllonite and muscovite-quartz-schist (Figure 10b), and are also present at the microscopic scale in thin sections. They too indicate dextral simple shearing.

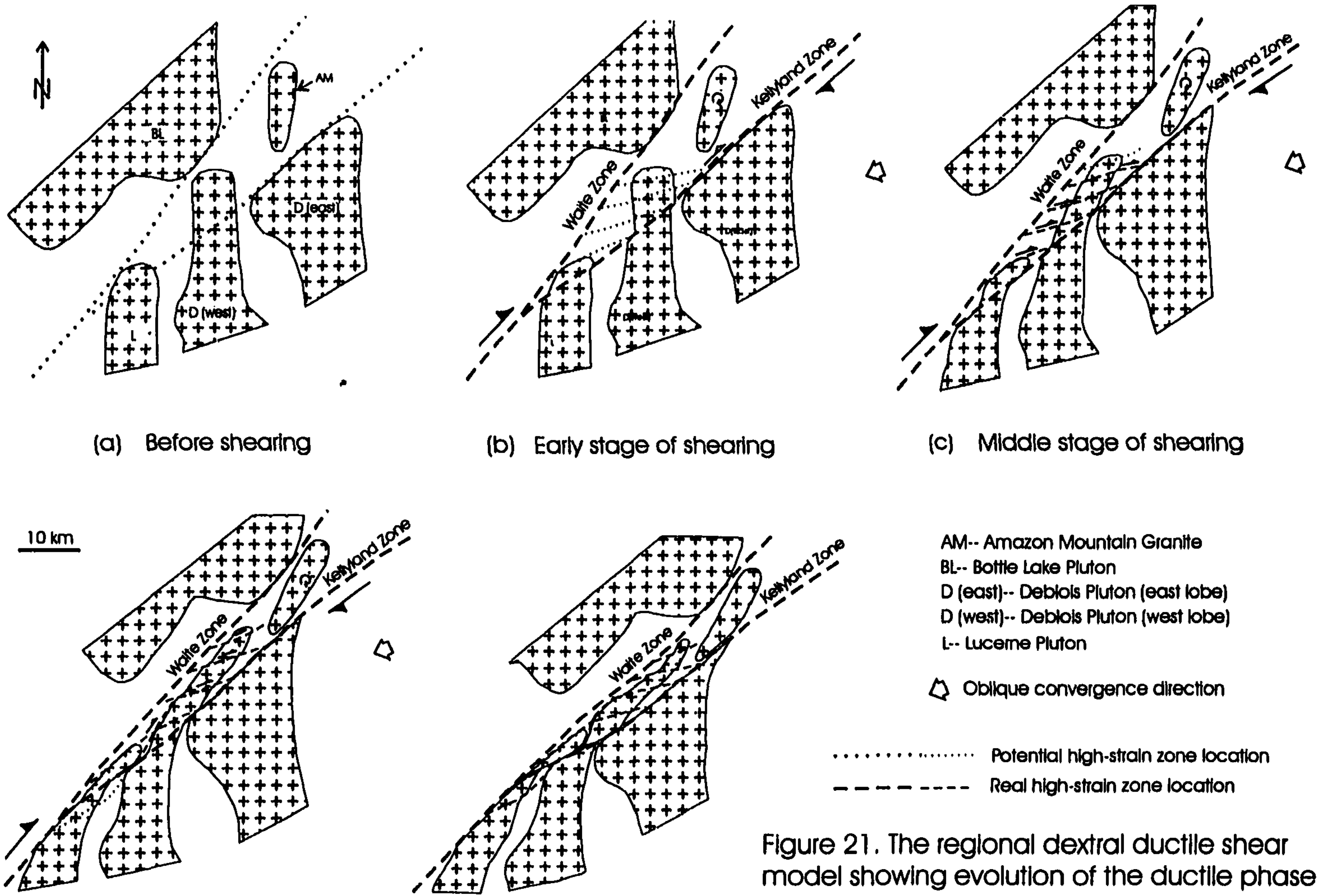
Microstructural kinematic indicators. Asymmetric, σ and δ feldspar and quartz porphyroclasts are common in granitic mylonite and ultramylonite, and even in some of the high-strain phyllonite (e. g. Figures 8b and 16b). Imbricate domino-style fractured feldspars are also developed in granitic mylonite (Figure 15b), and abundant mica fish have been observed in the coarse muscovite-quartz-schist (e.g. Figure 10b) and in granitic mylonite (e. g. Figure 14a). These microstructures and kinematic indicators consistently demonstrate that the ductile faulting was dextral, and dominantly strike-slip in character.

5.3. Evolution of Norumbega Ductile Shearing in Eastern Maine

Megascopic, outcrop-scale, and microscopic kinematic indicators confirm the dextral strike-slip movement along the Norumbega system during ductile shearing, and agree with previous studies which suggested that the ductile shearing occurred during oblique transpressional convergence in the Northern Appalachians (e. g., Keppie, 1989; Swanson, 1999b). Figure 21 is a model for the evolution of the Norumbega ductile shearing in eastern Maine constructed from data acquired during this study. A continuous, progressive transpressional and convergent deformation history is envisaged for the Norumbega shear system in eastern Maine that can be divided into three main stages.

(1) Early stage of dextral shearing and deformation partitioning (Figure 21b)

Norumbega shearing began as ductile deformation and strain was partitioned into two master ductile shear zones in the study area, the Waite and Kellyland fault zones. These strands appear to splay from a single high-strain zone northeastward from the Great Pond area. The Waite zone maintains its high-strain character all the way to the New Brunswick border, whereas strain in the Kellyland zone becomes more diffuse east of the town of Grand Lake Stream. Strain partitioning may have been at least partially due to lithologic anisotropy, as the Kellyland zone largely follows the contact between the Deblois pluton and its host Flume Ridge Formation. The northern part of the Lucerne pluton was also cut by the Kellyland zone and progressively dragged toward the



(a) Before shearing

(b) Early stage of shearing

(c) Middle stage of shearing

(d) Late stage of shearing

(e) Final

Figure 21. The regional dextral ductile shear model showing evolution of the ductile phase in the Norumbega fault system in eastern Maine. See text for explanation.

northeast. The originally elongated west lobe of Deblois pluton was cut by the Kellyland zone as well, and its northern part was progressively dragged northeastward.

(2) Middle stage of dextral shearing and development of synthetic shears (Figure 21c)

Dextral movement continued in the Waite and Kellyland zones, dragging the displaced segments of the Lucerne (Morrison Ridge sliver) and the west lobe of the Deblois (Third Lake Ridge sliver) farther northeastward from their original positions. Shear strain was distributed broadly in the area between the Waite and Kellyland zones, causing the granite slivers to be completely sheared and foliated. Synthetic shears began to develop in the Third Lake Ridge granite sliver at this time. The progressive dextral shearing in these synthetic shears dragged this granite sliver farther northeastward in a stepwise manner.

Interestingly, the relationship of these synthetic shears to the master shear zones resembles that of typical small-scale c' bands, so that the geometry involving the synthetic and first order shear zones can be viewed as a megascopic s-c' structure. Small-scale c' bands are generally considered to reflect a component of continued extension, and are therefore called "extensional crenulation cleavage" (e.g. Platt and Vissers, 1980). Passchier and Trouw (1996) claim that c' bands are particularly well developed in stretching shear zones. Therefore this megascopic s-c′ structure may reflect a local component of extension parallel to the Norumbega shear system during the development of the synthetic shears. It is suggested that although the overall tectonic environment was oblique transpressional and convergent, the block between the Waite and Kellyland ductile shear zones was caught in an escaping or releasing environment that caused the local extension component parallel to the fault system.

(3) Late stage of extended dextral shearing (Figure 21d)

Protracted dextral shearing and displacement continued along both the Waite and Kellyland zones, but more shear strain was concentrated in the synthetic shears, displacing the Morrison Ridge and Third Lake Ridge granite slivers farther from their original positions. With continued dextral shearing, these slivers became extremely elongate and attained their present shapes. At this time, a few very narrow (around 1-10 m in width) dextral shear zones striking at 020-035^0 developed in the Amazon Mountain granite.

Throughout this evolution, the block between the Waite and Kellyland master shear zones was thinned and extended due to transpressional convergence along the shear system, leading to the c′-band-like synthetic shears. This thinning demonstrates that there was apparently increasing amount of flattening toward the conjunction between the Kellyland and Waite ductile shear zones and that the non-coaxial dextral shear is not a strict simple shear but a kind of sub-simple shear defined by De Paor (1983).

While intense shearing in the apex of the zone of convergence of the Waite and Kellyland fault zones was causing intense strain in the Third Lake Ridge and Morrison Ridge slivers, the Amazon Mountain granite is believed to have been an independent rigid body located in a region of much less stress where the Waite and Kellyland ductile shear zones are separated by a greater distance. In this model, the Amazon Mountain granite could have begun clockwise rotation during the first stage of ductile shearing, but there is insufficient evidence in the granite and surrounding metasedimentary rocks to confirm such behavior. Ductile shear strain in the Amazon Mountain sliver is low and was likely concentrated in the relatively "soft" Flume Ridge metasedimentary rocks surrounding this pluton, with the exception of the few narrow shear zones mentioned above.

5.4. Estimated Shear Strain and Displacement

Shear strain (γ) is a function of the angle (θ') between shear bands, i.e. s-foliation in sheared granites, and the shear zone boundary or shear direction: $\gamma=2/\tan 2\theta'$ (Ramsay and Huber, 1983). Since the amount of shear strain is heterogeneous in the shear zones in the study area, this angle changes from about 45° at the shear zone margin to near 0° in the zone of highest strain where s-foliation is essentially parallel to the c-bands. For example, θ' ranges from 15° to 10° in the transition between the protomylonite and s-c mylonite sub-zones in the sheared Deblois granite in the Kellyland ductile shear zone between Wabassus Mountain and Fletcher Peak, yielding an estimate of shear strain between 3.5 and 5.5. Shear strain increases sharply through the s-c mylonite, mylonite, and ultramylonite sub-zones, where θ' becomes very small (near 0).

The displacement along the Kellyland master ductile shear zone and the synthetic shears can be estimated assuming the origins of the Morrison Ridge and Third Lake Ridge granite slivers have been correctly identified as the Lucerne and western lobe of the Deblois pluton, respectively. Because the subsequent multiple brittle faulting episodes along the Norumbega fault system were concentrated in the Waite zone, the earlier ductile shear pattern and geometry southeast of the Waite zone have been well preserved.

This enables us to measure the original displacement made by the earlier ductile shearing. Based on the dextral sub-simple shear character of the shear system and using the shear model discussed above, restoration of both the Morrison Ridge and Third Lake Ridge granite slivers to their assumed original positions yields approximately 25 km of dextral strike-slip offset (Figure 22). This figure applies to only the Kellyland zone and the synthetic shears. Motion on the Waite and Codyville zones is not readily estimated due to lack of offset markers and superposition of subsequent multiple brittle faulting and displacement.

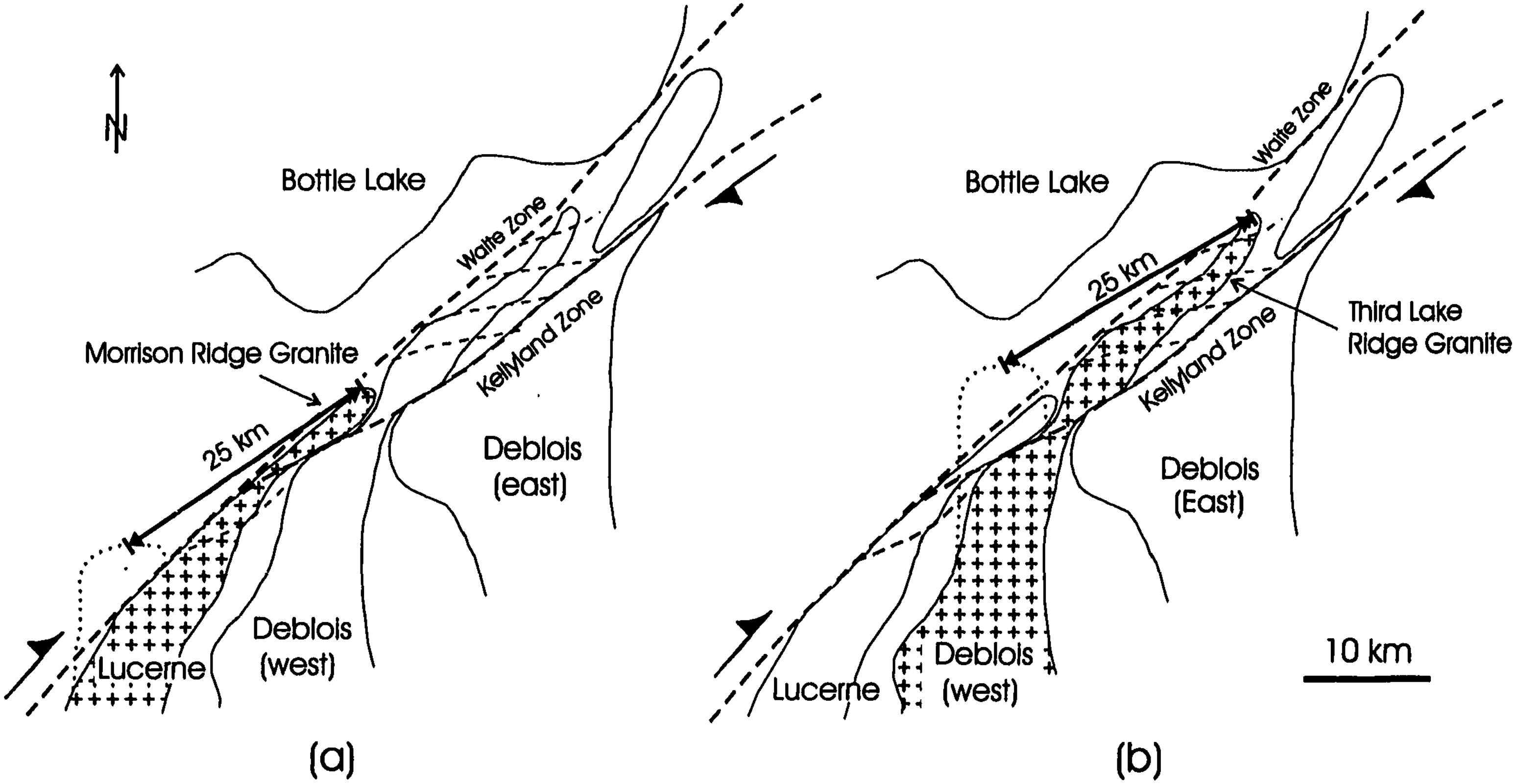


Figure 22. Displacement estimates from restoration of displaced Morrison Ridge granite sliver (a) and the Third Lake Ridge granite sliver (b).

CHAPTER 6

BRITTLE FAULTING:

MULTIPLE REACTIVATION OF THE NORUMBEGA FAULT SYSTEM

6.1. Introduction

This chapter focuses on the late-stage brittle faulting activities along the Norumbega fault system in eastern Maine, where evidence for these events is well exposed. Little attention has been paid to post-Acadian brittle deformation in Maine (Ludman and Gibbons, 1999; Ludman et al., 1999) because it scarcely affects older structures and the regional map pattern. However, field work in the Norumbega fault system in eastern Maine has shown that outcrop-scale structures, such as brittle faults, veins, and joints, are extensively superimposed on the Fredericton belt metamorphic rocks, the Devonian plutons, the 380 Ma ductile shear zones, and the redbeds.

Although brittle reactivation of early Norumbega ductile shear zones has been documented in both metasedimentary (Ludman, 1998) and granitic rocks (Ludman and Gibbons, 1999), this study is the first attempt to analyze the changing dynamics and stress fields associated with the brittle events. Because these brittle structures record the orientation of the post-Acadian stress fields, their analysis is critical for an understanding of the evolution of intraplate deformation in the Appalachian orogen and the nature of brittle reactivation of the pre-existing Norumbega ductile shear system discussed in Chapters 4 and 5. Therefore, an intensive investigation has been made of the small-scale brittle structures throughout the study area.

Cross-cutting relationships among outcrop scale faults and conjugate fault pairs permit recognition of three distinct episodes of compressional brittle faulting (Brittle Episodes 1, 2, and 3) that followed a transitional event involving mostly brittle mechanisms but still exhibiting some ductile features. Evidence for these events and their relative temporal positions will be presented first, followed by an analysis of the stress fields accompanying each. A discussion of the absolute ages of these events is presented in Chapter 7.

6.2. Study Methods

Small- or outcrop-scale vertical- or near-vertical "X" conjugate faults and joints are well developed both within and outside of the NFS in eastern Maine. Basically, they are not R shears produced by strike-slip faulting, but rather products of regional tectonic compression events. Based on Anderson's theory of faulting (Anderson, 1942, 1951) and Hartman's rule that the maximum principal stress direction bisects the acute angle between conjugate faults, the maximum principal stress directions could be deduced from the attitudes of these conjugate faults. However, care must be taken to insure that small-scale conjugate faults measured in the field are systematic Coulomb-Mohr shear fractures rather than tension cracks. Sub-horizontal slickenlines observed on conjugate fault pairs are indicative of shear surfaces (i.e., faults) rather than tension cracks. Only those small-scale faults that passed this test were included in this study. Most slickenlines observed in the study area are sub-horizontal (Figure 23a), indicating that the maximum principal stresses responsible for the conjugate pairs (e.g., Figure 23 a and 23b) were dominantly horizontal. 305 pairs of conjugate faults were identified during this study. They and their

(A)

(B)

Figure 23. (A) Near-horizontal slickenlines shown on Episode-1 conjugate fault surfaces in Amazon Mountain granite. Grand Lake Stream. (B) Episode-1 conjugate faults in metasedimentary rocks. Kellyland dam. Big arrows in both photos indicate inferred maximum principal stress orientations. Plan view.

maximum principal stress directions are shown as rose diagrams (Figure 24) and stereonets (Figure 25), and on geologic maps (Figure 26).

These small-scale conjugate faults are interpreted to have been generated during reactivated (brittle) faulting along the Waite, and to a lesser extent, the Kellyland fault zones. Reconstruction of the paleostress fields for these conjugate faults thus helps to reveal the late-stage regional-scale history of the Norumbega fault system. Cross-cutting relationships among these features help to decipher the number and sequence of compressional tectonic events and the reactivated brittle faulting episodes along the Norumbega fault system.

6.3. The Transition from Ductile to Brittle Shearing in the Norumbega Fault System in Eastern Maine

Outcrop-scale conjugate faults have been identified within the sheared Deblois granite along the Kellyland ductile shear zone that exhibit a combination of ductile and brittle features. These faults are superimposed on mylonitized granite and are cut by all other brittle structures and fractures (Figure 27). In the Wabassus Mountain area, they also cut and offset fine-grained granitic dikes (Figures 27 and 28). One set of this brittle/ductile conjugate system strikes at around 010° and the other 050° (Figure 29). All displacement indicators show that the former set is sinistral and the latter one dextral, demonstrating that the maximum stress is in the direction of about 120° (Figure 29). Obviously the maximum principal stress orientation bisects the *obtuse* angle between two sets, suggesting ductile deformational mechanisms consistent with the following observations:

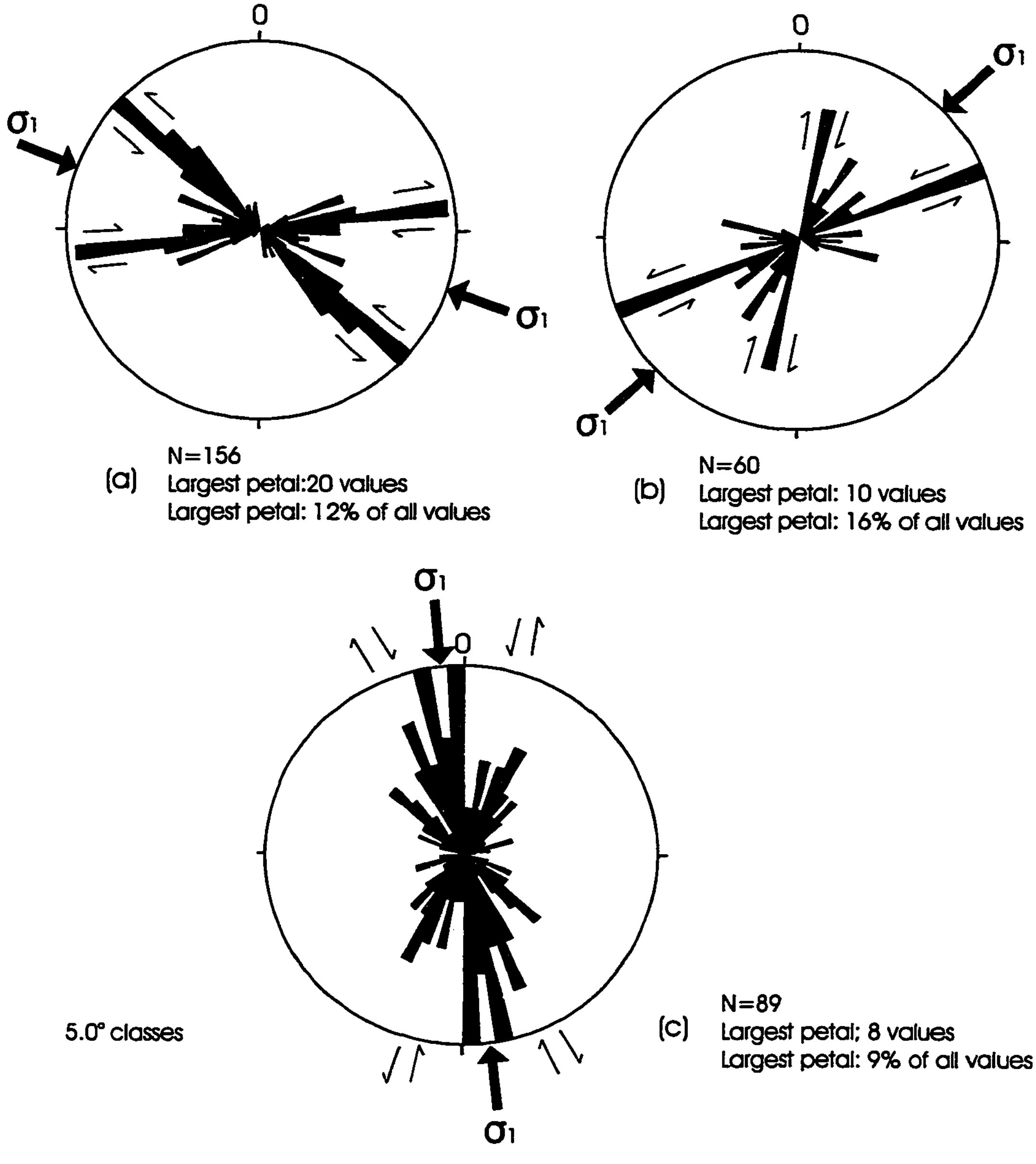


Figure 24. Strike rose diagrams of small-scale second-order conjugate faults of (a) Episode-1, (b) Episode-2, and (c) Episode-3.

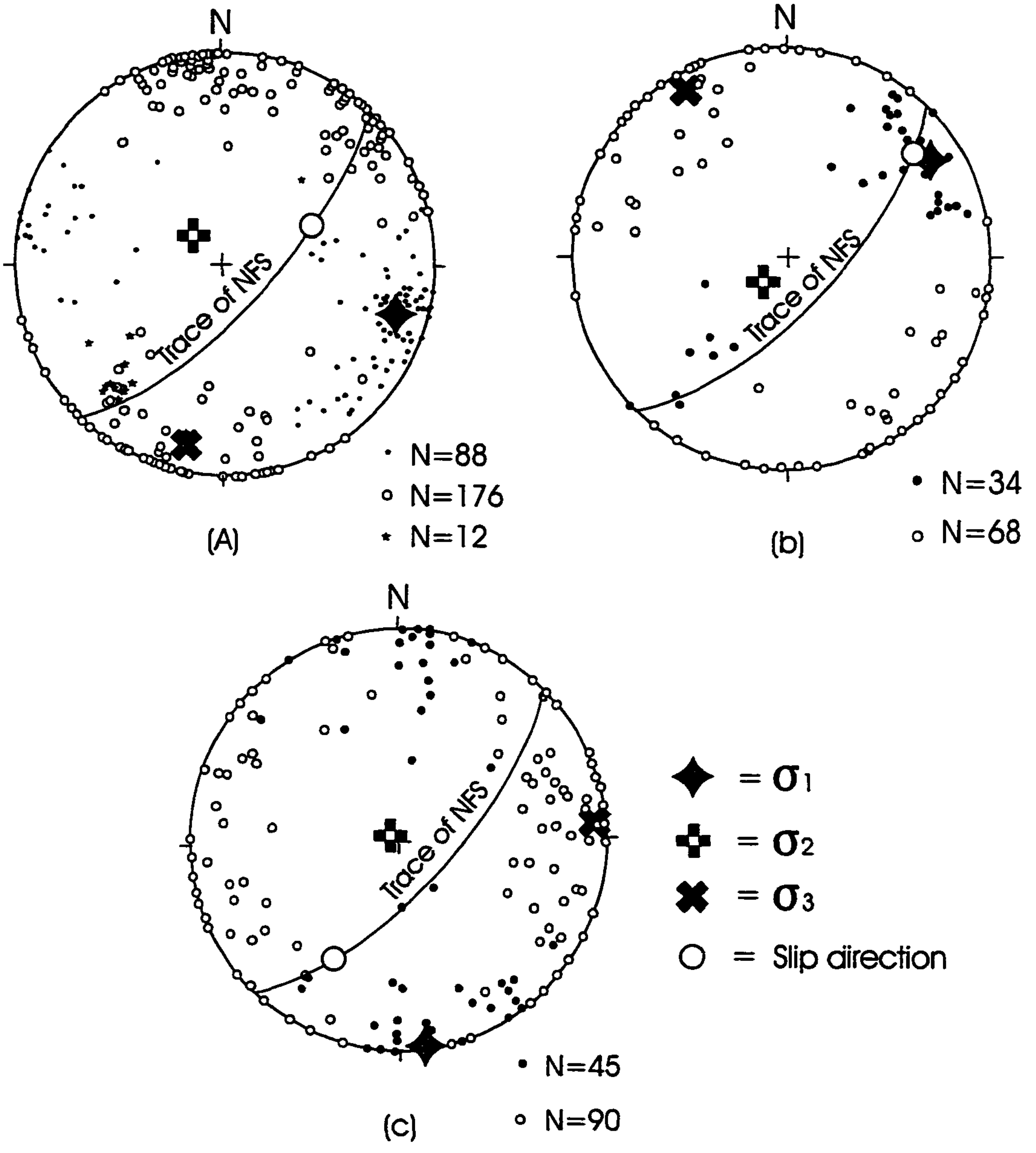


Figure 25. Equal-area stereograms showing poles to small-scale conjugate faults (open circles) and deduced maximum principal stresses (dots) for each measured pair of conjugate faults of (a) Episode-1,(b) Episode-2, and (c) Episode-3. Stars in (a) are projection of small-scale asymmetric fold hinges. Slip direction are determined by Angelier method (1994) with assumption that the magnitude of the intermediate principal stress equals to that of the minimum principal stress.

