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Field Relationships, Petrology, Structure, and Intrusion History of the Waldoboro Pluton Granitoid Complex, Maine, U.S.A.

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ABSTRACT

The Waldoboro Pluton Complex, Maine, formed by multiple intrusive episodes of Acadian-age granitoids in an unassigned Proterozoic Z-Ordovician assemblage of migmatitic, peraluminous, calc-silicate gneisses and schists. Seven granitoid units comprise the complex (area >378 km^2), part of which probably sutures the St. George thrust fault. Field and petrological evidence very strongly suggests in-situ formation of these syntectonic granitoids, and that the magmas, once formed, did not migrate far from the site of anatexis. Specific lines of evidence include: cryptic, transitional, concordant margins; prolific metasedimentary enclaves; evidence for melting in the migmatitic envelope and metasedimentary enclaves; and the presence of abundant restitic clusters of garnet, sillimanite, and biotite identical to that in the country rock. Lithologic variations among the granitoids reflect varying degrees of melt-restite segregation. Gneissic granitoids and granodiorites contain abundant restitic material, whereas granites and leucogranites more closely approximate melt compositions. The abundance of garnet and rarity of cordierite in granitoid and country rock, together with the presence of primary, magmatic muscovite, indicate minimum pressures of formation of 0.3-0.4 GPa. Magmatic features have been overprinted to varying degrees by solid-state deformation resulting in protomylonites, mylonites, S-C foliations, mineral and enclave boudinage, imbrication, augen rotation, and intrafolial folding. Foliations in the granitoids are continuous with those in the country rocks, and deformation was related to regional tectonic events rather than granite intrusion. Alleged exotic, greenschist-grade, Avalon composite terranes may be juxtaposed against amphibolite proximal terranes along the westward-vergent St. George fault in the vicinity of the Waldoboro Pluton Complex. The shift from earlier Acadian compressive, cataclastic-induced fabrics to later shearing is recorded in the S-type granitoids. Extensive shearing, mylonitization, and late vapor-fluid enrichment leading to tourmalinization and feldspar blastesis along the eastern margin of the Waldoboro Pluton Complex mark the trace of the St. George fault in this area. Upper amphibolite-grade metamorphism and melting may be the result of crustal thickening along the St. George fault, but additional heat for metamorphism and melting may have been provided by coeval intrusion of gabbroic and dioritic magmas in this region.

INTRODUCTION

Reconstructions of the geologic evolution of coastal Maine are difficult because of the uncertain origin of voluminous silicic plutonics. The latter hinder correlations based on stratigraphy or metamorphic paragenesis and mask inferred boundaries between different lithotectonic elements. Furthermore, one difficulty with terrane identification lies in recognition of the basement. Studies of the widespread intrusions may reveal the nature of the deeper source materials underlying exposed stratigraphic sequences. Preliminary geochemical analyses of some plutons across the Gander-Avalon terrane suture(s) (Andrew et al., 1983; Ayuso et al., 1988) suggest different sources for magmatism in each composite terrane. However, these reconnaissance geochemical studies do not discriminate among the many lithotectonic units that make up the composite terranes. It should be emphasized that over reliance on source-classification schemes for granitoids (eg. I vs S-types) (Pitcher, 1983), which are useful for regional correlations, may obscure the true petrogenetic relationships and history of specific plutons. The strategic selection of plutons for detailed study, such as those which suture major faults, provides a basis for integrating pluton characteristics and tectonic development. Studies of the structure,

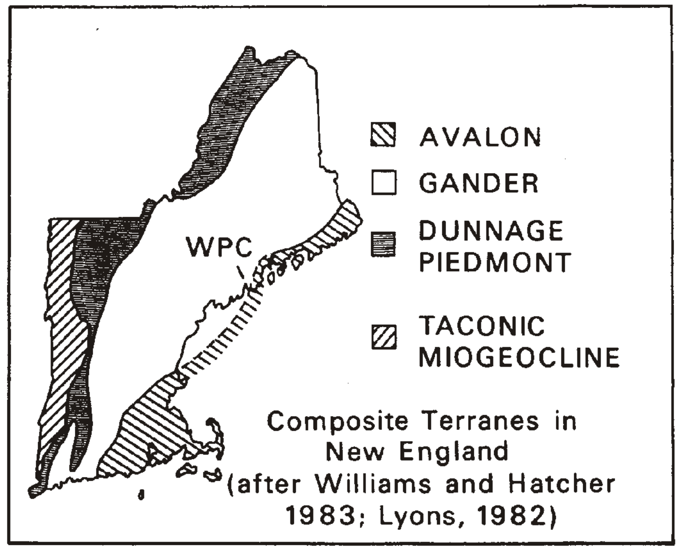


Figure 1. Summary of composite terranes in New England. WPC = Waldoboro Pluton Complex.

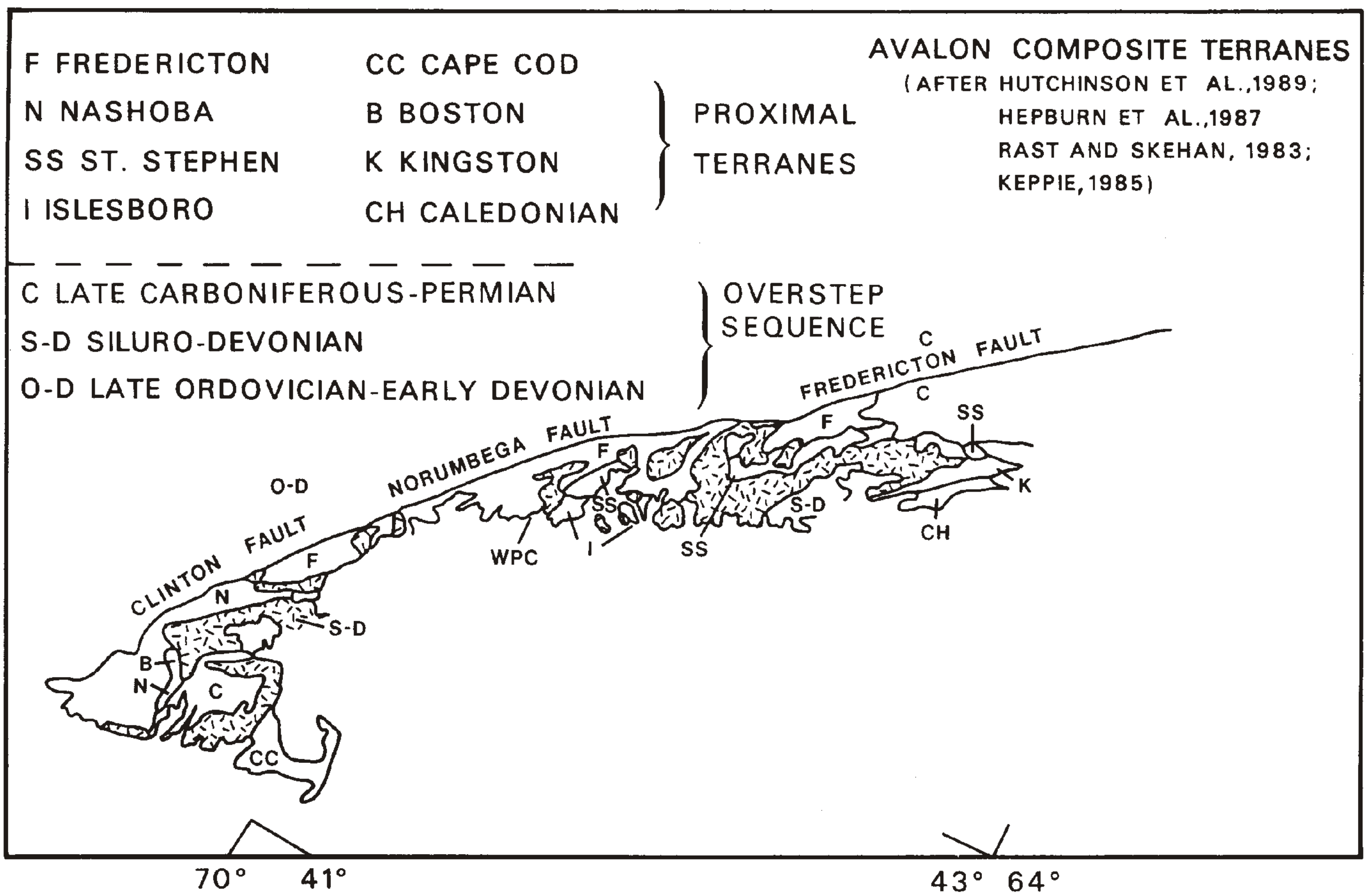


Figure 2. Proposed Avalonian terranes in New England. WPC = Waldoboro Pluton Complex.

petrology, geochemistry, and geochronology of plutons should therefore provide important clues to the accretionary history of the northern Appalachian orogen.

We have undertaken a comprehensive study of the Waldoboro Pluton Complex, which surrounds Muscongus Bay in central coastal Maine (Figs. 1 and 2). The Waldoboro Pluton Complex was selected for study because: (a) reconnaissance field work indicated a deeper level of emplacement than inferred for other discordant plutons in the region, suggesting that evidence for extensive magma-crust interaction (including melt-restite relations) might be preserved; (b) the Waldoboro Pluton Complex appears to suture different terranes (Osberg et al., 1985; Keppie, 1985, 1989) and thus affords the opportunity to study the relationship between granitoid genesis and terrane accretion; (c) petrologic and structural relationships in the country rocks, at the margins and within the complex, can be established fairly easily because of the large outcrop area (>280 km^2 according to Osberg et al., 1985), good exposure, and accessibility.

In this paper we describe the field relationships, petrography, and structure of the Waldoboro Pluton Complex. These data provide the framework necessary for petrological and geochemical studies which will be described in separate publications (Sidle and Barton, in prep.).

SUMMARY OF PREVIOUS WORK

The earliest descriptions of the Waldoboro pluton date from Bastin (1908). Work by Hussey (1971), Newberg (1979) and by Smith et al. (1982) defined the northern and eastern boundary of the pluton and also revealed the presence of migmatites in the region. Newberg (1979) described several large metasedimentary inliers within the pluton as well as a large-scale oblique slip fault at Havener Cove and suggested multiple episodes of deformation in the area. Osberg et al. (1985) compiled the results of previous workers and inferred the locations of the northern, southern, and southwestern margins. A K/Ar muscovite date of 295   9 Ma (Zartman et al., 1970) and a fission track apatite date of 207   21 Ma (Naeser and Brookins, 1975) were obtained on samples from the same locality. A whole-rock Rb/Sr date of 367   4 Ma was assigned to the Waldoboro pluton by Knight and Gaudette (1987).

The first detailed mapping of the Waldoboro Pluton Complex and surrounding areas was carried out by Sidle (1990a), who identified seven major igneous units. Sidle's maps, together with geologic descriptions, were published by the Maine Geological Survey (Sidle, 1991). Preliminary descriptions of the Waldoboro Pluton Complex and Meduncook-South Cushing granitoids, together with some geochemical analyses, are given by Sidle (1990a, 1991). The results reported in this publication reveal a complex magmatic and tectonic history for the Waldoboro Pluton Complex, which is now estimated to be exposed over at least 378 km^2.

REGIONAL GEOLOGY AND TECTONIC SETTING

There is much uncertainty in assigning the Waldoboro Pluton Complex to a specific geologic and tectonic setting because of widely differing interpretations of the evolutionary history of the northern Appalachian orogen. In view of this, a brief review of the regional geology and tectonics is given here.

Some regional tectonic maps show the Waldoboro Pluton Complex located within the Gander, an amphibolite-grade, Andean-style composite terrane, and near to the Avalon, an Atlantic-faunal, greenschist-grade, platformal composite terrane (Figs. 1 and 2) which includes Proterozoic Z basement (Bradley, 1983; Rast and Skehan, 1983; Williams and Hatcher, 1983; Zen, 1983). However, Keppie (1985, 1989) emphasizes the collage nature of lithotectonic or proximal terranes in the northern Appalachian orogen and the difficulty of correlating suspect super terranes along-strike. Certainly, tectonic models must accommodate a continental-scale shear fault, locally expressed as the Norumbega fault zone in Maine (Fig. 2). Along the Norumbega fault zone are juxtaposed an exotic array of diverse tectonic elements to a suspect sliver of gneissoid basement, presumably of North American affinity, episodically from mid-Paleozoic through Alleghenian times (Ludman, 1981, 1986; Zen, 1983; Keppie, 1985).

