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Compositional Variation of Plutonism in the Coastal Maine Magmatic Province: Mode of Origin and Tectonic Setting

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ABSTRACT

Proterozoic(?) to Devonian metasedimentary and metavolcanic rocks of the northeast-trending, fault-bounded lithotectonic terranes of eastern coastal Maine, between Penobscot and Passamaquoddy Bay, have been pervasively intruded by over one hundred individual Silurian to Early Carboniferous mafic and felsic plutons. Mafic magmatism generally preceded felsic magmatism, although field evidence suggests that commonly these magmas were spatially and temporally related. The large volume and close spatial and temporal relationship of mafic and felsic plutonism within this area suggest a possible genetic relationship. We propose that mafic and felsic plutonic rocks within this region be considered collectively as the coastal Maine magmatic province.

On the basis of the presence of syn-plutonic mafic dikes, gradational contacts between mafic and felsic plutons, and the presence of mafic enclaves, plutons in the coastal Maine magmatic province can be divided into four types representing the relative degree of association of mafic and felsic magmas. End members are mafic plutons that have crystallized without interaction with a felsic magma (type I) and felsic plutons that have crystallized without interaction with a mafic magma (type II). Types III and IV are hybrid granitoid and gabbroic plutons that have had their original compositions modified by interaction with a magma(s) of markedly different composition during the course of crystallization. Using this classification scheme, contact relationships, subsurface distribution, modal mineralogy, and mineral and whole rock chemistry are examined for the plutons to determine possible compatible tectonic settings and thermal history for eastern coastal Maine during the Early to Middle Paleozoic.

Plutonism within the magmatic province is compatible with an extensional tectonic regime. Underplating (Wones, 1976a) and intraplating of mantle-derived mafic magmas, represented by type I plutons, provided the heat source to induce partial melting of a variably dehydrated crustal source region(s) for generation of the type II felsic plutons. The diversity of granitic plutons present in the coastal Maine magmatic province reflects the potential diversity in mineral assemblages present in the source region during partial melting as well as the possibility of later modification of the original magma composition through mixing/mingling with mafic magmas to produce hybrid pluton types III and IV. In general, the bimodal plutonism with alkalic tendencies that characterizes the coastal Maine magmatic province postdates assembly of the proposed lithotectonic terranes. Pluton emplacement may have been structurally controlled by preexisting faults. The presence of prominent dextral transcurrent faults suggests that rift-related magmatism could have occurred within a region of transtension in a transcurrent fault system. However, the orientation of relatively younger, Devonian, felsic batholiths coincides with a system of step-over faults that would require a change from a transtensional to transpressional regime prior to their intrusion, suggesting that plutonism within this region is sensitive to changes in the geometry of the transcurrent fault system.

INTRODUCTION

Large geographic areas intruded by voluminous plutonic rocks, such as the Mesozoic-Cenozoic coastal batholith of Peru (Pitcher, 1978) or the Lachlan fold belt of southeastern Australia (White and Chappell, 1983) are classified as magmatic provinces. Eastern coastal Maine, from west of Penobscot Bay north to Passamaquoddy Bay, has been pervasively intruded by over one hundred mafic and felsic plutons, spanning ages from Late Silurian to Early Carboniferous (Fig. 1, Tables 1 and 2). These plutons range in size from less than 1 km^2 to the 1670 km^2 Deblois granitoid batholith. Mafic plutonic rocks, such as gabbro, diorite, quartz-gabbro, and anorthosite, account for approximately 8% and felsic granitoids, predominantly granite with some quartz monzonite, and minor granodiorite represent 37% of the total 14,694 km^2 of the study area. Extended and repeated intrusion of plutons has resulted in younger intrusions transecting large portions of older plutons, suggesting that this represents a minimum estimate of mafic and felsic magmatic activity within the area. Previous reviews of plutonism in eastern coastal Maine have generally considered mafic and felsic plutonism separately (Chapman, 1962b, 1968; Page, 1968; Thompson, 1984). However, the large volume of magmatism and the close spatial and potential temporal relationship of mafic

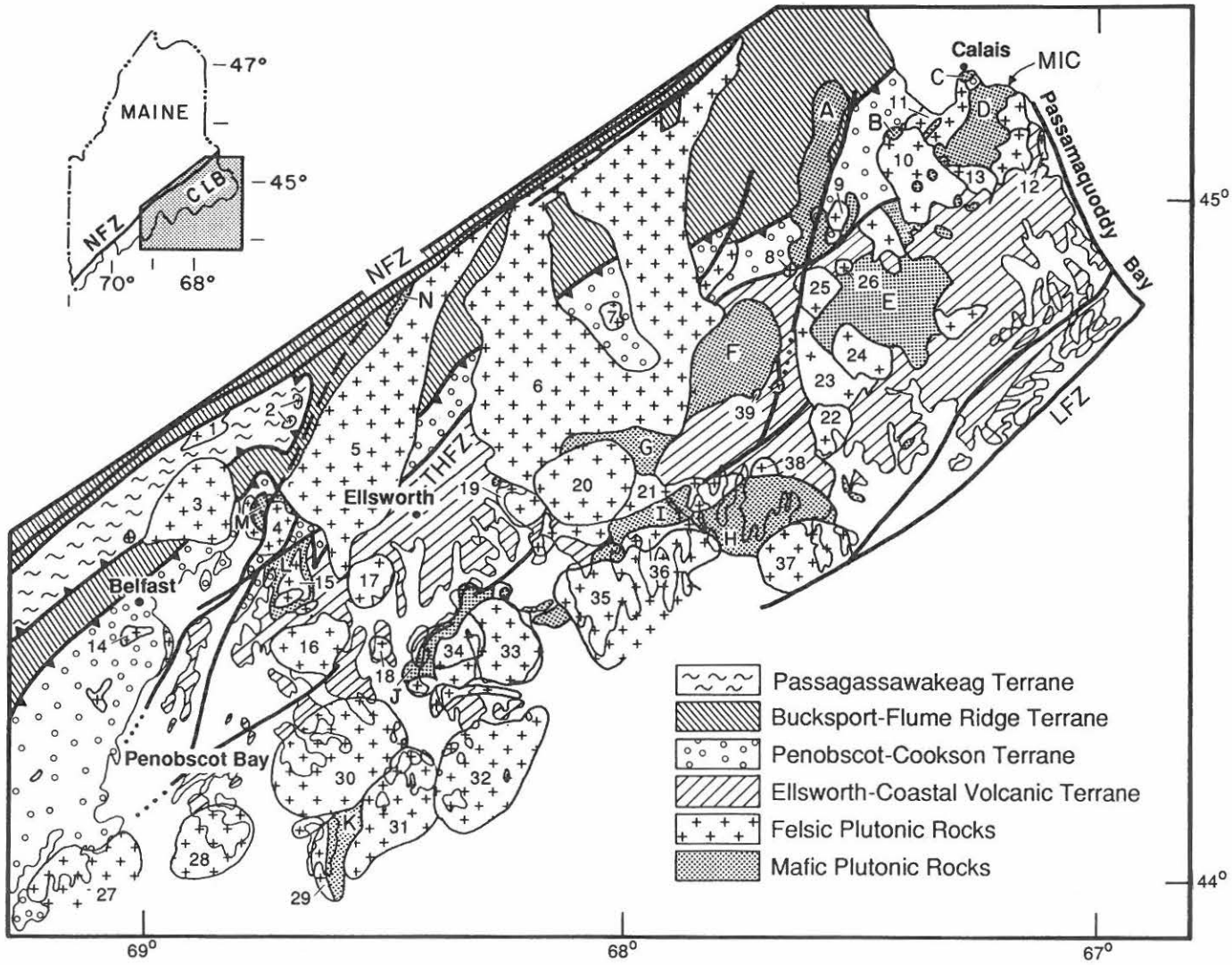

Figure 1. Generalized geologic map of a portion of the Fredrickton Trough and the coastal lithotectonic block, southeastern Maine, as modified from Osberg et al. (1985). Major tectonic elements include northeast-southwest trending lithotectonic terranes as well as prominent dextral transcurrent fault zones, such as the Norumbega fault zone (NFZ), the Turtle Head fault zone (THFZ), and the Lubec fault zone (LFZ), as well as associated N20-30°E step-over faults. Numbers correspond to felsic plutons and letters to mafic plutons identified in Table 1. The location of the Moosehorn Igneous Complex (MIC) referred to in the text is shown by the arrow.

TABLE 1. APPROXIMATE AREA OF PLUTONIC ROCKS IN THE COASTAL MAINE MAGMATIC PROVINCE.
(Pluton number and letter correspond to those in Figure 1).

FELSIC PLUTONS			MAFIC PLUTONS		
	Pluton Name	Area (km^2)		Pluton Name	Area (km^2)
1	Winterport	n.i.	A	Pocomoonshine	137
2	Stricklen Ridge	n.i.	B	Staples Mt.	3
3	Mt. Waldo	157	C	St. Stephen	2
4	Wallamatogus	34	D	Calais gabbro/diorite	105
5	Lucerne	625	E	Gardner Lake	244
6	Deblois	1670	F	Peaked Mt./Tibbettstown	190
7	Spruce Mt.	36	G	Cherryfield/Tibbettstown	44
8	Indian Lake	6	H	Pleasant Bay/Jonesport	169
9	Rocky Brook	14	I	Milbridge	44
10	Meddybemps	126	J	Mt. Desert	41
11	Baring	44	K	Isle Au Haut	51
12	Red Beach	36	L	South Penobscot	37
13	Charlotte	23	M	Leaches Point	16
14	Northport	14	N	Parks Pond	6
15	South Penobscot	31	O	Miscellaneous	79
16	Sedgwick	88			
17	Blue Hill	41			
18	Long Island	12			
19	Sullivan	36		Total area considered	14694
20	Tunk Lake	175			
21	Cherryfield	60		Area of felsic plutonic rocks	5422
22	Jonesboro	46			
23	Whitneyville	95		Area of mafic plutonic rocks	1134
24	Marshfield	58			
25	Bog Lake	36		Total area of plutonic rocks	6556
26	Round Lake Hills	5			
27	Spruce Head/Clark Island	147			
28	Vinalhaven	128			
29	Isle Au Haut	28			
30	Deer Isle	308			
31	Swans Lake	174		Percentage of total area considered	
32	Frenchboro	245			
33	Cadillac Mt.	158		Felsic plutonic rocks	37
34	Somesville	59			
35	Gouldsboro	360		Mafic plutonic rocks	8
36	Steuben	119			
37	Great Wass Island	124		Total for plutonic rocks	45
38	Highlands	8			
39	Pyroxene Granite	2			
	Miscellaneous	95		n.i. = not included	

and felsic plutons in eastern coastal Maine suggest a genetic relationship. Because of this we prefer to view plutonism in this area collectively as the coastal Maine magmatic province.