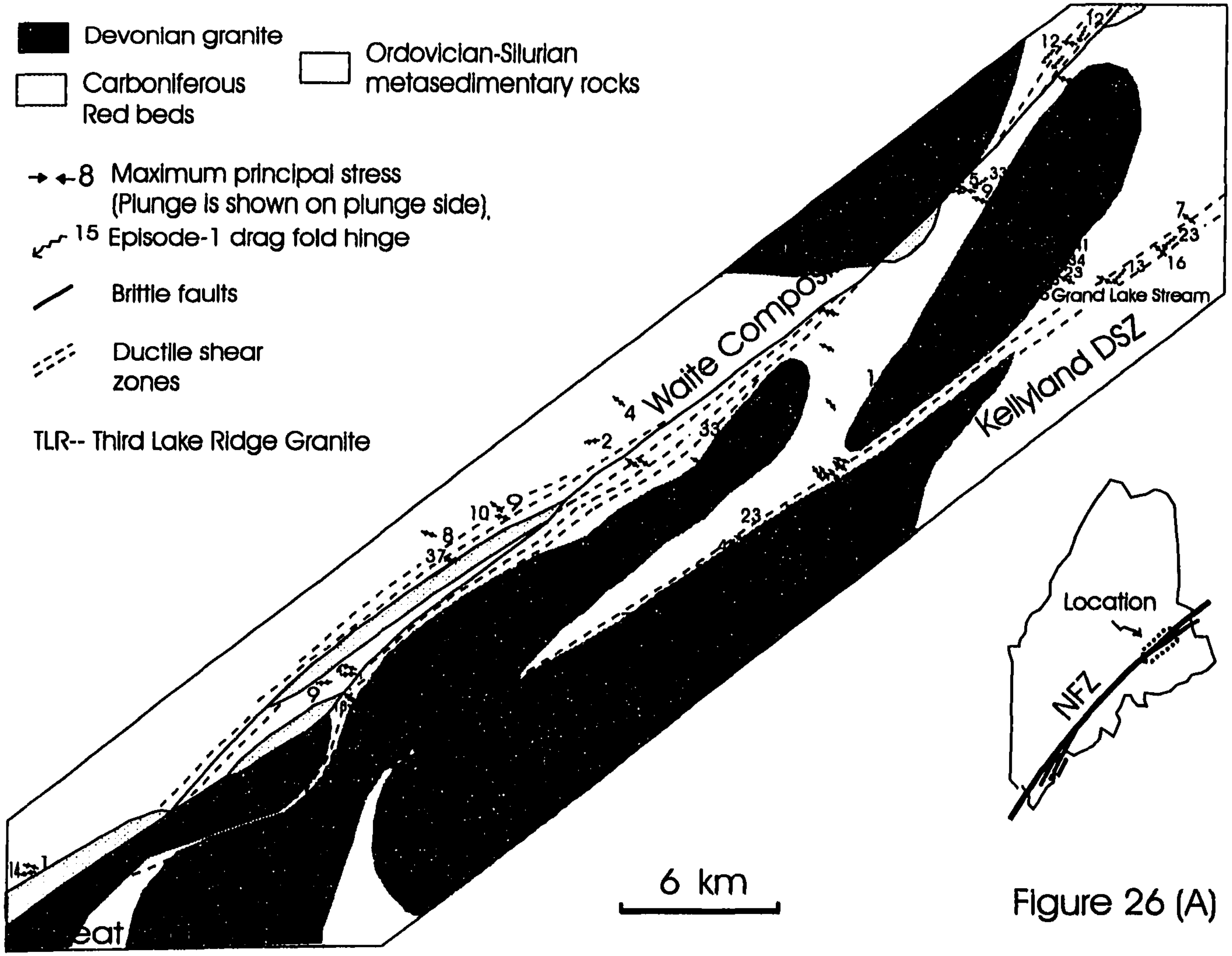

Devonian granite
Carboniferous Red beds
Ordovician-Silurian metasedimentary rocks
8 Maximum principal stress (Plunge is shown on plunge side).
15 Episode-1 drag fold hinge
Brittle faults
Ductile shear zones
TLR-- Third Lake Ridge Granite
Waite Compos
Kellyland DSZ
Grand Lake Stream
Location
NFZ
6 km
eat

Figure 26 (A)

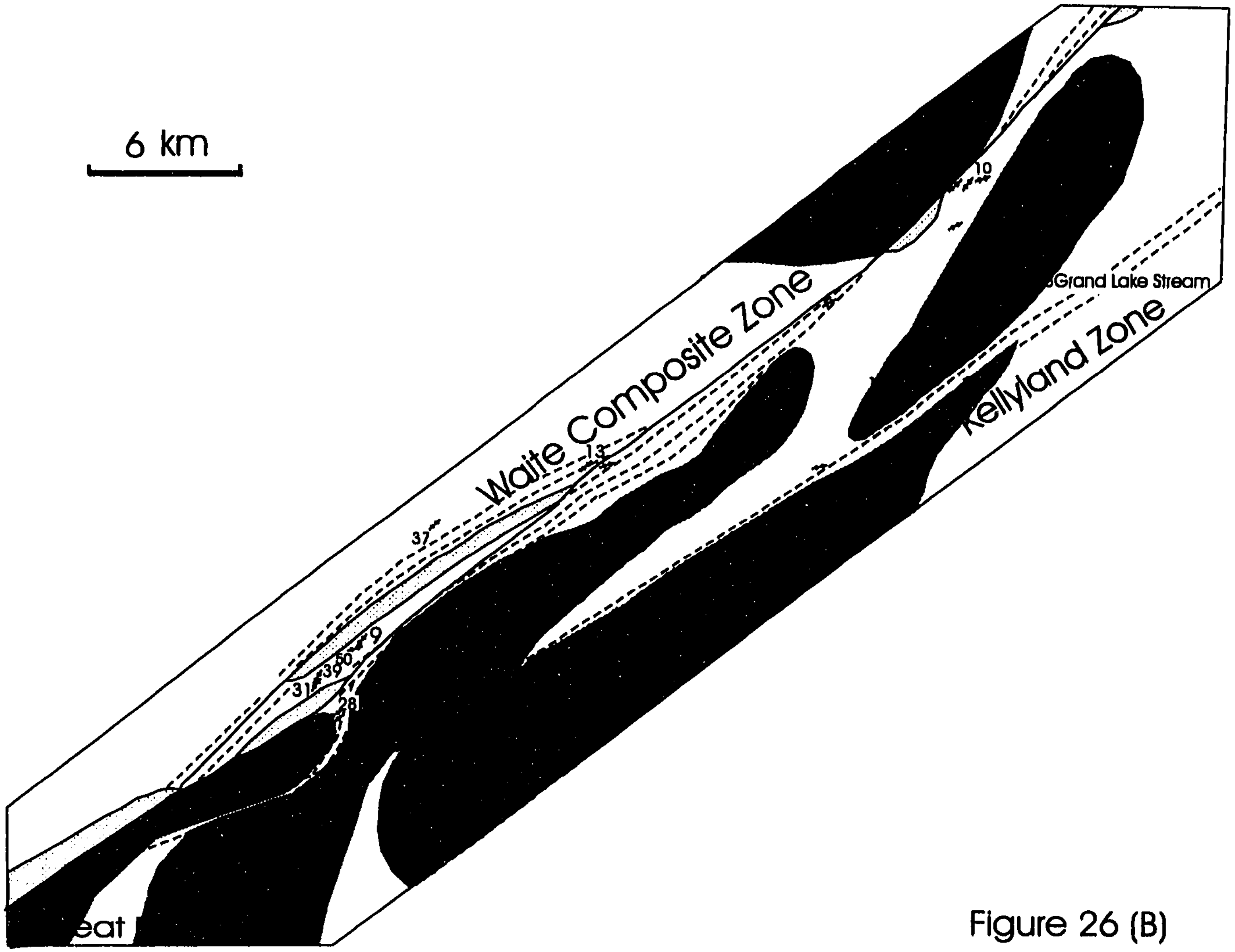
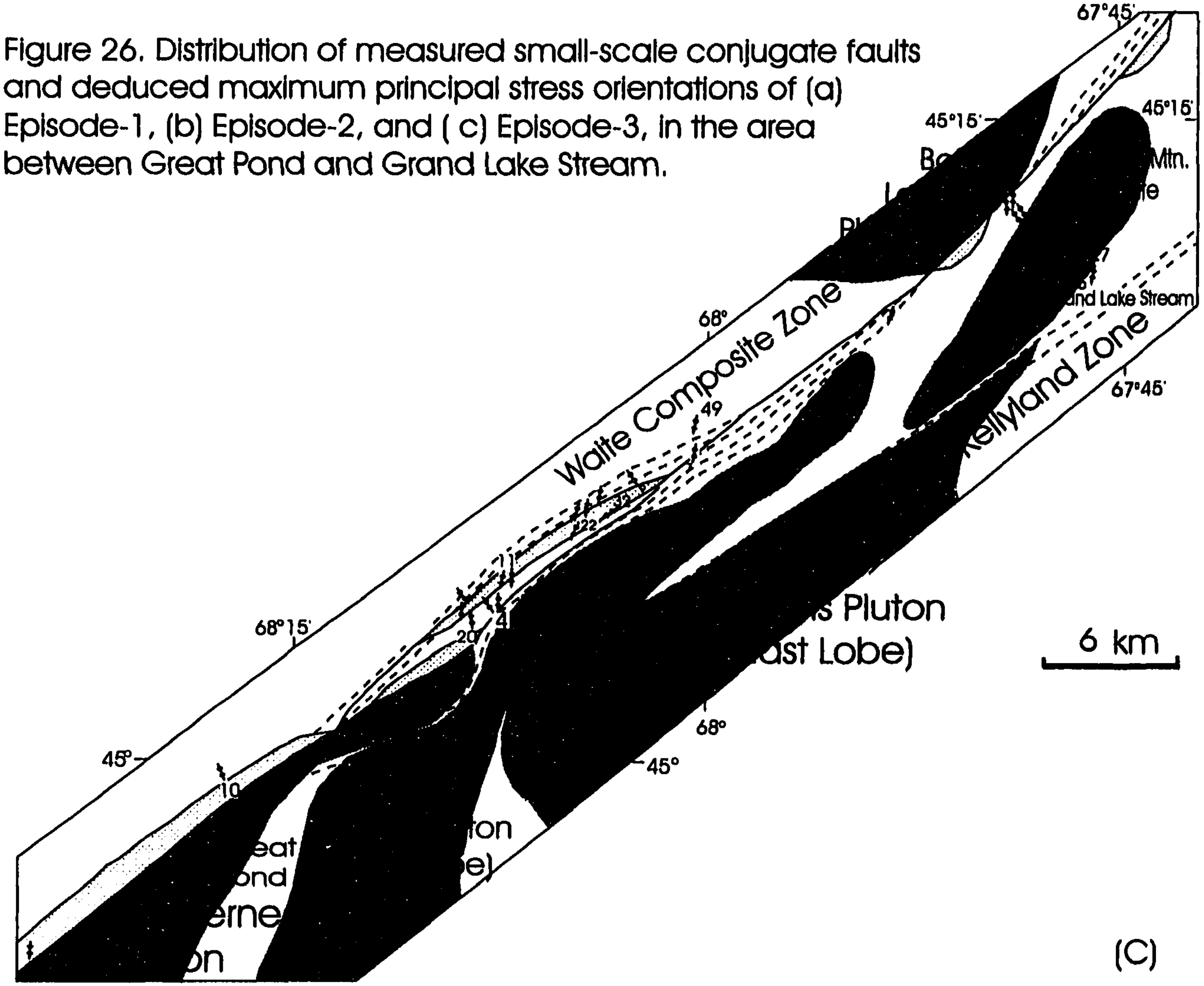

6 km
10
Grand Lake Stream
Kellyland Zone
Waite Composite Zone
13
37
9
50
39
31
28
eat

Figure 26 (B)

Figure 26. Distribution of measured small-scale conjugate faults and deduced maximum principal stress orientations of (a) Episode-1, (b) Episode-2, and (c) Episode-3, in the area between Great Pond and Grand Lake Stream.



(C)

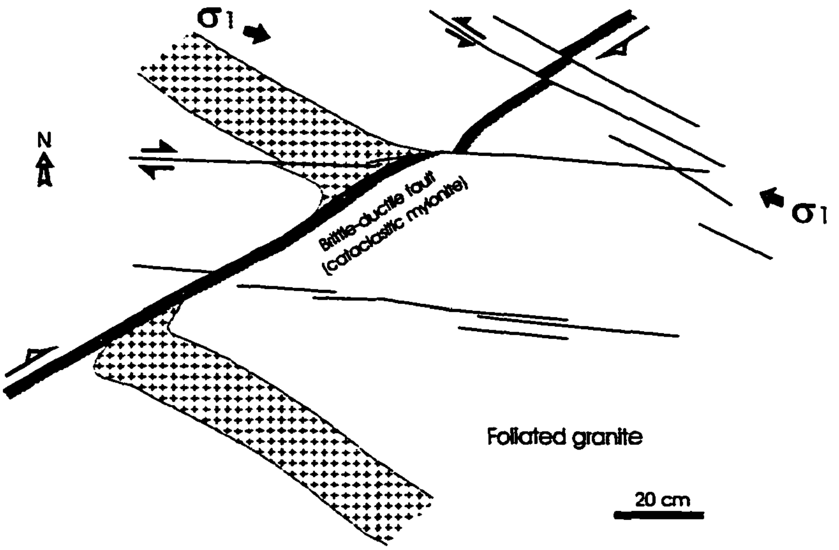


Figure 27. A 050°-striking brittle-ductile fault cuts fine-grained granite dike, and is itself cut by Episode 1 conjugate faults. Short arrows point to maximum principal stress directions. Kellyland ductile shear zone. Southwest side of Wabassus Mountain.

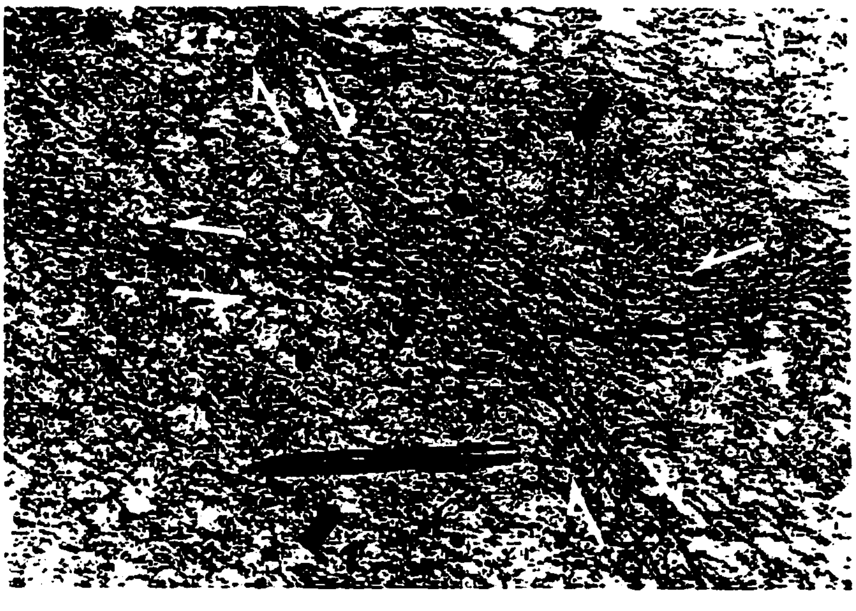


Figure 29. A pair of brittle-ductile conjugate shear zones in Deblois mylonitic granite. Pen is pointing north. Big arrows show maximum principal stress orientation. Southeast side of Slewgundy Ridge.

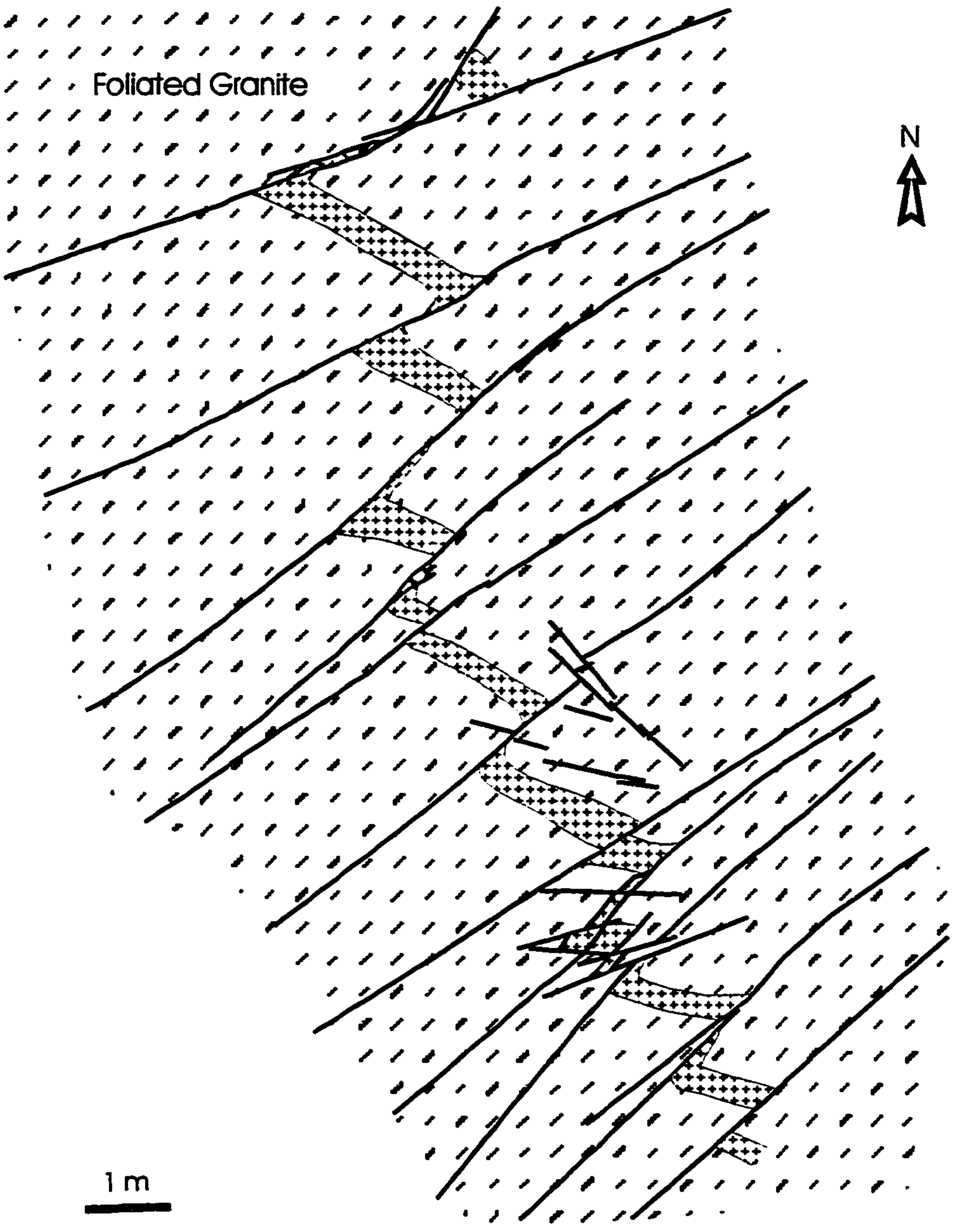


Figure 28. Sketch showing a fine-grained granite dike is offset by a series of 050°-striking ductile-brittle faults in foliated coarse-grained Deblois granite. West side of Wabassus Mountain.

This conjugate system generated outcrop-scale brittle-ductile shear zones 2cm-1.5m-wide (typically several centimeters). The faulted rocks are partly mylonitic and partly cataclastic. The shear zones are fundamentally ductile, meaning that the feldspar crystals are elongated and the quartz grains plastically deformed and ribboned to become banded or laminated mylonite (Figures 27 and 29), and that abundant features of plastic deformation have been seen within quartz grains. However, at least one side of these mylonite zones has a sharp and straight fault contact with granite foliated during early ductile shearing (Figures 27 and 29), and the change from mylonite to granite is so abrupt that only brittle fracturing is likely to have been responsible for this relationship. In fact, these contacts are generally delineated by very narrow bands of cataclasite. It is also common for the offset fine-grained granitic dikes to show drag folding, but they are abruptly broken at the contacts (Figures 27 and 28). According to Ramsay and Huber (1983) and Davis and Reynolds (1996), these small-scale fault zones are best defined as brittle-ductile shear zones. They most likely began as continuous ductile shear zones but developed sharp, fault-like features along their margins when the physical conditions changed during deformation.

The maximum principal stress orientation (in the direction of about 120^0) deduced from this brittle-ductile conjugate system is about the same as that from the Episode 1 small-scale conjugate system discussed next, implying that they were generated under similar dynamic environments, and simply predated Episode 1. Therefore these brittle-ductile structures may represent a period of ductile-brittle transition after the early ductile shearing and before the Episode 1 brittle compressive event.

6.4. Brittle Episode 1: Dextral-Oblique-Reverse Faulting

A broad, continuous zone of cataclasite and breccia is distributed along the Waite fault, indicating that the Waite ductile shear zone was reactivated during later brittle activity. In contrast, only minor cataclasis and brecciation are found in granite, granitic mylonite, and phyllonite in the Kellyland fault zone. Two other sets of brittle structures in the Waite composite fault zone overprint this cataclasite and breccia zone (see below). Therefore it is believed that this zone represents the earliest episode of brittle faulting, here termed Brittle Episode 1.

For the most part, the Episode 1 brittle fault zone followed the pre-existing Waite ductile shear zone (Figures 5, 7, and 30), affecting the Flume Ridge Formation, granite of the Bottle Lake pluton, and ductilely sheared rocks produced during the earliest activity in the fault zone. Faults associated with Episode 1 brittle activity have not been recognized in the redbeds. In the Nicatous Lake-Gassabias Lake area, the Waite ductile shear zone has an anastomosing nature and branches locally into two major sub-zones (Figure 30). Both sub-zones were reactivated during the Episode 1 event, with mappable cataclasite and breccia belts. Compressional fabrics generated by the brittle faulting dip steeply (65-75°) to the southeast. The more competent siltstone layers and quartz veins in Flume Ridge phyllonite and metasedimentary rocks are boudinaged, and the boudin arrays also dip southeast at about 65-75° (Figures 31a and 31b), as do the fault displacement surfaces. All these features suggest that the master fault of brittle Episode 1 dips steeply to the southeast.

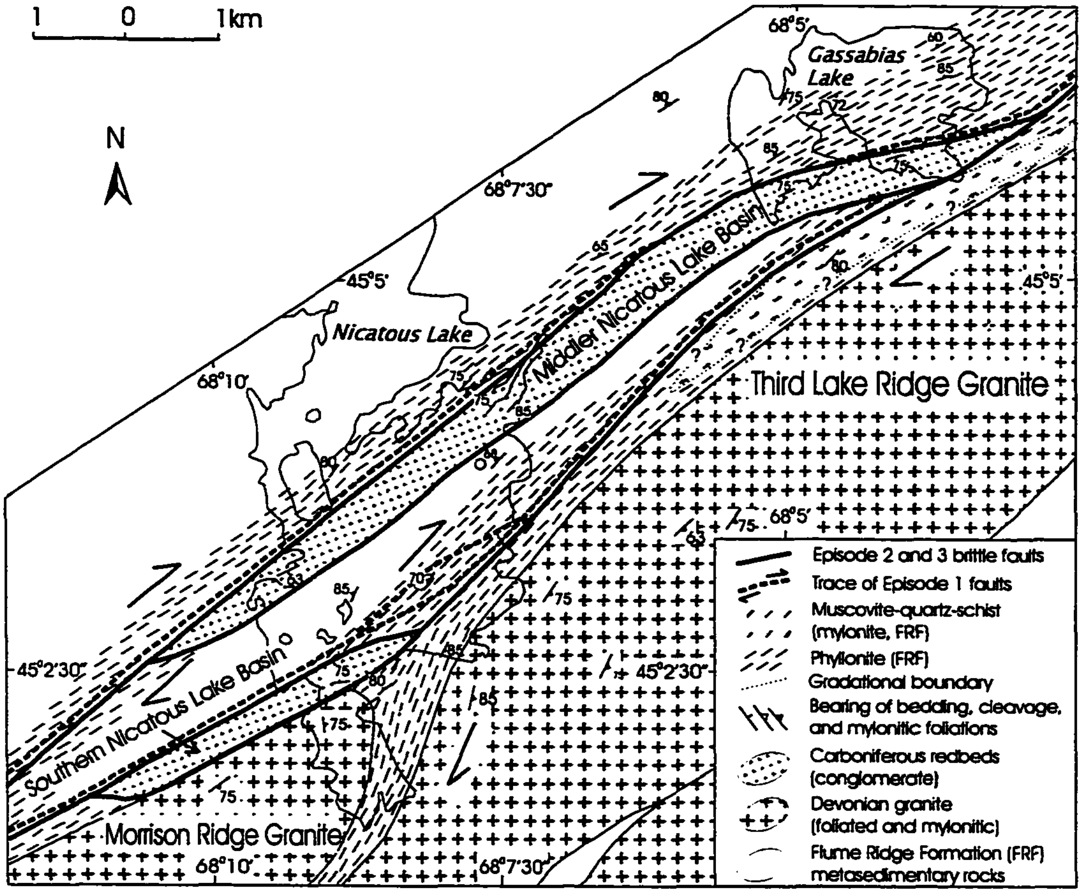
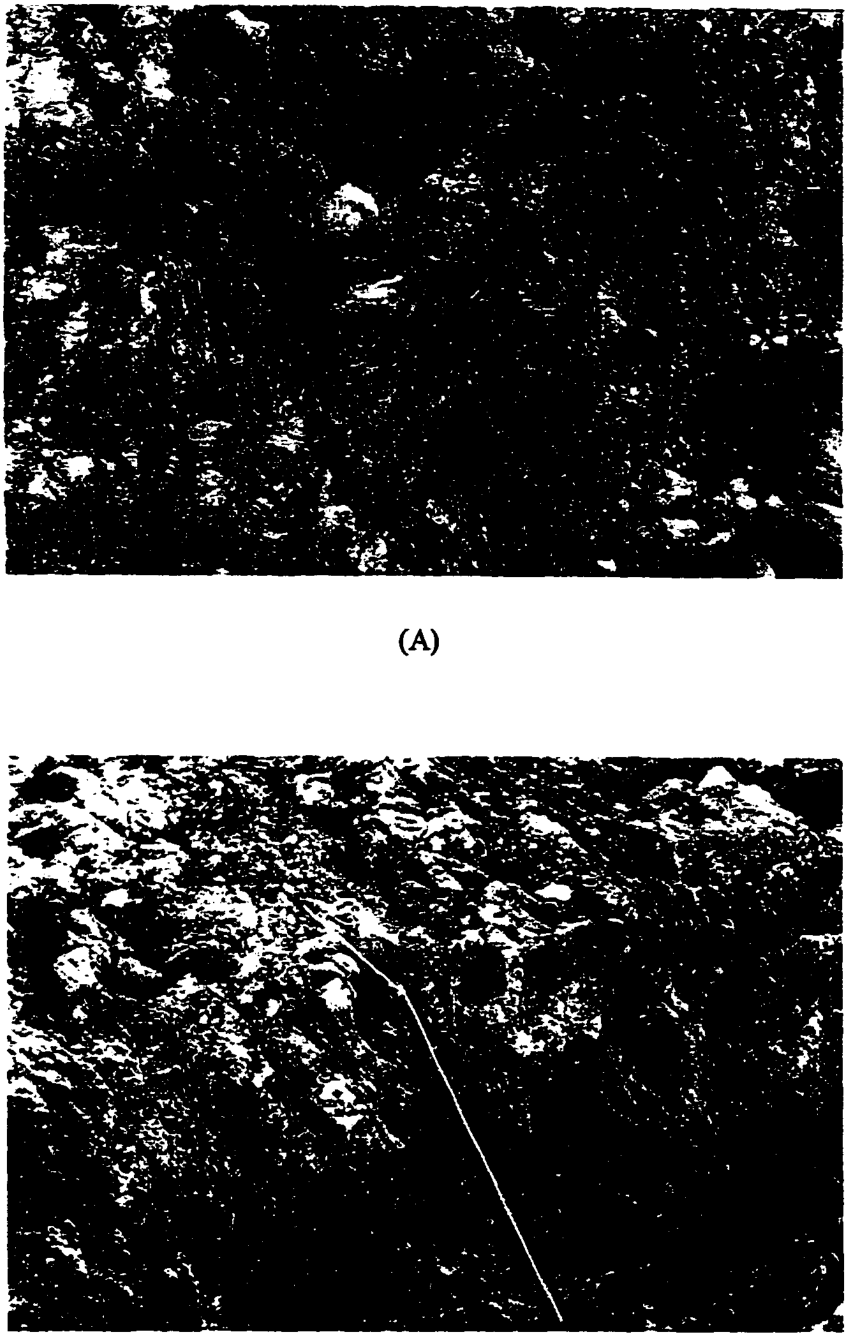


Figure 30. Schematic structural map showing interpreted internal structures of the Waite composite fault zone in the Nicatous Lake-Gassabias Lake area. See Figure 4 for location.