The proliferation of proximal terrane assignments is evident from Figure 3 (Osberg, 1978; Zen, 1983; Hogan and Sinha, 1989). In general, the rocks west of the Waldoboro Pluton Complex comprising the Falmouth-Brunswick, Saco-Harpswell, Bucksport-Flume Ridge, and possibly Passagassawakeag sequences/terranes are Ordovician deep marine turbidites unconformably overlain by Siluro-Devonian turbidites, which are themselves unconformably overlain by Devono-Carboniferous nonmarine sediments and volcanics. Keppie (1989) has included these terranes in his Fredericton terrrane projected from the Canadian Maritimes. East of the Waldoboro Pluton Complex, the rocks comprising the Penobscot-Cookson and Ellsworth-coastal terranes (Fig. 3) mostly are Cambro-Ordovician euxinic sedimentary rocks overlain by Siluro-Devonian bimodal, within-plate, tholeiitic, rift volcanic rocks and shelf sedimentary rocks. Keppie (1989) suggests that these terranes correlate with the St. Stephen terrane. In fact, the probable correlative terrane embodying the lithotectonic features surrounding the Waldoboro Pluton Complex is the Nashoba terrane (Aleinikoff et al., 1979; Hepburn et al., 1987; Hutchinson et al., 1989). The migmatitic granitoids in the Nashoba terrane are strikingly similar to those in the Waldoboro Pluton Complex area. Projection of the Nashoba terrane from southeastern New England offshore and into mid-coastal Maine is suggested by seismic studies in the Gulf of Maine (Stewart et al., 1986; Klitgord et al., 1988; Hutchinson et al., 1989).

Many of these proximal terrane assignments are based on the assumption that the lithotectonic bounding faults (Osberg, 1978; Osberg et al., 1985) are deep-seated, high-angle faults. However, Klitgord et al. (1988), Hutchinson et al. (1989), and

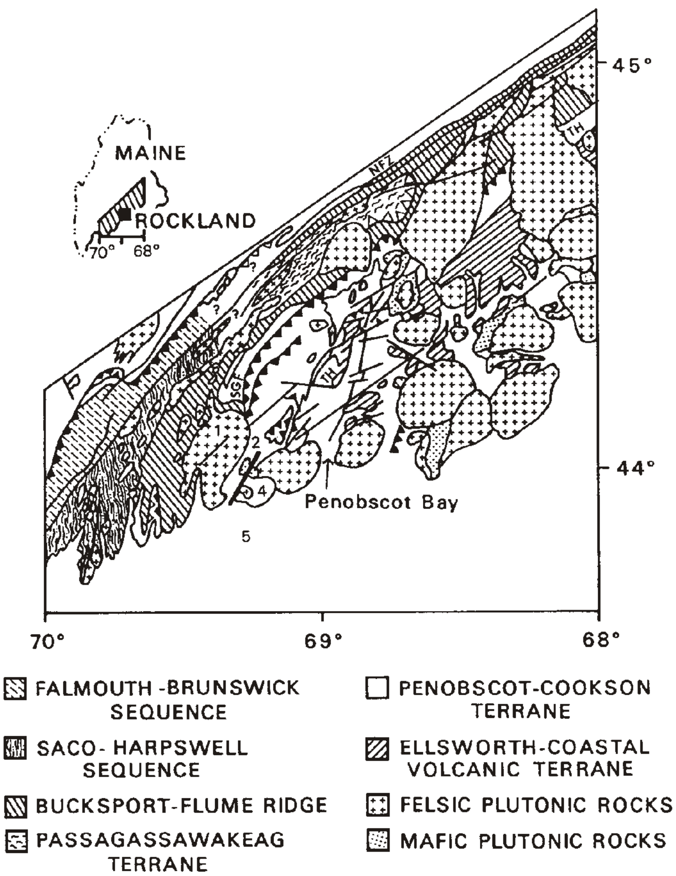


Figure 3. Regional lithotectonic sequences/terranes in coastal Maine and location of the Waldoboro Pluton Complex and various other intrusives. 1 - Waldoboro Pluton Complex; 2 - Raccoon intrusions; 3 - Spruce Head; 4 - Port Clyde; 5 - Monhegan. SGF = St. George fault; TH = Turtle Head fault.

Stewart et al. (1986) indicate that the major boundaries are listric faults, implying major westward-directed thrusting. Seismic data suggest that the crust beneath the Gulf of Maine thins to about 34 km without anomalous variations indicative of high angle discontinuities or faults.

One of these thrusts, the St. George fault (Fig. 3), may have juxtaposed Avalonian-type terrane onto Gander-type terrane (locally Nashoba?). Sidle and Barton (1990) suggest that the Waldoboro Pluton Complex sutures this regional fault (see also Hussey, 1971, 1986; Osberg et al., 1985). West of the St. George fault is an unassigned collage of generally upper amphibolite facies migmatitic and volcanogenic units. The Waldoboro Pluton Complex appears to partly intrude the Saco-Harpswell lithotectonic sequence of Hussey (1989) (Fig. 3), but the correlation of this lithology with those of the Bucksport-Flume Ridge sequence is unknown. Bucksport-type volcanogenic rocks are shown by Osberg et al. (1985) to border the northern and western parts of the Waldoboro Pluton Complex, but Hussey (pers. commun., 1989) suggests that those rocks west of the Waldoboro Pluton Complex belong to the Sebascodegan Formation. In any case, they are predominantly calc-silicate paragneisses and schists (cf. Bucksport Formation) of presumed Proterozoic Z to Ordovician age.

The rocks comprising the upper plate of the St. George fault consist of Ordovician quartzites and amphibolites (Benner Hill Formation) and gneisses (Penobscot Formation) (Guidotti, 1979; Osberg et al., 1985). Structural relationships suggest that the western border of the Maine Avalon segment is close to the trace of the St. George fault (Hussey, 1971; Guidotti, 1979; Osberg et al., 1985; Keppie, 1989). The distribution of Atlantic fauna just east of the St. George fault in low amphibolite facies rocks (Boucot et al., 1972) lends credence to this proposal. Accordingly, the Waldoboro Pluton Complex may suture the western margin of the Maine Avalon composite terrane. Hutchinson et al. (1989) argue, however, that the Turtle Head fault (Fig. 3) marks the western boundary of the Maine Avalon segment.

PETROGRAPHY

The Waldoboro Pluton Complex (Figs. 4 and 5) is exposed over approximately 378 km^2. Only detailed descriptions of the granitoids are given here. Full descriptions of the pegmatites, migmatites, other metamorphic rocks, and basaltic/diabasic dikes appear in Sidle (1990a).

Seven major igneous units are recognized in the Waldoboro Pluton Complex. Modal data are plotted in the QAP diagram of Streckeisen (1976) (Fig. 6) and are listed for representative samples in Tables 1 and 2. Granitoids of the Waldoboro Pluton Complex appear to define two clusters. One includes the Waldoboro granite (Wg), Medomak granite/granodiorite (Wgn), leucogranite (Wgl), Willet Hill granite (Wgt), and Cranberry Island granite (Wga). The other is dominated by the Waterman Creek unit (Wqd) and includes tonalites and quartz-diorites. The overall trend is similar to the high-K, calc-alkaline monzonitic series (Lameyre and Bowden, 1982). However, field relations suggest that Wqd intruded before the main Waldoboro Pluton Complex granitoid phases, and Wqd is similar petrologically to numerous dioritic/gabbroic lenses in the country rocks and other smaller intrusions in the area (Sidle, 1990a, 1991, in prep.). Lithologically, the South Pond unit (Wgp) is very coarse-grained and variable in modal composition and is not plotted on Figure 6. This unit contains pervasive alkali-feldspar megacrysts and thus is easily distinguished in the field.

Waldoboro Phase (Wg)

The Waldoboro Phase is an equigranular, medium-grained, weakly foliated, two-mica granite. It is muscovite-rich, schlieren-free, and includes most of the more massive, quarried granites of the complex. Low biotite/muscovite ratios and low An/(An+Ab) ratios (<0.20) characterize this phase. Very

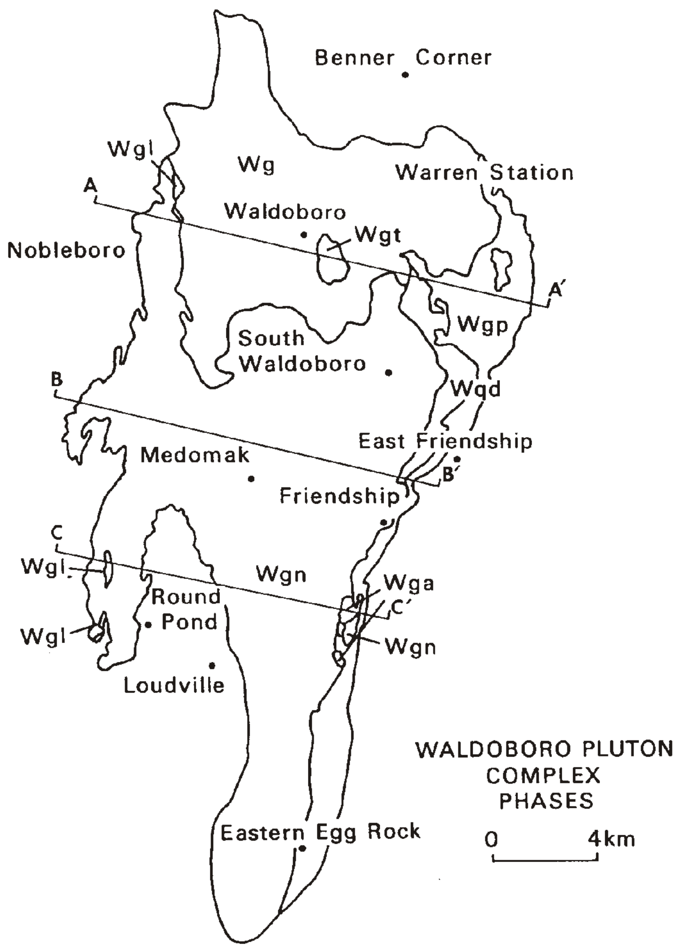


Figure 4. Simplified geologic map of the Waldoboro Pluton Complex showing the distribution of the major lithologic units. Wg - Waldoboro; Wgn - Medomak; Wqd - Waterman Brook; Wgp - South Pond; Wgt - Willet Hill; Wga - Cranberry Island; Wgl - lecogranites.

coarse-grained to porphyritic sheets are common and blanket more massive medium-grained granites.

Wg has been recrystallized and deformed, but to a lesser extent than other phases of the Waldoboro Pluton Complex. Quartz shows undulose extinction and is fractured; grain boundaries are annealed with occasional consertal and mortar textures. Plagioclase (average - An_{18}) exhibits occasional kinked albite twin lamellae, synneusis twinning, and weak normal zoning. Microcline is common and in the eastern part of Wg, a second set of perthite lamellae penetrate earlier microclines. Myrmekite is more common and occurs as rims bordering granular plagioclase and as intergranular blebs between adjacent microperthitic feldspars. Micas are euhedral, bent, and butt-ended (Zen, 1983). Muscovite crystals are frequently the largest grains in the rock. Biotite is metamict with zircon and apatite, and is clearly less abundant than other phases. Apatite is prismatic and evenly distributed throughout the granite. Trace amounts of garnet, tourmaline, sillimanite, and anhedral magnetite occur. Rare fractures are filled with sericite and some biotite is replaced by chlorite, but generally the rocks are fresh.

Willet Hill Phase (Wgt)

This is a medium to coarse-grained, tourmaline-bearing, non-foliated granite exposed in the center of Wg. Muscovite is more abundant than biotite, and prismatic schorl, which cuts euhedral butt-ended muscovite, occurs in coarse-grained varieties. Spectacular segregations of black tourmaline up to 23 cm long occur in coarse-grained lenses which exhibit local autobrecciation. Color zoning in schorl is common and blue indicolite occurs. The fabric is similar to that of Wg, but alteration is more extensive.