A correspondence between the composition of plutonic rock suites that comprise magmatic provinces and their associated tectonic environment has long been recognized by geologists (Harker, 1909; Benson, 1926; Martin and Piniwinskii, 1972; Petro et al., 1979; Pitcher, 1982, 1983). In well studied tectonic settings where magmatism is related to subduction, systematic variations in geochemical and isotopic characteristics exist for plutons with respect to their location from the trench (Kistler and Peterman, 1973; Taylor and Silver, 1978; DePaolo, 1981). The constant replenishment of source material through the subduction process to the site of melting is reflected in the repetition of intrusive sequences of magma types, ± gabbro, quartz-diorite, tonalite, granodiorite, and granite, within the overlying arc (Bateman et al., 1963; Bateman, 1983). In contrast, incremental melting of the same source region material can result first in the generation of low temperature, hydrous, peraluminous magmas followed by progressively higher temperature, drier, metaluminous melts and finally by anhydrous, peralkaline plutons (Brown and Fyfe, 1970). This sequence of magma types is compatible with rift-related tectonic settings where underplating of mantle derived magmas can provide the heat to melt the overlying source region (Wones and Sinha, 1988). In magmatic provinces where the tectonic setting is poorly constrained, analysis of the physical, petrographic, chemical, and isotopic characteristics of the plutonic rocks as well as establishment of sequences of magma types can be used to develop tectonic models that will be compatible with the characteristics of the

TABLE 2: RADIOMETRIC AGES OF PLUTONIC ROCKS IN THE COASTAL MAINE MAGMATIC PROVINCE.
(Pluton name and number correspond to those in Table 1 and Figure 1)

No.	Pluton Name	U/Pb (Zircon)	Rb/Sr (Whole Rock†)	Rb/Sr (Mineral†)	K/Ar (Mineral)
1	Winterport	412±14[14]*			
2	Stricklen Ridge	412±16[14]			
3	Mt. Waldo		382±10[4]		325±10(B)[15]
4	Wallamatogus		367±20[4]	323(B)[5]	330(B)[5]
				382(M)[5]	384(M)[5]
5	Lucerne	380±4[14]	371±21[6]	325(B)[5]	356(B)[5]
			393±13[4]		
6	Deblois		393±17[6]		367(B)[5]
10	Meddybemps			354(B)[5]	404(B)[5]
					354(B)[5]
12	Red Beach		385±6[9]	372(B)[5]	407(B)[5]
					401(B)[5]
13	Charlotte			382(B)[5]	406(B)[5]
15	South Penobscot	424±6[10]	394±15[4]		360+15[4]
		436±9[10]			
16	Sedgwick		387±15[4]		413±15[4]
17	Blue Hill		374±10[4]	362(B)[5]	387(B)[5]
19	Sullivan				369(B)[5]
20	Tunk Lake				357±10(B)[1]
22	Jonesboro				363(B)[5]
25	Bog Lake				363(B)[5]
27	Spruce Head/ Clark Island				367±11(B)[15]
28	Vinalhaven		353±7[2]		399(B)[4]
30	Deer Isle				
	Oak Point Phase		349±1[3]	336±12(B)[15]	354(B)[5]
				258±15(F)[15]	
	Stonington Phase		334±21[3]		350(B)[5]
					360(B)[5]
33	Cadillac Mt.		361±35[7]		397(Hfls)[5]
34	Somesville		410±16[7]		389(B)[5]
35	Gouldsboro		377±19[8]		
A	Pocomoonshine				423±24(H)[12]
					408±14(B)[12]
C	St. Stephen				407±20(H)[11]
					357±16(B)[11]
N	Parks Pond	410±4[13]	388±6[13]		365(B)[5]

* References indicated by superscripts, and the mineral used for dating in ( )
† All Rb/Sr ages reported are for $\lambda Rb^{87} = 1.42 \times 10^{-11}$ /yr.

1) Brookins, 1976
2) Brookins et al., 1973
3) Brookins and Spooner, 1970
4) Brookins, in Wones, 1976a
5) Faul et al., 1963
6) Loiselle et al., 1983
7) Metzger and Bickford, 1972
8) Metzger et al., 1982
9) Spooner and Fairbairn, 1970
10) Stewart et al., 1988
11) Wanless et al., 1973
12) Westerman, 1972
13) Eriksson and Williams, in press
14) Zartman and Gallego, 1979
15) Zartman et al., 1970

(B) Biotite
(M) Muscovite
(H) Hornblende
(F) Feldspar
(Hfls) Hornfels

associated plutonism. The purpose of this paper is to examine plutonism within the coastal Maine magmatic province in terms of the physical, petrographic, major element, and selected trace element characteristics of the associated plutons and interpret their role in the tectono-thermal evolution of the crust of eastern coastal Maine during Early to Mid-Paleozoic times.

The composition of plutonic rock suites has also been interpreted to be inherited from their source region (Chappell and White, 1974; White and Chappell, 1977). However, besides restite unmixing, compositional variation in plutons can also be produced by processes such as fractional crystallization, assimilation, or magma mixing. Modification of the original composition of the magma by these processes, except for restite unmixing, can act to obscure information about source region characteristics. In the coastal Maine magmatic province, the spatially intimate association of mafic and felsic plutons suggests that magmas of distinct composition may have been temporally and genetically related. Compositional variation of plutonism within this region has the possibility of reflecting various degrees of hybridization of felsic and mafic magmas through magma mixing and/or mingling during the course of crystallization. This process is important to identify because the chemistry of a magma that has interacted with melts of markedly different composition can be significantly modified (Eichelberger, 1978; Gamble, 1979; Reid et al., 1983). The resultant magma may even retain isotopic characteristics formed during magma mixing and therefore may not yield a meaningful whole rock Rb-Sr isotopic age (Faure, 1977). Therefore, the chemical characteristics of plutons derived from interaction of several magmas should be viewed with some caution, as their chemical signature may no longer reflect those of a single source region and could lead to erroneous tectonic interpretations.

With this caveat in mind, we have chosen to group plutons in the coastal Maine magmatic province into four broad types based on the possibility that mixing/mingling of felsic and mafic magmas may have been a viable process during the crystallization of a particular pluton. In this paper we use field observations such as gradational contacts between mafic and felsic plutons, the presence of syn-plutonic dikes, bimodal mafic/felsic dikes, and the presence of mafic enclaves to initially classify plutonic rocks of this province. The end member compositions of the four intrusive types are represented by mafic plutons (type I) and felsic plutons (type II) which, at the present level of exposure, appear to have crystallized without any interaction with a magma(s) of markedly different composition.

The two hybrid types are plutons where field evidence suggests that mixing and/or mingling of mafic and felsic magmas may have been an important process in their petrogenesis. Type III plutons are dominantly granitic, but have interacted to some degree with mafic magma(s). Type IV plutons are dominantly gabbroic, but have interacted with felsic magma(s) during the course of crystallization. Assignment of a pluton to type III or type IV in this paper is not intended as a final conclusion that magma mixing is the process responsible for the compositional

variation observed in these plutons; it is a preliminary classification based on field observations and needs to be considered in future investigations of plutons belonging to these two types. Detailed petrologic studies are required to determine the extent to which processes, such as assimilation, restite unmixing, fractional crystallization, or magma mixing may have operated in a pluton to produce the observed compositional variation. Several such detailed studies on plutonic rocks in the coastal Maine magmatic province, classified in this paper as either type III or type IV plutons, have recently been completed that stress the importance of magma mixing in the petrogenesis of these plutons (Mitchell, 1986; Stewart et al., 1988; Hill and Abbott, this volume; Mitchell and Rhodes, this volume).

Type II plutons, because they are the least likely to have interacted with a mafic magma(s), have the greatest potential for retrieval of information concerning the nature of the crustal source region(s) beneath the coastal Maine magmatic province. Although comparisons of modal, whole rock, and selected trace element chemistry support distinctions made by this classification scheme, these data also indicate that type II plutons can be further subdivided into units/superunits in the sense of Pitcher (1979) and potentially into suites in the sense of White and Chappell (1983). Identification of potential plutonic suites will provide a framework for geochemical and isotopic analysis to determine the geometry and spatial distribution of source regions beneath the coastal Maine magmatic province. This information will further constrain tectonic models proposed for eastern coastal Maine.

Modal and whole rock chemical data for selected plutons in the coastal Maine magmatic province have been compiled from a wide range of sources. The data presented have not been normalized in terms of areal extent of the pluton vs. the number of analyses. Several plutons that have been well studied and adequately sampled are used as type examples (Table 3) to illustrate major characteristics of the coastal Maine magmatic province. However, many of the plutons have either limited or no data available on the distribution, relationship, or chemistry of rock types present. This necessitates that some plutons be left

TABLE 3. CHARACTERISTICS OF INTRUSIVE TYPES IN THE COASTAL MAINE MAGMATIC PROVINCE.

	Type I	Type IIa	Type IIb	Type III	Type IV
Principal rock types	Gabbro, norite, diorite ± anorthosite	Granite	Granite ± alkali-feldspar granite	Granite, granodiorite quartz monzonite ± alkali-feldspar granite	Quartz monzodiorite-monzogabbro, gabbro, diorite, monzonite
Primary phases	Ol, Opx, Cpx Hbl ± Bio	Bio-Mu ± Gar Bio	Bio ± Hbl Bio	Bio-Mu ± Gar Bio ± Hbl, Bio	Bio ± Hbl ± Opx ± Cpx ± Ol(?)
Accessory mineralogy	Apatite, ilmenite pyrrhotite, pentlandite chalcopyrite	Ilmenite, monazite zircon, tourmaline apatite	Ilmenite, zircon apatite, +allanite +tourmaline	Magnetite, ilmenite, sphene, fayalite, aegerine-augite reibeckite, apatite, allanite	Magnetite, zircon apatite, sphene
Textures	Magmatic layering, cryptic layering,	Variable, medium to coarse grained, seriate to subporphrytic	Homogeneous coarse grained seriate to porphyritic	Variable, medium to coarse grained, seriate to porphyritic	Variable, medium to fine grained
Intrusive style	Stratiform sills, dikes, laccoliths	Subcircular stocks	Large elongated batholiths	Subcircular stocks, or multiple intrusions forming igneous complexes e.g. Moosehorn Igneous Complex	
Enclave types	Metasedimentary xenoliths, autoliths	Metasedimentary xenoliths, autoliths		Mafic enclaves common in zones and evenly distributed Autoliths, metasedimentary xenoliths	
Dikes	Tonalitic pegmatites	Aplites and pegmatites Common	Uncommon	Aplites and pegmatites, Mafic dikes	
Alumina saturation index	0.73 ± .1	1.13 ± .1 (1.34-0.99)	1.05 ± .02 (1.09-1.00)	1.00 ± .1 (1.26-0.89)	0.72 ± .2 (Gabbros) 0.68 ± .05 (Parks Pond)
Mean SiO_2 content	47.5 ± 3.7	74.6 ± 1.1	71.9 ± 2.0	72.5 ± 1.8	47.3 ± 7.4 (Gabbros) 57.9 ± 1.2 (Parks Pond)
Rb/Sr ratio	<1 : 2	>2 : 1	>2 : 1	<2 : 1	<2 : 1
Type examples	Pocomoonshine Pleasant Bay	Blue Hill Wallamatogus	Lucerne Deblois	Deer Isle Spruce Head Cadillac Mt.	Parks Pond gabbro, diorite in igneous complexes

unassigned, while other plutons may be prematurely classified and may require a more in-depth study before a final assignment of type is made. Therefore, inferences drawn from this limited data base represent guidelines for future work designed to test and evaluate preliminary conclusions presented in this paper.

REGIONAL GEOLOGY

Recent analyses of the Appalachian-Caledonide orogen have proposed that it can be viewed as a mosaic of suspect terranes (Williams and Hatcher, 1982, 1983; Zen, 1983). Terrane analysis has been in progress in Maine where geochemical and isotopic studies of granitic plutons within a transect across central to coastal Maine defined three distinct crustal source regions (Loiselle and Ayuso, 1980; Andrews et al., 1983; Ayuso, 1986) that are consistent with terranes defined on the basis of gravity gradients (Phillips et al., 1985), deep seismic reflection traverses (Stewart et al., 1985), and contrasting stratigraphic and structural features (Zen, 1983). In southeastern Maine, the steeply dipping, northeast-trending, dextral, Norumbega fault zone (Wones and Thompson, 1979; Johnson and Wones, 1984) is suggested to represent the boundary which separates the crustal block of central Maine from the coastal lithotectonic block (Fig. 1) (Stewart and Wones, 1974; Wones and Stewart, 1976; Zen, 1983). The regional geology of the coastal lithotectonic block, from Penobscot to Passamaquoddy Bay, consists of a series of northeast-trending, fault-bounded lithotectonic belts (Osberg et al., 1985). Each belt consists of a unique package of lithologies, regional metamorphic mineral assemblages, and deformational history suggesting that the coastal lithotectonic block can also be considered as a collage of several distinct crustal blocks or terranes (Stewart and Wones, 1974; Wones and Stewart, 1976; Osberg, 1974, 1978; Zen, 1983).