(A)

(B)

Figure 31. Compressive fabrics dip southeast at about 70° in the Flume Ridge breccia and cataclasite in the Waite fault zone. (A) Viewer facing north. Big Mayberry Cove. (B)Viewer facing east. South side of Fourth Machias Lake.

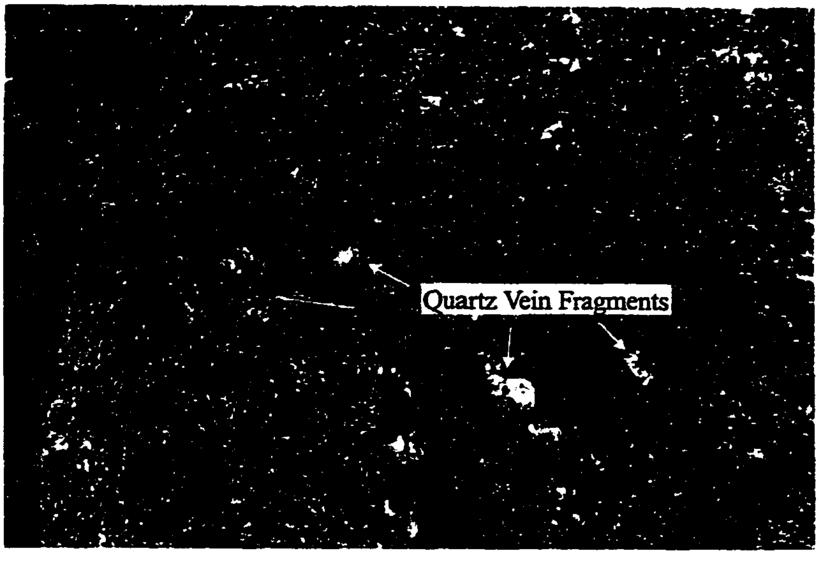
Zonation of faulted rocks in the Waite composite fault zone

As mentioned above, Episode 1 brittle faulting followed the pre-existing Waite ductile shear zone between Great Pond and the New Brunswick border. Most of the Waite zone in that area is hosted by the Flume Ridge Formation; it and the phyllonite generated by early ductile shearing have been brecciated (Figure 32a), cataclasized (Figures 32b and 33a,b), boudinaged (Figures 31 and 34a), and fractured or jointed.

The brittle component of the Waite composite fault zone is well zoned, with a central chaotic belt flanked by progressively more coherent packages that have been faulted and broken but remained essentially coherent. The central part of the brittle component is a belt of cataclasite and breccia around 50 meters wide that represents the greatest brittle strain in the Waite fault zone. Fabrics range from cataclastic to chaotic, with nearly all bedding, foliation, and quartz veins or boudins completely destroyed (Figure 32b). Intensely fractured Flume Ridge Formation strata are symmetrically distributed on both sides of this central cataclasite/breccia belt. Within these less badly deformed belts, bedding and foliation produced by ductile shearing are well preserved but typically cross-cut by joints. The width of the flanking belts of lower brittle strain is estimated to be more than 50 meters. The transition from the central belt to the less fractured belts that flank it is gradational, and tectonic lenses have been well developed within the transition zone (Figure 34a).

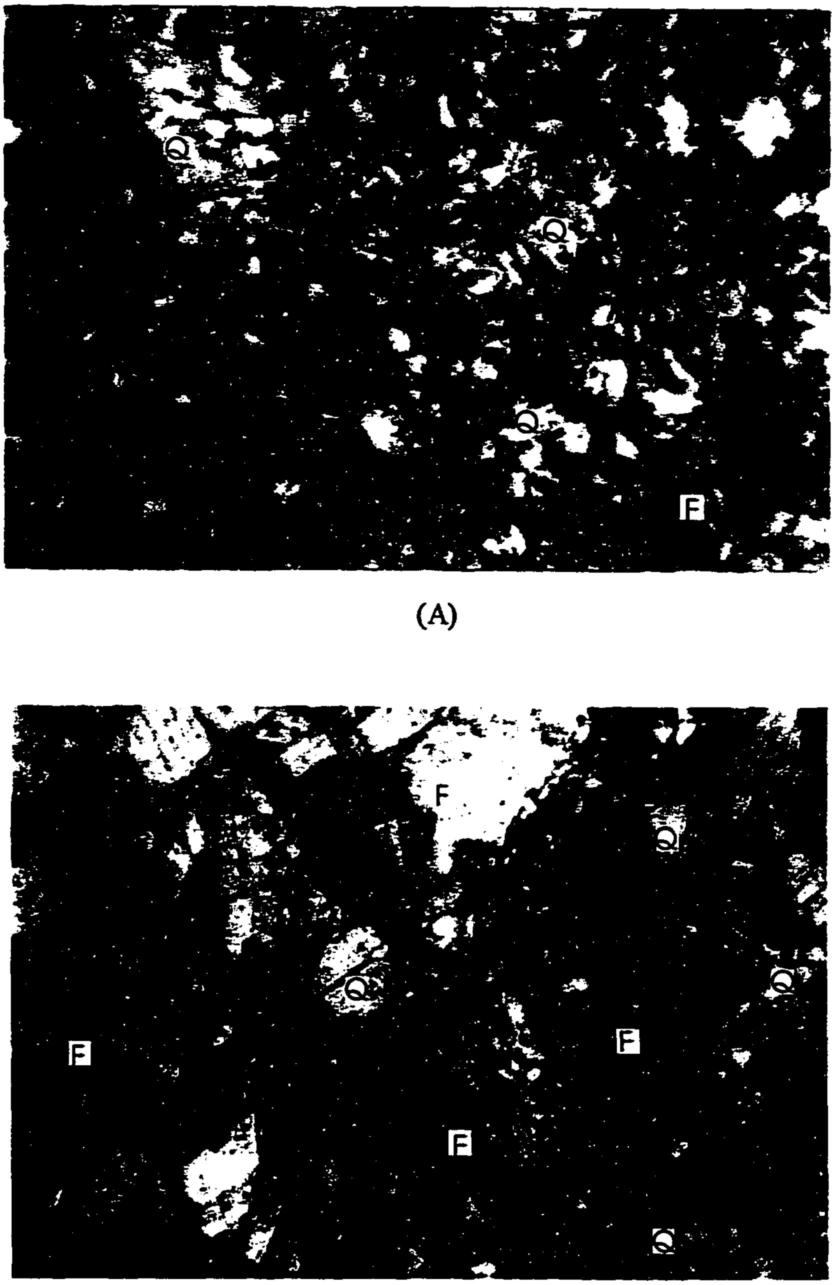
Episode 1 brittle zonation is very well exposed in the area of Big Mayberry Cove and Farm Cove dam, on the south side of West Grand Lake in the Grand Lake Stream quadrangle (see Figure 41b for location). There, the Waite cataclasite and breccia zone separates the Flume Ridge Formation from the Bottle Lake pluton. The coarse-grained

(A)



(B)

Figure 32. Breccia (A) and cataclasite (B) generated by Episode-1 brittle faulting in the Flume Ridge metasedimentary rocks. See text for explanation.
(A) is at stop 99E46, south side of Fourth Machias Lake, and (B) stop 99E1, middle-south of Nicatous Lake.

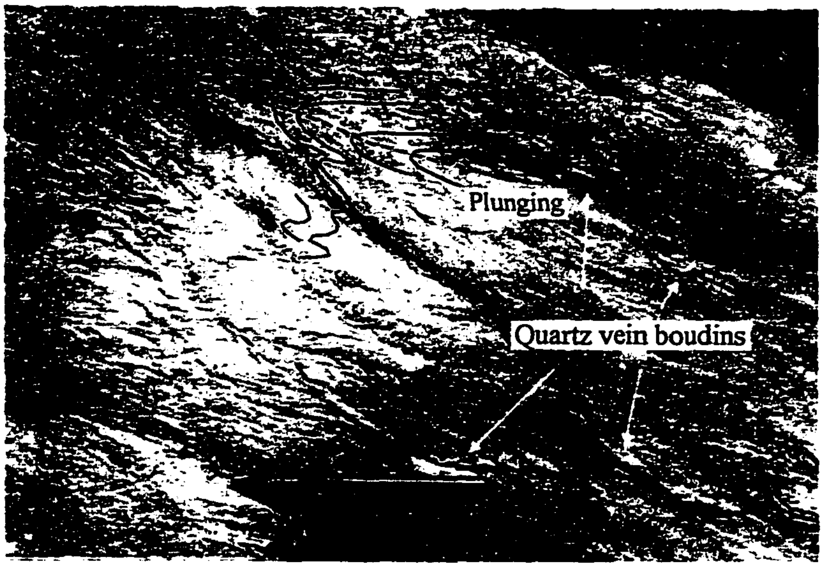


(A)

(B)

Figure33. Photomicrographs of cataclasite of metasedimentary rocks (A) and Bottle Lake pluton granite (B) by brittle Episode 1 brittle faulting. Both (A) and (B) have width of view 3.5 mm. (A) Plane polarized and (B) cross-polarized light. (A) is from Stop 99E16 and (B) 99D23.

(A)



(B)

Figure 34. (A) Boudinaged sandstone in Flume Ridge metasedimentary rocks. Pen is pointing north. Stop 99D79 at Big Mayberry Cove, southwest side of Grand Lake. (B) Small-scale asymmetric folds in the Flume Ridge metasedimentary rocks in the Waite fault zone. Pen is pointing north. Stop 99D29, north side of Amazon Mtn.

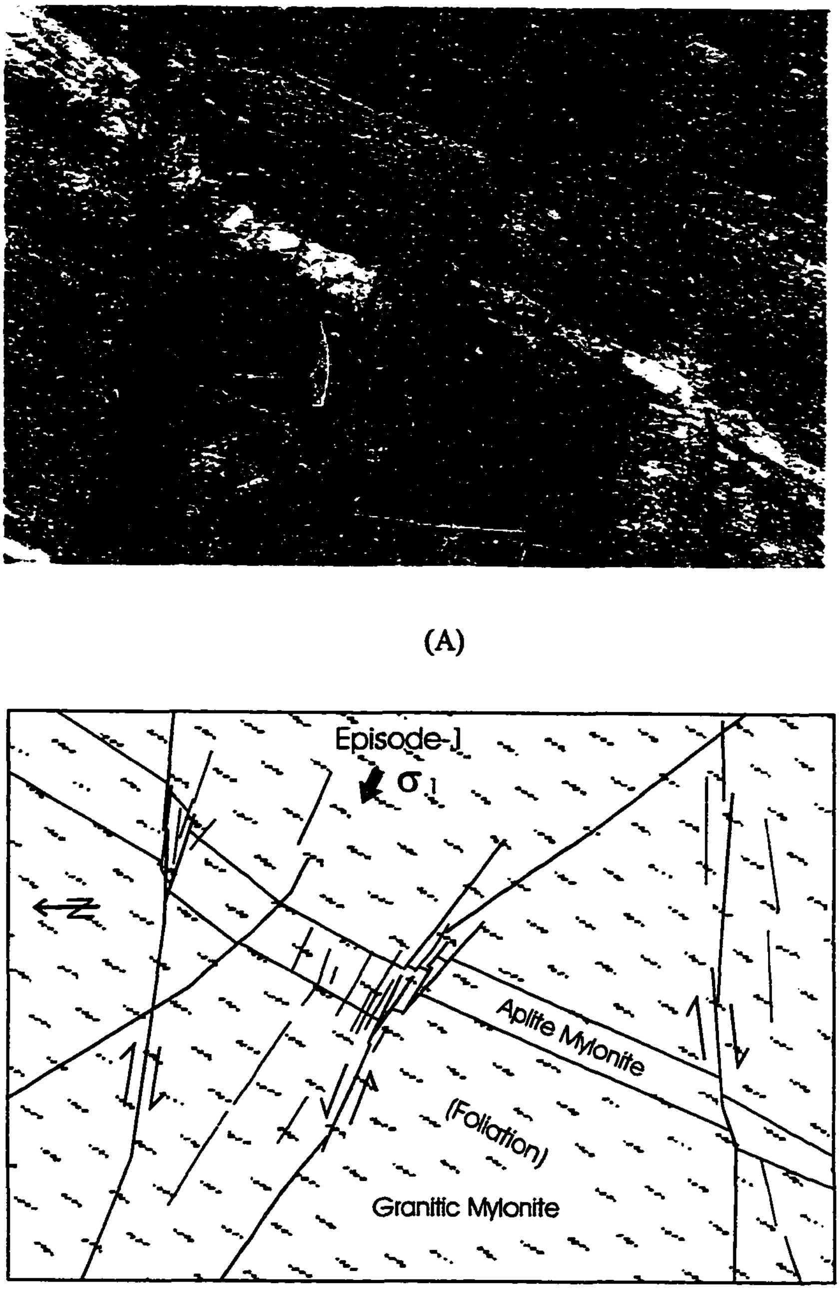
granite at the contact is intensely fractured to become typical granitic cataclasite (Figure 33b) and exhibits the highest brittle shear strain observed in the Waite zone. This zone of granitic cataclasite is at least 35 m wide and is best exposed on the southeast side of the dam and at Big Mayberry Cove. Fine calcite veins and minor chlorite veins are common in cataclasite throughout the fault. They cut early foliation and fill cracks and fissures, suggesting association with the cataclasis.

Kinematics

Episode 1 brittle faulting produced outcrop- and specimen-scale asymmetric folds which are best exposed east of Waite and north of Amazon Mountain (Figure 34b). Phyllonitic foliation is folded with hinges that plunge gently (10°-15°) to the southwest (Figures 25a, 34b). They are asymmetric with southeastward-dipping axial-plane surfaces and are Z-shaped when viewed down-plunge, indicating a southeast-side-upward movement, i.e. a reverse motion. Slickenlines on some anastomosing fault surfaces also indicate dominantly dip-slip movement. Compressional tectonic boudin lenses with near-horizontal necklines are developed within the transition zone from cataclasite/breccia to fractured/jointed rock. These and other kinematic indicators suggest that Episode 1 was an episode of dextral-oblique-reverse brittle faulting along the Waite fault zone.

Episode 1 stress field analysis

The system of small-scale conjugate faults attributed to Brittle Episode 1 has been observed in metasedimentary and granitic rocks along the fault system, one set striking around 080° with dextral displacement and the other 130° with sinistral displacement (Figures 23, 24, 25, 26, and 35). These are interpreted to be the oldest brittle features, because they are cut by all other small-scale faults. Some conjugate kink bands have also



(A)

(B)

Figure 35. Episode 1 conjugate faults (near vertical) in granitic mylonite at Fletcher Peak Cliff. (A) Outcrop; (B) Line drawing. Black arrow points to the maximum principal stress orientation. Plan view. Outcrop station 98A72.

been observed in pelite and interbeded wacke. Development of some small valleys or streams was obviously controlled by these two sets, e.g. on the north side of Washington Bald Mountain and cliffs such as Fletcher Peak, Horseshoe Mountain, Eagle Mountain, and parts of Slewgundy Ridge and Knox Mountain (See Plate 1 for locations).

Numerous narrow (5 cm) cataclasite bands were generated within these conjugate faults, most commonly in granite, but also within the metasedimentary rocks. Some conjugate faults exhibit an *en echelon* pattern (Figure 36), and some in granite are filled by epidote veins. The offset by Episode 1 conjugate faults is commonly around 30-50 cm. The largest displacement recorded is 20 m in a dextral fault striking 080° in the phyllonite zone on the east side of Third Machias Lake. Most of these conjugate faults contain slickenlines (e. g. Figure 23a) that plunge gently northeastward on the 080° set and at 1°-15° southeastward on the 130° set, implying a nearly horizontal compressional maximum principal stress (plunge slightly to the southeast; Figures 25a and 26a).

The trend of the maximum Episode 1 compressive principal stress (σ_1) is interpreted from these small-scale conjugate faults to average 115°-125° (Figures 25a and 26a), at an average angle of 70°-80° with faults of the Norumbega fault system. The kinematics discussed above indicate that the Episode 1 brittle reactivation was mostly dip-slip with a slight dextral strike-slip component. Therefore, it is likely that the Episode 1 brittle reactivation was in a reverse motion. The compressive fabrics and structures such as tectonic lenses observed in Episode 1 brittle zones also suggest a compressional environment. Reactivation during Episode 1 is interpreted as an event of dextral-oblique-reverse faulting, consistent with Swanson's oblique convergence model (Figure 37) for

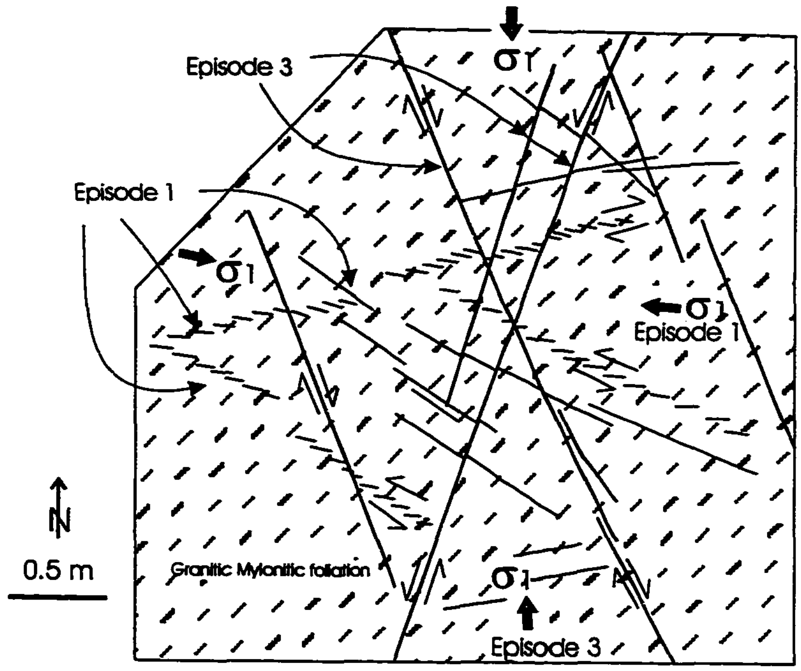


Figure 36. Sketch showing Episode 1 conjugate faults and en enchelon fractures cut by Episode 3 conjugate faults in the foliated Deblois granite. Short black arrows point to maximum principal stress directions. Stop 99D85, Wabassus Mountain.

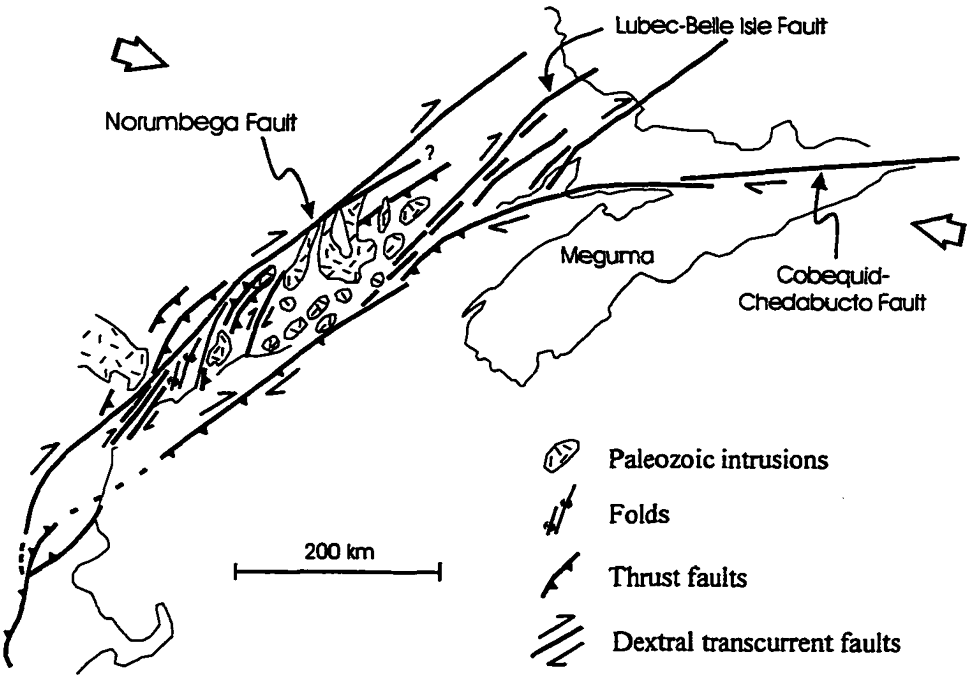


Figure 37. The oblique convergence and the right-stepping en echelon transcurrent fault system in northern Appalachians developed in late Paleozoic Era (After Swanson, 1999b).

the Norumbega system. However, the fact that the intermediate principal stress deduced from small-scale Episode 1 conjugate faults is nearly vertical (Figure 25a), suggests that reverse faulting is unlikely. Reverse faulting in such a stress field (Figure 25a) can only take place when the intermediate principal stress is equal or nearly equal to the minimum principal stress (Davis and Reynolds, 1996).

Angelier (1984) found that the intermediate and minimum stresses are about equal in many orogenic belts. In the Quebec and northern New Brunswick Appalachians, Faure et al. (1996) identified three compressive tectonic events after a numerical paleostress tensor analysis using striated fault planes. All three paleostress fields had very similar $\sigma 2$ and $\sigma 3$ magnitudes compared to $\sigma 1$. Correlation of these fault events with those reported in this study will be discussed below, but the results reported by Faure et al (1996) support the possibility that the Episode 1 compressive stress field in eastern Maine may also have very similar $\sigma 2$ and $\sigma 3$ magnitudes compared to $\sigma 1$, thereby facilitating the Episode 1 reverse reactivation of the Waite fault zone postulated above. Steeply-dipping reverse-slip faults (typically dipping 60° or more) are common and accommodate crustal shortening in orogenic belts around the world. Most of them are also interpreted as a result of fault reactivation, i.e., pre-existing steeply-dipping faults are reactivated as reverse-slip faults (Davis and Reynolds, 1996).

Angelier (1979, 1994) has emphasized that the actual rake of slip along a reactivated fracture or fault surfaces depends on the magnitude of the intermediate principal stress relative to that of the maximum and minimum principal stresses. He also demonstrated that the slip direction will be parallel to the direction of maximum shear stress resolved along the preexisting fracture surface. With Angelier's method, one is able to determine slip directions on preexisting fault surfaces stereographically. The slip direction on the preexisting Waite fault zone for Episode 1 brittle reactivation determined in this way is consistent with the kinematic and dynamic analysis results presented earlier (Figure 25a.)

6.5. Brittle Episode 2: Dextral Strike-slip Faulting

Faults attributed to a second reactivation of the Waite fault zone (Brittle Episode 2) cut and offset those of Episode 1 and are themselves overprinted by faults assigned to Episode 3 (Figures 27, 29, 30). Episode 2 structures are concentrated geographically along the Episode 1 master faults, but occur in much narrower zones only a few centimeters to meters wide. Like brittle faults of Episode 1, they affect metasedimentary, granitic, and ductile fault rocks but have not been observed in the redbeds.