Medomak Phase (Wgn)

This is the largest phase of the Waldoboro Pluton Complex and mostly consists of foliated, gneissic granites and granodiorites. Ubiquitous schlieren, boudinaged enclaves, inliers of convoluted metasedimentary lithologies, and common garnet characterize this phase.

Foliated varieties are medium to very coarse-grained, commonly garnet-bearing, and are interlayered with porphyritic varieties. Massive, medium-grained varieties are much less common.

Gneissic granites and granodiorites occur especially in the southwestern areas of Wgn. Banding ranges from 0.6 m to fine striping, and discontinuous streaking is common. Textures are gradational between true-igneous and gneissic varieties (Fig. 7) exhibiting original S_0/S_1 banded granofels structures which project along strike into intermixed calc-silicate gneisses of the Bucksport Formation. These gradational granitoids are as much as 70% schlieren and grade into nebulitic migmatites. Garnet-bearing paragneisses and schists are usually admixed with granitic layers. Locally, porphyroblastic granitoids with serrated subrounded feldspars up to 15 cm in diameter occur. Prolate, deformed, feldspathic porphyroblasts commonly transect margins with the country rocks (Sidle, 1990b). In outcrop, the gneissic granitoids are frequently indistinguishable from the biotite-rich paragneisses and schists of the Bucksport Formation (Sidle and Barton, 1990).

Wgn appears to represent a transitional phase between the country rock and the more homogeneous granitic phases of the Waldoboro Pluton Complex. Recrystallization and deformation are pronounced. Evidence of dynamic recrystallization is widespread in the microfabric and ranges from kinked foliations and subgrain polygonization to fluxion textures in protomylonites. Quartz commonly is annealed with feldspar subgrains. Quartz ribbons and neocrystallization appear in fringes and pressure shadows of feldspar augens. Quartz droplets are also associated with poikiloblastic, fractured garnets. Seriate plagioclases may

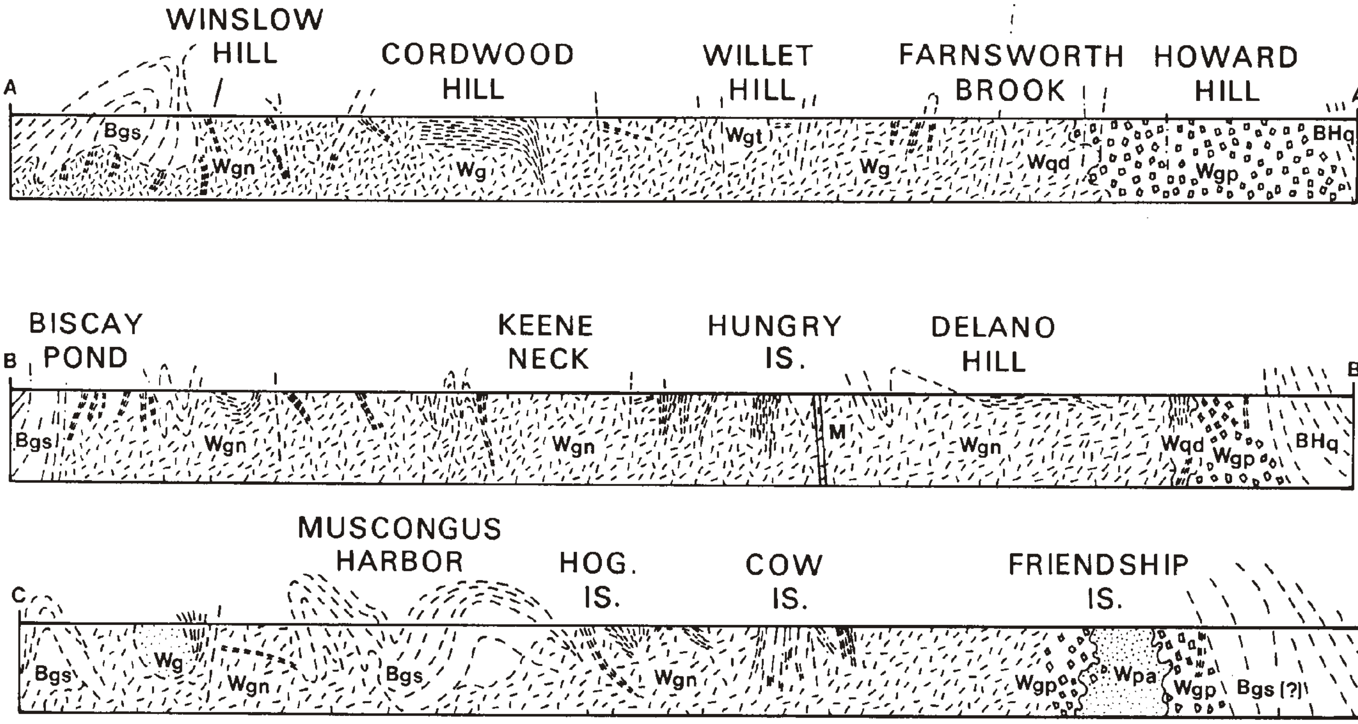


Figure 5. Schematic scaled cross sections of the Waldoboro Pluton Complex. Location of sections given on Figure 4. Labeling of major lithologic units from Figure 4 except: Bgs - Bucksport Formation; BHq - Benner Hill Formation; M - basalt and diabase dikes.

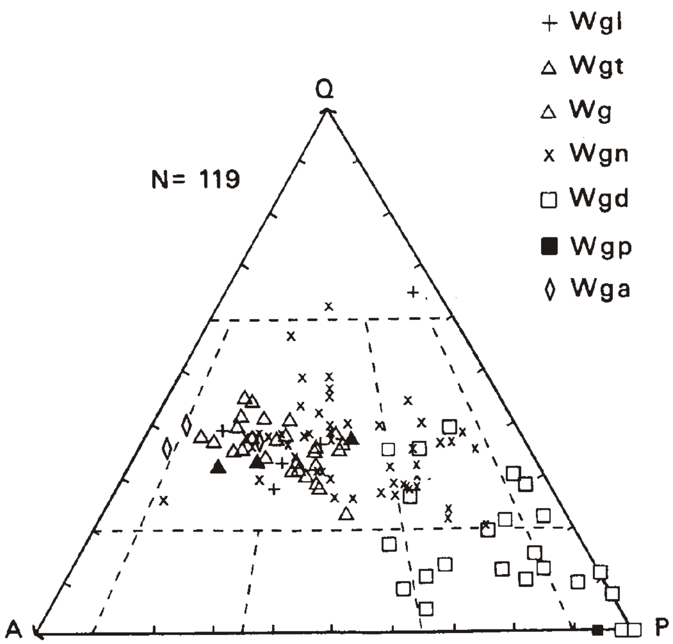


Figure 6. Modal and normative compositions of Waldoboro Pluton Complex granitoids plotted in the Quartz-Alkali feldspar-Plagioclase feldspar diagram of Streckeisen (1976).

show idioblastic cores and xenoblastic rims in transitional granitoids associated with possible shearing. Broken plagioclase crystals frequently have deformation lamellae which show thinning due to stretching. Zoning is patchy and weak or absent. Anorthite contents are An_{10-41} (average - An_{30}) in transitional granitoid types and An_{21} in granites. These values are higher than those in the Wg phase. Plagioclase inclusions in alkali feldspars are randomly oriented, clustered, or occur in sericitized cores. No crystallographic control is apparent for the inclusions or for patchy zoning developed in larger plagioclase grains.

Microclines occasionally form augens in transitional granitoids. Lobate, bulbous masses of myrmekite occur as mantles of microcline augens and ovoid alkali-feldspar porphyroclasts, but myrmekite is not restricted to pressure shadows. Rare intergranular myrmekite occurs between perthitic feldspars. Some alkali feldspars form porphyroblasts and do not have myrmekite mantles. Some areas of cataclasis contain poikiloblastic alkali feldspars and quartz penetrated by fractures filled with perthite   sericite. Late formation of alkali feldspar is also indicated by interpenetration perthites and rare flame perthites.

Biotite predominates over muscovite, and is ubiquitously metamict around zircons up to 0.3 mm. Biotite also occurs with sillimanite in clusters and ribbons that have been deformed into microfolds. Muscovite crystals are smaller than in the Wg phase. Micas in the transitional granitoids define foliations parallel to

TABLE 1: REPRESENTATIVE MODAL ANALYSES OF THE WALDOBORO PLUTON COMPLEX

	Wg	Wg	Wg	Wg	Wgn	Wgn	Wgn	Wgn	Wgn	Wgn	Wgn	Wgt	Wgl	Wqd	Wqd	Wqd	Wgp	Wgp	Wgp
QTZ	33.9	31.9	35.4	34	24.2	25.6	28.9	36.3	31.8	35.6	38.1	28.4	38.1	14.3	8.3	26.1	18.1	12.4	21.5
KSP	35.2	28.9	40.1	39.6	18.5	23.9	23.2	30.3	34.3	14.7	28.7	36.1	41.2	-	6.6	18.5	42.9	18.5	27.6
PLG	21.9	30.3	17.8	11.4	35.8	31.8	40.9	21.3	17.9	36.1	28.4	23.5	15.7	46.1	48	36.6	20.6	61.2	27.7
BIO	3	2.6	2.5	3.3	16.5	14.3	5.7	9.8	3.5	8.7	2.2	0.8	2.3	10.5	1.2	10.7	2.2	7.1	3.7
HBL	-	-	-	-	-	-	-	-	-	-	-	-	-	24	33.9	7.7	15.9	-	18.6
MSV	5.4	5.4	3.6	5.6	1.2	2.1	1.1	0.8	7.8	2.5	2.1	5	2.1	-	-	-	-	-	-
GNT	0.2	-	-	tr	2.6	1.7	-	1.2	2.1	1.8	0.2	-	0.2	-	-	-	0.2	-	-
SIL	-	0.8	-	-	0.3	-	-	-	2.1	-	-	-	-	-	-	-	-	-	-
MNT	tr	0.1	0.2	tr	0.3	tr	0.1	tr	tr	0.2	tr	tr	tr	2.4	1.7	0.3	0.1	0.9	0.1
HEM	-	-	-	-	-	-	-	tr	-	tr	-	-	-	-	-	-	-	-	-
ILM	0.1	tr	-	0.2	0.6	-	tr	0.1	-	tr	tr	-	-	1.1	0.1	-	tr	-	0.2
APT	0.3	tr	0.4	tr	tr	tr	tr	0.2	tr	tr	0.1	1.1	0.2	0.1	0.2	tr	tr	tr	tr
SPH	-	-	-	-	-	-	-	-	-	-	-	-	-	0.9	tr	0.1	tr	tr	0.6
TRM	-	-	-	-	-	-	-	-	-	-	-	5.1	-	-	-	-	-	-	-
ZIR	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr

TABLE 2: REPRESENTATIVE MODAL ANALYSES OF THE COUNTRY ROCKS

	Bgs	Bgs	Bgs	Bgs	Bgs	Bgs	Bgs
QTZ	6.1	8.7	9	26.1	18	9.6	20.9
KSP	-	4.1	6.1	10.6	3.2	25.2	4.1
PLG	39.4	59	56	41.5	61.1	45.4	29.9
BIO	4.6	5.8	-	20.2	15.6	18.2	3
HBL	38.6	22.2	28.2	-	2	-	-
MSV	-	-	-	tr	tr	tr	30.8
GNT	-	-	-	1.2	1.6	-	-
SIL	7.4	-	-	tr	tr	tr	tr
MNT	1.4	tr	tr	tr	tr	0.1	-
HEM	-	-	-	-	-	tr	0.1
ILM	0.6	-	tr	-	-	tr	-
APT	tr	-	0.1	tr	tr	tr	-
SPH	-	0.2	0.6	-	tr	-	-
TRM	-	-	-	-	-	-	11.2
ZIR	tr	tr	tr	tr	tr	tr	tr

those in adjacent metasedimentary lithologies. S_1 and S_2 foliation planes are developed on the original mica ribbon surfaces. Oblique foliations of recrystallized quartz aggregates and mica fish (Fig. 8) occur on type II S surfaces.