In the Penobscot Bay area, the Passagassawakeag terrane (Wones and Stewart, 1976; Bickel, 1976) consists of complexly deformed, migmatitic, quartzo-feldspathic augen gneiss, metavolcanics, and calc-silicates all of suggested Precambrian or Proterozoic age (Stewart and Wones, 1974) as well as Cambro-Ordovician pelitic schists, siltstones, and quartzites. This lithologic package is pervasively intruded by numerous pre- to syn-tectonic granitoid dikes, sills, pegmatites, and small stocks (Trefethen, 1944; Stewart and Wones, 1974; Wones, 1976a; Kaszuba, 1986). The Passagassawakeag terrane is interpreted to be in fault contact with rocks of the Bucksport-Flume Ridge terrane (Stewart and Wones, 1974; Kaszuba and Wones, 1985; Osberg et al., 1985; Hussey, 1985). However, detailed mapping along this contact did not reveal any structural or metamorphic discontinuity (Kaszuba, 1986). The finely laminated and calcareous siltstones and minor sulfidic pelite of the Bucksport-Flume Ridge terrane are separated from the graphitic, sulfidic, aluminous pelites, siltstones, quartzites, graywacke, metabasalt, slates, and schists of the Penobscot-Cookson terrane by a high-angle reverse fault (Stewart and Wones, 1974; Ludman, 1981a). The Turtle Head fault zone separates the Ellsworth-coastal volcanic terrane from the Penobscot-Cookson terrane (Stewart and Wones, 1974). The Ellsworth-coastal volcanic terrane consists of polydeformed low-grade greenstones and quartzo-feldspathic chlorite schists which are unconformably overlain by a series of bimodal suites of basalts and rhyolites, agglomerates, pyroclastics, breccias, and flow-banded auto-brecciated domes, interbedded with minor calcareous siltstones, limestones, shales, and conglomerates (Gilman, 1961; McGregor, 1964; Wingard, 1961; Stewart and Wones, 1974; Gates and Moench, 1981; Pinette, 1983). Previous interpretations of the Norumbega fault zone and Turtle Head fault zone as terrane boundaries are supported by seismic reflection and refraction studies which suggest that these fault zones are steeply dipping to near-vertical tectonic boundaries. They separate distinct crustal packages that consist of approximately 12 km of Lower Paleozoic cover rocks that overlie Precambrian gneissic basement (Stewart et al., 1986; Unger et al., 1986).

Timing of Terrane Accretion in Coastal Maine

The exact timing of terrane accretion in eastern Maine remains unresolved. In the Penobscot Bay area, faults juxtaposing the Bucksport-Flume Ridge terrane, Penobscot-Cookson terrane and the Ellsworth-coastal volcanic terrane are intruded by the Lucerne pluton (Wones, 1980a) which has a $^{207/206}$Pb age of 380±4 Ma (Zartman and Gallego, 1979) and a Rb-Sr whole rock age of 371±21 Ma (Loiselle et al., 1983), establishing a minimum age for docking of terranes in the coastal region. In extreme southeastern Maine these terranes have been shown to share sedimentological as well as deformational histories since the Early Devonian, and radiometric ages on plutons intruding terrane boundaries suggest that these terranes acted as a structural entity since this time (Ludman, 1981a, 1986). Isolated occurrences of conglomeratic units basal to the Siluro-Devonian volcanic sequence along the southeastern Maine coast may be correlative based on stratigraphic position and lithologic similarities (Gates, 1969). These basal conglomerates unconformably overlie units of both the Penobscot-Cookson terrane and the Ellsworth-coastal volcanic terrane. If they prove to be correlative, it would require juxtaposition of these terranes in coastal Maine by the latest Silurian.

Juxtaposition of these terranes with the proposed crustal block of central Maine has been suggested to occur by movement along the Norumbega fault zone during the early Carboniferous after emplacement of the plutons (Zen, 1983; Ayuso, 1986). However, overlapping Silurian and Devonian cover sequences suggest that collectively these terranes, from the Ellsworth-coastal volcanic belt through central Maine, interacted and accreted to form a complex composite block during Cambro-Ordovician time that was sutured to cratonic North America prior to the Silurian (Ludman, 1986). Limited post-Acadian offset of plutons and cover rocks along major southwest-northeast-trending fault zones, such as the Norumbega fault zone, resulted from

reactivation of the earlier sutures which join distinct basement terranes and would not necessitate large-scale lateral transport along these faults during the Siluro-Devonian or later (Ludman, 1981a, 1986).

TYPE I PLUTONS

Type I plutons of the coastal Maine magmatic province consist of stratiform mafic plutons that crystallized, uninterrupted by the intrusion of felsic magmas, to produce layered intrusions comparable to the Skaergaard pluton (Wager and Brown, 1968). The Pocomoonshine (Westerman, 1972) and Pleasant Bay (Bickford, 1963) plutons (Fig. 1) have been chosen to represent the type examples for this category of plutons (Table 3).

Contact Relationships

The Pocomoonshine pluton intrudes both the Bucksport-Flume Ridge and the Penobscot-Cookson terranes. Contacts with the country rock are sharp and discordant, crosscutting the regional fabric and truncating tight, upright, isoclinal folds (Westerman, 1972; Ludman, 1981b). The intrusion is elongated in a N30°E direction and is discordant to the regional trend. A 2.4 to 3.2 km wide metamorphic aureole overprints chlorite-grade, lower greenschist regional metamorphism with a low pressure-high temperature contact facies assemblage (Westerman, 1972; Ludman, 1981b; Ludman et al., this volume). Local zones of partially melted country rock are present adjacent to the intrusion, and similar observations have been reported for other mafic intrusions within the coastal Maine magmatic province (Gilman, 1961; Westerman, 1972; Ludman, 1981b). Igneous layering is disrupted by high-angle dip-slip and strike-slip faulting with locally developed weak to strong foliation, brittle fracturing, and mylonites (Westerman, 1972; Ludman, 1981b). The Pocomoonshine pluton has been intruded by small felsic stocks which crosscut igneous layering and enclose xenoliths of the Pocomoonshine pluton. The pluton may have intruded by forceful injection with minor assimilation (Westerman, 1972). The presence of abundant xenoliths associated with roof pendants (Westerman, 1972) suggests that stoping may have been important. Emplacement of the pluton is suggested to have been strongly controlled by a preexisting N30°E fault system (Ludman, 1974; Biggi and Hodge, 1982).

The Pleasant Bay gabbro-diorite pluton is emplaced entirely within the Ellsworth-coastal volcanic terrane. Igneous laminations and layering in the Pleasant Bay gabbro-diorite pluton demonstrate that the pluton is a trough-shaped intrusion (Ward, 1972) which is discordant to the regional folding, rather than a folded sill as suggested by Bickford (1963). Magmatic layering and lithologic units within the Pleasant Bay pluton have also been truncated and disrupted by post-emplacement faulting (Terzaghi, 1946; Bickford, 1963).

Subsurface Distribution

The subsurface distribution of rock types related to the Pocomoonshine gabbro-diorite pluton is inferred from gravity data (Biggi and Hodge, 1982) and changes in the width of the contact aureole (Westerman, 1972). The pluton is believed to be a 1.5 km thick, sheet-like sill, that dips approximately 45° to the west, although the eastern contact has been modified by post-emplacement faulting and is now nearly vertical (Westerman, 1972; Ludman, 1981b). A pronounced positive Bouger anomaly over the northern portion of the complex supports Westerman's (1972) suggestion for accumulation of denser mafic minerals along the floor of the intrusion. Gravity data indicate a maximum thickness of 4.0 km for the Pleasant Bay pluton (Biggi and Hodge, 1982).

Textural Variation

Characteristic features of stratiform mafic intrusions such as igneous lamination, rhythmic layering, cryptic layering, and phase layering are displayed by one or both of these plutons. In the Pleasant Bay gabbro-diorite pluton, high concentrations of olivine, hypersthene, and augite form dark bands that alternate with layers modally abundant in plagioclase, giving an appearance similar to graded bedding (Bickford, 1963). These rhythmic layers may truncate other rhythmic layers in a manner suggestive of cross-bedding.

The Pocomoonshine pluton is compositionally zoned (Westerman, 1972). Troctolites at the roof of the intrusion are replaced by progressively more felsic rock types, quartz-biotite-hornblende diorite, towards the interior of the sill, forming a reverse phase layered sequence. A sequence, symmetrical to the reverse phase layered upper portion of the chamber, is believed to have accumulated on the unexposed floor, indicating crystallization proceeded from the walls inward to the center of the pluton (Westerman, 1972). The stratiform nature of phase layering in the Pleasant Bay pluton has been disrupted by post-emplacement faulting, making correlation with stratigraphic position difficult (Bickford, 1963). A proposed section based on field and petrographic observations places cumulate mafic rocks at the base, grading progressively upwards into extremely differentiated quartz-bearing, fayalitic, leuco-gabbronorites (Bickford, 1963).

Modal Analysis and Mineralogy

Modal data for the Pocomoonshine (Westerman, 1972) and Pleasant Bay plutons (Bickford, 1963) indicate that rocks in both plutons can contain both pyroxene and hornblende, in excess of 5%, as well as biotite in amounts that vary from 0 to 11% for rocks of the Pleasant Bay pluton and 0 to 20% in the Pocomoonshine pluton. Rocks have been divided into two groups on the basis of the presence or absence of olivine before being plotted in the ternary systems olivine-plagioclase-pyroxene and

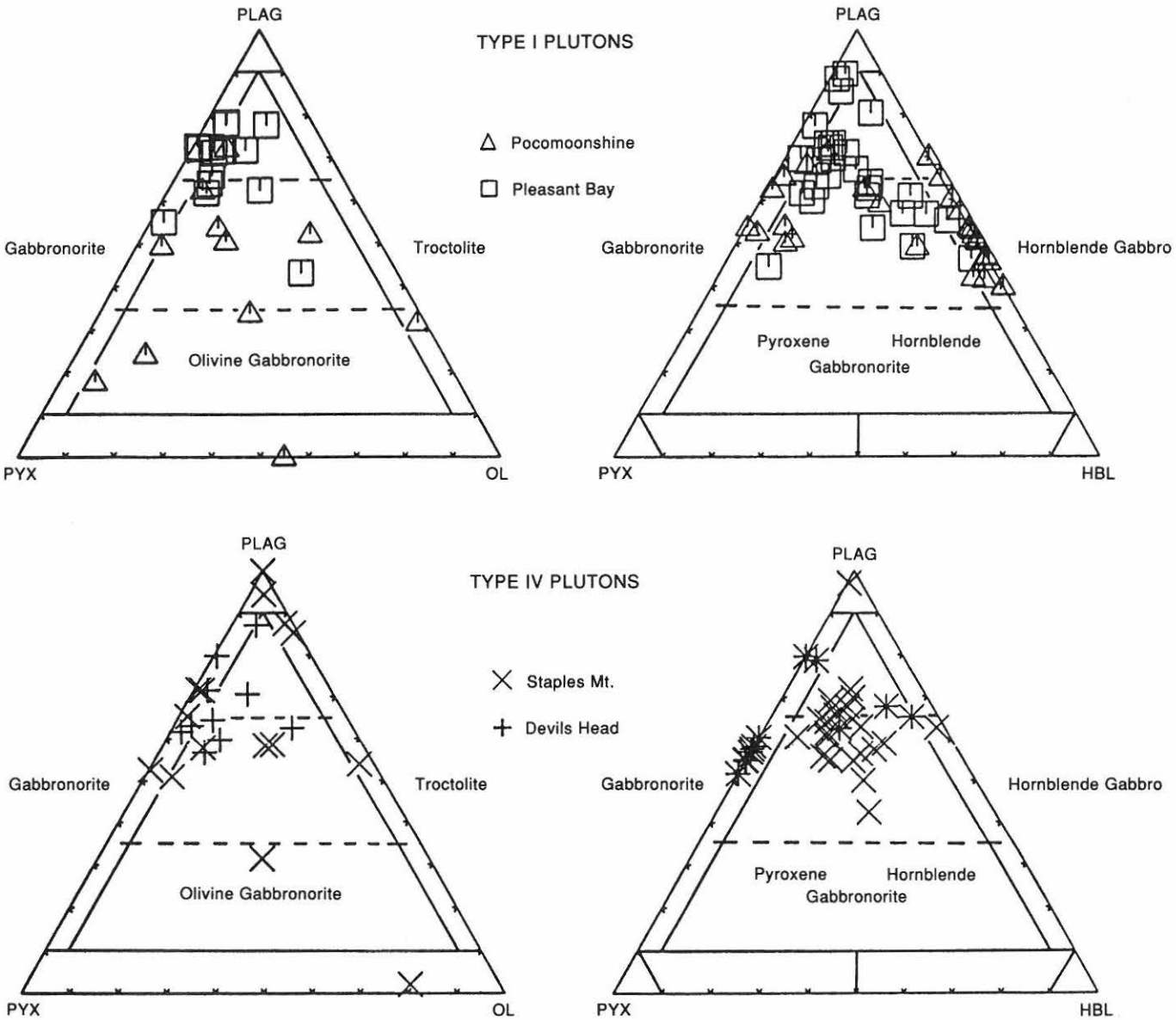

Figure 2. Modal analysis of selected mafic plutonic rocks from the coastal Maine magmatic province. Data for the type I Pocomoonshine and Pleasant Bay plutons are compiled from Westerman (1972) and Bickford (1963). Data for the type IV Staples Mountain and Devils Head mafic plutonic rocks associated with the Moosehorn Igneous Complex (Jurinski, 1987) are compiled from Coughlin (1986), Amos (1963), and Jurinski (1987). Field boundaries are those of Streckeisen (1976).

hornblende-plagioclase-pyroxene (Fig. 2) for classification purposes using the nomenclature suggested by Streckeisen (1976).