Fault dynamics and kinematics

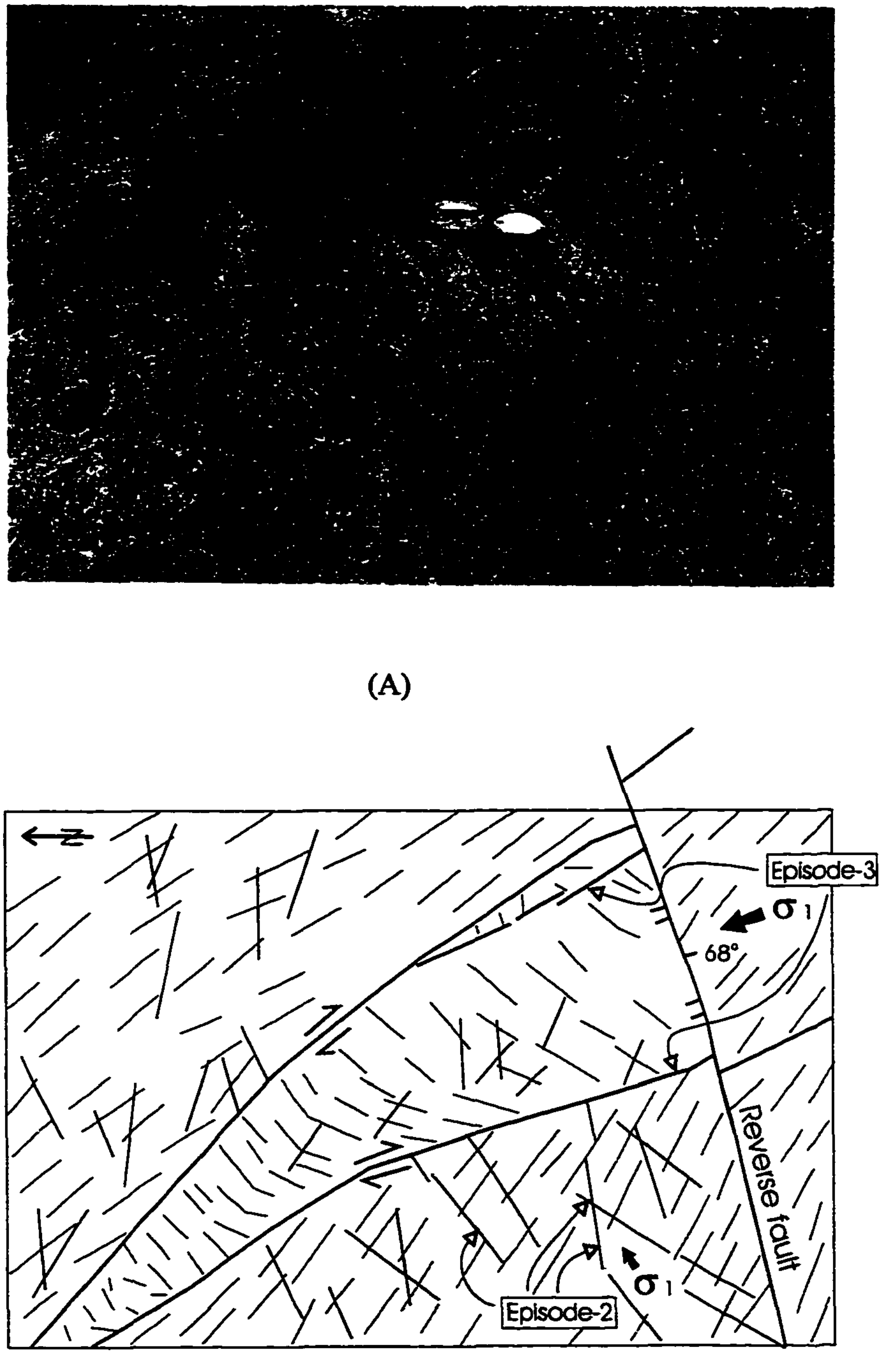
The narrowness of Episode 2 fault zones and sparse exposures severely limit direct observation of kinematic indicators comparable to those seen in the broad Episode 1 fault zone. As a result, Episode 2 is reconstructed solely through its small-scale conjugate faults.

Episode 2 stress field analysis

The Episode 2 conjugate system typically has a set of dextral faults oriented around 010°-020°, and a sinistral set oriented 060°-070° (Figure 24b). More easterly attitudes are found in the Nicatous Lake-Gassabias Lake area where the Waite zone splits into two sub-zones that merge again on the eastern side of Gassabias Lake, forming a fault-bounded block 10 km long and 1 km wide (see Figure 30). Next to this block on the southeast is the Third Lake Ridge granite sliver which is believed to have acted as a rigid block that caused the local stress field to change slightly. In this area σ_1 rotated easterly, generating a locally well-developed conjugate fault system with one dextral set of faults oriented around 050° and a sinistral, set around 080°. Slickenlines on the conjugate fault surfaces are generally sub-horizontal, proving again that the maximum principal stress orientation was sub-horizontal. The maximum principal stress (σ_1) deduced from Episode 2 conjugate structures is oriented 045°-075° (Figures 24b, 25b and 26b), making a small angle (average 15°) with the trace of the inferred master fault. This relationship would probably have caused dextral strike-slip movement along the pre-existing Waite brittle fault zone. The slip direction for Episode 2 brittle reactivation based on Angelier's method supports this assertion, showing nearly horizontal slip (Figure 25b).

6.6. Brittle Episode 3: Reverse-sinistral (Oblique) Faulting

Small-scale faults of Brittle Episode 3 cut metasedimentary, granitic, and ductile fault rocks, and also overprint Episode 1 and Episode 2 faults and cataclasite zones (Figures 36 and 38). In contrast to features associated with Episodes 1 and 2, Episode 3 faults also cut conglomerates, sandstones, and mudstones in the post-Acadian redbed slivers. Mapping during this study and by previous workers shows that the redbeds are everywhere in fault contact with granite, metasedimentary rocks, mylonite, or phyllonite, and these rocks are steeply tilted with variable dip directions along those faults (Figures



(A)

(B)

Figure 38. Episode 2 and 3 conjugate faults in Flume Ridge phyllonitic metasedimentary rocks in the Kellyland shear zone. (A) Outcrop; (B) Line drawing. Black arrows point to maximum principal stress orientations. The minor reverse fault is determined as a progressive deformation product of the conjugate system. Northeast side of Third Machias Lake.

39 and 40). These faults are considered to be map-scale examples of Episode 3 brittle structures.

Kinematics

Stratification in redbeds in the "Norumbega basin" (Bradley, 1982), and the middle Nicatous Lake, and Southern Nicatous Lake redbed basins identified during this study (Figures 30 and 41), strikes around 065°-090° and dips steeply at 75°-90°. Based on the reversals of SE- and NW-dipping beds, a series of large-scale, upright, tight anticlines and synclines is inferred with their axes trending around 065°-090°. These folds are now interpreted to exist in all of the redbed slivers along the Waite fault zone where bedding has been observed. The axes of the folds make an angle of 20°-45° with the fault system, implying that there could have been sinistral strike-slip movement. However, these reversals could be also due to the occurrence of the redbeds in variably tilted, fault-bounded slivers.

Fault dynamics and stress field analysis

Small-scale Episode 3 conjugate faults include a sinistral set striking around 010°-020° and a dextral set oriented at 160°-170° (Figures 24c, 39). From these attitudes, σ_1 for Episode 3 is estimated to be around 165°-190° (Figures 24c, 25c, and 26c), suggesting that the brittle reactivation along the Norumbega fault was oblique with both sinistral strike-slip and reverse components. The determination of the slip direction on the preexisting Waite fault zone for Episode 3 brittle reactivation with Angelier method is shown in Figure 26c, and also suggests oblique motion.

Figure 39. Redbed conglomerate and small-scale southeast-striking vertical faults in the Upper Nicatous Lake Basin. Compass pointing to north. Southeast side of Nicatous Lake.

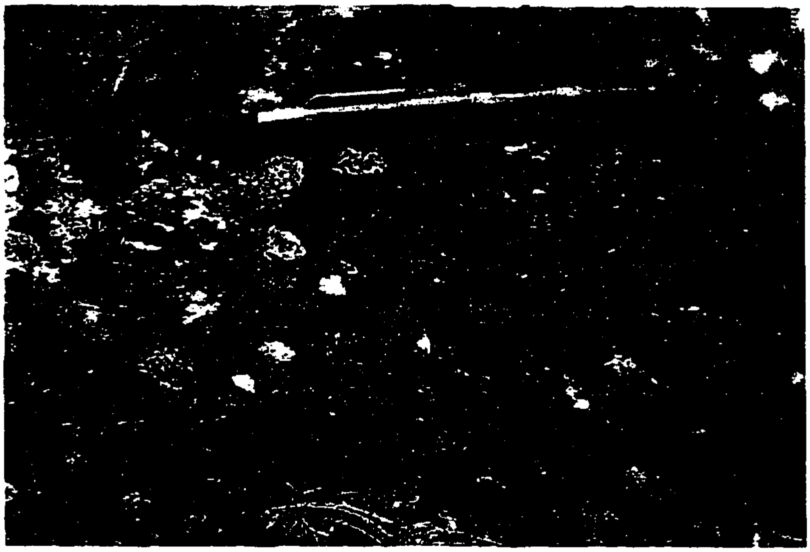


Figure 40. Conglomerate in a redbed sliver located in southwestern Waite (sliver C labeled in Figure 41b).

In addition, a third set of small-scale secondary faults has been observed in the redbeds in the Nicatous Lake area, striking 099°-110° and dipping gently to the north. This set shows reverse or thrust motion based on offset markers and inclined slickenlines observed on the fault surfaces. This observation implies north-south compressional stress, agreeing with the σ_1 direction deduced from Episode 3 conjugate faults.

The inferred oblique movement juxtaposed the redbeds against older Fredericton belt rocks and was responsible for the current steep dip (mostly around 75°-90°) of the red conglomerates and sandstones (Figure 39). The axes of the inferred tight upright anticlines and synclines developed in the Norumbega and middle Nicatous Lake basins are roughly perpendicular to the orientation of the maximum principal stress, supporting the reverse-sinistral-strike-slip kinematics and fault dynamics deduced from the small-scale structures. However, most steeply dipping beds in the smaller basins (e. g., basins labeled A, B, C, D, and E in Figure 41b), strike around 035°-055° and typically parallel the bounding faults. This may have been caused by sinistral strike-slip movements in which bedding was easily rotated toward and finally into parallelism with the faults in these much smaller basins.

6.7. Displacement During Brittle Faulting

It is difficult to estimate the amount of displacement associated with the individual episodes of brittle faulting, partly because of the superposition of the three different events and partly because of the paucity of outcrops and displaced markers.

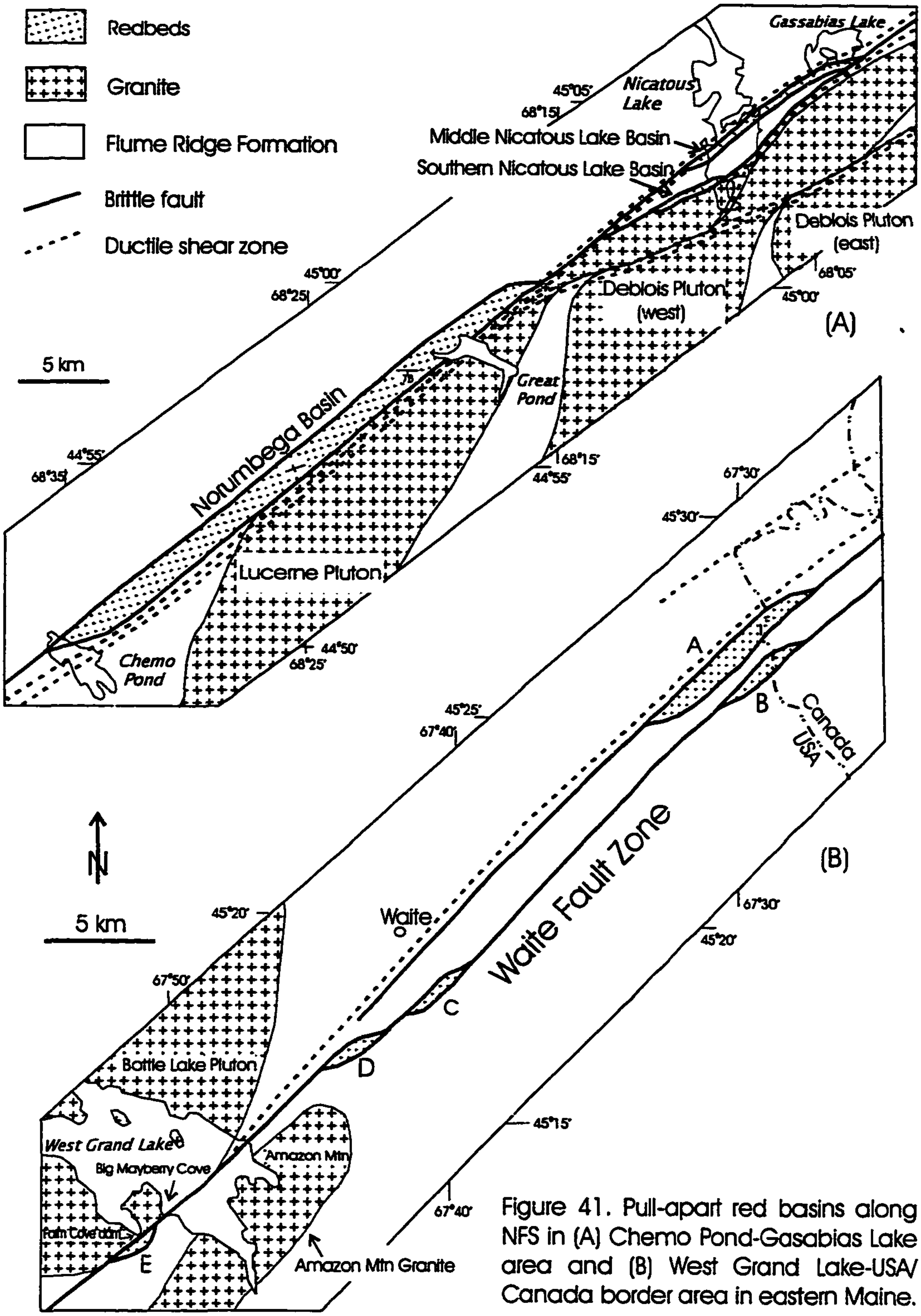


Figure 41. Pull-apart red basins along NFS in (A) Chemo Pond-Gasabias Lake area and (B) West Grand Lake-USA/Canada border area in eastern Maine.

Indeed, although the senses of motion associated with Episodes 1 and 3 are known, the amount of displacement during those events cannot even be approximated.

Dextral strike-slip movement along Episode 2 brittle faults must have added to the estimated 25 km of dextral ductile displacement caused by the early shearing in the Great Pond-Wabassus Lake area (see Chapter 5). Although there is generally a lack of offset markers that could be associated with Norumbega brittle faulting, the early-stage zone of ductile phyllonite in the Waite fault zone appears to have been dextrally offset in the Third Machias Lake-Amazon Mountain area by approximately 13 km (Figure 4). This offset may represent a composite of motions associated with all three episodes of brittle faulting, but is of the correct order of magnitude for an estimate for Episode 2 displacement based on interpretation of the origin of the redbed basins (see Chapter 8).

CHAPTER 7

TIMING AND CORRELATION OF NORUMBEGA ACTIVITY IN EASTERN MAINE

7.1. Introduction

Chapters 4 through 6 describe the contributions made by this study to recognizing a sequence of four distinct episodes of ductile and brittle faulting in the epizonal segment of the Norumbega fault system in eastern Maine. This chapter discusses recent attempts to date several of these events in the Codyville, Waite, and Kellyland fault zones, and suggests correlation of Norumbega faulting episodes with orogenic activity throughout the Appalachian Mountain System.

Three different approaches have been used to date the multiple Norumbega events in eastern Maine. Two of these attempted to date the faulting directly: isotopic dating of synkinematic minerals; and thermochronologic studies designed to pinpoint the time at which granitic rocks would have been at temperatures appropriate for their observed deformation mechanisms. The third utilizes geochronologic and stratigraphic age dating in order to bracket the age of individual fault episodes. Similar geochronologic and thermochronologic techniques have been applied in the southwestern Maine segment of the Norumbega fault system, making it possible to compare the evolution of this structure at shallow and moderate crustal levels.

7.2. Timing of ductile faulting

The age of the ductile shearing event is the most tightly constrained of all Norumbega activity in eastern Maine because nearly identical ages have been inferred for all three major fault strands using the three different approaches (Ludman et al., 1999, 2000). The Codyville fault zone produced ductile shear fabrics in granite of the Whitney Cove pluton (Bottle Lake complex), but these are absent and the Codyville fault zone is apparently intruded by the Passadumkeag River pluton of the same complex. Because Ayuso et al. (1984) reported identical Rb/Sr ages of 380 Ma for both plutons, ductile activity in the Codyville fault zone is tightly constrained to around 380 Ma.

The Waite fault zone truncates both the Whitney Cove pluton (380 Ma) and the Amazon Mountain granite, but only the late brittle effects have been detected in these plutons. The lack of ductile deformation within the Whitney Cove places a lower limit of ~380 Ma on the ductile deformation in this area. Along other sections of the Waite composite fault zone, brittle structures overprint an earlier ductile fabric developed in the largely chlorite-grade Flume Ridge Formation. $^{40}Ar/^{39}Ar$ ages of approximately 380 Ma were reported by Ludman and West (1994) for synkinematic biotite and actinolite from the Flume Ridge protomylonites. These relationships also constrain the age of the ductile deformation within the Waite fault zone to be about 380 Ma.

Ductile deformation in the Kellyland fault zone is not as well constrained by standard geochronologic methods as in the Waite and Codyville fault zones, but a study of the cooling history of the Deblois pluton adds important constraints. A maximum age for the ductile deformation in the Kellyland zone is set by a U-Pb zircon date of 384±5

Ma reported by Ludman et al. (1999) for the Deblois granite at Wabassus Mountain. Similar $^{40}Ar/^{39}Ar$ ages of 383±2 and 384±2 Ma were obtained by Idleman and Ludman (1998a, b) for hornblende and biotite, respectively, from the same outcrop. The concordance of the zircon, hornblende, and biotite ages, despite their disparate closure temperatures of ~800°C, 550°C, and 360°C, respectively, implies very rapid initial cooling, on the order of 100°C/m.y.

Coupled with $^{40}Ar/^{39}Ar$ low-temperature thermochronology of feldspars these dates enabled Ludman et al. (2000) to reconstruct the complete cooling history for the pluton (Figure 42). The differential behavior of quartz (ductile) and feldspars (brittle) during ductile shearing in the Kellyland fault zone was cited in Chapter 4 as evidence for deformation temperatures of 300-350°C, *assuming that experimental results can be applied to this natural system*. Based upon the thermal history shown in Figure 42, the Deblois pluton would have entered this temperature range by ~380 Ma and by 360 Ma would have cooled below the minimum temperature necessary to support ductile deformation.

Because of the steepness of the initial stages of the cooling curve, and the fact that the Kellyland and Waite fault zone merge a few tens of kilometers from the exposures where the dated samples were collected, and the 380 Ma age of ductile shearing in the Waite and Codyville fault zones, the earlier part of this range (~380 Ma; Middle Devonian) is considered most likely for the Kellyland fault zone and for the entire Norumbega system in eastern Maine.

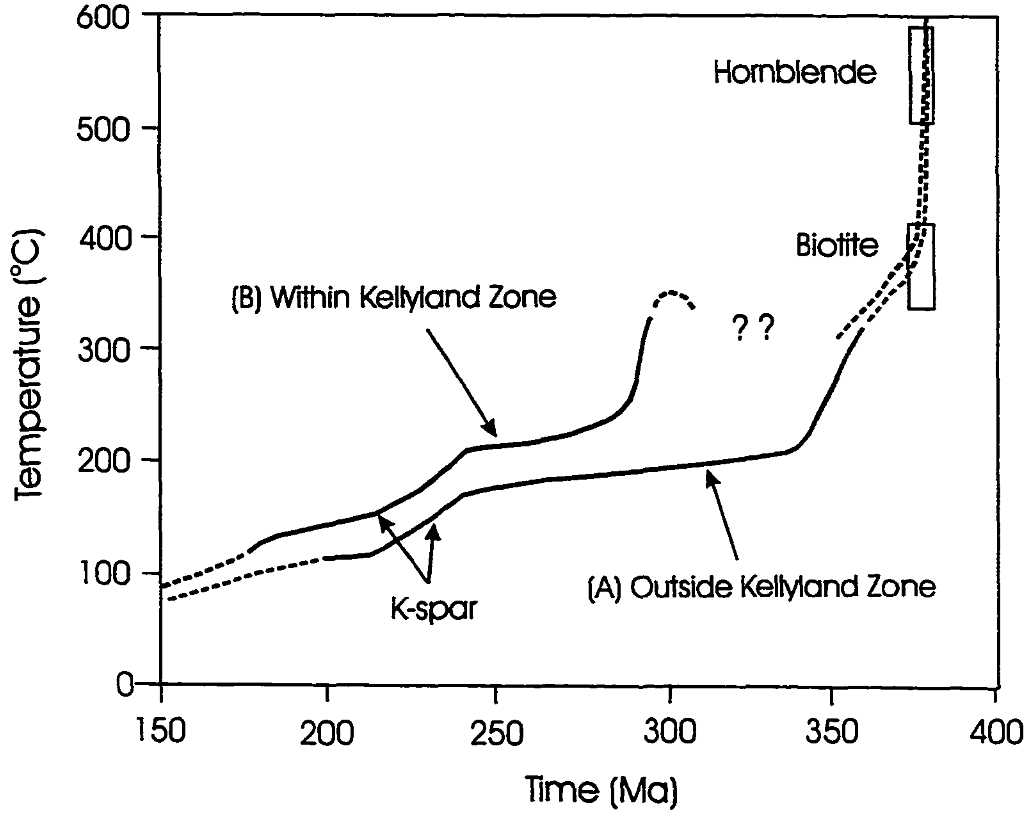


Figure 42. Thermal histories for portions of the Deblois pluton within and outside the Kellyland shear zone, as deduced from $^{40}Ar/^{39}Ar$ data. Rectangular boxes represent closure temperature ranges for hornblende and biotite at 100°C/m.y. Solid curves are average histories derived from multi-diffusion domain modeling of K-feldspar data. (After Ludman et al., 2000)

7.3. Timing of Brittle Episodes 1, 2, and 3

The timing of the three episodes of brittle faulting remains problematic. It is impossible to date them directly because no new mineral phases crystallized during these events and, although the ages of the granitic plutons and the early ductile shearing provide a maximum age, there is little constraint on how young the last episode might have been. The age of the redbeds is critical in dating the brittle episodes because their deposition separates Episodes 1 and 2 from Episode 3. This interpretation is based on the facts that (1) Episodes 1 and 2 are not recorded in any of the redbeds even though their small-scale conjugate faults are extensively developed in the adjacent metasedimentary and mylonitic rocks, and (2) Episode 3 faults are found throughout the entire area, including the redbeds.

Unfortunately, as mentioned in Chapter 1, there is little control on the time of redbed deposition, leaving their age and that of the brittle deformation events uncertain. Since neither macro- nor microfossils have been found in the redbeds, their age can only be inferred by structural position and regional correlation. Analogous post-Acadian molasse ranges from as old as Late Devonian (the Perry Formation of southeasternmost Maine), to as young as Mississippian and Pennsylvanian in the large Carboniferous basins of Maritime Canada and the Plaster Rock outlier in northwestern New Brunswick. In addition, an unknown but probably significant amount of time must have separated the Middle Devonian (380 Ma) ductile shearing event from redbed deposition, during which span Episode 1 brittle faulting occurred, followed by erosion of Acadian metasedimentary and granitic rocks to form first-cycle pale gray to white molasse. There must also have been enough time for the first-cycle molasse to be lithified completely, uplifted, and eroded, and its fragments added to the second-cycle red molasse beds found today along the Waite and Fredericton faults. Study of Carboniferous and Permian drainage patterns in the Northern Appalachians by Gibling et al. (1992) has shown that rivers at that time followed northeast-oriented structural lineaments—such as the Waite-Fredericton fault—through the older Acadian mountains, and the paleoflow was northeasterly in the Carboniferous basins of southwestern New Brunswick. Chapter 8 evaluates models for the evolution of the basins in which the redbeds were deposited, and suggests that Brittle Episode 2 was involved in opening those basins.

A Pennsylvanian age is preferred for the red molasse because its slivers in the Waite fault zone are *along* strike with Pennsylvanian counterparts along the Fredericton fault, the continuation of the Waite zone in New Brunswick, whereas the Perry basin is located more than 60 km *across* strike to the southeast. A Pennsylvanian (?) age will be assumed in the following discussions, to avoid overly complex wording, with the *caveat* that this is by no means certain.

Episode 1 brittle reactivation is bracketed between the Middle Devonian age of the ductile fabrics that it overprints and the age of the redbeds. Episode 2 may have played a role in opening the basins in which the first-cycle molasse was deposited; reactivation of these faults is thought to have provided the depocenters for the second-cycle redbeds. Middle to Late Devonian and Mississippian ages are considered most likely, respectively for these events, but cannot be proven.

Episode 3 obviously happened after the deposition of the redbeds because it affected them after they had completely lithified. If the redbeds were indeed deposited in Pennsylvanian (?) times, a late- or post-Carboniferous age is required. Because Episode 3 was compressional in nature, it is not likely to have been associated with the early Mesozoic rifting that led to the opening of the Fundy basin and the modern Atlantic Ocean. This suggests that Episode 3 activity was bracketed between the Pennsylvanian (?) deposition of the redbeds and the onset of extensional block faulting in Triassic times.

7.4. Comparison of the timing of Norumbega faulting in eastern and southwestern Maine

West (1993, 1997) identified two episodes of mineral growth during ductile shear along the deeper crustal segment of the Norumbega fault system in south-central and southwestern Maine. The first, interpreted as the age of broad, system-wide shearing, occurred shortly after the peak of regional metamorphism at 380 Ma. The second, ~290 Ma (Late Pennsylvanian - Early Permian) appears to be restricted to narrow zones of extremely high strain mylonites distributed within the system, e.g. the Sandhill Corner, Flying Point, and Sunny Side faults. West and Hubbard (1997) suggest that shearing may have been continuous during this 90 million year span in the deeper segment, perhaps accompanied by progressive unroofing. Indeed, fabrics in the second mylonite are identical to those of some of the highest strain rocks from the Kellyland fault zone, exhibiting a combination of ductile (quartz) and brittle (feldspars, hornblende) features.

Early deformation was therefore coeval at approximately 380 Ma along the entire Norumbega system in Maine. However, this study identifies only a single phase of ductile shearing (~380 Ma) in eastern Maine. The second (290 Ma) ductile shear event reported in southwestern Maine is probably represented by brittle shearing in the study area in eastern Maine, although the sense of motion during Episode 3, the most likely candidate, does not match the dextral movement reported by West (1993). The different behaviors were probably due, at least in part, to different thermal histories for the two areas that are as yet not fully understood. The simplest explanation, supported by the higher regional metamorphic grade of the rocks in southwestern Maine, is that at ~ 290 Ma, the currently exposed eastern Maine segment was uplifted to a shallower crustal level, while rocks currently exposed in southwestern Maine were still buried beneath the "Casco Bay Uplift" proposed by Swanson (1999b). Alternatively, the two areas might have experienced different geothermal gradients (related to the large plutons in eastern Maine?) and the study area could have cooled to a lower temperature (less than ~200°C; Figure 42). Resolution of this issue requires detailed thermochronologic work in both areas to document their thermal evolution.

Mesozoic reactivation of Norumbega structures with at least some component of vertical offset was reported in both southwestern (West et al., 1993) and eastern segments (Doll et al., 1996). The Flying Point fault, one of the 290 Ma high-strain ductile zones, is today a major thermochronological discontinuity. Regional cooling patterns suggest that this discontinuity cannot be related to Late Paleozoic movement, and could not have been caused earlier than Triassic times. West et al. (1993) suggested Mesozoic offset of approximately 4 km, with a normal, east-side-down displacement. Doll et al. (1996) based their interpretation on a seismic reflection image that shows that the Moho has been offset by approximately 1.5-2.0 km beneath the Waite fault zone, also with an east-side-down sense of movement.

Brittle Episode 3 is the only event recognized in the field in the study area that could possibly be associated with the Mesozoic reactivation, because it alone post-dates the redbeds. The compressional nature of Episode 3, however, argues against this correlation and contrasts with the extensional nature of the environment in which West et al. (1993) envisage the Mesozoic deformation to have occurred.