Garnet interpreted to be restitic is more common than magmatic garnet as substantiated by mineral chemical data (Sidle and Barton, in prep.). Restitic garnets are subrounded to rounded (0.3 to 1.1 mm) and may form trains or clusters with sillimanite or fibrolite (Fig. 9). Many of them have fractures filled with sericite and polygonal quartz, and are partly or completely surrounded by sheaths of biotite and quartz-feldspar aggregates. Rotation of garnet porphyroblasts is indicated by structures (Passchier and Simpson, 1986) which suggests low shear strains and recrystallization rates higher than rotation rates. Isolated subhedral garnets occur which are not associated with restitic clots or deformation textures. They appear to have formed late and probably continued to grow on earlier phenocrystic or restitic garnets during cooling (Sidle and Barton, in prep.). No euhedral garnets were observed in Wgn.

Prismatic schorl is scattered throughout Wgn. Cordierite was identified in one sample, and amphibole, with inclusions of subrounded to subhedral zircon, is rare. Free zircon (ie. not as inclusions in biotite or amphibole) is often embayed. Apatite occurs most commonly as stubby prisms, but needles of this

Figure 7. Incompletely digested metasediments within a granitoid exhibiting pronounced attenuation and banding; note quartz-feldspar parallel injections. Southwestern Cow Island.

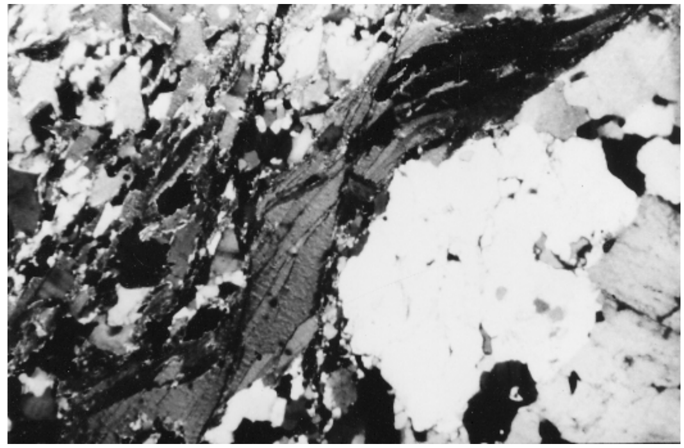


Figure 8. Sigmoidal, metamict biotite mica fish in type II S-C mylonitic granitoid, western Hall Island (80x cross polarized).

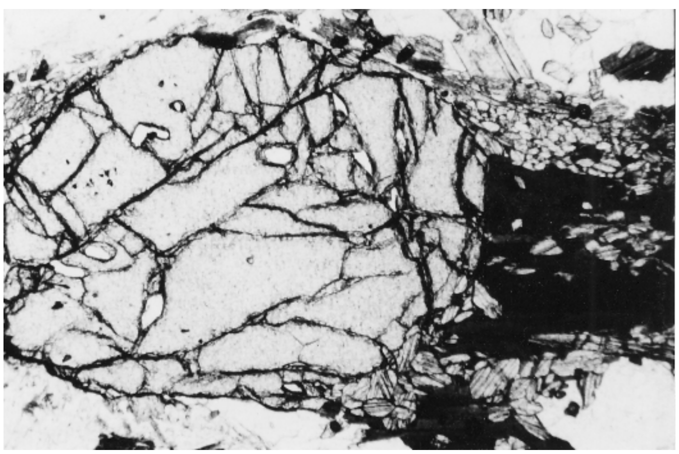


Figure 9. Restitic cluster of fractured almandine garnet with biotite, and sillimanite in pressure shadow, in granodiorite, southwestern Hungry Island (80x plane polarized).

mineral are also present. Apatite is predominantly included in biotites. Ilmenite and titaniferous magnetite occur as needles or anhedral masses. Traces of sphene are present.

Leucogranites (Wgl)

The leucogranites are fine- to medium-grained, weakly foliated, and grade into granite. The weak foliation undoubtedly reflects the paucity of ferromagnesian minerals. Leucogranitic lenses a few meters wide or long pervade Wgn and probably extend beyond the mapped western margin of the Waldoboro Pluton Complex. They are in some cases identical to leucosomes in migmatites within and surrounding the Waldoboro Pluton Complex. Microfabrics are similar to those of the Wgn granites.

Waterman Brook Unit (Wqd)

The Waterman Brook unit consists of equigranular to recrystallized quartz diorite and tonalite. Massive varieties are coarse-grained. Weakly foliated to strongly lineated, medium to coarse-grained varieties form an arcuate outcrop pattern near the east margin of the Waldoboro Pluton Complex (Fig. 4). Abundant diffuse autolithic enclaves, rare angular metasedimentary xenoliths, and rare xenocrystal garnets occur in the quartz diorites.

Locally, quartz and feldspar augens (<1.5 cm) occur. Plagioclase ranges from An_{36-48} (average An_{43}), although porphyroclastic areas contain rare albite. Alkali feldspars are restricted to poikilitic perthites. Decussate amphiboles are commonly microboudinaged and zoned unlike those that occur in Wqd-like bodies scattered throughout Wgn. Clinopyroxene is extremely rare, whereas biotite is streaked with chlorite plus other unidentified minerals. Euhedral, late indicolite occurs in biotite. Euhedral sphene up to 3.0 mm (0.9 vol%) and stubby prisms of apatite are ubiquitous minor constituents.

Microveining with shearing is pronounced in the southeastern part of Wqd. These protomylonitic textures include late sericite-filled fractures crosscutting anhedral amphibole phenocrysts and earlier areas of neocrystallization. Veinlets with radiating tourmaline and blebs of secondary pyrite and arsenopyrite occur next to amphibolites and amphibolite schists (see below). Also, fluxion textures and alteration increase southeastward toward Wgp and the eastern Waldoboro Pluton Complex boundary.

Recrystallized amphibolites and schists that cannot be easily distinguished from quartz diorites/tonalites occur in the southern part of Wqd and in small lenses and irregular bodies within Wgn. Some of these Wqd-like bodies are gradational with metasediments. For example, xenocrystal garnets occur in the quartz diorites. Shear pods of coarse-grained uralitized gabbro and dioritic lenses (<0.3 m) occur in calc-silicate gneisses and amphibolite schists. Much of Wqd may actually represent recrystallized metasediment as is inferred for rocks east of the Waldoboro Pluton Complex near the Raccoon mafic intrusion (Sidle, 1990a, 1991).

South Pond Unit (Wgp)

This is a megacrystic granite porphyry which forms a more massive body in the north and a protomylonitic to mylonitic margin between Wqd and Wgn and the country rocks in the southeast. Non-orientated microcline megacrysts (up to 7 cm) and quartz occur in porphyritic sheets and irregular pegmatitic bodies. These sheets are intercalated with finer-grained varieties. Thin (<0.5 m), poorly-defined lenses of greisen are frequent in the eastern Waldoboro Pluton Complex and consist of quartz, muscovite, biotite, zinwaldite(?) tourmaline.

In the south, the whole of Wgp is a sheared feldspathic meta-granite porphyry. Protomylonite and porphyroclastic mylonites, and intrafolial blastomylonites are clearly visible. Strongly lineated quartz and feldspar augens up to 11 cm have serrated margins. Pressure shadows filled with fine-grained mineral aggregates exhibiting -structures are present in the type II S-C mylonites. Numerous displaced crystals and bookshelf sliding of feldspar megacrysts also occur.

In some mylonitic varieties, intense recrystallization is associated with a blastomylonitic fabric. Elsewhere, the alkali feldspar megacrysts are mantled with bulbous myrmekite which corresponds to the serrated feldspar margins observed in pressure shadows suggesting growth from the resistant feldspar crystals outward. Augens occur in swarms of megacrystic bands (10 cm to several meters) that are intercalated with boudinaged metasedimentary enclaves several tens of meters long (Fig. 10). Individual megacrysts often cut the contact with metasediments. The size of the megacrysts decreases westward toward the Wgn phase. Two generations of alkali feldspar occur in Wgn as noted above. In Wgp, a late blastic(?) perthitic feldspar may envelop earlier microclines. Plagioclases (An_{16-42}) are smaller, often strongly sericitized, and less abundant than the alkali feldspars.

Biotite ribbons and type II S fish are commonly altered to chlorite, and sericite-filled fractures are common in biotite. Amphibole and sphene, like biotite, are variable in abundance and this reflects the mixing of granitoids and Bucksport-type lithologies. Sporadic garnet, sillimanite, and tourmaline occur, whereas cordierite has been identified in the extreme southeast Wgp. Its presence may be related to local thermal perturbations accompanying strain in this area of Wgp (cf. Clemens and Wall, 1981).

Figure 10. Strongly, attenuated, intercalated amphibole-biotite gneiss of Bucksport Formation with megacrystic-rich South Pond porphyry, amidst shear zones. Note sinistral offsets of a quartzo-feldspathic vein (hammer length is 55 cm). North central Friendship Long Island.

Cranberry Island Phase (Wga)

This phase is a fine- to medium-grained aplitic granite. It is weak to moderately foliated with occasional garnet and, in contrast to Wgn, contains few angular xenoliths. Rhythmic, garnet-banded aplites associated with pegmatite-aplite complexes (Sidle, 1990a) may be related to the Wga phase. Biotite is absent and Fe-Ti oxides are rare. Weakly zoned plagioclase (average - An_{12}), scarce subhedral garnet (<1.3 mm) and ragged, subhedral muscovite also occur.

Metamorphic Rocks

Rocks surrounding and intermixed with the main Waldoboro Pluton Complex granitoid phases belong mostly either to the Proterozoic Z to Ordovician Bucksport Formation or Sebascodegan Formation (Bgs) (see earlier discussion), and are exposed in the underplate of the St. George fault. The protoliths may be proximal volcanogenic graywackes and shales (Hussey, 1989). The dominant lithologies are calc-silicate and biotite granofels and paragneisses with banding up to 17 cm wide. Typically, the gneisses are foliated, variably strained, and granoblastic. Plagioclase/K-feldspar ratios are quite variable, reflecting the range of lithologies, and gneisses close to the transitional granitoids exhibit some form of blastesis. These include pearl gneisses, flecky-types (Mehnert, 1968), and show all stages of megacrystic growth with incipient blastesis grading into swarms of porphyroblasts in Bgs. Garnet-bearing gneisses are sporadic west of the Waldoboro Pluton Complex margin and in inliers. In contrast, porphyroblastic garnets in gneisses along the eastern Waldoboro Pluton Complex margin are up to 3 cm in diameter. Garnet rotations are due to ductile shear and are not an