Olivine-bearing lithologies of the Pleasant Bay pluton are in general more leucocratic than rocks from the Pocomoonshine pluton. The majority of olivine-bearing lithologies from the Pocomoonshine pluton are dispersed throughout the olivine-plagioclase-pyroxene ternary diagram (Fig. 2). Rock types present in the Pocomoonshine pluton (ultramafic to leuco-olivine-gabbronorite, mela-troctolites and mela-gabbronorites) reflect accumulation of mafic minerals in contrast to the plagioclase cumulates present in the Pleasant Bay pluton.

Olivine-absent samples from the Pleasant Bay pluton display an antipathetic modal variation of plagioclase and pyroxene with hornblende (Fig. 2). Rocks range from leuco-gabbronorites and leuco-pyroxene-hornblende-gabbronorites, through the pyroxene-hornblende-gabbronorite field towards the hornblende-gabbro field and along the plagioclase-hornblende join. In contrast, olivine-absent samples from the Pocomoonshine pluton plot along or close to either the plagioclase-pyroxene join, as gabbronorite, or the plagioclase-hornblende join as hornblende-gabbro. Relatively few samples from the Pocomoonshine pluton plot within the pyroxene-hornblende-

gabbronorite field; those that do are biased toward either the gabbronorite field or the hornblende-gabbro field. The presence of a continuous modal variation within the Pleasant Bay pluton and its absence in the Pocomoonshine pluton is a marked difference between these otherwise similar intrusions.

Rocks of the Pocomoonshine pluton become increasingly more felsic from the roof towards the core of the body (Westerman, 1972). Cumulate troctolites, which occur within 50 meters of the roof, are underlain by olivine-gabbronorite and gabbronorite with minor amounts of olivine. Underlying this zone is a layer of olivine-absent gabbronorite and pyroxene-hornblende-gabbronorite, below which is found pyroxene-hornblende-gabbronorite with minor amounts of pyroxene. The core of the pluton consists of hornblende-gabbro and hornblende-diorite. Some of the hornblende-diorites contain significant amounts of biotite (2-12%) and quartz (tr-14%). Rare, sporadic occurrences of olivine-norite and feldspathic-hornblende-biotite-peridotite are believed to represent autoliths of ultramafic layers (Westerman, 1972). The peridotites all contain numerous xenoliths. A similar stratiform sequence has been proposed for the Pleasant Bay pluton (Bickford, 1963). Mafic cumulates (olivine-gabbronorite) are believed to have formed along the floor of the intrusion and grade progressively upward to more felsic, quartz-bearing leuco-gabbronorite.

Mineral Compositional Variation

Cryptic layering is present in both plutons. Mineral compositional changes, as determined by optical methods (Bickford, 1963; Westerman, 1972), indicate overall trends of Fe and Na enrichment as crystallization proceeds in both magmas. Plagioclase in the Pocomoonshine varies from An_{95} in cumulate troctolite to An_{38} in biotite-quartz-hornblende-diorite. Plagioclase compositions vary from An_{95} to An_{85} as olivine varies from Fo_{86} to Fo_{64} with orthopyroxene exhibiting little compositional variability (En_{83}-En_{80}). A larger compositional range exists for plagioclase (An_{65}-An_{38}) and orthopyroxene (En_{73}-En_{47}) in olivine-absent rocks. Plagioclase in hornblende-gabbros that contain minor amounts of pyroxene are discontinuously zoned with cores of $An_{85\text{-}75}$ mantled by rims of $An_{55\text{-}50}$. The transition from core to rim is sharp. This compositional gap in An content is mimicked in the pluton by a bimodal distribution of plagioclase compositions in olivine-bearing samples (An_{95}-An_{85}) vs. olivine-absent samples (An_{65}-An_{38}).

Mineral compositions for rocks of the Pleasant Bay pluton are more evolved than the Pocomoonshine pluton. Olivine and pyroxene compositions (Fo_{62}; En_{52}; $Wo_{44}En_{42}Fs_{14}$) in the more mafic rocks are iron-rich and coexist with normally zoned plagioclase (An_{87core}-An_{22rim}). Pyroxene compositions become progressively more iron-rich (En_{49}; $Wo_{43}En_{37}Fs_{17}$) and plagioclase more sodic (An_{60core}-An_{25rim}) in the quartz-bearing gabbronorite. Final crystallization in the Pleasant Bay pluton is represented by extreme iron enrichment. Quartz-bearing leuco-olivine-gabbronorite contains iron-rich pyroxenes (En_{37}; $Wo_{42}En_{21}Fs_{36}$), plagioclase (An_{65core}-An_{15rim}), and the appearance of fayalitic olivine ($Fo_{8.6}$) in contrast to the crystallization sequence observed in the Pocomoonshine pluton. Early crystallization of anhydrous phases progressively enriches the H_2O content in the magmas of the Pocomoonshine and Pleasant Bay plutons as expressed by the appearance of magmatic hornblende and finally magmatic biotite during the later stages of crystallization (Westerman, 1972).

Chemistry

The Pocomoonshine pluton has a mean SiO_2 content of 46±3.2 wt% with a range from 38.3 to 54.1 wt% (Fig. 3). The mean value of Fm, (FeO*/FeO*+MgO wt%, where FeO* = FeO + .89 Fe_2O_3) is 48 and TiO_2 ranges from 0.1 to 2.6 wt%. Available analyses from the Pleasant Bay pluton are characterized by a mean SiO_2 content of 52.8±3.4 wt%, Fm of 64, and TiO_2 of 1.2-2.1 wt%, suggesting that these rocks formed from a slightly more fractionated magma than the Pocomoonshine pluton. Three analyses from the Pocomoonshine pluton exhibit a range in Ba of 52-200 ppm, in Sr of 176-402 ppm, and Rb of 23-44 ppm (Fig. 4).

TYPE II PLUTONS

Type II granitic plutons are those in which mafic enclaves, bimodal dikes, syn-plutonic mafic dikes, or other field observations suggestive of mixing or commingling of mafic and felsic magmas have not been recognized. They are considered on the basis of field observations to have crystallized without interaction with mafic magma(s). Significant differences in textures, modal mineralogy, major element chemistry, trace element chemistry, abundance of aplites and pegmatites, as well as the volume of intrusion allow the broad category of type II plutons to be provisionally subdivided into two suites. The first suite, type IIa, is high silica (74.6±1.1 wt%), peraluminous, medium to coarse grained, seriate to subporphyritic, subcircular granitic stocks (Table 3). In contrast, type IIb plutons have a lower average silica content (71.9±2.0 wt%), are metaluminous, coarse grained with megacrystic alkali-feldspar phenocrysts, seriate to porphyritic, elongated granitoid batholiths. Recognition of granitic suites, such as type IIa and IIb, in the coastal Maine magmatic province may yield important information on the nature and distribution of the source regions for these magmas and therefore aid in constraining the tectono-thermal evolution of the crust beneath the coastal Maine magmatic province during the Paleozoic.

Type IIa

This group is well represented throughout the coastal Maine magmatic province and includes plutons such as the Spruce Mt.,

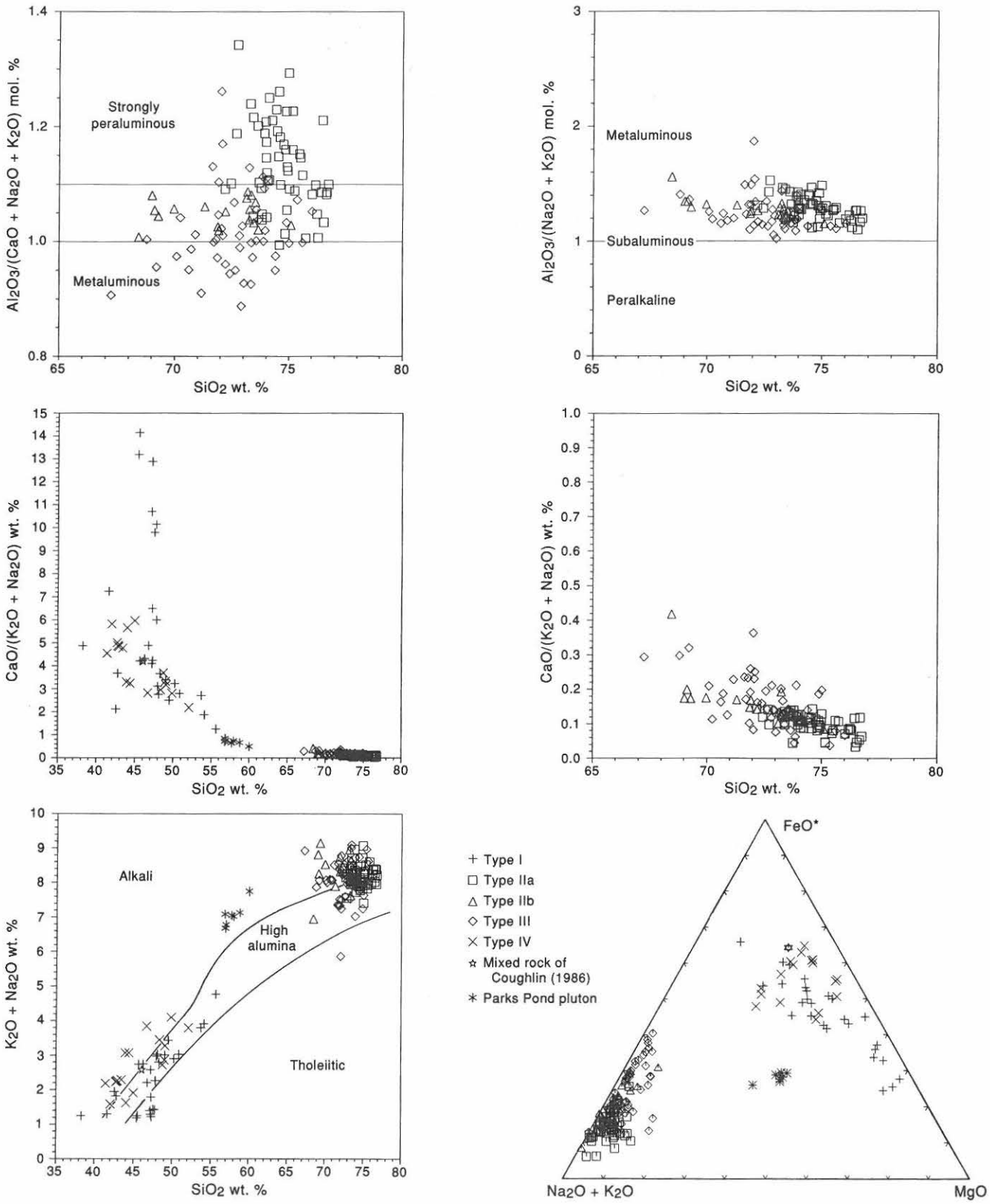

Figure 3. Comparative major element chemistry of pluton types of the coastal Maine magmatic province. Data compiled from Carl et al. (1984), Carl (pers. commun., 1985), Coughlin (1986), Eriksson (pers. commun., 1986), Stewart (1956), Westerman (pers. commun., 1985), Wones (unpubl. data), and Hogan and Sinha (unpubl. data).