7.5. Correlation of Norumbega faulting in eastern Maine with tectonic events of the Appalachian Mountain System

Based on the timing deduced for the ductile and brittle activity in the study area, and on the paleostress analyses for the late-stage brittle deformation, it is possible to correlate the Norumbega deformation investigated in this study with major tectonic events in the Appalachian Mountain System.

Early ductile shearing — Late Acadian plate adjustments

The oldest shearing recognized in the Norumbega fault system in eastern Maine occurred in Middle Devonian times (~380 Ma), and is attributed to late-stage activity associated with the Acadian orogeny. West et al. (1992) demonstrated that the climax of Acadian deformation in the Fredericton belt was late Silurian. Bradley et al (1998) showed that the beginning of the Acadian event was regionally diachronous, beginning in eastern Maine in late Silurian time and becoming progressively younger (to Middle Devonian) in central and north-central Maine. Some Early Devonian folding also occurred in easternmost Maine, explained by Bradley et al. (1998) as the result of a "tectonic backstop". Thermal adjustments to Acadian tectonism led to melting and emplacement of numerous Devonian plutons such as the Bottle Lake, Deblois and Lucerne, and continued adjustment of plates whose oblique collision caused the Acadian orogeny led to the dextral ductile shearing.

The timing and dextral sense of motion associated with the ductile shearing are thus consistent with the timing and kinematics of plate collision generally interpreted for the Acadian orogeny (e.g., Bradley et al., 1998; Gates et al., 1988).

Brittle Episodes 1, 2, and 3: post-Acadian – Alleghanian transition

Paleostress analyses described in Chapter 6 have yielded three major compressive stress directions for late-stage, post 380 Ma, brittle reactivations of the Norumbega fault system in eastern Maine. σ_1 for the earliest (Episode 1) and most intense event was oriented approximately WNW-ESE, but rotated to NE-SW for Episode 2 and changed drastically to N-S for Episode 3. These paleostress results share some similarities with those from other segments of the Appalachian orogen but also contain significant differences, both in orientation and time.

In Quebec and northern New Brunswick, ductile fault structures comparable to those of the Kellyland and Waite fault zones are absent, but conjugate sets of reverse and strike-slip brittle faults are abundant (Faure et al., 1996). A numerical paleostress tensor analysis of striated fault planes by Faure et al. (1996) identified stress fields associated with three distinct brittle compressional events. The earliest and most intense had σ_1 oriented NNW-SSE, σ_1 for the second was NNE-SSW, and σ_1 for the last was WNW-ESE. Interestingly, the third compressive event in Quebec, like Episode 3 in the study area, is also mostly recorded in Carboniferous rocks although its maximum stress direction is oriented differently from that inferred along the Waite fault zone.

Faure et al. (1996) described a counterclockwise rotation of compressional axes in the Quebec and northern New Brunswick Appalachians. A counterclockwise rotation of compressional axes from Episode 1 to Episode 2 in eastern Maine is in this respect consistent with their results. The ages of faulting, however, are not. Faure et al. (1996) suggested that the first two compressive tectonic events in the Quebec Appalachians took place during Late Carboniferous to Early Permian, and the third from Early to Late Permian time, and are the principal results of the Alleghanian orogeny in the region. Because Episodes 1 and 2 in eastern Maine predated deposition of Pennsylvanian (?) redbeds, they cannot be related to Alleghanian compression and most likely predate all three events described by Faure et al. (1996). Only Episode 3 is potentially young enough to correlate with the features reported by Faure et al. (1996); based on the similar orientations of the stress fields, Episode 3 appears to correlate best with the *first* Alleghanian compressional event in Quebec and northern New Brunswick.

Farther south, analysis of joint distributions and layer-parallel shortening fabrics in the Appalachian foreland sequence reveals two main directions of compression; an older one oriented north-south and a younger oriented WNW-ESE (Engelder and Geiser, 1980; Dean et al., 1988; Evans, 1994). In the northern part of the Appalachian Plateau, two sets of joints oriented NNW-SSE and NNE-SSW were attributed, respectively, to the Lackawana phase and to the main phase of the Alleghanian orogeny (Engelder and Geiser, 1980). In the central Appalachian foreland, both north-south and WNW-ESE shortening directions have been reported (Dean et al., 1988; Evans, 1994). Further south in the central Appalachian Plateau in Virginia, Dean et al. (1988) also found an earlier compression axis oriented between 330° and 350° that was followed by a progressive counterclockwise rotation of the compressional axis to 275°. Limestones of the Appalachian Plateau and of the Hudson River Valley also record north-south- and west-northwest-east-southeast-oriented compressive directions (Craddock et al., 1993; Sierra et al., 1993).

If the ages inferred for Episodes 1 and 2 are correct, it appears that these events record a previously poorly-known part of Northern Appalachian history—the transition from Acadian stress regimes related to one set of plate collisions to Alleghanian stresses associated with very different plate interactions. Effects of Alleghanian deformation in the study area are probably restricted to Episode 3.

CHAPTER 8

ORIGIN OF THE REDBED BASINS

8.1. Origin of the Redbeds in East-central and Eastern Maine

Nine narrow slivers of unmetamorphosed redbeds have now been mapped along the Norumbega fault (mostly the Waite fault zone) in the area between Chemo Pond and the New Brunswick border (Figure 41; Larrabee, 1964; Wones, 1980; Osberg et al., 1985; Ludman, 1994; and this study, Figures 4 and 30). This number includes two hitherto unknown slivers, here named the Middle Nicatous Lake basin in the area between Nicatous Lake and Gassabias Lake, and the Southern Nicatous Lake basin (Figures 30 and 41). The origin of these narrow redbed slivers has seldom been mentioned by previous workers and is problematic, with three likely scenarios:

(1) The redbeds were originally part of an extensive post-Acadian molasse sheet, possibly connected to similar rocks in New Brunswick. Post-depositional dip-slip faulting could have down-dropped and therefore preserved the slivers, while uplifting the remainder of the sheet and leading to its erosion. Larrabee (1964) mentioned this possibility but without any further discussion.

(2) An episode of brittle faulting following Episode 1 could have formed small pull-apart basins in which the rocks were deposited. Pull-apart basins comparable to those envisaged in this second model are common along major strike-slip faults throughout the world (Burchfiel, et al, 1966). Bradley (1982) mentioned the possible pull-apart mechanism for the Norumbega basin (Figure 41) but without a detailed explanation.

(3) The third possibility, not mentioned by previous workers, is that the redbeds were deposited in grabens or half grabens generated by extensional deformation along the fault system.

This study strongly favors the second scenario, the strike-slip pull-apart model, and suggests that all the redbeds were deposited in pull-apart basins generated by Episode 2 dextral strike-slip faulting. This conclusion is based on the following observations and arguments.

(1) Rocks in the nine individual redbed slivers do not fit readily into a simple facies model, and each sliver possesses its own, slightly to distinctly different, stratigraphic package. This does not disprove the molasse sheet model as rapid facies changes would be expected in a complex intermontane fluvial system, but does raise some questions and keeps the second model in contention.

(2) All the redbed slivers now have elongate, narrow shapes and are bounded by brittle faults of the Waite composite fault zone. No other similar rocks have been found outside of the Norumbega fault system in east-central and eastern Maine. This implies that the redbeds were associated with brittle faulting. If the first model is valid, the redbed slivers would have to have been down-dropped in the Waite fault zone while the rest of the broad molasse sheet would have been uplifted and completely eroded all around the Waite fault. This is very unlikely. The fact is that is no evidence of post-Episode-1 dip-slip fault events with appropriate kinematics to have down-dropped the redbed slivers anywhere along the Norumbega fault system in eastern Maine. Episode-3, the only brittle fault event that affected the redbeds, was compressional and oblique according to this study. It deformed the redbeds but did not down-drop them. The

Fredericton fault in New Brunswick offsets the Carboniferous redbeds, but no significant down-dropping has been reported there either. Therefore the first model should be discarded.

(3) Previous studies of post-Acadian molasse in New Brunswick, Nova Scotia, and Prince Edward Island show that these rocks were deposited in large Carboniferous continental redbed basins which initiated as independent pull-apart basins (e.g. Bradley 1982, 1988). Bradley (1982, 1988) proposed that these basins, all associated with orogen-parallel transcurrent fault systems in the Northern and Maritime Appalachians, formed as a result of pull-apart activity following the Acadian orogeny. The Norumbega fault system is one of these transcurrent fault systems. The late Devonian-early Carboniferous rhomboidal Magdalen pull-apart basin located in the Gulf of St. Lawrence, is believed to have been generated by dextral strike-slip movement along the Fredericton fault, the northeastern extension of the Norumbega fault system in New Brunswick. Therefore the same pull-apart mechanism could also have occurred farther to the southwest, along the Maine segment of the fault system.

(4) No regional scale extensional structures have been observed along the Norumbega fault system in eastern Maine, suggesting that third model cited above is not appropriate. This study suggests that the kinematics of brittle Episode 2 is consistent with the pull-apart fault basin model. A strike-slip movement regime with local extensional environment is indicated if the redbeds were initially deposited in fault-bounded pull-apart basins. Episode 1 could not have been the basin-forming event, because of its oblique *compressional* nature described earlier. Small-scale faults associated with brittle Episode 2 structures have not been identified in any of the redbed slivers, suggesting that

it predated or perhaps was synchronous with their deposition. Episode 2 also experienced the dextral strike-slip motion appropriate for the pull-apart model. Episode 3 post-dated the redbeds, leaving Episode 2 as the best candidate for a basin-forming event.

8.2. Strike-slip Pull-apart Mechanism and Redbed Basin Formation

Pull-apart basins (Burchfiel et al., 1966) are commonly developed along regional strike-slip fault systems. Studies of these natural pull-apart basins and experiments (e. g. Aydin and Nur, 1982; Mann et al., 1983, 1997; Peacock, 1991; Peacock and Sanderson, 1995; McClay and Dooley, 1995) have proposed two models to explain the formation and evolution of large, transtensional basins along strike-slip faults: one model of transtensional and rhombohedral pull-apart basins at step-overs or releasing bends and a second model of more elongate and rift-like basins produced by fault-normal extension coeval with strike-slip motion (Ben-Avraham and Zoback, 1992). In addition, Mann (1997) proposed a third model for such basins involving tectonic escape.

The first pull-apart model is the most common one. The extensive New Brunswick Carboniferous redbed basin, into which the Waite fault zone continues northeastward as the Fredericton fault, was associated with the late Devonian-early Carboniferous rhomboidal Magdalen pull-apart basin in the Gulf of St. Lawrence (Bradley, 1982). This pull-apart basin was generated at a releasing bend of a northeast-trending dextral strike-slip system, and the subsequent thermal subsidence affected a large area including most of New Brunswick during middle and late Carboniferous time (Bradley, 1982). The Moncton basin in southern New Brunswick is also viewed as a pull-apart basin associated with the same strike-slip system, and smaller pull-aparts created by similar strike-slip systems in the Northern Appalachians are possible (Bradley, 1982).

The mechanisms for redbed basin development along the Norumbega fault system in eastern Maine have not been adequately addressed by previous workers. This study suggests that all the redbed basins in the Norumbega fault system in eastern Maine are pull-apart basins formed at releasing bends during a brittle phase of activity along the Waite fault zone (Figure 41a,b). Episode 1 master faults are not always straight but curve, bend, and anastomose locally, and Episode 2 faulting mostly reactivated the Episode 1 faults (e.g. Figure 30), so that some releasing bends would have been expected to form. The pull-apart mechanism at the releasing bends basically fits the continuum model proposed by Mann et al. (1983). In this mechanism, pull-apart basins nucleate at releasing bend fault segments along the fault system, and initial opening across the bends produce spindle-shaped basins. Increased displacement on the strike-slip faults results in rhomboidal pull-aparts. The small redbed basins labeled A, B, C, D, and E on Figure 41b appear to be examples of such rhomboidal pull-apart basins. With continued strike-slip displacement and a constant regional horizontal maximum principal stress orientation, the rhomboidal pull-apart basins would evolve into narrow elongate basins whose basin width might remain fixed by the width of the releasing bends or the initial fault separation if the shear strain is plane strain (Mann et al., 1983). The Norumbega (Figure 43a; Wones 1980; Fig. 2 of Bradley 1982), middle Nicatous Lake, and lower Nicatous Lake basins mapped in this study are examples of such long, narrow basins (Figure 41b). These basins were clearly synkinematic and sedimentation may have accompanied their progressive opening.

Most of the redbed basins within the Norumbega fault system are small and narrow and characteristically contain pebble- and cobble-size sediments. These sediments are thick bedded (greater than 1 m), generally poorly sorted, and range in shape from well rounded to angular and sub-angular. Only scarce outcrops of finer-grained redbeds such as red sandstone have been observed in the middle of Norumbega basin and basins labeled A and B in Figure 41b. This further supports the proposed dynamic synkinematic sedimentation environment. Because conglomerate predominates in almost all the redbed basins and the redbeds are uniformly steeply tilted, it is hard to reconstruct the distribution pattern of sedimentary facies and facies variations.

8.3. Brittle Episode 2 Strike-slip Displacement Estimate Based on Basin-length Measurement

It was mentioned earlier that estimates of Episode 2 brittle fault displacement are problematic because of the lack of offset markers. Another approach to estimating Episode 2 displacement involves analysis of the pull-apart basins. A simple model proposed by Aydin and Nur (1982) and Mann et al. (1983) states that pull-apart basins lengthen with increasing master fault offset and that the basin width remains fixed by the width of the releasing bend or the initial separation. With steady strike-slip offset/displacement and enough time, a pull-apart basin would evolve into a very long and narrow shape, the "extreme development" of Mann et al. (1983). This assumes that the direction of relative motion is constant and the shear strain is a plane strain. Basin length is therefore a function of the displacement and the basin length could be taken as minimum displacement (Mann et al., 1983). Measurements of the nine pull-apart basins along the Norumbega fault system yield "basin lengths" (without considering post-redbed deformation such as Episode 3) ranging from about 1.5 km to 32 km. Changes in basin length could possibly be caused by differential displacement along the fault system. Nevertheless, it must be pointed out that individual pull-apart basins could nucleate and open at different times along the same strike-slip system. The earliest and most long-lived basins should have greater lengths which more closely approximate the true strike-slip displacement and thus can be used to estimate the displacement based on the model of Mann et al. (1983).

It is speculated that due to a prolonged displacement and steady offset, some very narrow and deep pull-apart basins such as the Norumbega basin, the Middle Nicatous Lake basin, and the Southern Nicatous Lake basin, were generated along the Waite composite fault zone. The Norumbega basin on the northwest side of the Lucerne pluton is the longest, with a length of 32 km and width of 1.5 km (Figure 41a). According to the discussion above, this length could be taken as the minimum displacement along the fault system. However, it must be noted that, redbeds in all pull-apart basins, including the Norumbega basin, were tilted and possibly folded by a later brittle deformation event (Episode 3 discussed above) and thus the basins were shortened to some extent, implying that the basin lengths measured now are probably shorter than the original ones.

CHAPTER 9

DISCUSSION AND CONCLUSIONS

This study has made significant progress toward understanding the evolution of the Norumbega fault system and related regional geological issues in eastern Maine, including:

(1) **The shallow-crustal segment of the Norumbega fault system experienced a complex, multi-deformational history involving distinct ductile and brittle phases** (Chapters 3-6). The earliest deformation was by dominantly ductile processes, and was followed by sporadic, largely brittle episodes of fault reactivation summarized in Table 2.

Table 2. Summary of Multiple Ductile and Brittle Faulting Events

Fault Event	Timing	Mechanisms	Movement
Ductile Shearing	Middle Devonian (~380 Ma)	Plastic deformation in quartz and cataclastic flow in feldspar	Dextral strike-slip
Ductile-brittle transition	Initiation of Episode-1. Only minor conjugate ductile-brittle faults have been observed.		
Brittle Episode 1	Between Middle-Devonian and Early Carboniferous	Cataclastic flow	High-angle reverse
Brittle Episode 2	Carboniferous (?)	Cataclastic flow	Dextral strike-slip
Brittle Episode 3	Latest Carboniferous to Permian (?)	Cataclastic flow	Oblique: Reverse-sinistral

(2) **Initial Norumbega deformation involved significant ductile shearing.** (Chapter 4). Most ductile shear strain was partitioned into the distinct Kellyland, Waite, and Codyville ductile shear zones. Strain partitioning appears to have been controlled at least in part by lithologic anisotropy, with maximum strain developed at the contact between major plutons and their host rocks. Ductile shearing in the Waite and Kellyland ductile shear zones is characterized by broad zones of phyllonite generated from metasedimentary rocks and mylonites produced from granite protoliths. Strain facies distribution is best exposed in a 4-km wide swath of Deblois granite caught in the Kellyland ductile shear zone, where undeformed granite passes into weakly foliated granite, s-c mylonite, and interlayered mylonite and ultramylonite. Low-grade metawackes and metapelites into which the granite was emplaced were converted to high-strain phyllonites. Dioritic intrusions affected by the ductile shearing were sheared into dioritic mylonites.

(3) **Ductile deformation was controlled by quartz in granitic rocks and phyllosilicates in pelitic rocks** (Chapter 4) Quartz accommodated most of the ductile shear strain in the granite and exhibits numerous structures indicating intracrystalline plastic deformation. Well-defined quartz ribbons formed by coalescence of abundant quartz grains and subgrain rotation. In contrast, microcline, albite, and hornblende responded brittlely to the shear stress.

Shear strain in the metasedimentary rocks was concentrated in pelitic layers, with most strain absorbed by the phyllosilicates. Only minor ductile shear strain is recorded in the massive metawacke beds, propagated by mass transfer in a fault-generated pressure-solution cleavage.

***(4)* Early ductile shearing occurred at shallow crustal levels at relatively low temperatures and pressures** (Chapter 4). Based on different microstructures and mechanisms in quartz and feldspars, ductile shearing in the shallow segment of the Norumbega fault system in eastern Maine took place at conditions of the lower greenschist facies. Temperatures on the order of 300-350°C and pressures of 2-2.5 Kbars are estimated for the peak of ductile shearing. Conditions of deformation appear to have varied little within the study area. This inferred deformation temperature range is also identical to that suggested by Hubbard and Wang (1999) for the high-strain zones in east-central Maine segment from South Orrington to East Palermo, suggesting that there were no significant temperature variations as far south as East Palermo.

However, it has previously been suggested (Hubbard et al., 1995) that the Norumbega fault system was differentially exhumed during or following deformation, in which case the southwest part of the system should have been exhumed from deeper crustal levels and therefore higher temperatures than the northeastern part If this were true, temperature during deformation should decrease toward the northeast. Hubbard and Wang (1999) attributed the apparent lack of temperature variation between South Orrington to East Palermo to deformation that may have followed differential exhumation, and suggested that the high-strain deformation that took place at this temperature range occurred during a later phase, when rocks were at a shallower level than that associated with the broadly distributed 380 Ma deformation for which temperatures of 400-450°C are estimated. This explanation is consistent with the "progressive localization model" during exhumation presented by West and Hubbard

(1997). Thus the deformation temperature estimated by Hubbard and Wang (1999) is for the ~290 Ma ductile event, whereas the deformation temperature estimated by this study shown above is for the ~380 Ma ductile event.

This study has shown that there is only one phase of ductile deformation, i.e. the ~380 Ma ductile event, recognized in eastern Maine. This ductile event occurred throughout the Norumbega fault system from southwestern Maine to eastern Maine. If this "progressive localization model" is valid for south-central Maine, it should be also applicable to eastern Maine. Therefore the amphibolite-facies ~380 Ma ductile event that generated the *wide* zone in south-central Maine (West, 1993, 1999; West and Hubbard, 1997) would be synchronous with the ~380 Ma greenschist facies ductile shearing in eastern Maine, and the localized, high-strain *narrow* ductile shear zones of intense mylonitization developed ~ 290 Ma in south-central Maine would correlate with one of the three brittle events in eastern Maine. Future work is obviously needed in the transition between the localized high-strain ductile shear zones in south-central Maine and the reactivated brittle faults in eastern Maine.

***(5)* Initial ductile shearing began in Middle Devonian times (~380 Ma)** (Chapter 7). ^{40}Ar/^{39}Ar ages of synkinematic biotite and amphibole in the Waite fault zone, bracketing relationships in the Codyville fault zone, and comparison of differential mineral deformation fabrics and thermochronology of the Deblois pluton all suggest that the ductile event began around 380 Ma.

***(6)* Regional shear model for the Norumbega fault system in eastern Maine** (Chapter 5). The recognition of the Amazon Mountain, Third Lake Ridge, and Morrison Ridge granite slivers between the Waite and Kellyland zones and interpretation of their relationships to the major plutons in the region have greatly helped understanding the geometry of the shear system. Southwestward convergence of the Waite and Kellyland ductile shear zones produced complex fault geometries. Synthetic shears representing megascopic c'-bands developed between the two master faults, leading to shearing and stretching of granite slivers detached from the Lucerne and Deblois batholiths. Megascopic, outcrop-scale, and microscopic kinematic indicators all confirm the dextral strike-slip movement along the Norumbega system during ductile shearing.

A regional shear model proposed here suggests that strain in the study area was partitioned in the early stage of ductile shearing into the Waite and Kellyland zones. In later phases, strain between these master fault zones was accommodated by the development of synthetic shears within the Third Lake Ridge sliver and by possible clockwise rotation of the Amazon Mountain granite. The sheared northern portions of the Lucerne pluton and of the west lobe of the Deblois pluton were progressively and dextrally dragged by these stepwise synthetic shears to form the elongate Morrison Ridge and Third Lake Ridge granite slivers.

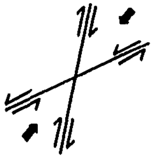
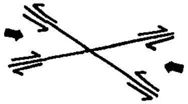
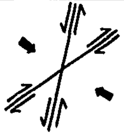
The environment for evolution of this shear system was an oblique transpressional convergence system in the Northern Appalachians (Keppie, 1989). Westward oblique convergence produced orogen-parallel dextral right-stepping *en echelon* strike-slip fault systems in middle to late Paleozoic times, including the Norumbega fault system (Swanson, 1999b; Figure 33). While oblique convergence shortened the crust in southwestern and southeastern Maine (Swanson, 1999b), the block in eastern Maine between the Waite and Kellyland ductile shear zones was caught in an escaping and releasing environment, consistent with the regional releasing offset or stepover fault pattern between the Norumbega and the Cobequid-Chedabucto zones suggested by Swanson (1999b; Figure 37). There was therefore a local extension component parallel to the system that was responsible for the development of a series of synthetic shears.

***(7)* The Waite fault zone was reactivated three times by compressive tectonic events** (Chapters 6, 7). Three separate episodes of reactivated brittle faulting followed early ductile shearing along the Norumbega fault system, each characterized by a different stress field and sense of motion. Episode 1 superimposed a wide and continuous cataclasite and breccia zone on the southeastern part of the pre-existing Waite ductile shear zone. It was transpressional (σ_1 = WNW-ENE) and involved large-scale high-angle reverse faulting. This event took place after middle Devonian and before Pennsylvanian times based on the 380 Ma age of the ductile shearing and the absence of Episode 1 structures in the Pennsylvanian (?) redbeds.

Episode 2 (σ_1 = NE-SW) involved brittle dextral strike-slip faulting and was probably responsible for the formation of a series of pull-apart redbed basins along the fault system. Steep tilting and folding of redbeds and their current juxtaposition against older metamorphic rocks and was caused by oblique (reverse-sinistral/strike-slip) brittle faulting of Episode 3 (σ_1 = N-S). Episode 3 was post-Pennsylvanian (?) and is tentatively correlated with the first stages of the Alleghanian orogeny described in Quebec and northern New Brunswick by Faure et al. (1996)

The results reported here significantly refine the multiple fault stage model proposed by Ludman (1998) and Ludman and Gibbons (1999) for NFS deformation in the metasedimentary and plutonic rocks of eastern Maine (Tables 2 and 3).

Table-3. Correlation of the refined multiple deformation events to previous study

Multiple Deformation Events		Minor Conjugate Faults			Ludman and Gibbons (1999)	Age
		Trend	Motion and σ_1 (Map view)	Faulted Rocks		
Brittle Phase	Episode-3	010°-020° 160°-170°		Lack of cataclasite.	Stage-4	Latest Carboniferous to Permian (?)
	Episode-2	010°-020° 060°-070°		Lack of cataclasite.		Carboniferous
	Episode-1	~080° ~130°		Well-developed cataclasite, epidote veins (in granite)	Stage-3	Between Middle Devonian and Early Carboniferous
Ductile-brittle Transition		~010° ~050°		Cataclasite co-exists with mylonite.	Stage-2	
Ductile Phase		No minor conjugate ductile shear zones found. Only large-scale master ductile shear zones such as the Kellyland and Waite zones.			Stage-2 Stage-1	Middle Devonian (~380 Ma)

(8) This study reveals details of the exhumation history of the Norumbega fault system in Maine, and may clarify the differential crustal exhumation mechanism proposed by previous workers (Chapter 7). Both brittle Episodes 2 and 3 were near-surface events in the rocks exposed in eastern Maine. There is no evidence that the redbeds were ever deeply buried, indicating that Acadian mountain building and post-Acadian uplift in eastern Maine had almost stopped by the time of Episode 2 brittle reactivation. By that time, the paleo-erosion level was very close to the current erosion level. Coupled with the early ductile shearing, these data suggest that only slight exhumation occurred in eastern Maine, despite reactivation of the Norumbega system over a 100 million year span.

In contrast, rocks in the southwestern segment of the Norumbega system in Maine apparently underwent more significant exhumation during the same time span. West and Hubbard (1997) imply that the "deep" segment of the fault system was unroofed enough so that rocks initially deformed at mid-crustal conditions during early 380 Ma shearing were at epizonal levels comparable to those of the study area by 290 Ma.