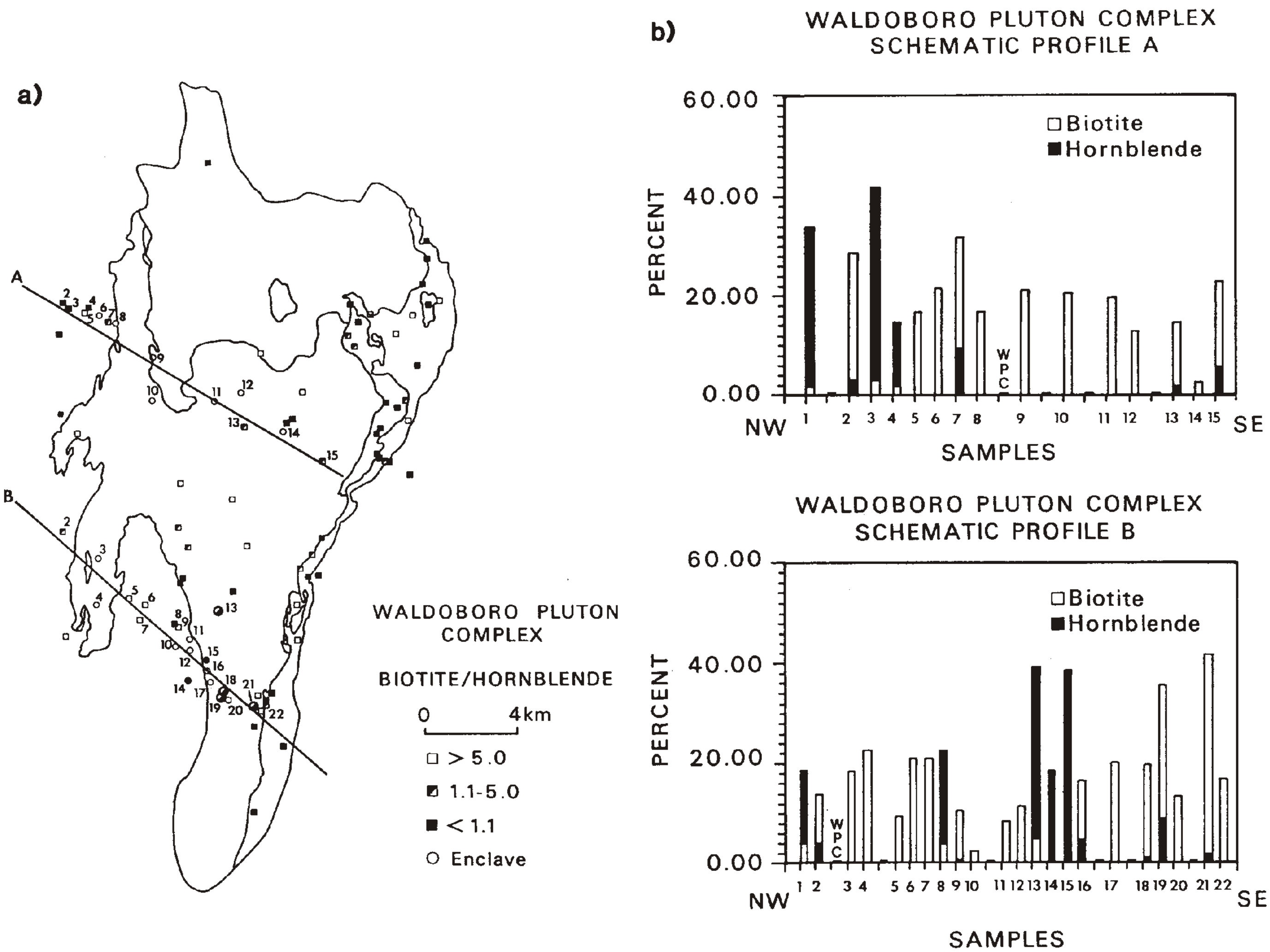


Figure 11. (a) Biotite/amphibole ratios in Bucksport-type lithologies in the Waldoboro Pluton Complex. (b) Biotite/amphibole ratios projected onto cross-sections A and B from Figure 11a. WPC = Waldoboro Pluton Complex.

artifact of successively overprinted foliations (Bell and Johnson, 1989). Those measured have dextral shear sense which contrasts with the predominant sinistral motion measured in the granitoids (Fig.13) discussed later. Volumetrically minor lithologies include biotite-muscovite schists garnet cordierite sillimanite, amphibolite schists garnet, sulfide-bearing mica schists, and tourmaline schists.

Biotite/amphibole ratios increase toward the contacts with the Waldoboro Pluton Complex (Fig. 11). Evidently, the Waldoboro Pluton Complex is situated in a biotite-rich part of Bgs. Comparison of the Bgs country rocks with the enclaves and metasedimentary inliers suggests that the latter are more refractory lithologies (Sidle, 1990a).

Quartzites of the Ordovician Benner Hill Formation (Guidotti, 1979) occur on the St. George fault upper plate close to the eastern boundary of the Waldoboro Pluton Complex. The steeply dipping, northeast-striking units locally consist of thin-bedded, biotite-laminated (<2 mm) quartzite with intercalations of quartz-mica schist and amphibolite. A distinctive mylonitic zone containing rotated blocks of quartzite occurs adjacent to the Wgp phase. The lateral extent of mylonitization is estimated at less than 20 m (Sidle, 1990a).

Other units of the country rocks include garnet-sillimanite gneisses of the Penobscot Formation or its equivalents (Osberg et al., 1985) along the northeast margin and gneisses of the Cross River Formation (Hussey, 1986) along the southwest margin. The country rocks along the southeast margin are clearly Bucksport-type lithologies and do not belong to the Penobscot or Benner Hill formations as inferred by Osberg et al. (1985) and Hussey (1986, 1989).

Finally, mafic dikes occur in the Waldoboro Pluton Complex and may be Early Triassic to Early Jurassic age (cf Mchone and Trygstad, 1982). Twenty eight dikes wider than 1 m were mapped (Sidle, 1990a, 1991). Most are relatively fresh aphanitic olivine basalts or diabases.

FIELD RELATIONS AND STRUCTURE

Contacts

The western, northern and southern margins of the Waldoboro Pluton Complex are predominantly gradational with the Bucksport-type country rocks. A few unambiguous intrusive-style contacts probably reflect late autointruded melt-rich phases within Wgn. The western margin of the Waldoboro Pluton Complex is mapped as the onset of more sharply defined disharmonic folded migmatites. East of this margin concordant transitional granitoids occur amidst nebulitic-type migmatites, permeate biotite-rich paragneisses, and contain swarms of restitic metasedimentary enclaves. Along the southwestern margin, the complete transition from country rocks into granite is preserved. Disintegration of country rock into relict enclaves (Vernon, 1983) (Fig. 12), segregations of recrystallized enclaves, ghost stratigraphies of former paragneisses exhibiting outlines of D_1 tight to isoclinal folding, and gradation from gneiss through granodiorite to granite is observed or inferred. The eastern margin of the Waldoboro Pluton Complex is often sheared, mylonitic, and associated with a narrow field of diktyonitic migmatites. Contacts between inliers of Bucksport-type rocks and the Waldoboro Pluton Complex are also gradational, particularly in the restite-rich Wgn phase.

Temporal relationships are summarized in Table 3. The two most voluminous granitoids, Wgn and Wg, were emplaced at about the same time, but the Wg phase was emplaced structurally above the Wgn phase. All contacts between the main Waldoboro Pluton Complex granitoids are gradational although crenulated contacts separate some granodioritic and granitic phases within Wgn.

Wg cuts Wqd in the northeast, whereas Wgn and Wqd are separated locally by jointed amphibolite schist. The eastern contact between Wqd and Wgp is discordant and coplanar, and angular xenoliths of quartz diorite occur in Wgp. Several quartz dioritic to dioritic lenses in Wgn and Wgp have gradational contacts with amphibolites and amphibolite schists. Other dioritic bodies are sharply defined in shear zones within Wgp. Wqd has striking similarities to quartz diorite and diorite bodies associated with the Raccoon intrusions just east of the Waldoboro Pluton Complex (Sidle, 1990a, 1991). Field relations suggest that Wgn is older than Wgp. Wgp is intercalated with Bucksport-type rocks; contacts are flattened and attenuated into concordant bands and streaks. Wga was probably intruded last as it cuts Wgp, contains angular xenoliths of Wgp at least 28 m from inferred contacts, and displays a 5-16 cm aplite contact zone. Wga intrudes Wgn although the contacts are cryptic, especially between leucocratic varieties.

Figure 12. Transition from relict metasedimentary-enclave swarms into isolated strongly attenuated ML_2 enclaves orientated N 23 E (hammer length is 55 cm). Southwestern Bremen Long Island.

TABLE 3: SUMMARY OF DEFORMATION AND EMPLACEMENT HISTORY OF THE WALDOBORO PLUTON COMPLEX

D1:F1:	Tight-isoclinal; gently inclined; recumbent
	S0/S1: compositional banding
	S1: schistosity
	ML1: boudinaged enclave; mineral lineation; pegmatoid boudins
	Emplacement: Wqd(?)
D2:F2:	Close; steeply inclined; F1+F2 non-coaxial sheaths
	S2: schistosity
	L2: rodding; bedding/cleavage intersection; crenulations
	ML2: mineral lineation; boudinaged enclave; pegmatoid boudins
D1-D2:	Amphibolite facies metamorphism
	Migmatization-anatexis
	Emplacement: Wgn, Wgl, Wg, Wgt
D3:	S3: mylonitization; type II S; schistosity
	ML3: mineral lineation; boudinaged enclave; banding
	Northeast shear faulting
	Emplacement: Wgp, Wga
D4:	ML4 (?): mineral lineation
	Northwest brittle faulting
	Retrograde metamorphism
D5:	Emplacement: basaltic dikes

Foliations and Lineations

Foliations are summarized in Figure 13. Foliations in Wg do not reveal zonal patterns while many steeply inclined foliations are evident in other phases or units. Magmatic folia-

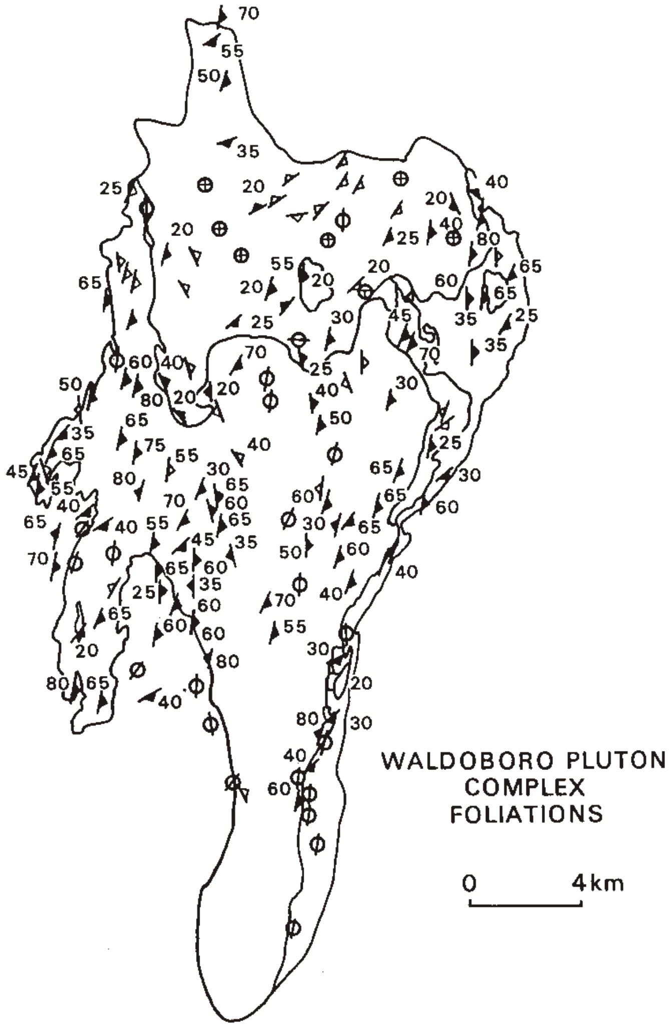
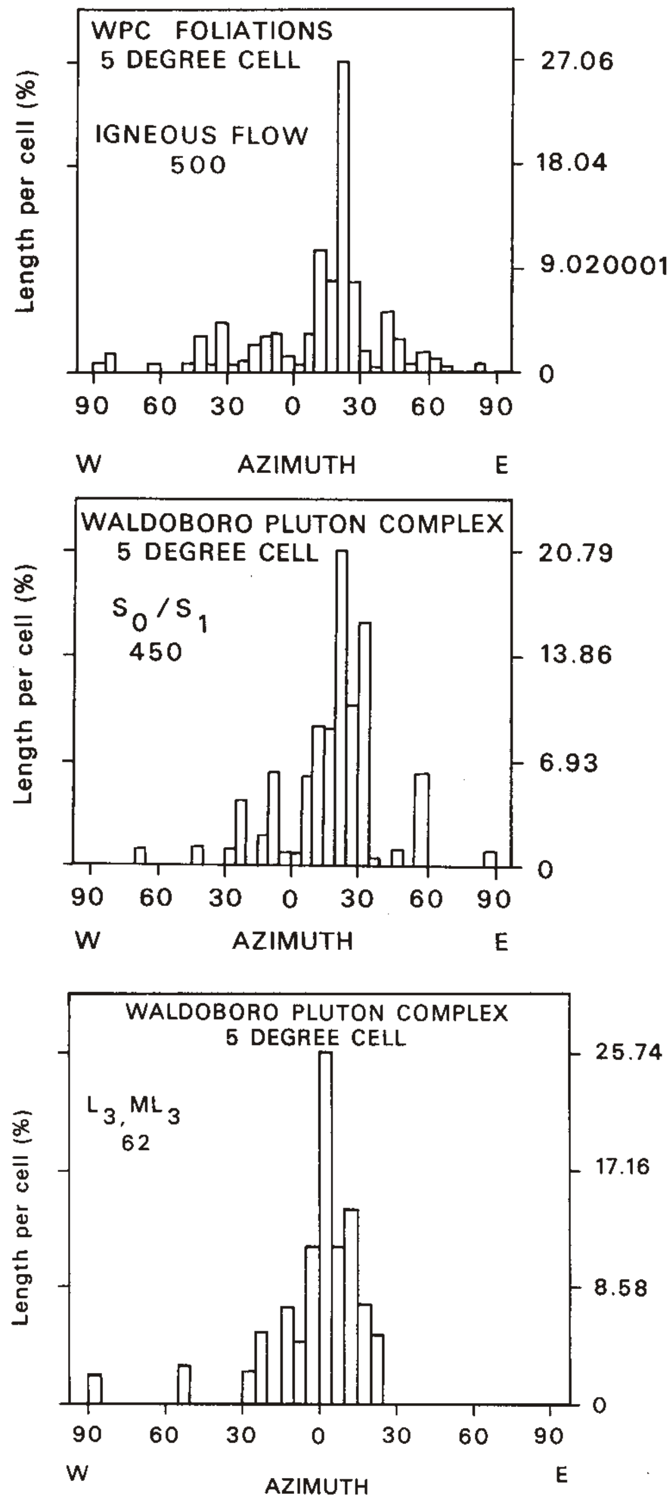


Figure 13. Summary of foliations in the Waldoboro Pluton Complex.



tion is most easily recognized in Wg and consists of flow lines with discoidal schlieren and platy laminations.