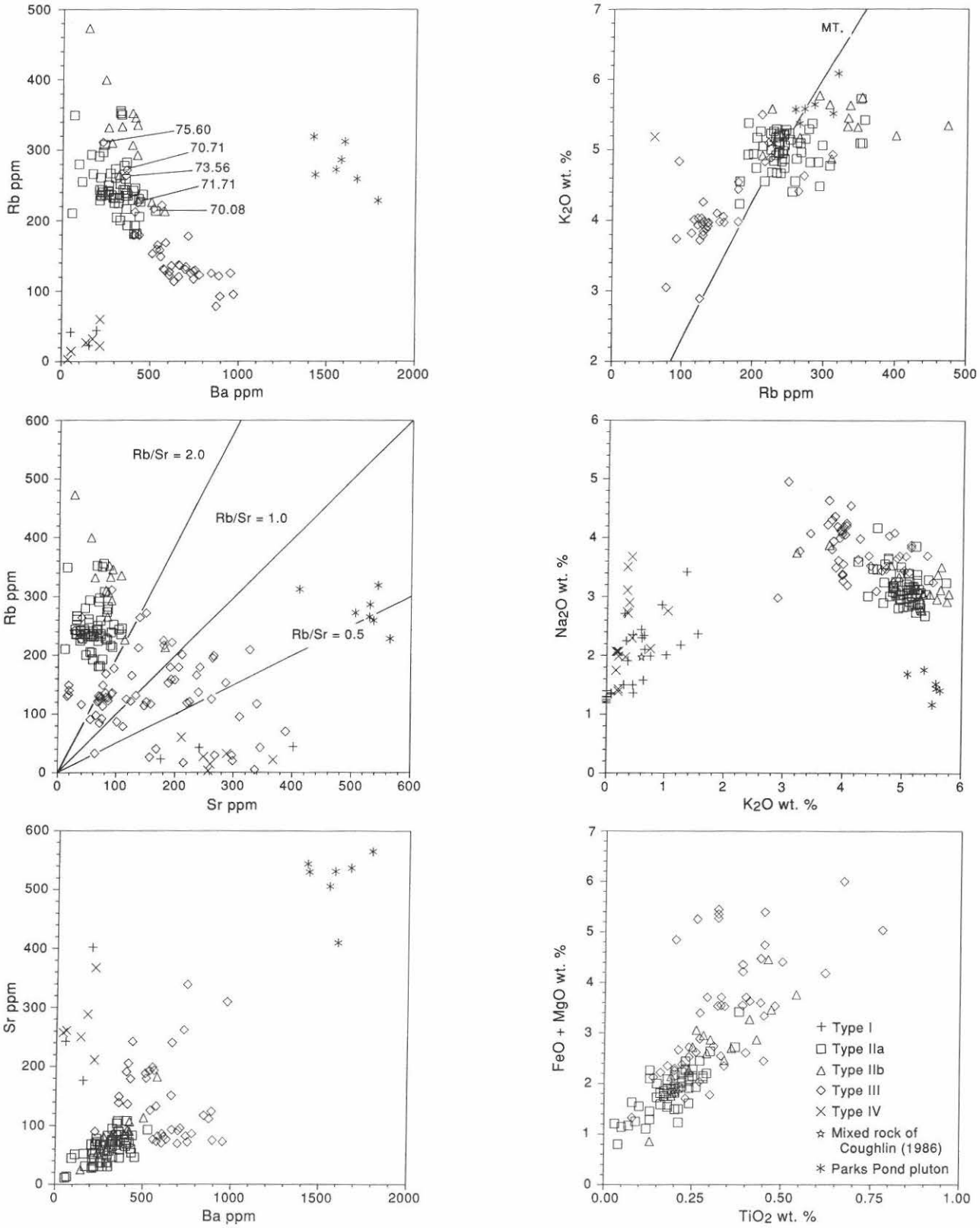

Figure 4. Comparative chemistry of selected trace elements and major elements for pluton types of the coastal Maine magmatic province. MT is the Main Trend of Shaw (1968). Values of SiO_2 for the Mount Waldo pluton are given in the Rb vs. Ba plot. Sources of data are the same as in Figure 3 except for additional Rb/Sr data from Spooner and Fairbairn (1970), Brookins and Spooner (1970), and Metzger et al. (1982).

Indian Lake, and Marshfield granites (Fig. 1). Typically, these plutons are small intrusions and range in size from less than a square kilometer to several tens of square kilometers. They may occur as isolated plutons (e.g. Long Island granite) or can form part of an igneous complex (e.g. Somesville pluton). The Wallamatogus and Blue Hill plutons are the representative examples of type IIa plutons (Table 3).

Contact Relationships. Contacts with country rocks are generally discordant, irregular, sharp, and truncate earlier folds and associated fabrics. Dikes emanating from the granites intrude the hornfelsed country rock, and commonly exploit joints and fractures associated with emplacement. The majority of plutons exhibit some form of alignment of platy minerals in a flow foliation. Fabrics related to deformation are localized to areas disrupted by post-emplacement faulting. Prominent faults cut and/or truncate contacts of the Wallamatogus pluton and many type IIa plutons experience some degree of post-emplacement deformation related to faulting.

Enclaves within these plutons can usually be related to the country rocks which they intrude. These xenoliths are generally larger, angular, and more abundant near the contacts and become progressively smaller and rounded towards the center of the intrusion. They occur within several meters of the contact, as in the Wallamatogus pluton, or more or less evenly distributed throughout, as in the Blue Hill pluton. Large, rotated, angular blocks of country rock near the margins of the Blue Hill, Wallamatogus, Sedgwick, and other plutons suggest that stoping was an important emplacement mechanism for intrusion of these plutons.

Contact aureoles 1-2 km wide , characterized by andalusite-cordierite + sillimanite assemblages, overprint the regional lower greenschist metamorphic assemblage (Wingard, 1961; Wones, 1976a). However, portions of contact aureoles may be complex, as in the case of the Wallamatogus pluton where part of the contact aureole is characterized by a wide zone of metasomatized hornfels, that in places is net-veined and plastically deformed. The aureole has been intruded by several generations of aplite, pegmatite and fine grained granitic dikes that often persist for several hundreds of meters from the contact of the main body of the pluton.

Subsurface Distribution. Gravity modeling over the Wallamatogus and Blue Hill pluton characterizes these intrusions as thin (~2 km) tabular sheets with gentle outward-dipping contacts (Sweeney, 1976). The Waldoboro pluton, a possible type II intrusion southwest of Penobscot Bay, is also modeled as a thin, 1.6 km or less, gently dipping sill (Hodge et al., 1982). This style of emplacement may be characteristic of some type IIa intrusions, but gravity and seismic data indicate steep to nearly vertical contacts and ~ 6.0 to 7.0 km thickness for the Sedgwick pluton (Stewart et al., 1986), demonstrating that more than one style of emplacement has been adopted by type IIa plutons.

Textural Variation. It is likely that the majority of type IIa plutons are texturally inhomogeneous as detailed mapping generally reveals that they can be subdivided into distinct facies based on textural and mineralogical changes. Several plutons exhibit narrow, discontinuous, and texturally variable border phases that are generally finer grained and may have formed as the result of quenching during intrusion (Chapman, 1968; Karner, 1968). However, the reverse is also true as in the Wallamatogus pluton where the marginal facies is generally coarse grained and in places characterized by megacrystic alkali-feldspar phenocrysts which decrease in abundance towards the center of the pluton (Hogan, in prep.). The granite progressively grades through a seriate and then porphyritic zone to a fine grained approximately equigranular interior. Intrusive contacts between these facies have not been observed. The Somesville pluton shows similar textural variation from a coarse grained facies through a subporphyritic facies to a generally finer grained equigranular core (Chapman, 1974).

In contrast, textural facies in the Blue Hill pluton have sharp intrusive internal contacts as well as gradational boundaries. At least seven textural varieties exist, which range in size from several square kilometers to discontinuous zones and pods at the outcrop scale. Unlike the approximate concentric zonation of the Wallamatogus pluton, they are asymmetrically distributed. Grain size and color variations are also present in the neighboring Sedgwick pluton and have been reported for the Long Island pluton (Wingard, 1961) as well as the Indian Lake pluton (Westerman, 1972), although the areal extent and distribution of these facies is unknown.

The abundance of aplite and pegmatite dikes varies in type IIa plutons. Dikes as well as irregular pegmatitic pods are common in the Blue Hill pluton. In this and the Sedgwick pluton, aplite and pegmatite dikes appear to be asymmetrically distributed and are more common along the southeastern margins. In contrast with its contact zone, aplite or pegmatite dikes are uncommon within the interior of the Wallamatogus pluton. Miarolitic cavities have also been observed in several of these plutons, and together with the abundance of aplites and pegmatites, they indicate that these plutons crystallized from magmas that were near vapor saturation for a portion of their crystallization history.

Modal Analysis and Mineralogy. The peraluminous nature of type IIa plutons is reflected in their minor and accessory mineralogy by the presence of aluminous biotite, ± muscovite, ± garnet, and ± tourmaline. Type IIa plutons which contain biotite as the dominant accessory phase, such as the Somesville, Sedgwick, and Blue Hill plutons, are compositionally restricted and plot in the center of the granite field (Fig. 5). The color index of these plutons is generally less than 10%, and the absence of a systematic variation with quartz, alkali-feldspar, or plagioclase emphasizes the mineralogically homogeneous nature of the plutons. Muscovite and biotite alternate as the dominant accessory mineral in various portions of the Wallamatogus pluton. Modally, the Wallamatogus pluton plots within the granite field, overlapping the biotite dominated type IIa intrusions, but with a considerably larger scatter. The noticeable decrease in color index with increasing plagioclase content in the Wallamatogus

pluton is in direct contrast to typical trends for granites and suggests the presence of feldspar cumulates. Primary muscovite and garnet have been observed in the Sedgwick and Blue Hill plutons as minor accessory phases, whereas they can be relatively common in portions of the Wallamatogus pluton. Tourmaline occurs in variable amounts as both a primary magmatic phase and with quartz as a late stage fracture filling.

Chemistry. Following the classification of Shand (1955), type IIa plutons are, in general, peraluminous to strongly peraluminous with a mean value of 1.1±0.1 for ANCK = (Al_2O_3/(CaO+Na_2O+K_2O) mol%) with a range from 1.0 to 1.3 (Fig. 3). Type IIa plutons form a well defined field in terms of their alkali content with a Na_2O/K_2O ratio slightly less than one. The low $CaO/(K_2O+Na_2O)$ ratios of type IIa plutons reflect the relatively low CaO contents of these plutons (CaO ~ 0.8±0.2 wt%). Type IIa plutons are characterized by a mean SiO_2 value of 74.7±1.1 wt% and range from 72.2 to 76.7 wt%. A positive correlation between FeO*+MgO against TiO_2 is displayed by type IIa plutons. Type IIa plutons, in general, form a well defined field at lower values of FeO*+MgO (1.9±0.4 wt%) with a narrow range in TiO_2 (0.2±0.1 wt%).

Type IIa plutons have Rb/Sr ratios > 2.0 with a range in Rb of 181 ppm to 356 ppm and a mean Sr content of 61±23 ppm (Fig. 4). K/Rb ratios of type IIa plot along the main fractionation trend for granitic magmas as discussed by Shaw (1968). They have a mean Rb content of 248±40 ppm and a mean K_2O content of 5.0±0.3 wt%. Type IIa plutons show a limited range in Rb/Ba and Sr/Ba ratios forming well defined fields.