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PLATE I

TOPOGRAPHIC AND GEOLOG OF THE GREAT POND-GRAN STREAM AREA, EASTERN

LOCATION OF OUTCROPS, PHOTOS, AND

SCALE 1:75,000

0 2 4 km

LEGEND

Brittle fault

Ductile shear zone

lithologic contact

Outcrop

C	Carbonife (Pennsylv
Dd	Devonian
Dg	Devonian
OSf	Ordovicia Fredricto metasedi
☐ Fig.38a	Sketch fi
📷 Fig.38a	Photo fig

Base map is based on U
Contour interval is 20
Lithologic contacts ou
area is based on Osber

OGIC MAP
AND LAKE
RN MAINE
AND SKETCHES

oniferous
nsylvanian?) redbeds

nian diorite

nian granite

vician-Silurian
dricton belt
asedimentary rocks

ch figure location

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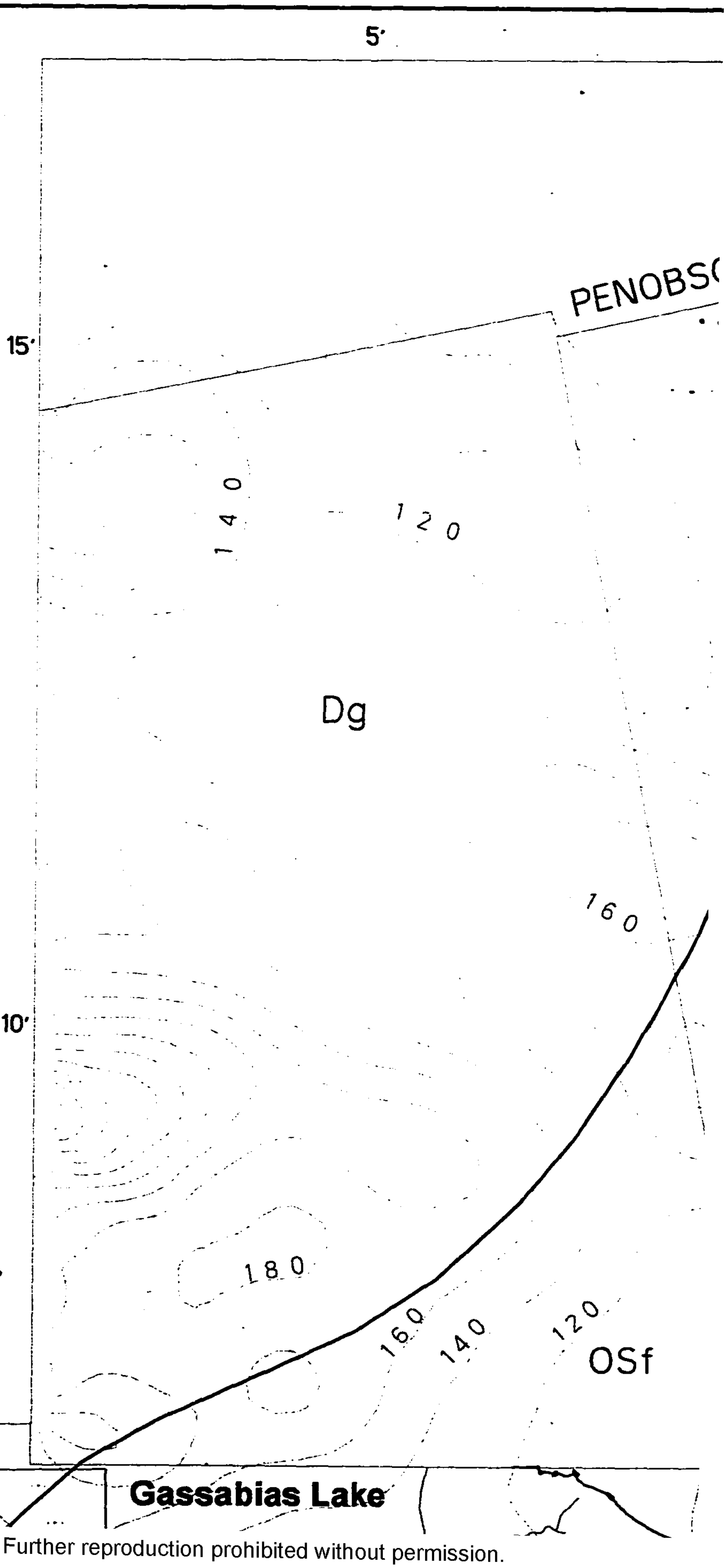
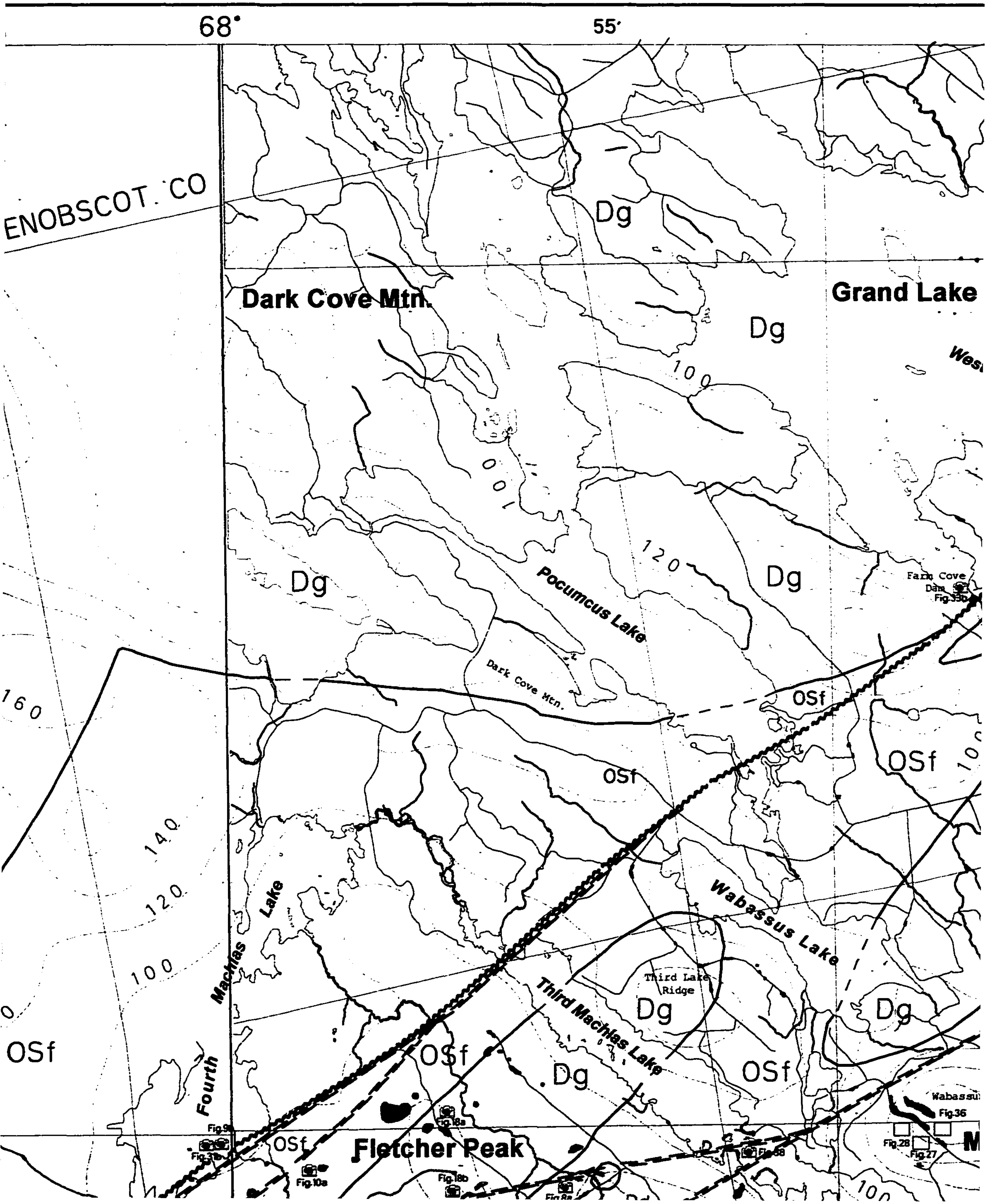
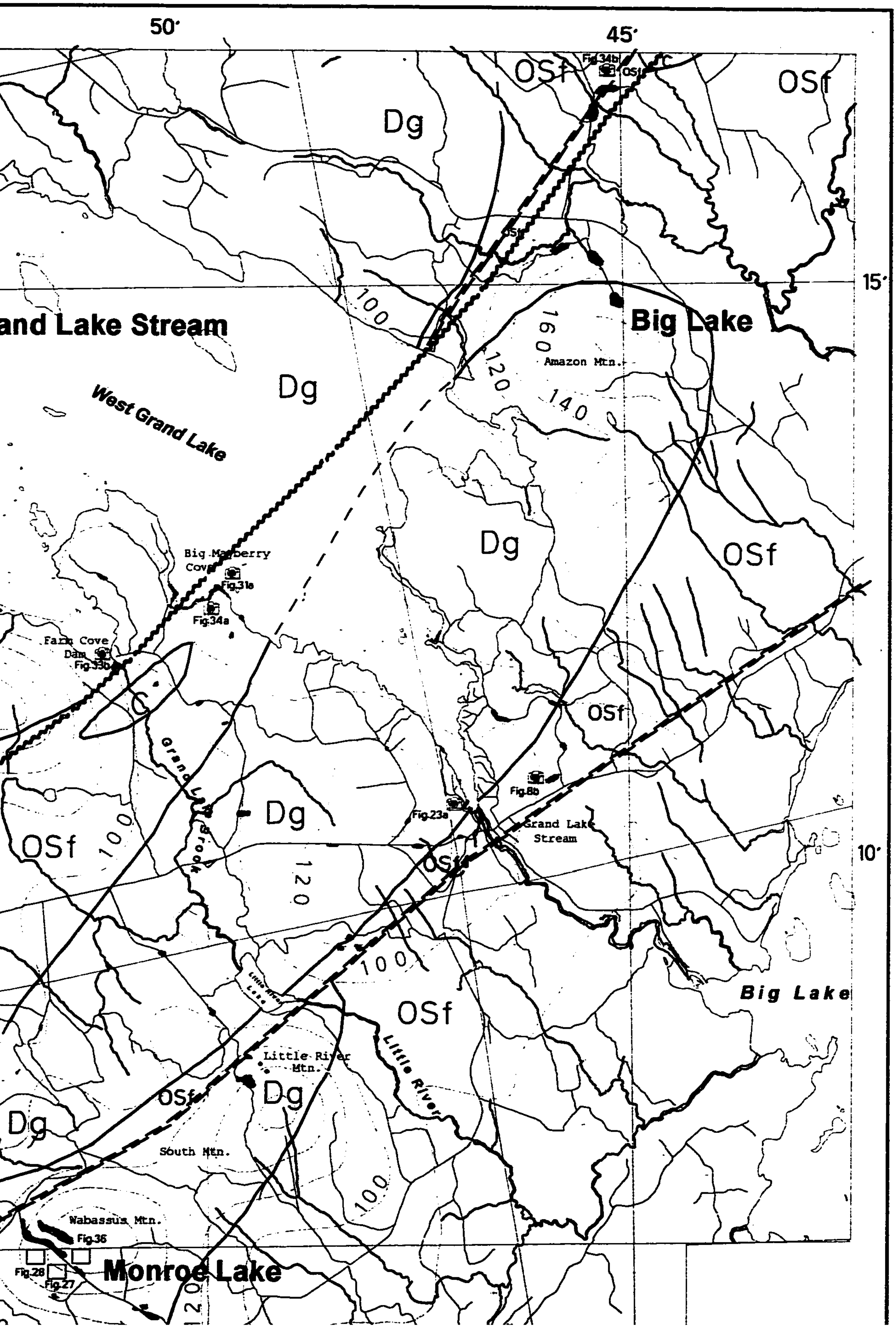
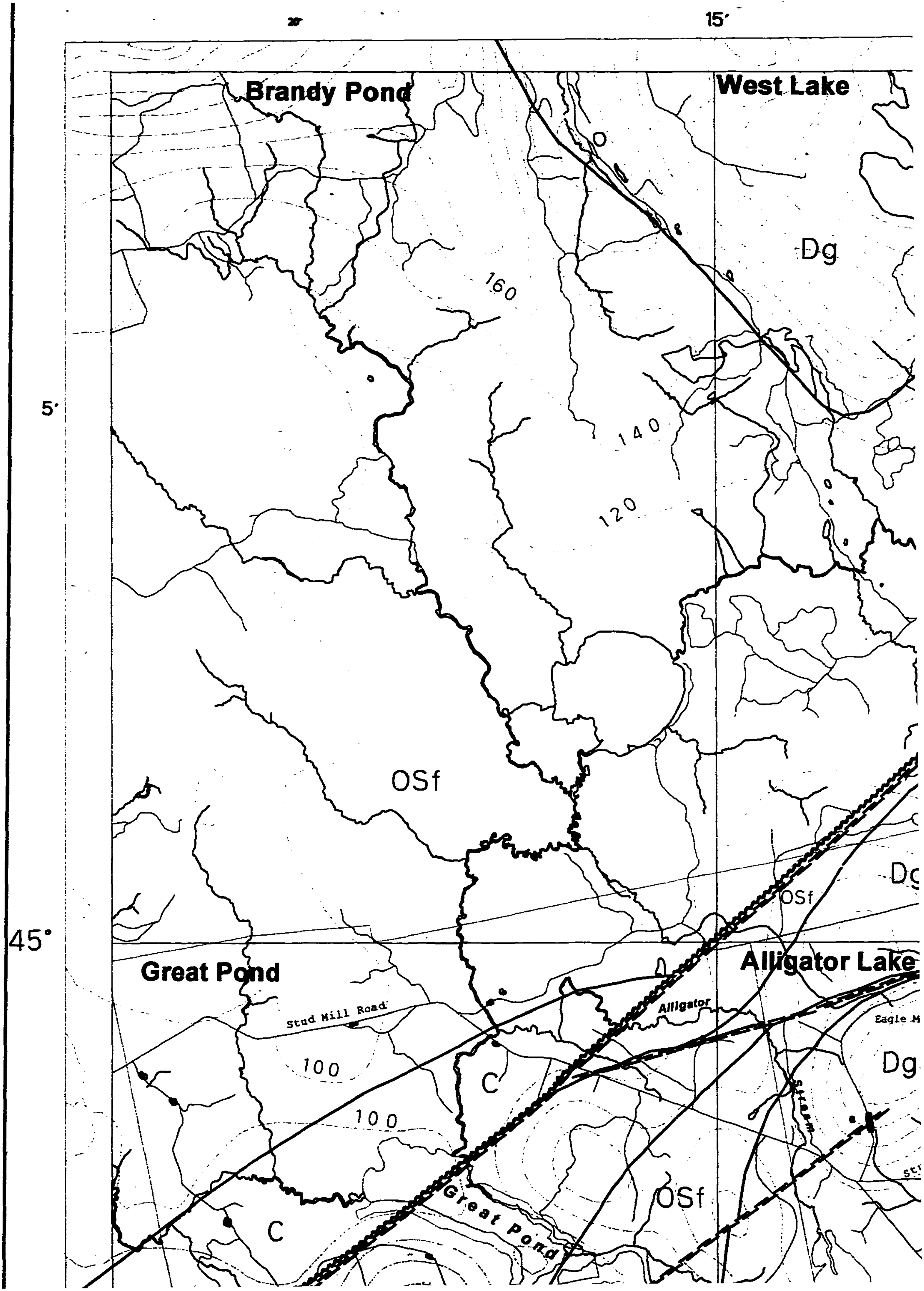
on USGS DEM and DLG data.
is 20 m.
ts outside of the study
Osberg et al. (1985).

10'




68°
55′
PENOBSCOT. CO
Dg
Dark Cove Mtn.
Grand Lake
Dg
West
100
100
120
Pocumcus Lake
Dg
Dg
Farm Cove
Dam
Fig.33b
Dark Cove Mtn.
160
OSf
OSf
OSf
100
140
120
100
Machias Lake
Wabassus Lake
Third Lake Ridge
Dg
Dg
Third Machias Lake
OSf
OSf
Dg
OSf
Fourth
Fig.9
Fig.31b
Fig.10a
Fig.18a
Fletcher Peak
Fig.18b
Fig.8a
Fig.38
Fig.28
Fig.27
Fig.36
Wabassu
100


50′
45′
15′
10′
OSf
Dg
Fig.34b
Big Lake
Amazon Mtn.
160
120
140
100
and Lake Stream
West Grand Lake
Big Mayberry Cove
Fig.31a
Fig.34a
Farm Cove Dam
Fig.33b
C
Grand Lake Brook
Fig.8b
Fig.23a
Grand Lake Stream
Little River Lake
Little River
Little River Mtn.
South Mtn.
Nabassus Mtn.
Fig.36
Fig.28
Fig.27
Monroe Lake
Big Lake


20'
15'
Brandy Pond
West Lake
Dg
160
5'
140
120
OSf
Dg
OSf
45°
Great Pond
Alligator Lake
Alligator
Stud Mill Road
Eagle M
100
Dg
C
100
Stream
Great Pond
OSf
C
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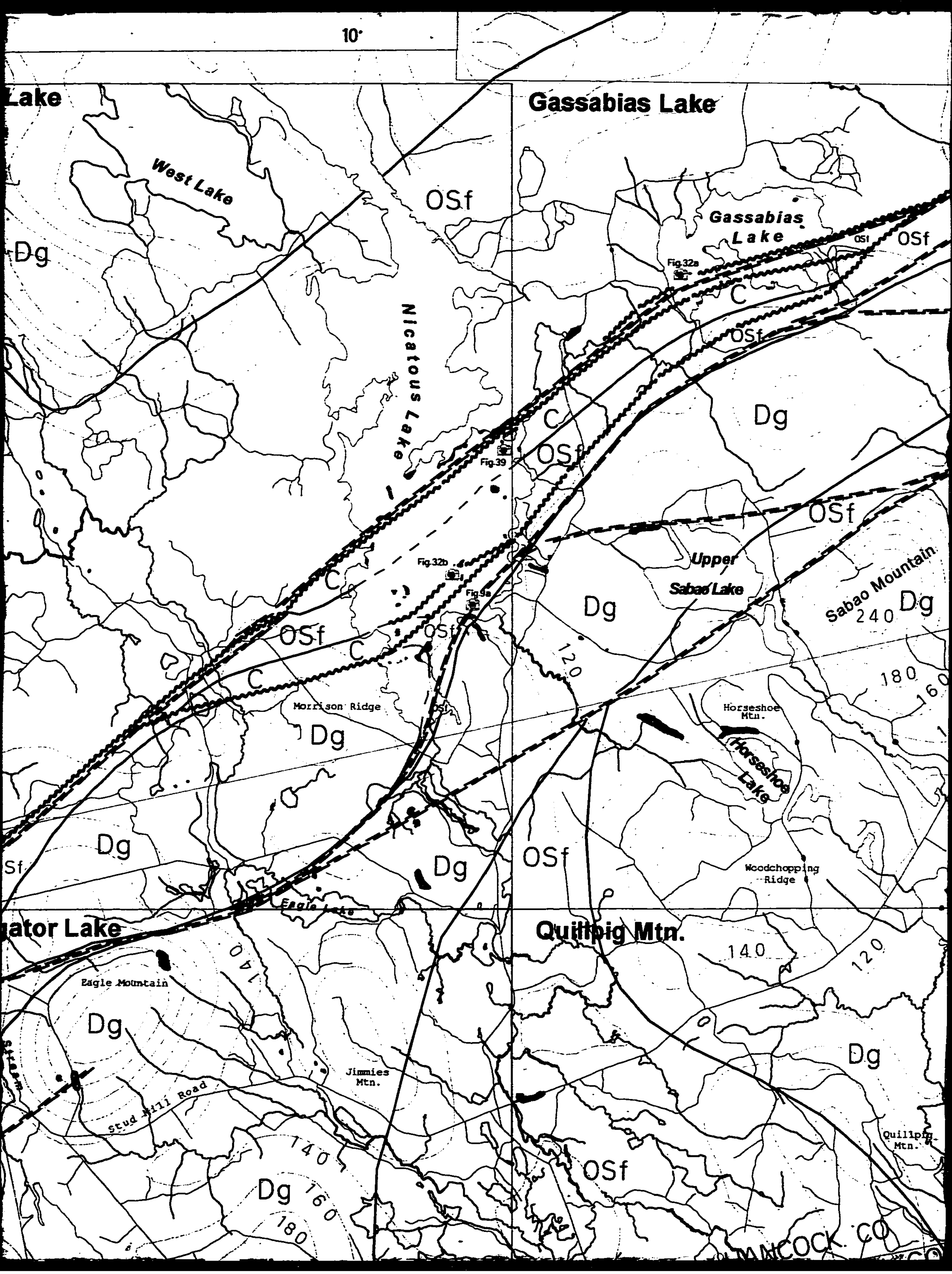
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Lake
Gassabias Lake
West Lake
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Dg
Nicatous Lake
Gassabias Lake
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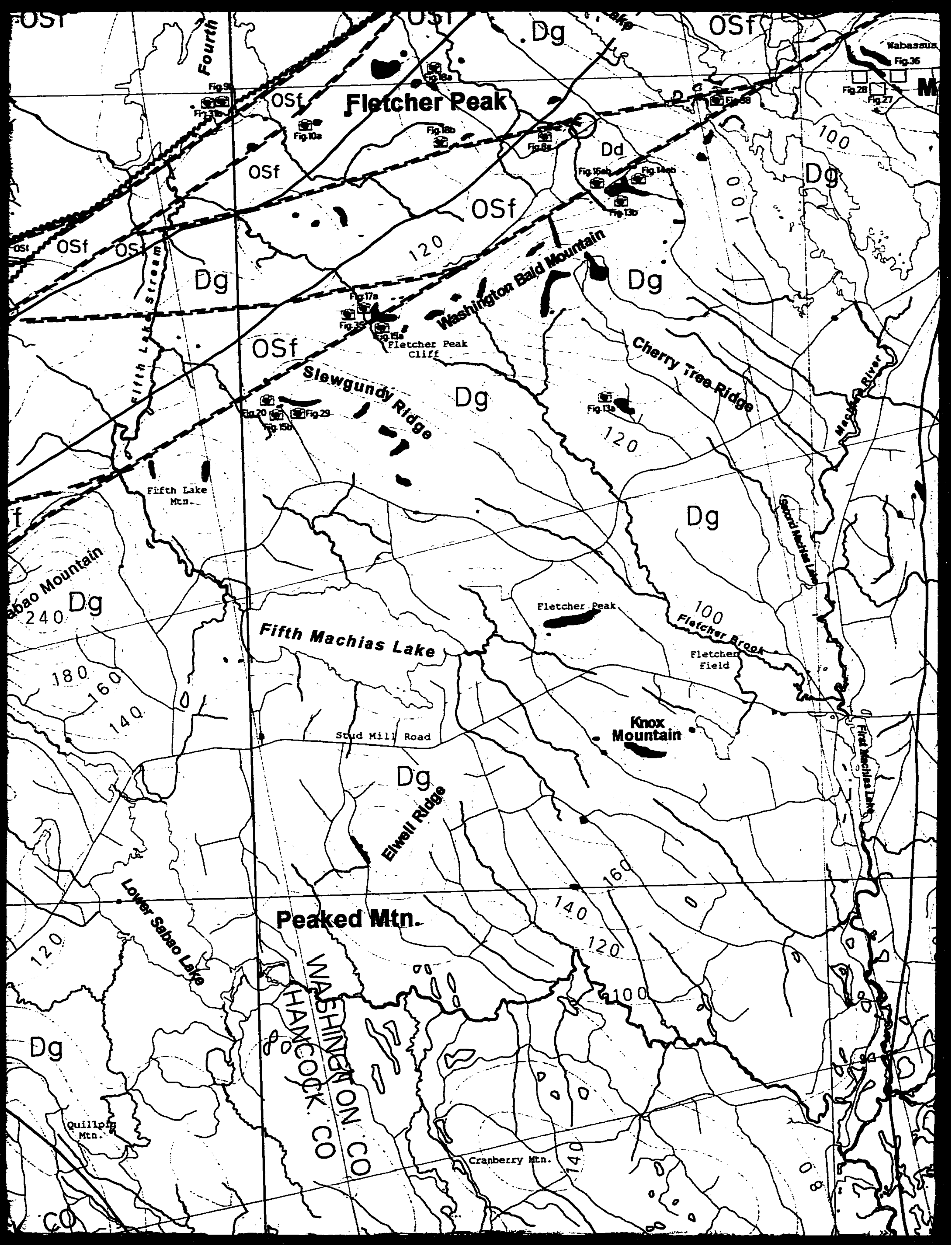
OSf
Fig.32a
C
OSf
Dg
C
OSf
Fig.39
OSf
Dg
Fig.32b
Upper Sabao Lake
Fig.9a
Dg
Sabao Mountain
240
Dg
C
OSf
OSf
C
120
C
180
160
Morrison Ridge
Horseshoe Mtn.
Dg
Horseshoe Lake
Dg
Sf
OSf
Dg
Woodchopping Ridge
Eagle Lake
ator Lake
Quillpig Mtn.
140
120
140
Eagle Mountain
Dg
Dg
Stream
Jimmies Mtn.
Stud Mill Road
Quillpig Mtn.
140
OSf
Dg
160
180
HANCOCK CO


OSf
Fourth
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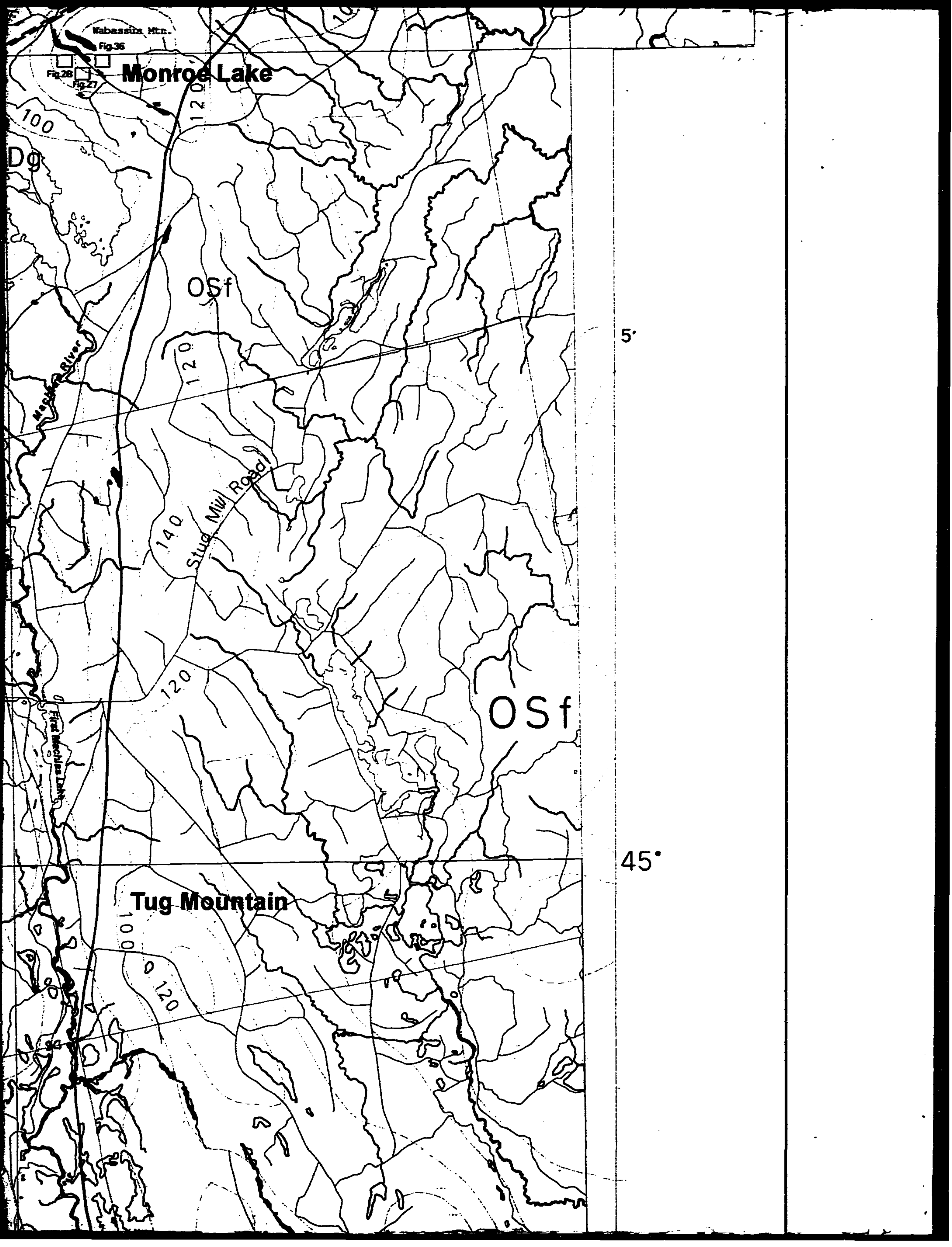
Wabassus
Fig.36
Fig.9a
Fig.18a
Fig.3b
OSf
Fletcher Peak
Fig.10a
Fig.18b
Fig.8a
Fig.38
Fig.28
Fig.27
Dd
Fig.16ab
Fig.14ab
Fig.13b
100
Dg
OSf
OSf
120
OSf
OSf
Dg
Fifth Lake Stream
Washington Bald Mountain
Dg
Fig.17a
Fig.35
Fig.15a
Fletcher Peak Cliff
OSf
Slewgundy Ridge
Dg
Cherry Tree Ridge
Fig.13a
120
Machias River
Fig.20
Fig.15b
Fig.29
Fifth Lake Mtn.
Dg
Second Machias Lake
Sabao Mountain
240
Dg
Fletcher Peak
100
Fletcher Brook
Fifth Machias Lake
Fletcher Field
180
160
140
Knox Mountain
Stud Mill Road
First Machias Lake
Dg
Elwell Ridge
Lower Sabao Lake
160
Peaked Mtn.
140
120
120
100
WASHINGTON CO
HANCOCK CO
Dg
Quillpig Mtn.
Cranberry Mtn.
140
80
CO