Many foliations in other units result from tectonic overprinting, and have a similar attitude (~N20°E) to S_0/S_1 surfaces in the Bucksport Formation. Sometimes they grade along strike into the Bucksport Formation. Original bedding surfaces in the latter cannot be distinguished from metamorphic banding (Hussey, 1989), and the S_0/S_1 surfaces represent either metamorphic foliation or compositional banding. Gneissic foliation essentially parallels the banding. S_1 banding has resulted from the transposition of tight to isoclinal microfolds (Fig. 14) during the development of recumbent F_1 folds, possibly accentuated by metamorphic differentiation. Many leucosomes are injected parallel to S_0/S_1, resulting in stromatic-type migmatites with a northeast-trending fabric (Fig. 15). ML_1 mineral alignment is ubiquitous.

S_2 foliations are most pronounced on the steep limbs of parasitic F_2 folds. Refolded magmatic foliations observed in thin section are interpreted to be coeval with S_2 foliations in the country rock. Continuous cleavage surfaces in a few inliers of

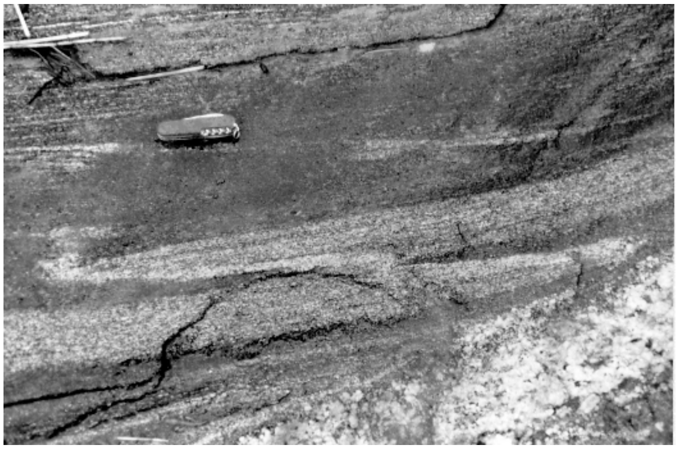


Figure 14. Arrested transposition of S_0/S_1 leucocratic bands. North Round Pond.

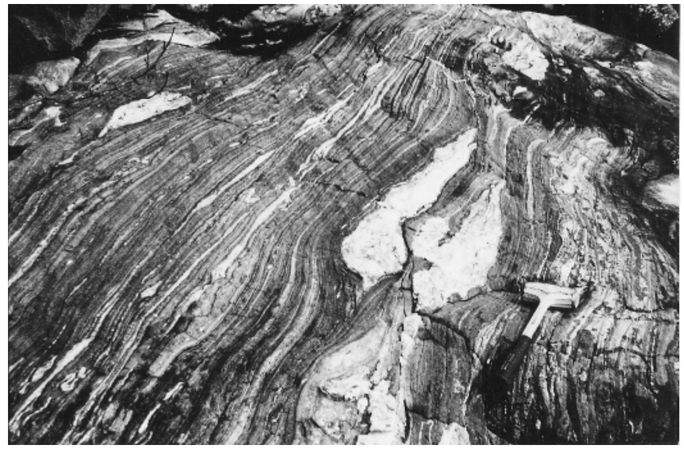


Figure 15. Compositional S_0/S_1 banding in Bucksport Formation gneiss exhibiting boudinage of stromatic-type migmatites (hammer length is 55 cm). Eastern Hog. Island.

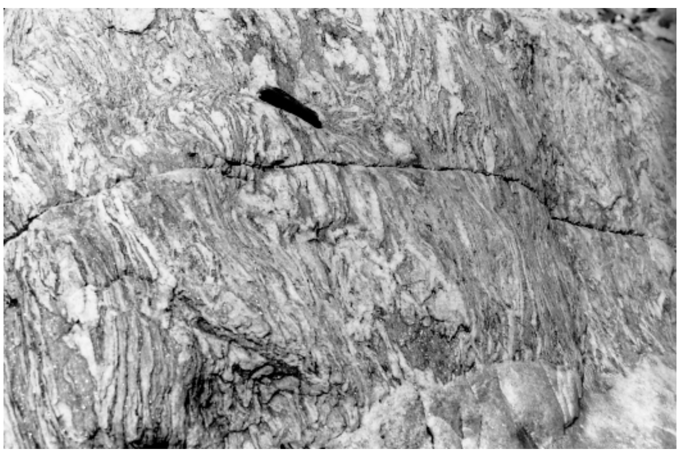


Figure 16. Well-developed northeast trending S_2 schistosity and shallow plunging ML_2 rodding frequently observed on steeply inclined F_2 folds in migmatitic gneisses of Bucksport Formation. Northwest Muscongus Harbor.

Figure 17. Megacrystic feldspar swarm protruding into Bucksport Formation.

Bucksport metapelite have a strong microlithon alignment. Axial plane foliations on F_2 fold hinges suggest continued strain after the main episode of S_2 folding. S_2 surfaces predominantly strike N25°E. ML_2 lineations include fold axes, mineral alignments, and boudinaged enclaves, leucosomes, or early pegmatoids. ML_2 rodding lineations are very common on weathered, tight, upright fold hinges (Fig. 16). They usually parallel axial surfaces of parasitic folds, predominantly trend N15-25°E, and plunge gently to the north.

S_3 penetrative foliations and ML_3 lineations cut earlier foliations as well as ML_2 lineations in the country rock. In thin section, this is represented by micas cutting across the earlier rock fabric. Type II C surfaces in mylonites are occasionally developed, but S surfaces are visible only in thin section (Fig. 8). The ubiquitous ML_3 swarms of {010} aligned tabular feldspar megacrysts, each up to 11cm, occur in near-vertical S_3 foliation planes. Megacryst swarms cut boudinaged enclaves and beds of Bucksport-type lithology (Fig. 17). S_3 foliations predominantly strike N0-15°E, and are most pronounced in the Wgp and Wgn phases, and in mylonitic zones along the eastern sheared margin. A general sigmoidal pattern of foliations is present near the eastern Waldoboro Pluton Complex margin. The near vertical foliations swing to the northeast beyond Friendship Long Island and to the north towards South Pond. This areal pattern may reflect resistance to folding in the vicinity of the Benner Hill quartzites. Given evidence for shearing in Wgp, this sigmoidal pattern has a sinistral sense. Common sympathetic shears (Fig. 10) also document the sinistral slip.

A few lineations of quartz and mica aggregates in Wgn are tentatively assigned to ML_4 (Table 3) and have a northwest bearing. These are not related to a later period of folding and may represent local swirls or areas of turbulent flow lines which are evident elsewhere.

Folds

At least two major folding episodes have affected the Waldoboro Pluton Complex. The folding was synchronous with amphibolite-grade anatexis of Bucksport-type protoliths. Recumbent to gently inclined axial F_1 fold surfaces are traceable from large-scale folds in the region (Hussey, 1986, 1989). Leucosome lenses and pegmatoid dikes/lenses are boudinaged and attenuated due to shortening on near-isoclinal limbs of F_1 folds, which also folded felsic dikes intruded during early anatexis. Biotite and amphibole gneisses/granofels display disharmonic-style folding and cuspate folds. F_1 parasitic fold axes consistently strike northeast (average - N20^{o}E) and plunge northeast. The second folding episode, F_2, generated mostly close folds which strike N20-25^{o}E and plunge up to 10-30 degrees towards the north and northeast.

Exceptional near-cylindrical(?) F_2 folds in the Muscongus Harbor-Hog Island area allow accurate attitude determination. Approximately 120 measurements of S_2 schistosity and cleavage define a northeast-trending fold axis and steep easterly dipping axial plane which is consistent with a major overturned F_2 syncline trending ~N30^{o}E mapped by Newberg (1979) east of the Waldoboro Pluton Complex in the Benner Hill Formation. Newberg (1979) suggests multiple folding during D_2 deformation. However, only two asymmetric populations, representing two nearly coaxial F_2 folds, is suggested by the plot in Figure 18, and it is possible that the spread of the girdle reflects simply heterogeneous strain and/or reorientation of S_2 by later F_3(?) folding. Westward vergence is indicated by the plot, by regional fold trends (Fig. 5), and by Z-type parasitic folds. However, fold interference prevents the universal determination of vergence. Fold interference results in culminations, saddles and rare eye folds.

Intense disharmonic folding occurs along the eastern Waldoboro Pluton Complex margin. Redundant and convergent-divergent patterns in folds are associated with a narrow migmatite belt along this margin (Fig. 19). Ptygmatic folds are common and a few intrafolial folds occur. Strong elongation has caused detached noses of folds. These folds appear to be coincidental with marked S_3/L_3 development and mylonitization (Fig. 20).

Enclaves

Enclave types, in decreasing order of abundance are: metasedimentary enclaves, microgranitoid enclaves (Didier,

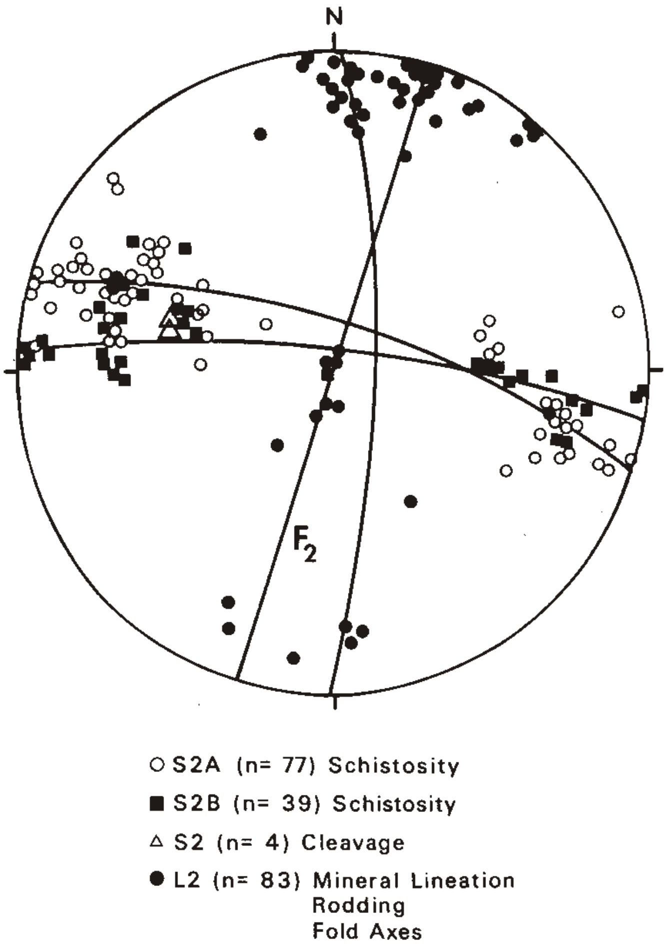


Figure 18. Stereographic projections of structural attitudes in Muscongus Harbor-Hog Island area.