Type IIb

The large volume of magma represented by the Lucerne (~625 km^2) and Deblois (~1670 km^2) plutons (Table 1) as well as their extremely coarse grained appearance, distinctive megacrystic alkali-feldspar phenocrysts, paucity of aplites and pegmatites, and metaluminous composition distinguishes these plutons from type IIa. A complete description of the petrology of the Lucerne pluton is given by Wones (1980a). It represents the type example for type IIb plutons.

Contact Relationships. In contrast to the common subcircular stocks of type IIa plutons, the Lucerne and Deblois granites form large elongated batholiths that intrude several lithotectonic terranes. Several of the faults associated with the terrane boundaries do not offset the contacts of these plutons, nor can any deformation be associated with the trace of these fault zones through the plutons. However, movement associated with the Norumbega fault zone truncates and/or offsets the northern contacts of both these plutons (Loiselle and Wones, 1979a; Wones, 1980a). Although the majority of the Lucerne pluton has been reported as being massive, ductile deformation zones within the granite produce mylonitic fabrics that parallel the intrusive western contact (Wones, 1980a).

Contacts of the Lucerne pluton with the country rock are sharp and, in general, the granite retains its megacrystic texture up to the contact, although in some instances a slight reduction in phenocryst size within 2-3 cm of the contact has been observed. A similar chill zone, less than a meter wide, has been

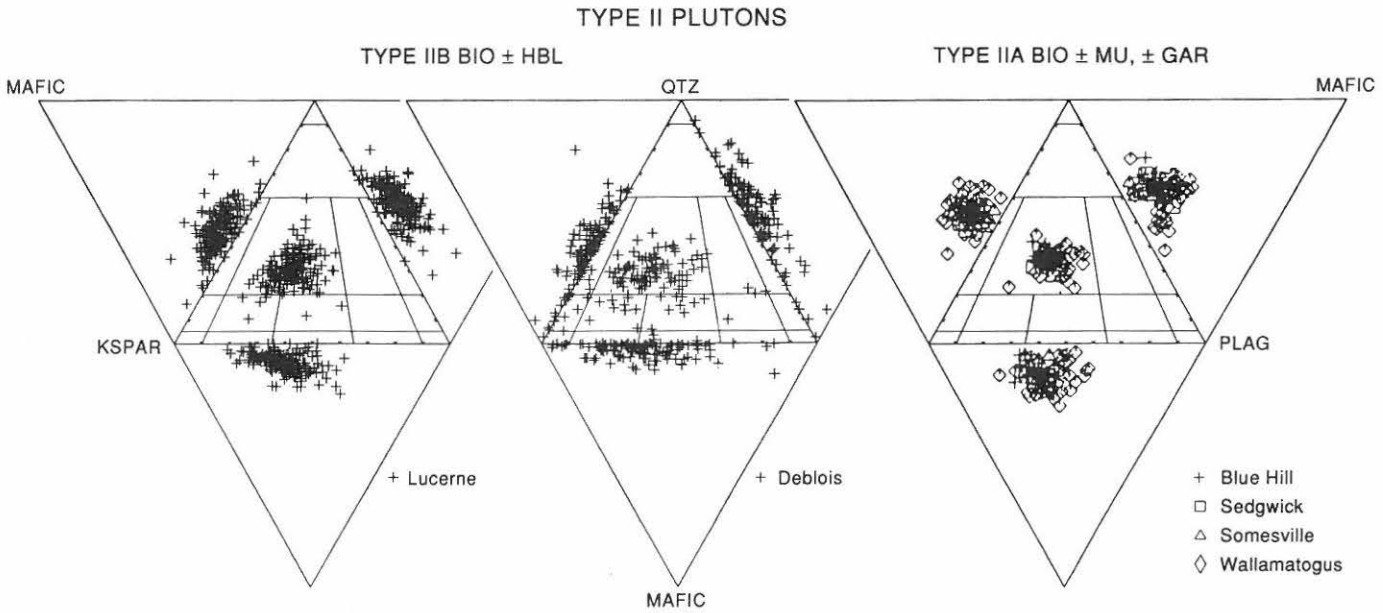

Figure 5. Modal analysis of selected type II plutons from the coastal Maine magmatic province. Data compiled from Wones (1980a), Wones (unpubl. data), Carl et al. (1984), Carl (pers. commun., 1986), and Hogan and Sinha (unpubl. data). Field boundaries are from Streckeisen (1976).

reported for the Deblois pluton (Gilman, 1961). Xenoliths of country rock occur within a few meters of the contact of the Lucerne pluton (Wones, 1980a), but enclaves commonly occur in swarms in the interior of the pluton. Roof pendants are present in both the Lucerne and Deblois plutons (Wones, 1980a; Loiselle and Wones, 1979a). Dikes of the Lucerne granite emanating from the pluton are rare and, when present, generally occur within several tens of meters of the contact.

Metamorphic effects of the Lucerne pluton persist for up to 1.0 km from the contact and overprint the lower greenschist facies assemblages (Novak, 1979). Calcareous country rocks near the contact contain tremolite-diopside-zoisite±wollastonite assemblages, and pelitic rocks are characterised by andalusite and corundum (Novak, 1979).

Subsurface Distribution. Gravity modeling of the subsurface distribution of these plutons indicates inwardly dipping contacts for the Deblois pluton, and straight, steep contacts for the Lucerne granite (Hodge et al., 1982). Apparently, upon reaching higher levels in the crust, the Deblois pluton spread out laterally, while the presence of a system of steeply dipping N30°E faults strongly influenced the shape of the Lucerne magma chamber. The Lead Mountain facies of the Deblois pluton is estimated to be a maximum of 12.5 km thick while the average thickness of the Lucerne granite is ~6.5 km, with zones thicker than 7.0 km showing a strong linear trend parallel to N30°E (Hodge et al., 1982). These two plutons together represent the most substantial contribution of felsic magma to the upper crust in the coastal Maine magmatic province.

Textural Variation. The bulk of the Lucerne pluton is a texturally homogeneous, coarse grained, seriate granite (Wones, 1980a). A central medium grained porphyritic core facies with 1-3 cm wide miarolitic cavities represents approximately 10% of the intrusion (Loiselle and Ayuso, 1980). This porphyritic variety has been observed in one place adjacent to the margin and exhibits gradational contacts with the seriate facies (Wones, 1980a).

Textural variations are present in the Deblois pluton, but little information is available about their extent and distribution. The Deblois pluton, previously considered as two separate intrusions -- the Lead Mountain granite to the west and Cranberry Lakes granite to the east -- may be a single coherent intrusion (Wones, 1984; Loiselle and Wones, 1979a). The Lead Mountain facies is generally coarser grained and shows less textural variability than the Cranberry Lakes facies which can vary from medium to coarse grained and porphyritic to equigranular (Gilman, 1961). Feldspars in a rapakivi relationship are more abundant in the Lead Mountain facies than in the Cranberry Lakes facies (Karner, 1962) and are similar to those in the Lucerne granite (Wones, 1980a). Aplite dikes and pegmatites are rare in both the Lucerne (Wones, 1980a) and Deblois (Gilman, 1961) plutons, indicative of the low volatile contents of these melts (Andrews et al., 1983).

Modal Analysis and Mineralogy. In general, type IIb plutons show greater variability in the relative percentages of quartz, alkali-feldspar, plagioclase, and mafic minerals than type IIa intrusions (Fig. 5). The majority of rock types in the Lucerne pluton and both facies of the Deblois pluton are granite. The dominant mafic phase in type IIb plutons is biotite with variable amounts of hornblende. This accessory mineralogy reflects the weakly peraluminous to dominantly metaluminous nature of these magmas.

In comparison to the well-studied Lucerne pluton, limited information is available for the Deblois pluton. The color index for the Deblois pluton is considerably lower than that of the Lucerne pluton and type IIa plutons. The Lead Mountain facies is characterized by the presence of hornblende, whereas the Cranberry Lakes facies is dominantly a biotite-granite (Loiselle and Wones, 1979a). Considerable scatter in the modal data for the pluton indicates the presence of alkali-feldspar-granite, alkali-feldspar-quartz-syenite, and quartz-syenite as well as the presence of quartz-monzonite, granodiorite, and quartz-monzodiorite (Fig. 5). It is not clear if this scatter is the result of cumulate processes, multiple intrusions, contamination, or reflects inherent properties of the magma.

Chemistry. Type IIb plutons have a mean ANCK of 1.05±0.02, with a range from 1.0 to 1.1 indicating they are metaluminous to weakly peraluminous (Fig. 3). They are slightly higher in K_2O for approximately the same Na_2O content (Loiselle and Ayuso, 1980) and have a higher mean CaO content (1.33±0.47 wt%) than type IIa plutons, whereas their mean SiO_2 content of 71.9±2.0 wt% and a range of 68.4 to 75.1 wt% is lower. Although the mean FeO*+MgO (2.7±0.8 wt%) and TiO_2 content (0.3±0.1 wt%) is higher than type IIa plutons, they also exhibit a positive correlation between FeO*+MgO and TiO_2 contents.

Type IIb plutons possess a larger range in Rb content (213 to 473 ppm) and slightly greater mean Sr content (87.85±36.25 ppm) than type IIa (Fig. 4). Type IIb plutons, as characterized by the Lucerne pluton, also have a higher mean Rb (322.00±68.52 ppm) and mean K_2O (5.55±0.30 wt%) content and have lower K/Rb ratios than the main K/Rb fractionation trend for granites as discussed by Shaw (1968). Rb/Ba plots distinguish between type IIa and IIb due to the Rb-enriched nature of the Lucerne pluton. However, type IIa and IIb plutons are indistinguishable from each other in a plot of Sr vs. Ba where they define a tight cluster with relatively low values of Sr and Ba in comparison with other granitoids in the coastal Maine magmatic province.

TYPE III PLUTONS

Type III granitic plutons are identified through field evidence which indicates possible involvement with a mafic magma at some time during the course of crystallization. The presence of mafic enclaves, mafic enclave swarms, crosscutting mafic dikes, the occurrence of composite dikes (dikes consisting of a mixture of mafic enclaves within a felsic matrix), or the existence of a gradational contact defined by a large compositional gradient within a short distance towards an adjacent gab-

broic pluton are the characteristics used to recognize type III plutons.

Type III plutons are represented by granite, granodiorite, alkali-feldspar granite, and quartz monzonite of diverse accessory mineralogy. Examples of hornblende-biotite, biotite, biotite-muscovite, biotite-muscovite-garnet, and alkali-feldspar dominated aegirine-augite-hornblende granitoid plutons exist. This wide variety is not really surprising as a somewhat similar diversity in accessory mineralogy is present in type IIa and IIb plutons. Type III plutons are potentially examples of type II partial melts that have been modified by interaction with a mafic magma.

Contact Relationships

In the coastal Maine magmatic province, type III plutons can occur as individual plutons, although they are more commonly represented by an assemblage of spatially and possibly temporally associated mafic and felsic magmas that have coalesced as a result of multiple intrusion. This collection of plutons will be referred to as an igneous complex, and it can consist of a variety of pluton types as defined in this paper. Igneous complexes represent an intrusive style that is a common characteristic of the coastal Maine magmatic province. Examples of these complexes include the Mount Desert Igneous Complex (Chapman, 1970, 1974), the South Penobscot Igneous Suite (Stewart et al., 1988), the Isle Au Haut Igneous Complex (Luce, 1962), as well as the Moosehorn Igneous Complex (Jurinski, 1987; Hill and Abbott, this volume).

Contacts with Gabbroic Plutons

The Baring granite, a seriate biotite-granite of the Moosehorn Igneous Complex, is in intrusive contact with the layered gabbro of the Staples Mountain pluton as well as the Calais gabbro-diorite (Jurinski, 1987). Contacts between gabbro and granite have been described as intrusive breccias with angular xenoliths of gabbro in a granitic matrix, as well as gradational, from gabbro to granite, with intervening zones of diorite and granodiorite (Amos, 1963; Coughlin, 1986; Jurinski, 1987). Within the contact zone, the modal mineralogy of the Baring granite exhibits progressive and variable changes towards granodiorite compositions while the gabbro changes progressively towards hornblende-quartz-gabbro and diorite (Coughlin, 1986).