Wabassus Mtn.
Fig.36
Fig.28
Fig.27
Monroe Lake
100
120
Dg
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120
5'
Machias River
Stud Mill Road
140
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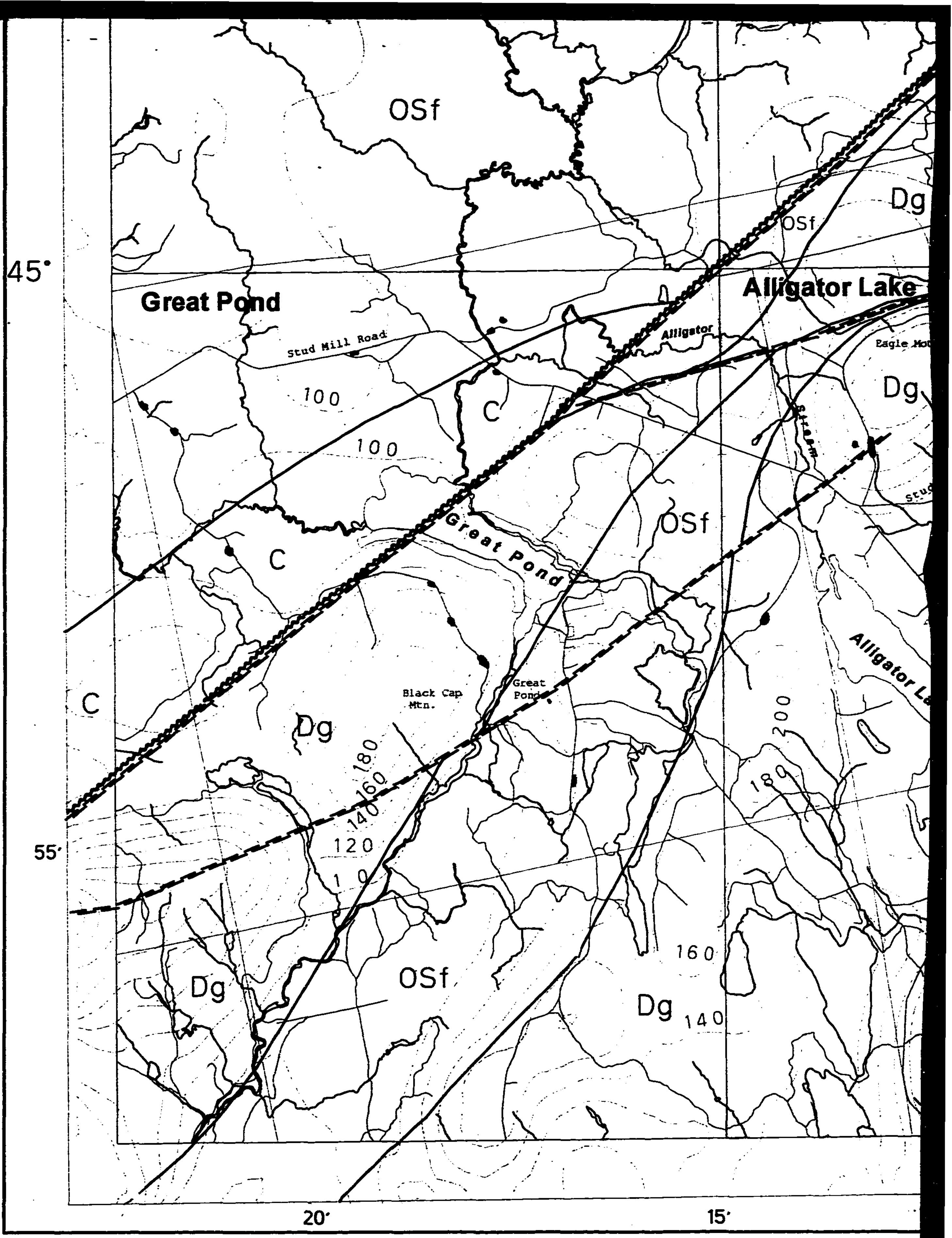
OSf
First Machias Lake
45°
Tug Mountain
100
120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Alligator Lake
Great Pond
Alligator
Stud Mill Road
Eagle Mo
Dg
100
C
100
Stream
Stud
OSf
Great Pond
C
Alligator La
C
Black Cap Mtn.
Great Pond
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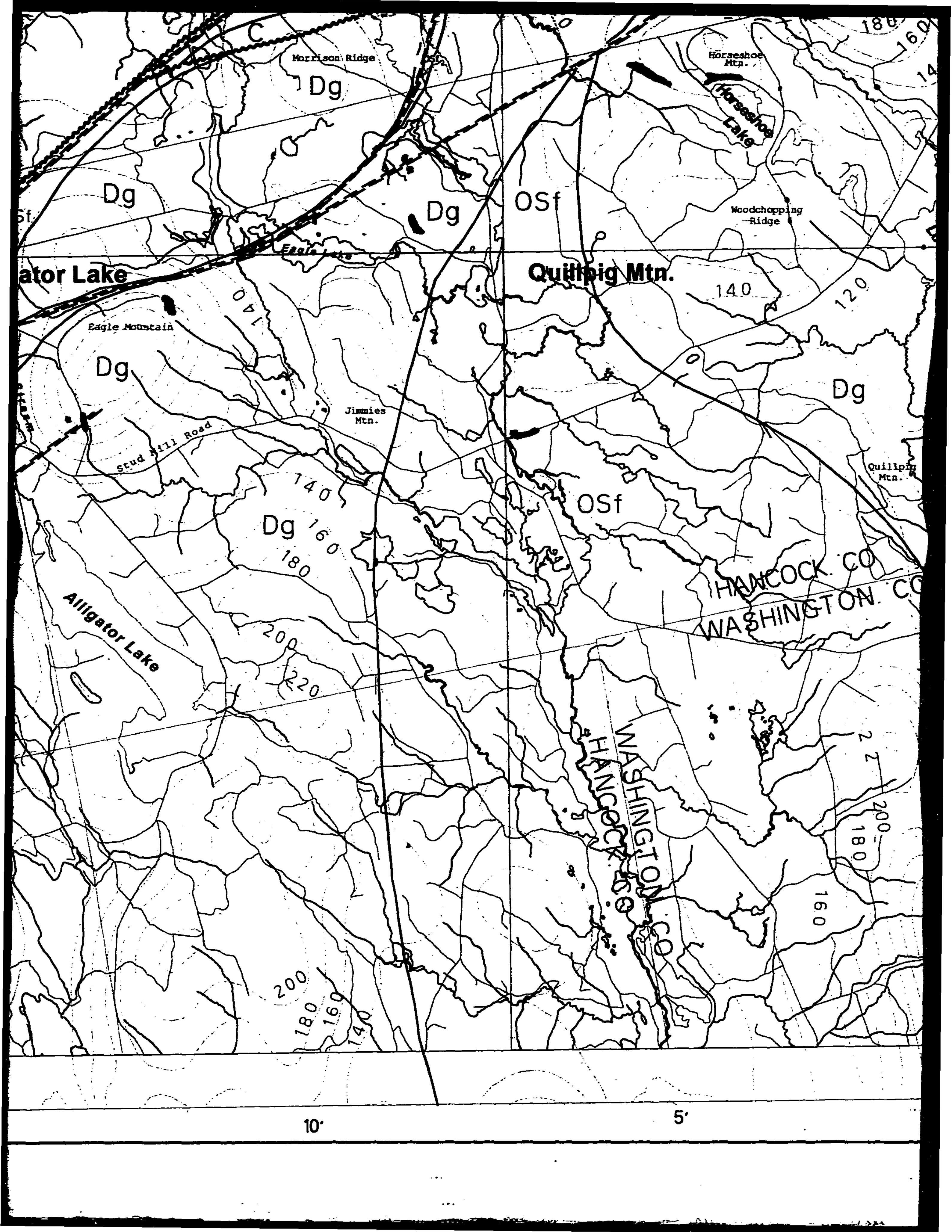
C
Morrison Ridge
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Eagle Lake
ator Lake
Quillpig Mtn.
140
120
140
Eagle Mountain
Dg
Dg
Jimmies Mtn.
Stud Hill Road
Quillpig Mtn.
140
OSf
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160
180
Alligator Lake
HANCOCK CO
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WASHINGTON CO
HANCOCK CO
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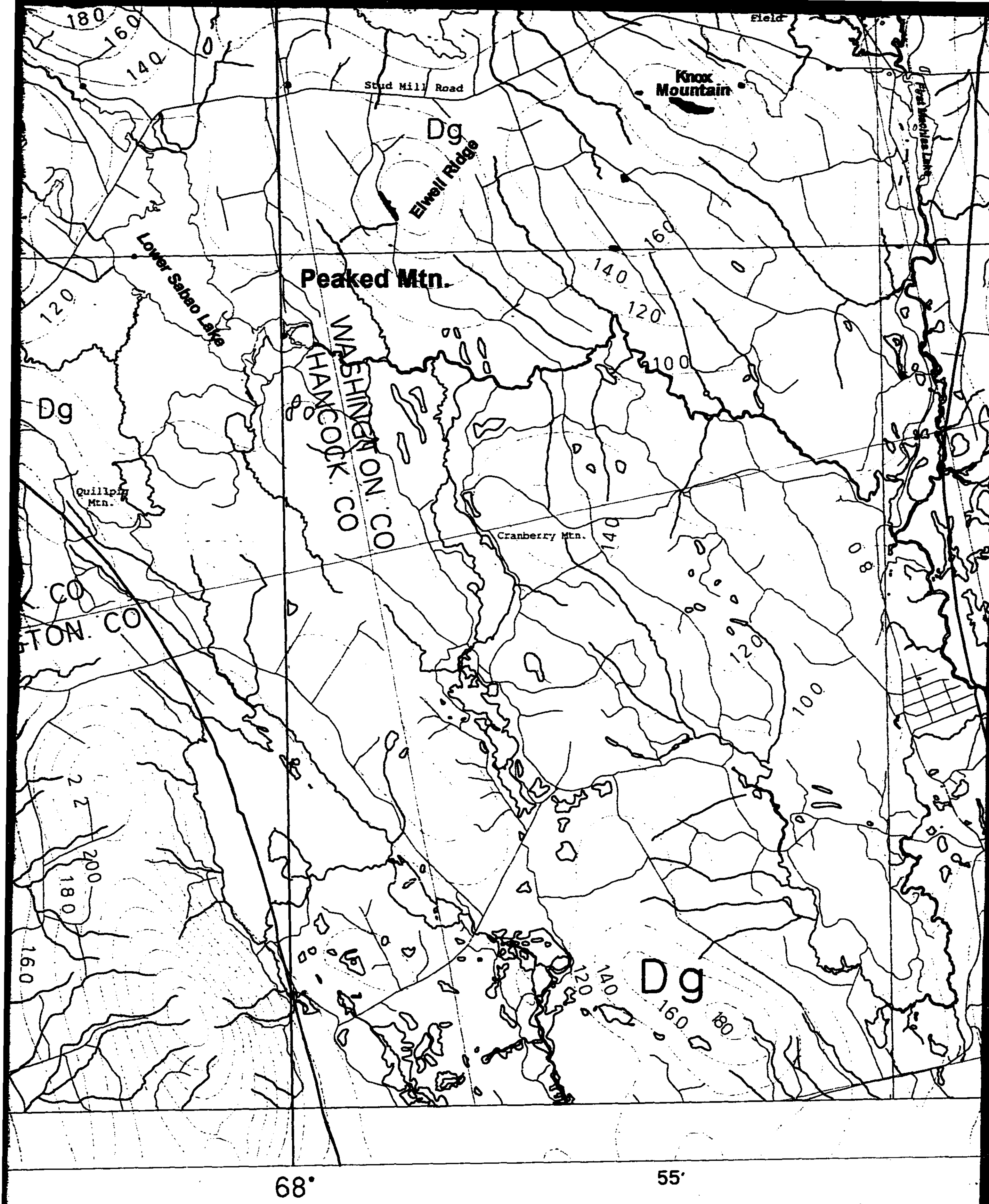
200
180
160
200
180
160
140
10'
5'


180
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Stud Mill Road
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Knox Mountain
First Machias Lake
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Elwell Ridge
Lower Sabao Lake
Peaked Mtn.
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100
120
WASHINGTON CO
HANCOCK CO
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Quillpig Mtn.
Cranberry Mtn.
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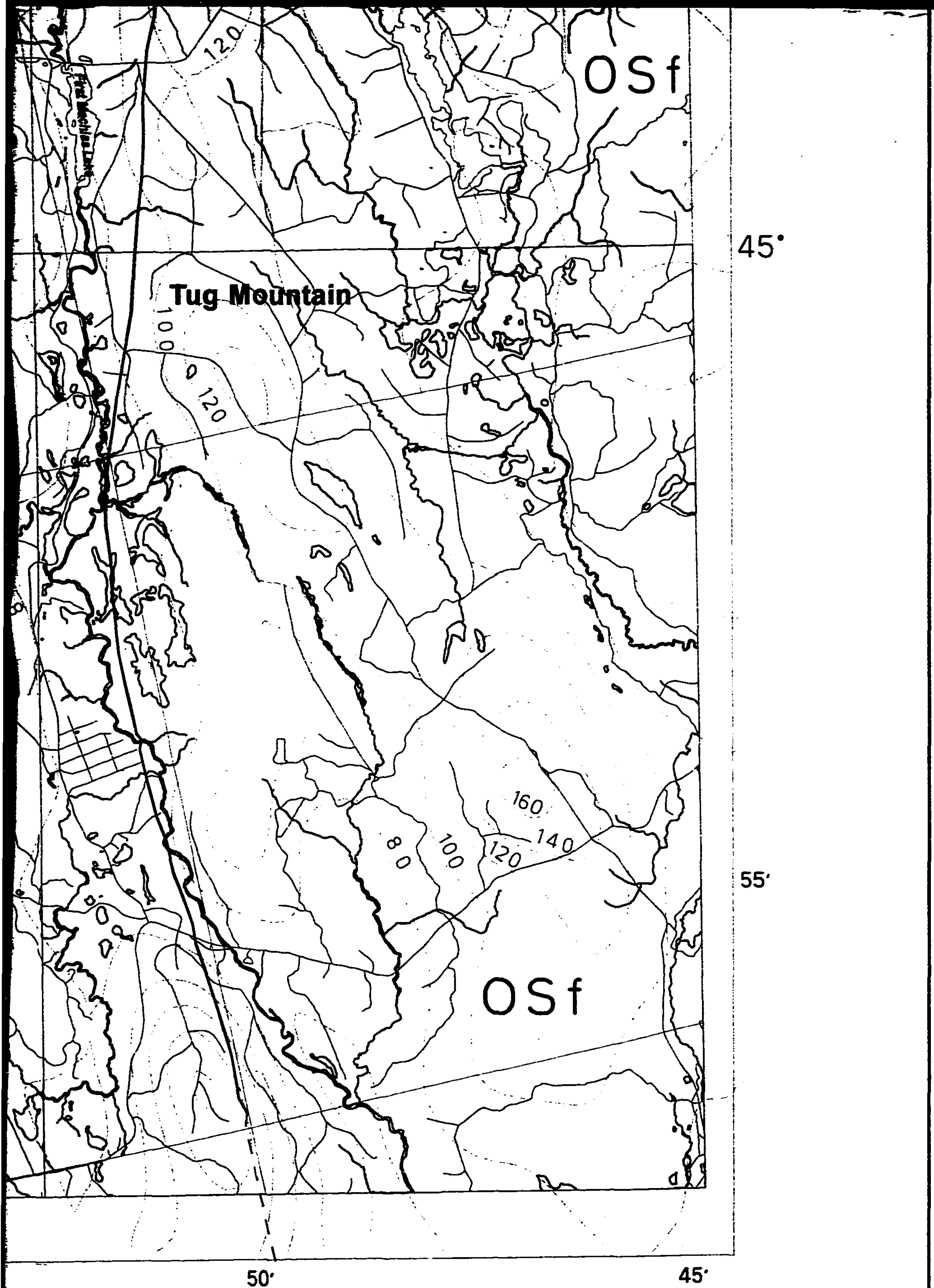
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First Machias Lake
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Tug Mountain
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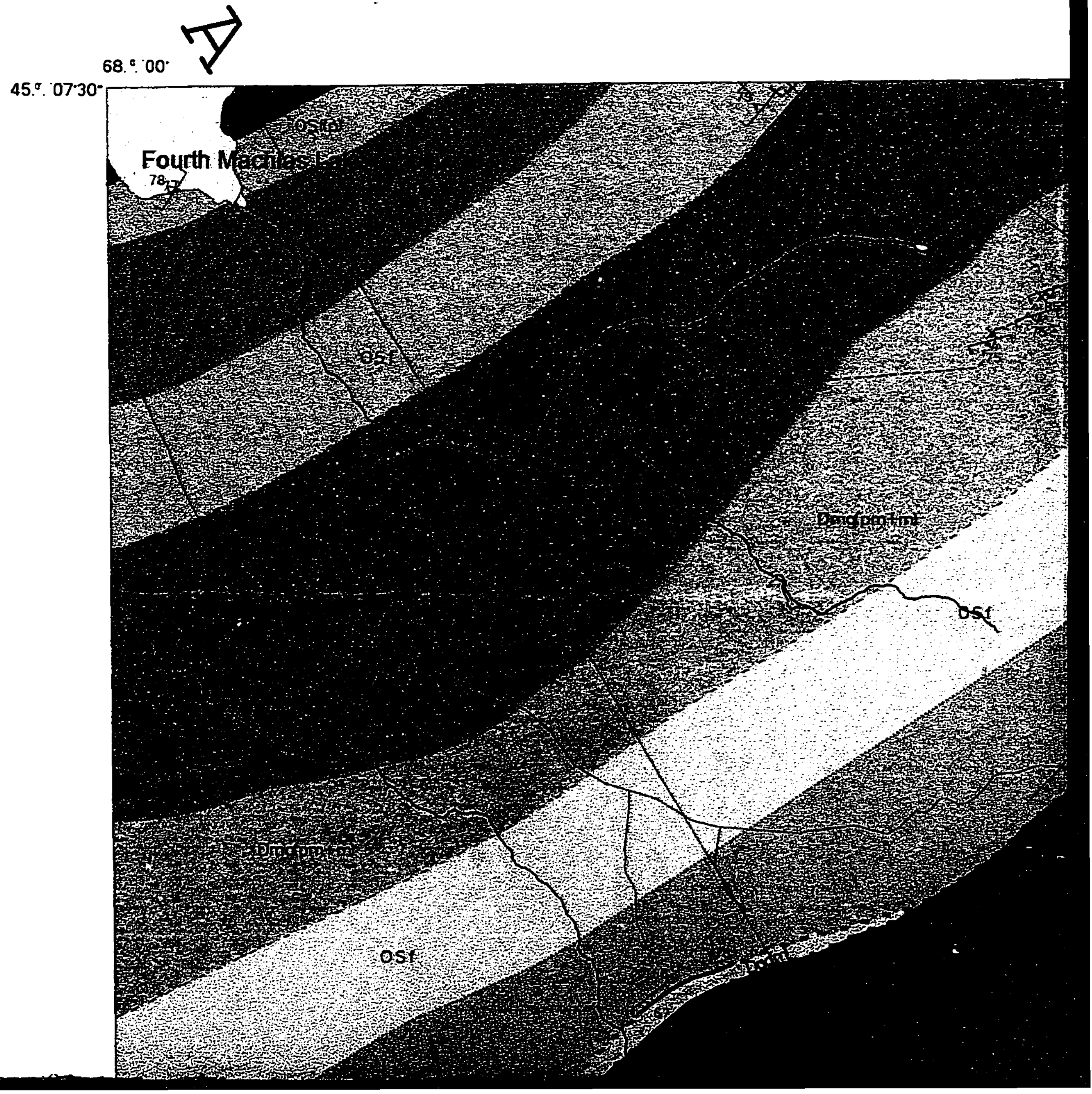
PLATE. II

BEDROCK G



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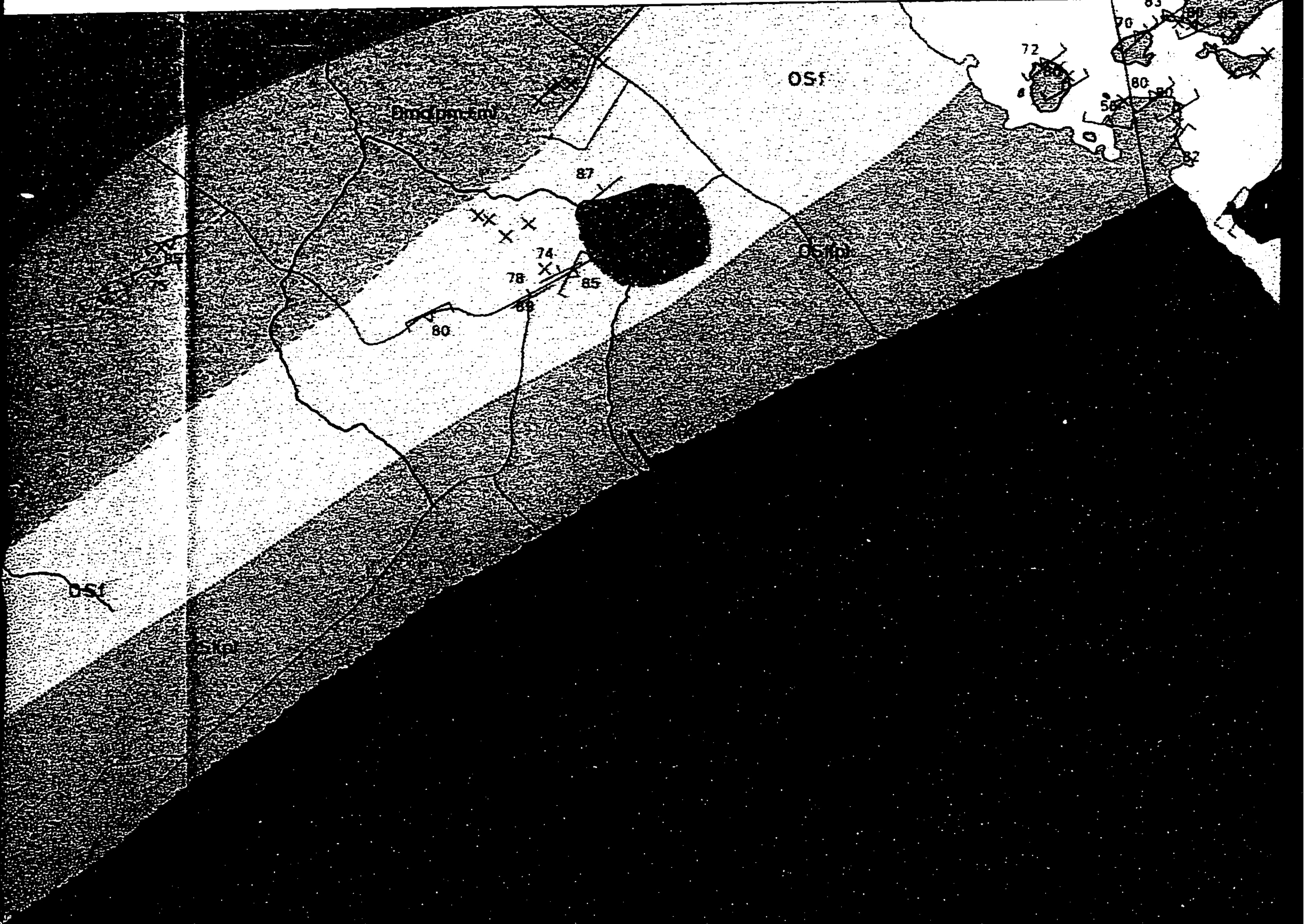


FLETCHER PEAK 7.5' QU

		Unname Fine to v
	Dqd(m)	Mylonite
Third Lake Ridge Granite	Dmg(pm+m)	Medium- Typically
		Coarse to Typically

QUADRANGLE, MAINE

Unnamed granodiorite
Fine to very fine-grained hornblende granodiorite

Mylonite derived from quartz-diorite

Medium-grained biotite granite
Typically foliated or mylonitized (protomylonite-myloni