Figure 19. Diktyonitic migmatites with attendant fold hinge separation. Northeastern Friendship Long Island.

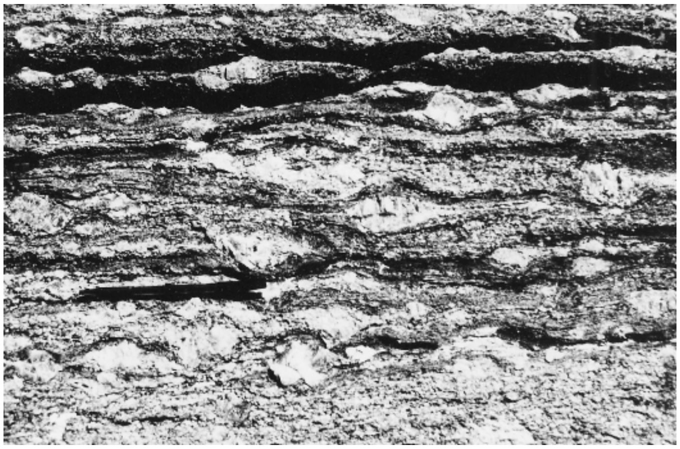


Figure 20. Sheared migmatite, exhibiting quartzo-feldspathic augens, on eastern Waldoboro Pluton Complex margin. Southeastern South Pond.

Figure 21. Relict, attenuated, gneissic enclaves, flattened parallel to S_2/S_3 foliation planes in a megacrystic Medomak granodiorite (hammer length is 55 cm). Southern Friendship Long Island.

1973; Vernon et al., 1988), xenoliths, and rare mingled-type tonalitic enclaves (Vernon et al., 1988). Enclave density approaches 40% of some outcrops, especially near the western margin. They are recrystallized and most parallel the foliations.

Metasedimentary enclaves are abundant in Wgn and Wgp. They are Bucksport-type rocks and are up to several tens of meters long, angular and/or convoluted, and retain original macroscopic structures. The transition to enclave swarms and eventually to more isolated lenticular enclaves (Fig. 12) is observed. Some relict enclaves may be screens due to partial granitoid injection while most grade into melanosomes and are admixed with leucosomes. Many of the relict enclaves have been boudinaged, flattened parallel to S_2/S_3 foliation planes in the granitoids (Fig. 21), and are occasionally rotated, reflecting northeastward elongation. Differences of competency in the layered gneisses resulted in severe pinch and swell structures and complete separation of boudins of these enclaves. Many of the relict enclaves have been partially melted with variable stages of anatexis preserved. Typically, the more refractory gneissic enclaves have biotite rims and are fine-grained. The leucosomes are coarser-grained while both are recrystallized. Eventually, only faint skialiths are observed in outcrop. Schlieren and igneous-flow foliations are not deflected around the enclaves.

Extensive relict enclave swarms and attenuated megacrystic bands are coeval with shearing in Wgp. These enclaves are amphibolite-rich gneisses. Dioritic pods and lenses occur within, crosscut, and form shear pods in amphibolite schists intercalated with Wgp.

Microgranitoid or autolithic (Didier, 1973) enclaves are common only in Wqd. The majority are fusiform and ovoid, and usually are oriented with the long axis trending toward the northeast. Aspect ratios of the autoliths average 4:1 and the margins become diffuse in the more massive areas of Wqd. Similar features are observed in smaller quartz dioritic and dioritic bodies in Wgn. Attenuated and mingled-type (Vernon et al., 1988) tonalitic enclaves are rarely observed.

An estimate of the strain ellipsoid variability amongst principal granitoid phases was obtained by measuring enclave shape ratios (Elliot, 1970; Hutton, 1982). The irrotational deformation varies systematically across the Waldoboro Pluton Complex (Fig. 22). The X/Y shape ratios in Wgn are variable, are consistently 2 to 3 in Wqd, whereas Wgp enclaves display the largest elongation with a maximum shape ratio of 42. These highly attenuated enclaves are uniaxially prolate (K>1) and have R_2 exceeding 5, F values <90 and R_f/ probably closed. All long X axes in Wgp are arrayed subhorizontally.

Angular xenoliths include quartzites, less than 0.2 m, northwest of Warren Station (Fig. 4) which are presumably from the Benner Hill Formation. Elsewhere, several quartzites less than 0.4 m also occur in a local mylonitic zone associated with the eastern Waldoboro Pluton Complex margin, and angular xenoliths less than 1.6 m of Wgp granite porphyry are rafted in Wga.

Joints, Faults, and Shear Zones

Joint types in the granitoids are, in order of frequency, primary flat-lying or parallel, near-vertical longitudinal, and hkl joints. Evenly-spaced, planar, parallel near-vertical joints are especially common in true granitic phases in Wgn and Wg. Many of the largest pegmatite dikes follow these northeast-trending planar joint sets which persist into the country rock. Bedding-type joints are numerous and follow the steeply-dipping S_0/S_1 bedding or banding in the Bucksport Formation. These may be continuous with faulting (eg. Biscay Pond fault).

A distinctive set of closely spaced hkl joints(?) strike consistently northwestward, cutting enclave swarms, and are linked to a D_4 brittle deformation event. These joints extend beyond the

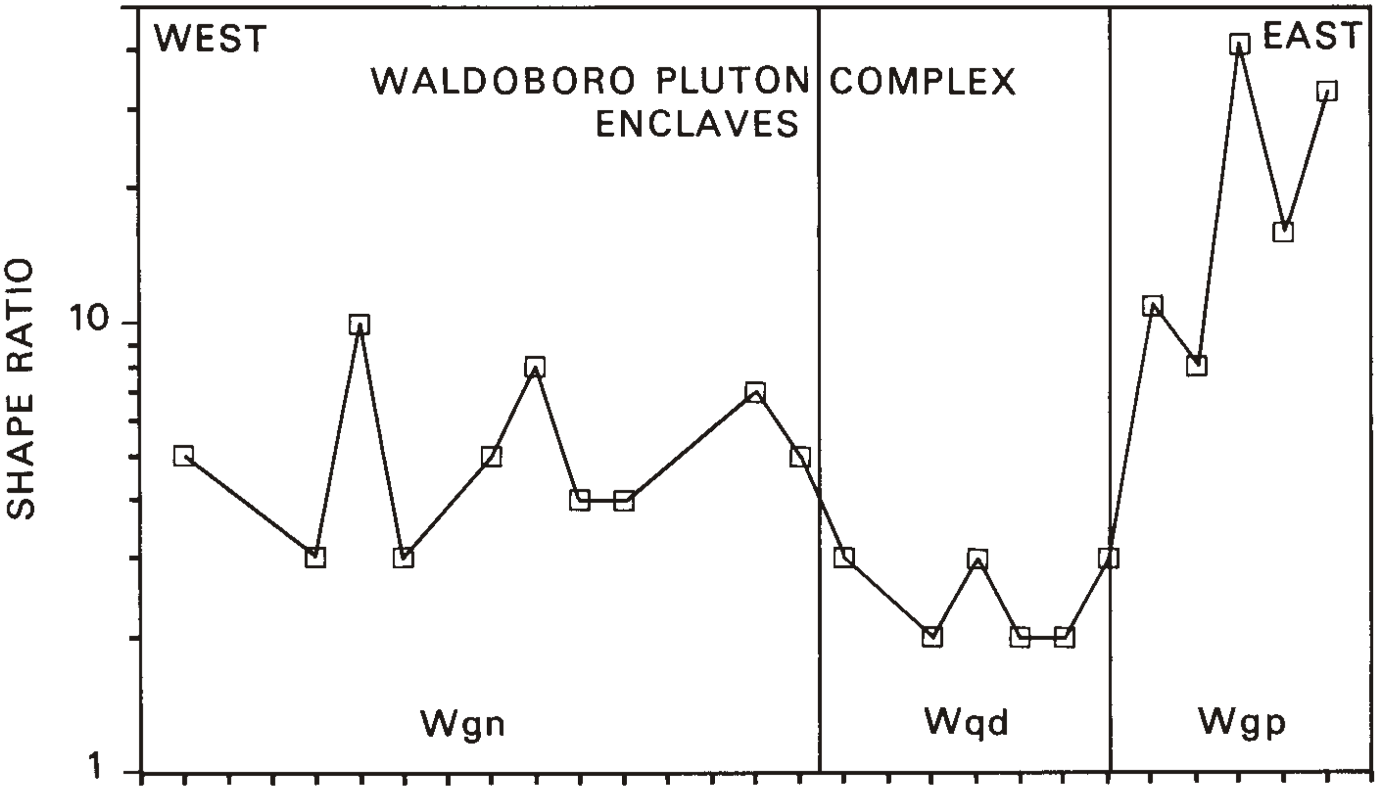


Figure 22. Enclave shape ratio profile of the southern Waldoboro Pluton Complex.

eastern Waldoboro Pluton Complex margin and are associated with very fine fractures normal to type II S surfaces. The relation between the northwest joint sets and the northwest ML_4 lineations is not known. Rare pinnate joints exhibit rakes less than 25 degrees and have 8-15 cm wavelengths. This demonstrates reactivation of some joints during D_4 (?) deformation.

87 faults were mapped in the country rock and the granitoids (Sidle, 1990a, 1991) and are summarized in Figure 23. A northeast-trending set is predominant and is cut by several northwest-trending faults. Two types of faults occur: a cataclastite-fault breccia type and a shear-mylonite type. The cataclastite-fault breccia zones occur throughout the Waldoboro Pluton Complex and have northeast and northwest strikes. They cut all structures except late basalt/diabase dikes and cut all granitoid phases, so that they are clearly postmagmatic. Minor kink faults are also observed in metapelites with tight upright F_2 folds. These brittle faults have a low angle of normal slip and either dextral or sinistral movement. Small-scale brittle faults are observed at a wide angle to northward-striking shear faults.

Numerous shears mylonite (not shown on Fig. 23) occur in the eastern part of the Waldoboro Pluton Complex (Wgn, Wgp, and Wqd). All major shear-mylonite faults strike north to northeast and have sinistral slip as determined from the offset of quartz veining, garnet and dioritic pod rotations, and mineral imbrication. D_3 shearing is most intense along the easternmost margin of the Waldoboro Pluton Complex across the trace of the St. George fault. Many shears were probably coeval with Wgp emplacement and formed in response to increased oblique-slip transcurrent fault strain in the region (Ludman, 1981; Keppie, 1989). Within the granitoids, narrow shear faults are also recognized from type II S structures, narrow channels of extremely attenuated, enclave-rich granitoids, and stair-step leucocratric veins.