Mafic Enclaves

Within the Baring pluton, removed from the gabbro-granite contacts, local zones with a high density of mafic enclaves are common and are similar to other type III plutons in close spatial association with gabbroic intrusions. Mafic enclaves are irregularly distributed throughout the Spruce Head pluton and in places comprise several percent of the rock mass (Chayes, 1952). An intervening contact zone of coarse grained, hornblende-diorite to granodiorite exists between the biotite-muscovite Spruce Head pluton (Fig. 1) and an adjacent hornblende-gabbro (Guidotti, 1979).

Mafic enclaves are also common in individual granitoid plutons isolated from known and mappable contacts with mafic intrusions. Mafic enclaves are a common occurrence in the Oak Point phase of the Deer Isle pluton (Stewart, 1956; Wones, 1976a). Enclaves range in size from tens of centimeters to a meter and generally have irregular cuspate margins. The mineralogy of these mafic enclaves consist of hornblende, plagioclase (An_{22-27}), biotite, quartz, sphene, apatite ± epidote, and ore and are modally very similar to mafic enclaves of the composite dikes which intrude the Oak Point granite (Stewart, 1956). Feldspars in rapakivi relationship are a common occurrence in the Oak Point granite and can also be found within the mafic enclaves, which in some cases host pods of finer-grained granite mineralogically similar to the enclosing Oak Point granite.

Mafic enclaves in the Tunk Lake pluton are usually gabbro-diorite with medium to coarse grained interiors and fine grained margins, although enclaves with no distinguishable interior are also present (Karner, 1974). Mafic enclaves tend to be concentrated towards the marginal zones of the Tunk Lake pluton (Karner, 1974), whereas in the Mount Waldo granite they occur throughout the pluton as finer grained suboval clots which are mineralogically similar to the granite, but with a higher color index (Trefethen, 1944). Alkali-feldspar has also been observed within these enclaves.

Mafic and Bimodal Dikes

Several episodes of basaltic dike emplacement (from pre-regional metamorphic to Late Triassic) have been established for part of the coastal Maine magmatic province (Wingard and Brookins, 1964). A detailed study of the relative ages of basaltic dikes on Mount Desert Island documented at least one set concurrent with intrusion of the Cadillac Mountain granite (Chapman and Wingard, 1958). Type III plutons such as the Deer Isle, Mount Waldo, Tunk Lake, Gouldsboro, Sullivan, and Cadillac Mountain plutons are commonly cut by quartz-diorite dikes and basaltic dikes as well as Mesozoic alkalic mafic dikes (Stewart, 1956; Trefethen, 1944; Karner, 1968; Chapman and Wingard, 1958).

Composite dikes, consisting of mafic enclaves in a felsic granitoid matrix, intrude layered gabbro of the Mount Desert Igneous Complex (Chapman, 1962a). Mafic enclaves within the dikes have cuspate margins and often exhibit pillow lava type structures. Typically, the mafic enclaves consist of a coarse grained interior encased in a fine grained shell. These textures may represent chill zones formed during quenching of the mafic magma (Wager and Bailey, 1953). Within the enclaves, plagioclase exhibits swallowtail or H-shaped skeletal morphologies, and alkali-feldspar xenocrysts are rimmed by

plagioclase overgrowths (Chapman, 1962a). These textures can be attributed to a magma mixing origin (Hibbard, 1981). A major element and REE study of these composite dikes suggested that commingling of mafic and felsic magmas best explained their origin (Taylor et al., 1980). Although these dikes occur within the gabbro of the Mount Desert Igneous Complex, similar composite dikes intrude the Oak Point phase of the Deer Isle pluton (Stewart, 1956).

Subsurface Distribution

Information concerning shapes and sizes of plutons and the possible presence of large bodies of mafic rocks at depth, beneath type III plutons, can be inferred from geophysical data. Seismic profiles across the Deer Isle pluton reveal steeply dipping sides and a possible floor at ~6.0 km depth (Stewart et al., 1986). Modeling of gravity data also indicated a maximum thickness of ~6.0 km, but suggested that the pluton's sides dip gently, forming a bowl-shaped intrusion (Hodge et al., 1982). Gravity measurements over the Deer Isle pluton preclude the presence of substantial mafic rocks at depth; however, both the Cadillac Mountain granite (2.5 km thick) and the Gouldsboro pluton (0.8 km thick) may be represented as thin sheets which lie structurally above a gently dipping, flat-bottomed, ~3.0 to 5.5 km thick mafic sill (Hodge et al., 1982).

Textural Variations

Type III plutons exhibit a similar range in textural variability as type II plutons. Texturally homogeneous type III plutons, such as the medium grained, hypidiomorphic-granular Sullivan pluton (Karner, 1962, 1968), are less common than the general case in which several textural varieties are recognized within a single pluton. For example, the majority of the Mount Waldo pluton is coarse grained, equigranular to seriate, but subporphyritic. Medium to fine grained varieties do occur, although their spatial distribution is not well mapped (Trefethen, 1944; Sweeney, 1972; King, 1977). Detailed mapping of the Tunk Lake pluton documented a systematic increase in the textural variability towards the core of the pluton (Karner, 1968). Coarse grained granites of the Tunk Lake pluton are hypidiomorphic-granular, seriate-porphyritic, subporphyritic, or porphyritic with gradational contacts. Fine grained and aplitic varieties, ranging in form from irregular sheet-like masses to dikes, as well as miarolitic cavities and granophyric textures are more common in the center of the intrusion (Karner, 1962, 1968).

Modal Analysis and Mineralogy

Type III plutons are characterized by a wide variety of granitoids with a diverse accessory mineralogy. Alkali-feldspar-granite and quartz-alkali-feldspar-syenite crop out in the type III Tunk Lake and Cadillac Mountain plutons (Fig. 6). Although limited modal data is available for the Cadillac Mountain granite, the distribution of various rock types in the Tunk Lake pluton is well documented (Karner, 1962, 1968). Like the type IIb Deblois pluton, the Tunk Lake granite varies in rock type from granite to alkali-feldspar-granite and quartz-alkali-feldspar-syenite. The color index for all three plutons is uniformly low.

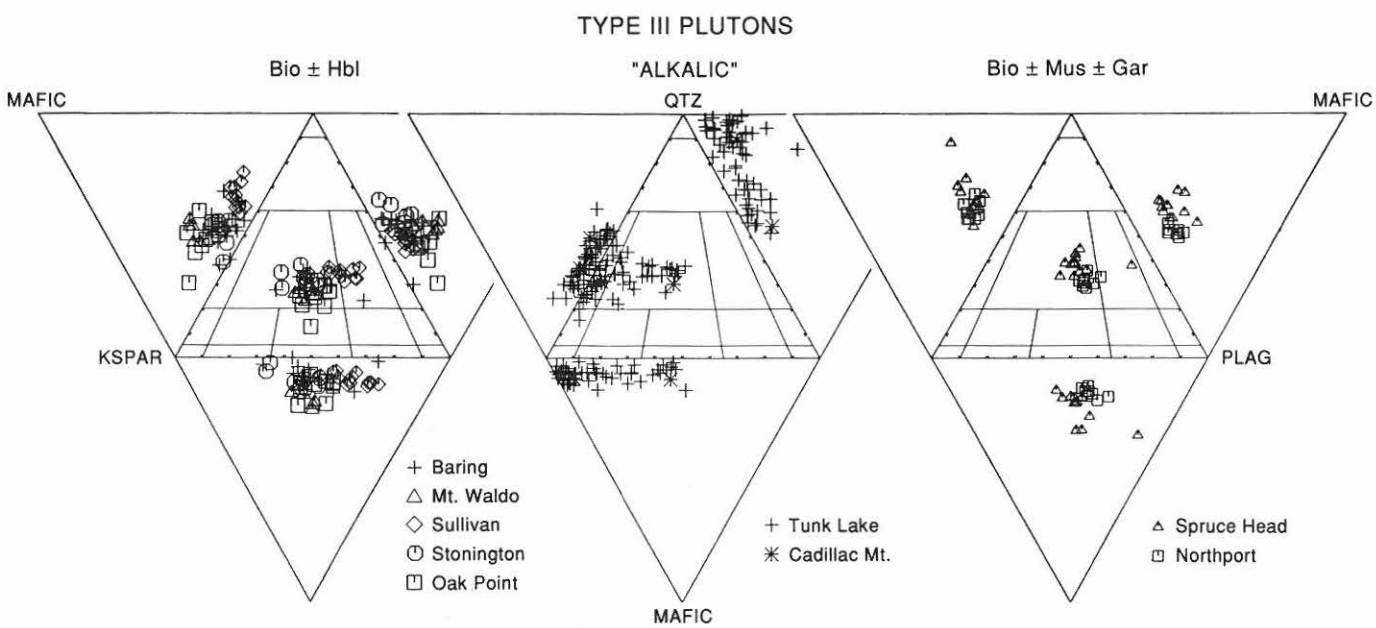

Figure 6. Modal analysis of selected type III plutons from the coastal Maine magmatic province. Data compiled from Carl et al. (1984), Carl (pers. commun., 1986), Chayes (1952), Jurinski (pers. commun., 1986), Karner (1968), Stewart (1956), and Hogan and Sinha (unpubl. data). Field boundaries from Streckeisen (1976).

The dominant mafic phase in the Cadillac Mountain pluton is hornblende; biotite is rare (Chapman, 1974).

Mineralogically distinct facies, as characterized by their mafic mineral assemblage, are concentrically arranged within the Tunk Lake pluton (Karner, 1968). The marginal assemblage consists of aegirine-augite, fayalite, and magnetite. These phases are progressively replaced inward by hornblende with minor amounts of riebeckite, then hornblende and biotite, and finally biotite alone as the dominant mafic phase. Alkali-feldspar-granite and its distinctive accessory mineralogy is restricted to within a few kilometers of the margin, whereas the bulk of the pluton is biotite-granite.

In contrast to the similarities that exist between the type III (Cadillac Mountain and Tunk Lake) and IIb (Deblois) plutons that have alkaline affinities, systematic differences do exist in the modal and accessory mineralogy between other type III plutons (Fig. 6) and their type II counterparts (Fig. 5). In general, type III plutons appear to have a higher color index than type II plutons. Type III biotite-muscovite + garnet plutons, such as the Northport and Spruce Head plutons, are more granodioritic in contrast to the biotite-muscovite + garnet type IIa plutons which plot in the granite field. Similarly, the dominantly biotite-bearing Sullivan pluton straddles the granite-granodiorite boundary in contrast with the type IIa biotite-granite of the Sedgwick pluton. Type III plutons where hornblende is present as an accessory phase in addition to biotite (e.g. the Oak Point phase of the Deer Isle pluton or the Mount Waldo granite) are modally lower in quartz and higher in plagioclase than the type IIb Lucerne pluton. Although the bulk of the Sullivan and Baring plutons is biotite-granite and the Spruce Head pluton a biotite-muscovite-granite, hornblende has been reported to occur in all three plutons (Karner, 1968; Jurinski, 1987; Chayes, 1952). The presence of hornblende in the Spruce Head pluton is spatially associated with the gradational gabbro-granite contact (Chayes, 1952) and is likely to be xenocrystic. The presence of hornblende in type IIb intrusions may reflect an intrinsic characteristic of the source region, whereas the hornblende in type III magmas may have a more complex origin and could be directly related to a mixing event or reflect an intrinsic characteristic of the source region, or both.

Chemistry

Type III plutons exhibit a greater diversity in chemistry than both suites of type II plutons (Figs. 3 and 4). Type III plutons range from approximately subaluminous, ANK=1.02, where ANK = ($Al_2O_3/(Na_2O+K_2O)$), to strongly peraluminous, ANCK=1.26. The mean SiO_2 content for type III plutons is 72.56±1.78 wt% with a large range from 67.24 to 76.02 wt%. Type III plutons have a higher mean CaO content, 1.31±0.54 wt%, and a range of 0.34-2.62 wt% with slightly lower K_2O contents for approximately the same Na_2O contents as type II plutons. The majority of high Na_2O values (>4.00 at $K_2O \sim 4.0$) for type III plutons are from the hypersolvus Cadillac Mountain granite. The Cadillac Mountain granite is an exception in that Na_2O/K_2O is greater than one (Carl et al., 1984), as is also true for one sample from the type IIb Deblois pluton. Type III plutons exhibit a large range in TiO_2 (0.08-0.78 wt%) and FeO*+MgO (1.33-6.01 wt%), with a positive correlation between FeO*+MgO and TiO_2 contents.