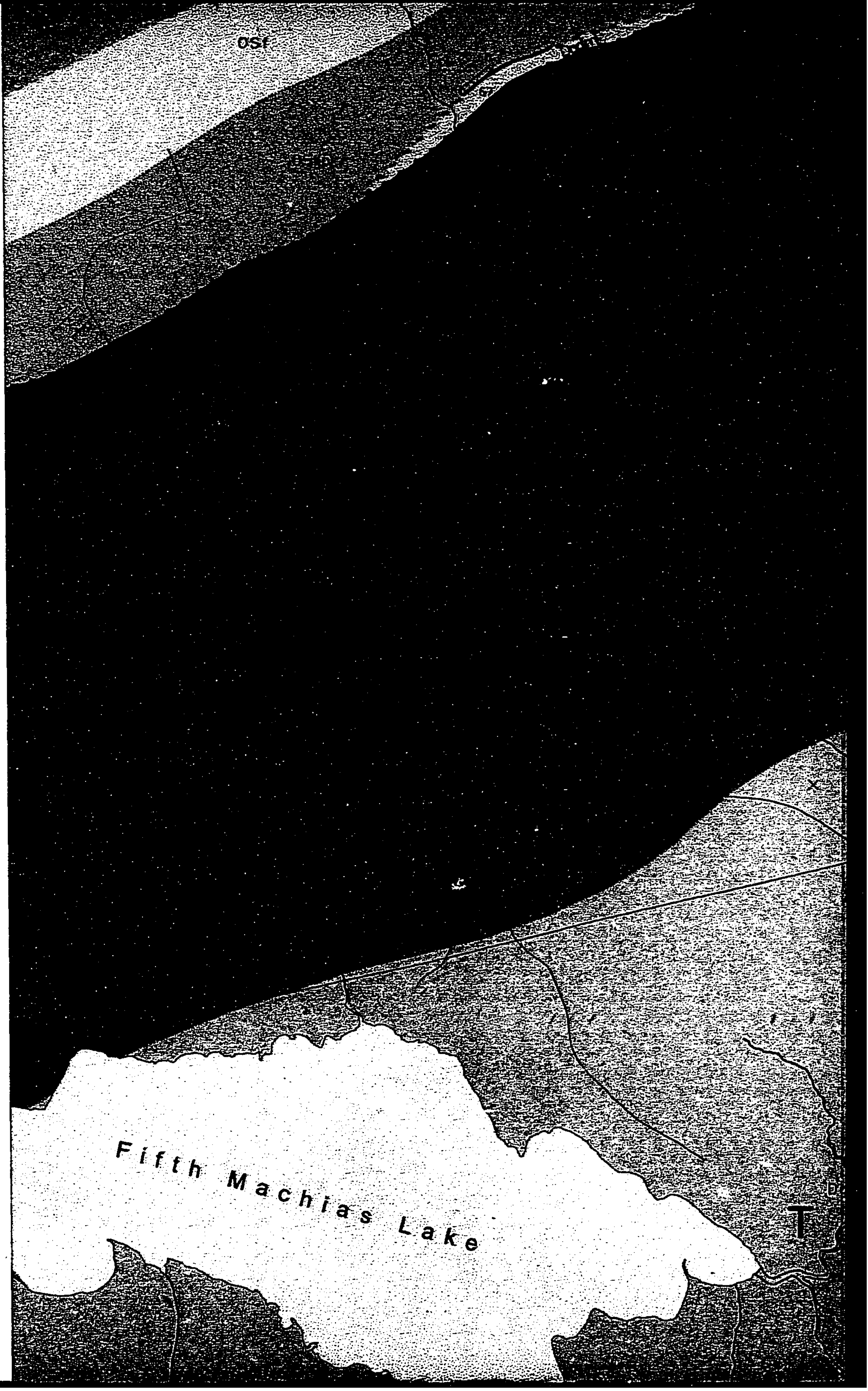
Coarse to megacrystic K-feldspar hornblende-biotite g
Typically foliated or mylonitized (protomylonite-myloni

MAINE

granodiorite

mylonite-mylonite)

nblende-biotite granite
mylonite-mylonite)


ost
Fifth Machias Lake
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Fletcher Peak
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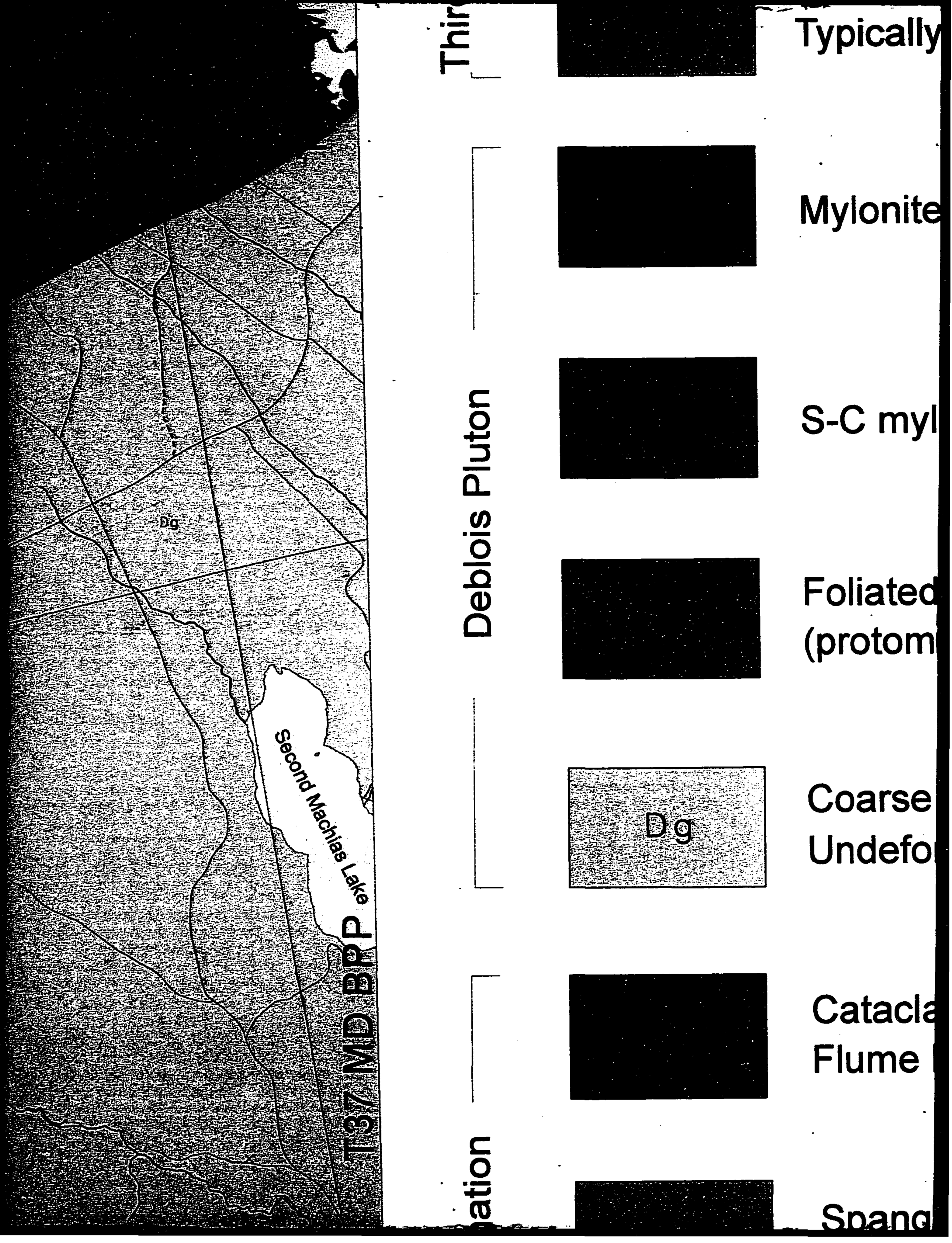
T 35 MD BPP



T37 MD BPP
Second Machias Lake
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Thir
Deblois Pluton
ation
Typically
Mylonite
S-C myl
Foliated
(protom
Coarse
Undefo
Dg
Catacla
Flume
Spang

Typically foliated or mylonitized (protomylonite-mylonit

Mylonite and ultramylonite derived from Deblois granit

S-C mylonite developed in coarse to megacrystic grar

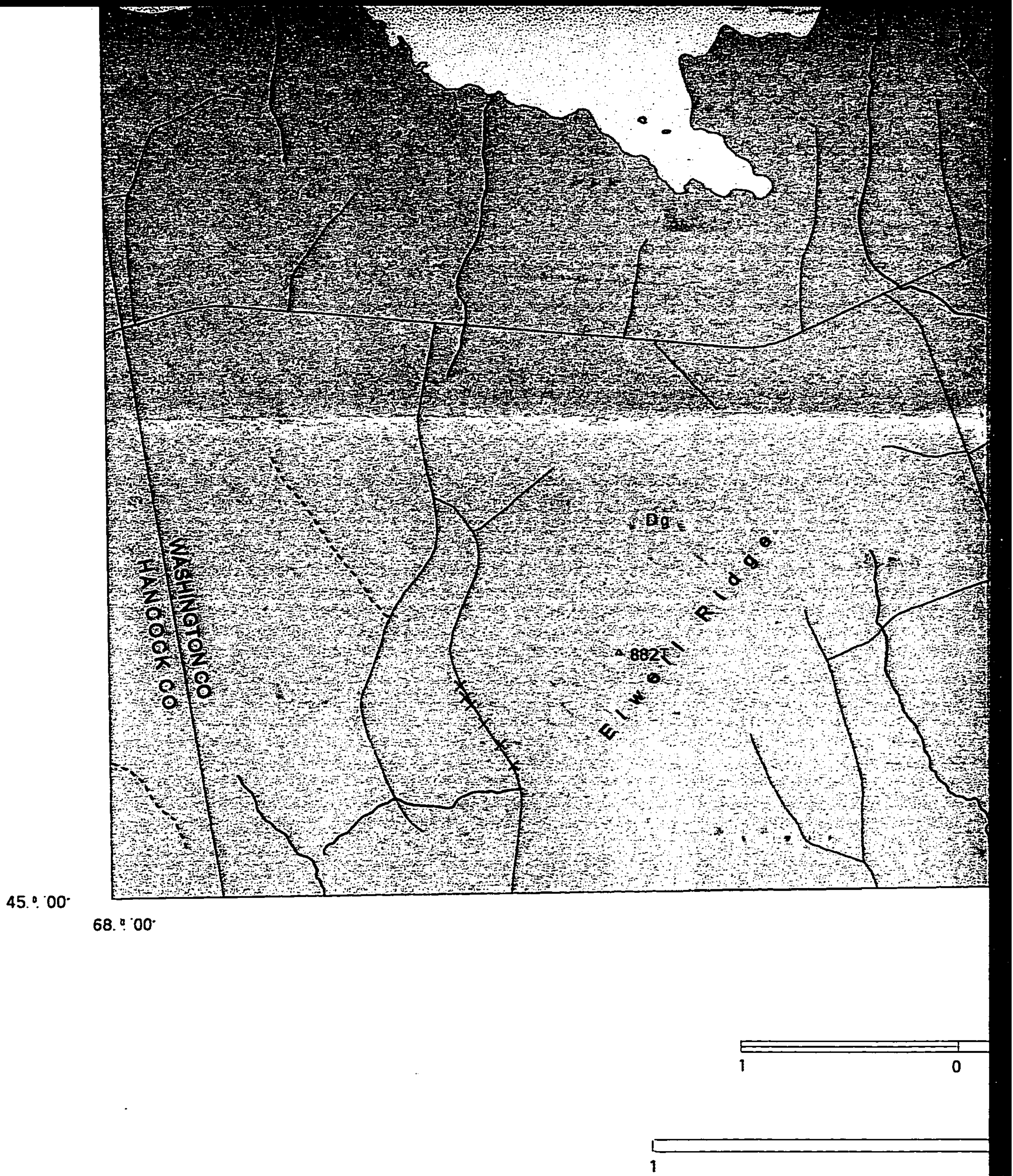
Foliated to slightly foliated coarse to megacrystic grar
(protomylonite)

Coarse to megacrystic K-feldspar hornblende-biotite
Undeformed with normal granitic texture

Cataclasite and coarse breccia produced by brittle sh
Flume Ridge Formation

Spangled muscovite-quartz-schist produced by inter

mylonite-mylonite)	
m Deblois granite	
megacrystic granite	
megacrystic granite	
rnblende-biotite granite ure	
uced by brittle shearing of	
oduced by intense	



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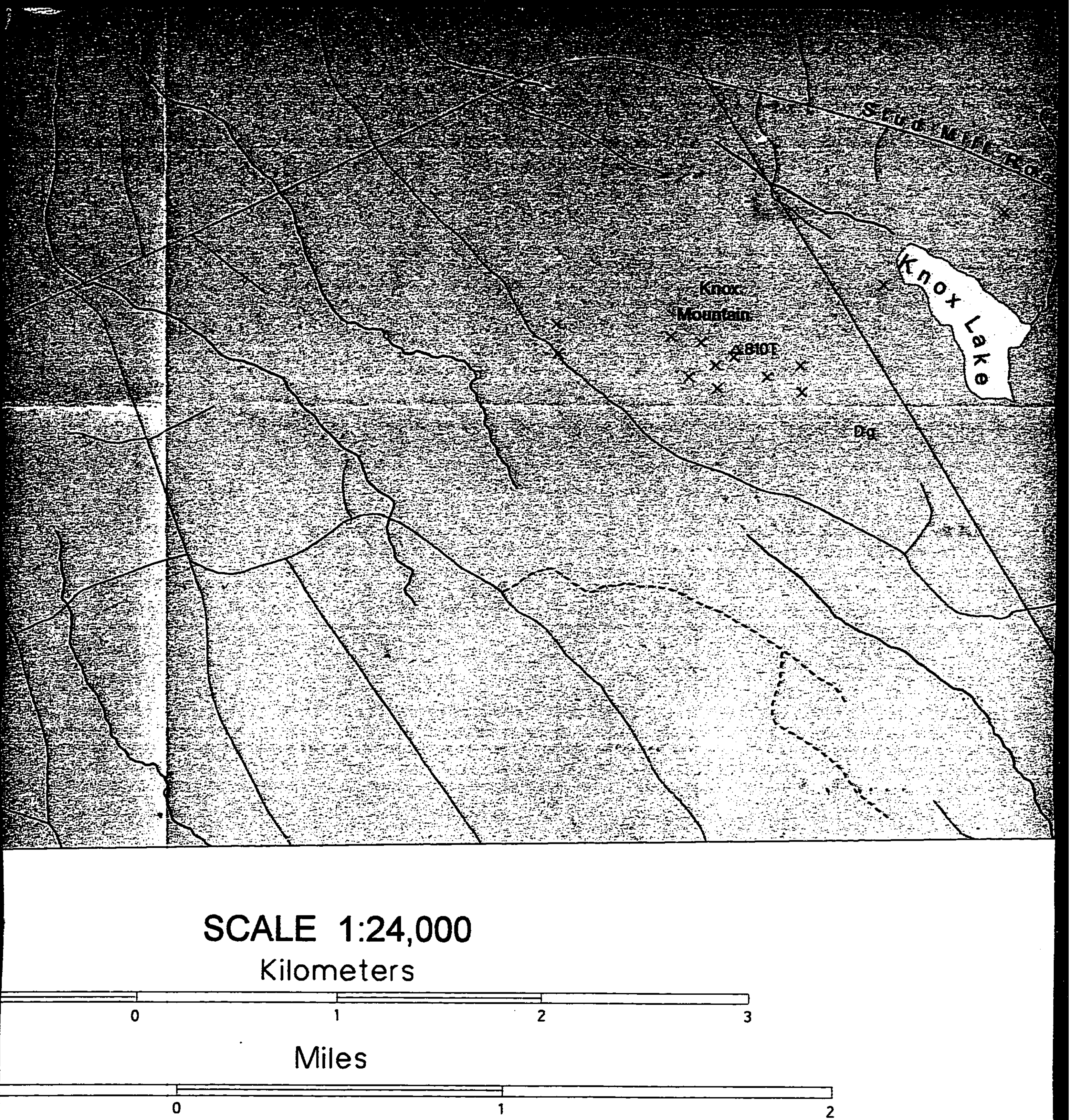

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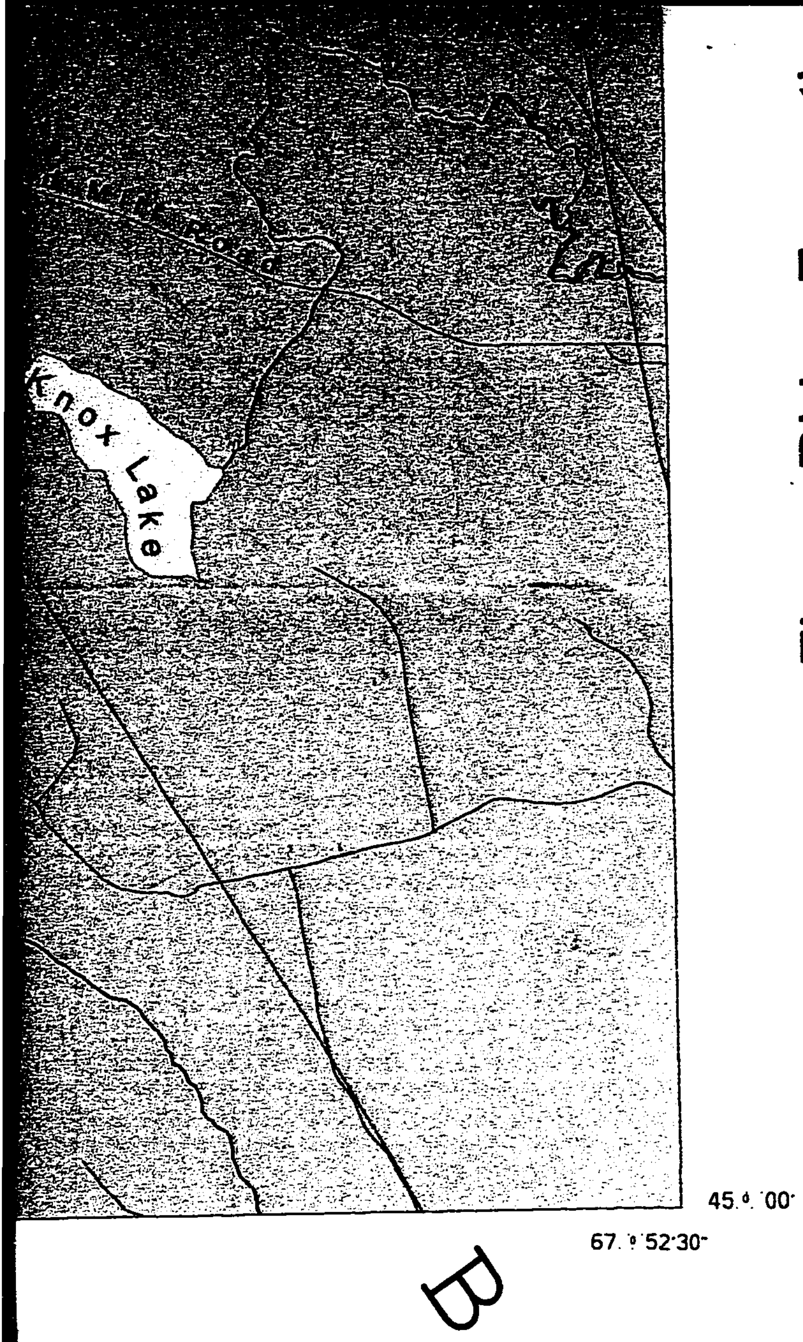


Flume Ridge Formatio

▨ Spang
ductile

OSf(p) Phyllo

OSf Flume
Variab
typica

75 Foliation, strike

× Outcrop, no stru

65 Bedding, strike

Inferred brittle fa

RONMENTAL SCIENCES

Spangled muscovite-quartz-schist produced by inten
ductile shearing of Flume Ridge Formation

Phyllonite derived from Flume Ridge Formation

Flume Ridge Formation (unsheared)
Variably calcareous turbiditic quartzofeldspathic wack
typically hornfelsed to biotite zone

, strike and dip	Ductilely sheared contact Ridge Formation and igne
, no structural data	Gradational ductile strain (inferred)
, strike and dip	Gradational ductile strain (defined)
brittle fault	Inferred normal geologic c

roduced by intense
mation

Formation

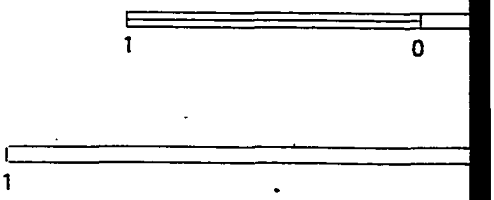
feldspathic wacke,

sheared contact between Flume
rmation and igneous rocks

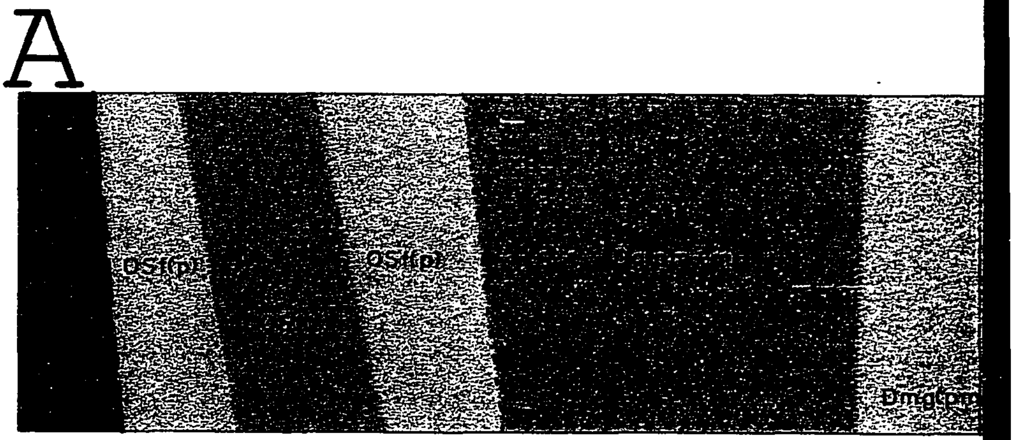
al ductile strain facies boundary

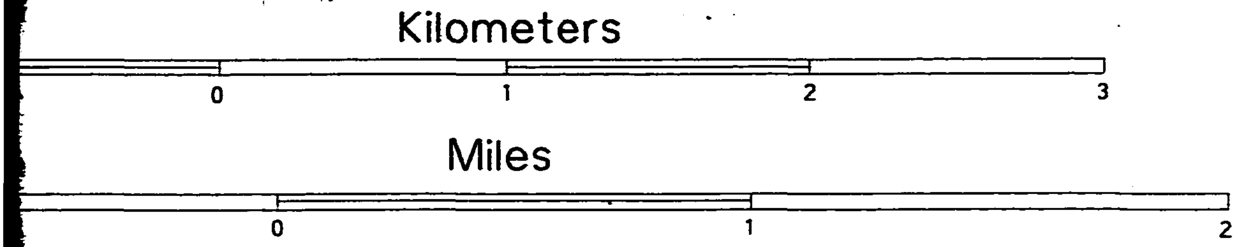
al ductile strain facies boundary

ormal geologic contact



MAPPED BY: CHUNZENG WANG
ASSISTED BY: BRIAN GAYRON
SUPERVISOR: DR. ALLAN LUDMAN



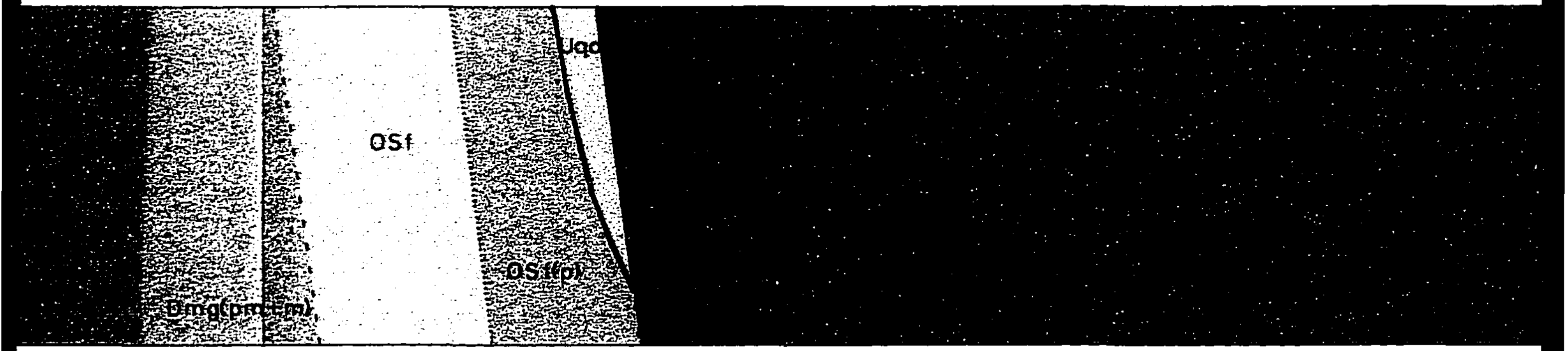


(1998-1999)

G

MAN

SCHOOL OF EARTH AND ENVIRONME
QUEENS COLLEGE (CITY UNIVERSITY
FLUSHING, NEW YORK 11367



×	Outcrop, no stru
⊤ 65	Bedding, strike
- - -	Inferred brittle f
—	Defined brittle f

RONMENTAL SCIENCES
ERSITY OF NEW YORK)

, no structural data

Gradational ductile strain (inferred)

, strike and dip

Gradational ductile strain (defined)

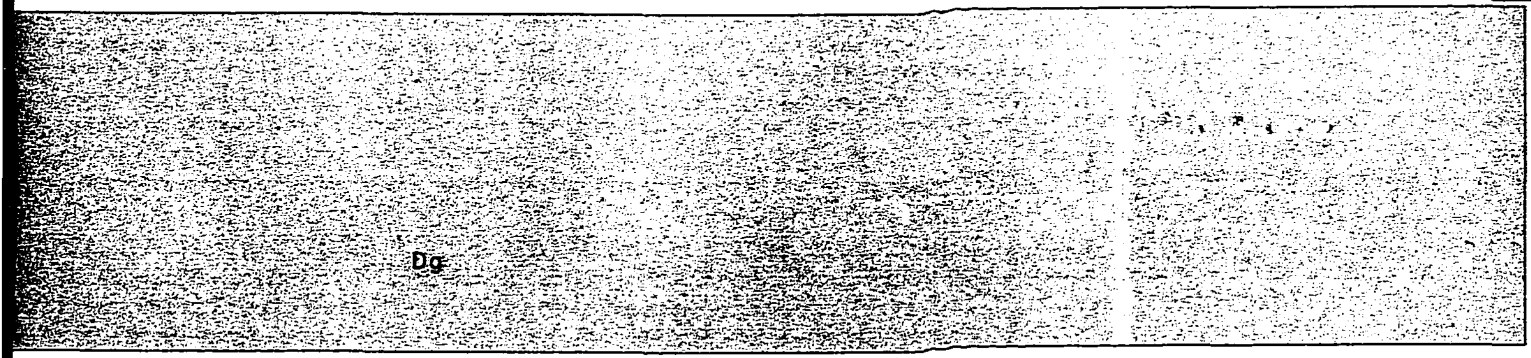
brittle fault

Inferred normal geologic

brittle fault

Defined normal geologic

B



al ductile strain facies boundary

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ormal geologic contact

B

▨