DISCUSSION

The Waldoboro Pluton Complex is an Acadian-age, syntectonic migmatitic igneous body which can be divided into several granitoid phases (Wgn, Wgl, Wg, Wgt, and Wga), a protomylonitic unit (Wgp), and an earlier intrusive body (Wqd). The granitoids were formed by melting of metasedimentary protoliths representing distal volcanic-sedimentary deposits in a Nashoba-type terrane. The gradational nature of the contacts with the country rocks provides compelling evidence for in-situ formation by melting predominantly of Bucksport-type metasedimentary rocks and for restricted migration of the melts from the site of melting. Indeed, the contacts display typical "granitization" features (Mehnert, 1987), but the presence of migmatites and upper amphibolite-facies metamorphic assemblages in the envelope surrounding the Waldoboro Pluton Complex, and evidence for melting in metasedimentary enclaves, leaves no doubt of the igneous origin of the granitoids. Neverthe-

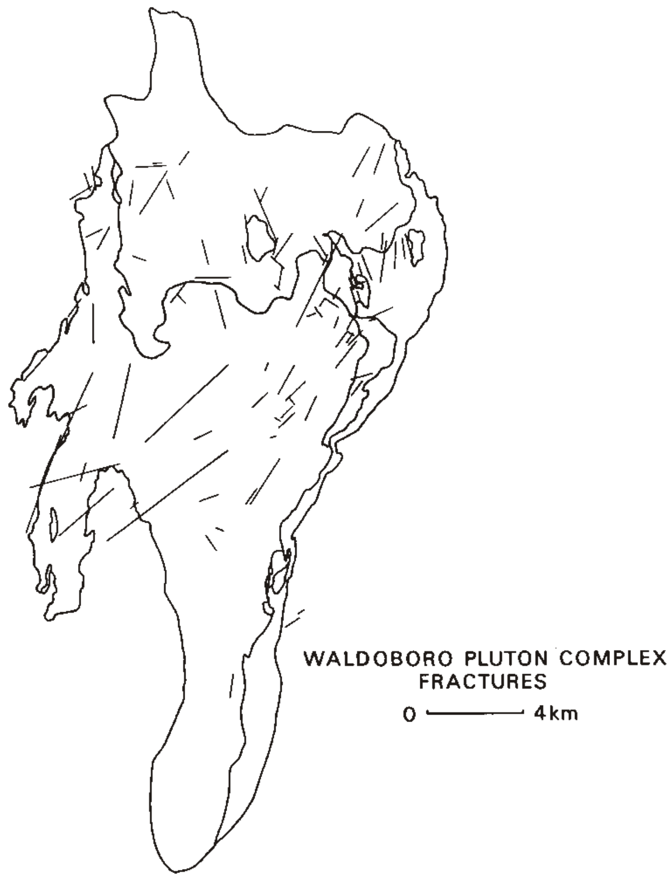


Figure 23. Summary of fracture distribution in the Waldoboro Pluton complex.

less, solid-state processes were responsible for recrystallization, metamorphic differentiation or transposition (ie. tectonic layering), and subsolidus differentiation induced by melting and are superimposed on the original igneous textures and mineralogy (see below). The absence of contact metamorphic aureoles also suggests limited segregation and ascent of the magmas. In fact, the lithologic variability of the granitoids is related to the extent of segregation of melt and host migmatitic metasediments. The gneissic granites and granodiorites (Wgn) contain abundant restitic material (limited phase separation), whereas the granites, leucogranites, and aplitic granites (Wg, Wgl, and Wga respectively) contain less restitic material and more closely approximate melt compositions.

The granitoids contain restitic minerals which are identical to those in the country rocks. Xenocrystic garnet sillimanite are the most obvious examples. Garnets do not exhibit regular size variations as do other mineral phases and form trains that transect contacts between paragneisses and gneissic granitoids of Wgn. Clusters of folded sillimanite and biotite garnet are also interpreted as restitic phases and the preferential occurrence of apatite in biotite may also reflect incomplete dissolution (Wall et al., 1987). The simple albite twinning and patchy (but not complex) zoning of plagioclase may indicate that this phase belongs to the residual assemblage (Chappell et al., 1987; Wall et al., 1987). However, Ca-rich cores in plagioclase, one of the criteria used by the workers listed above to identify residual assemblages, do not occur in the Waldoboro Pluton Complex (Sidle and Barton, in prep.).

The mineralogy of the granitoids and country rocks allows rough estimates to be made of the minimum pressure of magma genesis. Cordierite is rare in the Bucksport Formation and is extremely rare in the Waldoboro Pluton Complex, whereas garnet is abundant in some granitoids (eg. Wgn), and in biotite gneisses, amphibolite schists, and metapelites. The presence or absence of cordierite in S-type magmas (White et al., 1986) constrains the P-T conditions of the source. The dehydration reaction:

$$4\,\mathrm{Bio} + 3\,\mathrm{Crd} + 3\,\mathrm{Qtz} = 6\,\mathrm{Gnt} + 4\,\mathrm{Ksp} + 4\,H_2O \text{------------} (1)$$

(Holdaway and Lee, 1977), has a steep, negative dP/dT slope so that at fixed pressure and bulk composition, garnet is stable at higher temperatures and lower water contents. However, the presence of sillimanite in the Waldoboro Pluton Complex suggests that the reaction:

$$3\,\mathrm{Crd} = 2\,\mathrm{Gnt} + 4\,\mathrm{Sill} + 5\,\mathrm{Qtz} \text{--------------------------------} (2)$$

(Holdaway and Lee, 1977) also controls the stabilty of garnet. This reaction has a gentle negative dP/dT slope and shifts to higher pressure with increased Mg/(Mg+Fe)(Clemens and Wall, 1988). In the peraluminous Waldoboro Pluton Complex melts, Al_2O_3 activity may have been buffered by reactions involving sillimanite and quartz, indicating that pressure was the major factor stabilizing garnet. Comparison of the data of Holdaway and Lee (1977) and Currie (1971) with minimum melting temperatures (PH_2O=PT) for granite (Clemens and Wall, 1988) suggests pressures of at least 0.3-0.4 GPa for formation of the Waldoboro Pluton Complex. The presence of sillimanite and lack of kyanite in the area indicates pressures below about 0.8 GPa.

Primary magmatic muscovite is present in the Wg phase. The occurrence of large butt-ended crystals of cleanly terminated muscovite is evidence against a subsolidus origin (Zen, 1988). Two-mica granites may be typical of deeper levels of emplacement (White et al., 1986). Muscovite stability is favored by both high H_2O and Kspar activity according to the reaction:

$$\mathrm{Msv} + \mathrm{Bio} + \mathrm{Qtz} = \mathrm{Crd/Gnt} + \mathrm{Ksp} + H_2O \text{------------------} (3)$$

(Clemens and Wall, 1988). Garnet cordierite may have developed during the early cooling history, but primary muscovite crystallized late when the temperature was lower and H_2O activity was higher. According to Zen (1988), primary muscovite indicates pressures 0.3 GPa in agreement with inferences based on the presence of garnet. Field evidence suggests limited migration of the Wg melt phase which was emplaced structurally above the other anatectic phases in the Waldoboro Pluton Complex implying that the latter were also emplaced at P>0.3 GPa.

Solid-state deformation has overprinted much of the magmatic foliation in the Waldoboro Pluton Complex, especially in the Wgn, Wqd, and Wgp phases, and has resulted in protomylonites, mylonites, S-C foliations, mineral and enclave boudinage, mineral imbrication, augen rotation, intrafolial folding, and variable fluxion textures. Grain size reduction and elongation of finer mineral aggregates is reflected in the microfabric (mica ribbons, mica fish, polygonal quartz-feldspar trains, recrystallization of enclaves, S_1/S_2 foliations of micas, and paracrystalline microboudinage). The superposition of tectonic foliations on magmatic foliations could concievably have occurred while some melt was present. Hibbard (1986) suggests that this "dynamic crystallization" is indicated by fluid relocation textures. In the Waldoboro Pluton Complex, pressure shadows are filled with quartz and feldspar neograins or "microaplite," and myrmekite. But Simpson (1985) and La Tour (1987) argue that ductile flow processes can account for neocrystallization in pressure shadows and fringes. Furthermore, the polydeformational history of the granitoids under amphibolite facies conditions plus widespread porphyroblastesis argue against the continued presence of melt during deformation.

Solid-state processes were most intense along the eastern part of the Waldoboro Pluton Complex margin and produced ductile shear zones, mylonites, local ptygmatic-style folds, type II S foliations, synkinematic garnet growth, very acute angles between S_1 and S_2 in transitional granitoids, high aspect ratios of boudinaged enclaves, and extreme attenuation of banding and mineral lineations. These features, together with evidence of subsolidus plastic deformation, indicate high temperature, solid-state flow processes (Paterson et al., 1989). Syntectonic emplacement is strongly suggested by subparallel to parallel superposition of solid-state foliations and magmatic foliations. The solid-state foliations are continuous with country rocks. Mutual cross-cutting relationships between granitoid bodies and folds with ghosts of axial plane schistosity surfaces are especially important in suggesting syntectonic emplacement. Solid-state deformation was due largely to regional tectonic episodes rather than granite emplacement, based upon the above observations.

Feldspathization or alkali enrichment reflecting late vapor transport is apparent in the Wgn and Wgp phases. Feldspar megacryst swarms cut enclaves and country rocks several meters from granitoid contacts. Possible origins include: relict augens (Vernon, 1986); growth in partially crystallized dikes leading to interlocking unfractured crystals (Hibbard, 1986); filter pressing (Hibbard and Waters, 1984) whereby megacrysts concentrate between more competent rafts or bands; and undercooling (Swanson, 1977). These megacrysts, up to 11 cm, may be simply attributed to undercooling, resulting in low nucleation density and high growth rates. However, none of these mechanisms can explain all observations, especially the uninterrupted trains of megacrysts from granitoid into country rock. Also, near the eastern Waldoboro Pluton Complex margin, second generation perthites poikilitic after microcline, interpenetration perthites, late microveining, sericite-filled microshears, tension gashes filled with perthite, secondary albite, and tourmaline veins provide evidence for late replacement processes in the granitoids. Evidently, this porphyroblastesis began during ductile deformation which peaked during D_3 and continued when post-magmatic hydrothermal fluids were injected during thermal contraction or later D_4 cataclasis.

SUMMARY OF INTRUSIVE AND GEOLOGIC HISTORY

High-grade, amphibolite-facies metamorphism produced sillimanite-K-feldspar-garnet assemblages and was accompanied by two phases of deformation, D_1 and D_2. D_1 produced dominantly tight, near-recumbent F1 folds trending northeastward, whereas D_2 largely produced close, steeply-inclined F_2 folds, trending north to northeast, resulting in a pronounced northeast-southwest fabric. Anatexis was initiated with widespread migmatization throughout the area. Extensive melting occurred in biotite-rich lithologies. Partial melting may have occurred in response to crustal thickening along the St. George thrust fault, but emplacement of gabbroic and dioritic magmas could have provided additional heat in this westward vergent, overthickened underplate. The Wqd phase of the Waldoboro Pluton Complex was probably emplaced early, coeval with the Raccoon gabbroic and dioritic intrusions east of the Waldoboro Pluton Complex. The main syntectonic emplacement of granitoids Wgn, Wg, Wgl, and Wgt progressed as metamorphism peaked before completion of D_2 deformation. The early anatectic, leucocratic granitoid phase is represented by Wgl and other smaller bodies throughout the Waldoboro Pluton Complex. Wg was emplaced farthest from the site of melting following an extended period of melt-restite phase separation. Wgt was the last phase to crystallize within Wg.

Much of the solidification of the Waldoboro Pluton Complex was completed prior to the onset of transcurrent faulting in the region, although some aplitic melts persisted during the time that the Acadian regional stresses departed from a dominant orthogonal compressional regime. Intense ductile deformation climaxed during D_3 deformation. Sinistral transcurrent motions may have predominated along the upper thrust-plate of the St. George fault, which contained refractory lithologies. The changing stress regime is recorded by extensive shearing developed between megacrystic granitoid and the refractory country rocks along the eastern Waldoboro Pluton Complex margin. Mylonitization, convoluted migmatization, and blastesis signaled the development of these transcurrent accretionary tectonics which locally strongly overprint the Waldoboro Pluton Complex granitoids. During the later development of the protomylonitic border, fluid transport resulted in late-stage tourmalinization and alkali-enrichment. The protomylonitic border sutures part of the St. George fault. Finally, granitic melts represented by Wga were emplaced and volatile-rich residual melts crystallized throughout the area as pegmatites, which are abundant (Sidle, 1990a).

A post-magmatic episode of brittle faulting developed during D_4. The regional stress regime shifted to produce northwest-trending structures. However, this period of cataclasis or brittle deformation was weak compared to previous deformation events. Minor retrograde metamorphism (eg. chlorite after garnet and biotite, sericitization of plagioclase) probably occurred during this period of tectonic unloading(?). Fluids entered along the eastern margin of the Waldoboro Pluton Complex where intense alteration occurs locally along shear zones. Fluid transport pathways are suggested by microfractures cutting earlier neocrystallization areas and resistant phenocrysts, fine fractures cutting type II S structures, and tourmaline veining.

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