Type III plutons define a broad field in Rb vs. Sr plots with Rb/Sr ratios that are generally <2.0 (Fig. 4). The K/Rb ratios of type III plutons plot close to the main fractionation trend for granitic magmas (Shaw, 1968). However, they form two groups, one overlapping with type IIa plutons while the second group is characterized by higher K/Rb ratios than the main trend and lower mean Rb (139.33±64.27 ppm) and K_2O (4.23±0.60 wt%) contents. Type III plutons also form a broad field in the Sr vs Ba plots. The low Sr, high Ba analyses are from the hornblende-alkali-feldspar Cadillac Mountain granite. The other type III granites have significantly higher Sr concentrations and a large range in Ba and Sr content. Rb and Ba contents of most type III plutons form a well defined field with lower Rb and higher Ba content than type II plutons.

TYPE IV PLUTONS

Type IV plutons are mafic magma(s) that have interacted to varying degrees with felsic magma(s). They are characterized by quartz-monzodiorite, monzogabbro, monzonite, quartz-diorite, quartz-gabbro, and the mafic granitoids of the Parks Pond pluton. Type IV plutons can occur as isolated plutons as in the case of the Parks Pond pluton (Cavalero, 1965; Wones, 1976a, 1980a; Eriksson and Williams, in press), or more commonly they are associated with igneous complexes, such as the Moosehorn Igneous Complex (Jurinski, 1987; Hill and Abbott, this volume) or the South Penobscot Intrusive Suite (Stewart et al., 1988), as intervening zones of texturally variable hybrid rocks at the contact of gabbroic and granitoid rocks.

Contact Relationships

The Moosehorn Igneous Complex is comprised of an intimate association of plutons ranging from gabbro to granite near Calais, Maine (Amos, 1963; Jurinski, 1987) and may extend southwest to include granite plutons and gabbroic rocks associated with the Gardner Lake gabbro-diorite of Gilman (1961) and Westerman (1980). Isolated, discrete, irregularly shaped areas of layered and massive gabbronorite which crop out throughout the central portion of the Moosehorn Igneous Complex are similar to rock types cropping out at Staples Mountain (Amos, 1963). Complex contact relationships have been observed between isolated layered mafic gabbro and felsic rocks in the central portion of the Moosehorn Igneous Complex (Jurinski, 1987; Hill and Abbott, this volume). Mafic rocks in this zone are surrounded by progressively more felsic rock types. Contact relationships exhibit a regular gradation from gabbronorite through microcline-hornblende-gabbro to hornblende-

diorite and granodiorite (Amos, 1963). Hybrid rocks range from brecciated gabbro to gabbroic enclaves and diabase pillows in a dioritic-granodioritic matrix to granodiorite with sporadic enclaves of gabbro and can occur either as a border phase on the granodiorite or as isolated patches in the gabbro (Hill and Abbott, this volume). Bimodal composite dikes of diabase pillows in a granodioritic matrix crosscut the gabbroic rocks (Hill and Abbott, this volume). A similar relationship occurs in the South Penobscot Intrusive Suite where granitic magma of the central core comes in contact with the mafic rocks of the border zone, resulting in the development of hybrid intermediate rocks with numerous mafic enclaves (Stewart et al., 1988). In general, for the South Penobscot Intrusive Suite the transition from mafic gabbroic rocks at the margin to granitic rocks in the core is gradational (Stewart et al., 1988). The occurrence of several intermediate rock types associated with contact breccias in the igneous complexes has been attributed to both reaction of gabbroic rocks with the infiltrating Baring granite (Coughlin, 1986; Jurinski, 1987) or to magma mixing (Stewart et al., 1988; Hill and Abbott, this volume).

The Parks Pond pluton, an example of an isolated type IV pluton, is intruded by the Lucerne granite and itself intrudes the Bucksport Formation (Cavalero, 1965; Wones, 1976a, 1980a; Eriksson and Willaims, in press). Along the contact of the Parks Pond pluton, the Bucksport Formation has been partially melted (Russell and Wones, 1984; Russell, 1984). The northern contact of the pluton is truncated by the Norumbega fault zone (Wones, 1976a), and mylonite and fracture zones related to the Norumbega fault zone occur throughout the pluton (Eriksson and Wones, 1983). The pluton is fine to medium grained equigranular and is characterized by abundant mafic enclaves with features typical of magma mingling (Eriksson, 1985).

Subsurface Distribution

At least two different styles of intrusion for igneous complexes are suggested by geophysical modeling. Modeling of gravity data for the Gardner Lake gabbro-diorite suggests a limited thickness of gabbro (0.5 - 1.0 km) underlain by an extensive thickness (5.0 - 6.5 km) of coalescing granitic stocks (Biggi and Hodge, 1982). Modeling of gravity, magnetic, and seismic data over the South Penobscot Intrusive Suite as summarized in Stewart et al. (1988) suggests that this pluton has a steep-walled hopper shape, with mafic rocks of the border zone extending deeply below the northern and southwestern portions of the central granitic core.

Textural Variation

The mafic rocks at Staples Mountain reveal a well layered, differentiated sequence that crystallized from olivine-gabbronorite at the margins inward to a pyroxene-hornblende-gabbronorite in a manner similar to the type I Pocomoonshine pluton (Coughlin, 1986). Igneous layering consists of both phase layering and rhythmically alternating noritic and anorthositic layers (Amos, 1963; Coughlin, 1986). Other features commonly associated with stratiform mafic bodies, such as igneous lamination, cross-bedding and graded bedding have been reported, as well as a high density of cumulate olivine lenses (Coughlin, 1986). Similar layered gabbroic rocks crop out on the margin of the South Penobscot Intrusive Suite (Stewart et al., 1988). Remnants of layered gabbro associated with these igneous complexes are remarkably similar to the type I plutons.

Textures such as chill margins in mafic rocks along the contact with granite, irregular cuspate margins of felsic dikes intruding mafic rocks, and the incorporation of phenocrysts from felsic rocks into subrounded amorphous mafic enclaves suggest that two magmas of distinct composition were present at the same time. Mineral textures in the hornblende-diorite, such as embayed calcic plagioclase phenocrysts rimmed by alkali-feldspar and hornblende overgrowths on ragged remnants of clinopyroxene, (Amos, 1963) suggest that extensive interaction between granitic and gabbroic rocks may have occurred to produce this hybrid rock.

Modal Analysis and Mineralogy

Available modal data for the northern extent of the Moosehorn Igneous Complex (Amos, 1963; Abbott, 1977, 1978; Coughlin, 1986; Jurinski, 1987) reveals the compositionally expanded nature of these complexes (Fig. 7). High concentrations of samples occur within the gabbro/diorite/anorthosite field at the plagioclase apex, as well as within the granite field. Samples are scattered throughout the intermediate rock types, the quartz-bearing gabbro-diorite and monzo-gabbro-diorite, with some occurrences in the granite-granodiorite, tonalite, and quartz-monzonite fields. A similar modal distribution of rock types has been documented for the South Penobscot Intrusive Suite (Stewart et al., 1988). Type IV plutonic rocks occurring within igneous complexes are represented by these intermediate hybrid rock types.

Modal analysis of the Parks Pond pluton reveals the complex, heterogeneous nature of the body. It consists of granite, quartz-syenite, and quartz-monzonite, but has a color index that ranges from 35-66% with a large variability in the modes of mafic phenocrysts such as biotite (7-41%) and clinopyroxene (9-24%) (Eriksson and Wones, 1983).

Mineral Compositional Variation

Mineral analyses from the Staples Mountain pluton (Coughlin, 1981, 1986) exhibit a limited range of chemical variation. Olivine is iron-enriched (Fo_{55-53}) and plagioclase is normally zoned with the most calcic phenocrysts occurring in the cumulate layers (An_{70}-An_{53}) and the more sodic compositions (An_{56-53}) found in the rythmically layered norite and anorthosite in the core of the intrusion. Orthopyroxene ($En_{63.9}Fs_{34.0}Wo_{2.1}$-$En_{59.5}Fs_{38.4}Wo_{2.1}$) and clinopyroxene ($En_{42.1}Fs_{16.1}Wo_{41.8}$-

$En_{40.5}Fs_{15.4}Wo_{43.9}$) show a limited compositional range from the more mafic margin to the felsic core. Modally and mineralogically, the Staples Mountain pluton is similar to type I plutons.

In the Parks Pond pluton, orthopyroxene, clinopyroxene, and biotite crystallized early followed by plagioclase, alkali-feldspar, and quartz (Eriksson and Wones, 1983). Magnetite contains up to 7.5 wt.% Cr_2O_3 and a high temperature of intrusion (~900°C) has been calculated from the TiO_2 content of biotite (3.4-5.0 wt.%) and compositions of coexisting ortho- and clinopyroxene (Eriksson, 1985).

Chemistry

Limited chemical data is available for mafic and intermediate rock types from the Moosehorn Igneous Complex. Analyses from gabbroic rocks have a SiO_2 range of 41.04 to 52.08 wt% and a TiO_2 range of 1.02 to 4.81 wt% with a mean Fm ratio of 63.5 (Fig. 3). Analyses from the gradational contacts between the layered gabbro and granite, where hybridization of type I and II magmas is evident, are lacking. One analysis is available from the contact between the Baring granite and Staples Mountain pluton (Coughlin, 1986), and it has been plotted for comparison (Figs. 3 and 4). Limited analyses of type I and IV gabbroic plutons define a field that overlaps with the low Rb, high Sr side of type III intrusions (Fig. 4).

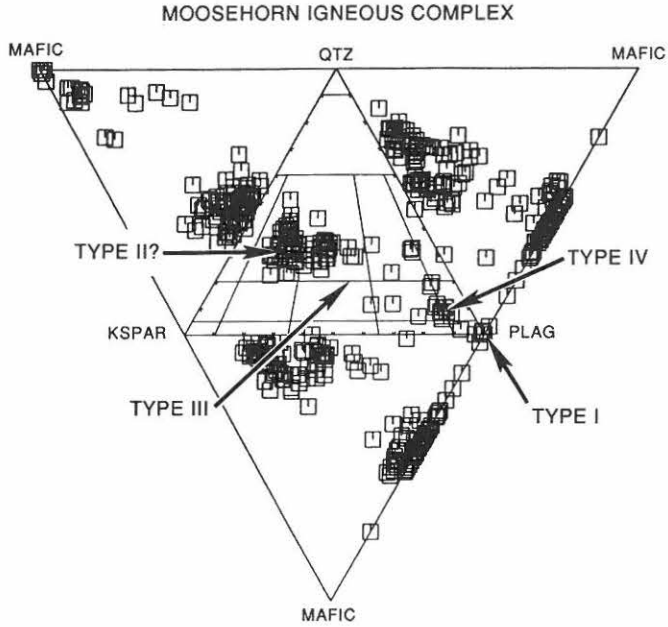

Figure 7. Modal analysis of mafic and felsic plutonic rocks associated with the Moosehorn Igneous Complex. Data compiled from Amos (1963), Abbott (1978), Coughlin (1986), and Jurinski (pers. commun., 1986). Field boundaries are those of Streckeisen (1976). Fields of rock types within the complex are similar to pluton types present in the coastal Maine magmatic province as a whole, suggesting that the processes operating in the igneous complexes may be equivalent to those which produced similar compositional variability within the coastal Maine magmatic province.

Data on mineral compositional variation within intermediate hybrid type IV plutonic rocks are scarce. Plagioclase phenocrysts exhibit a large compositional range (An_{50-28}) with calcic cores and oscillatory zoned rims (Amos, 1963). The marginal portions of plagioclase phenocrysts are commonly embayed and rimmed by alkali-feldspar, quartz, and hornblende (Amos, 1963). Alkali-feldspar occurs with quartz as coarse grained, interstitial aggregates, and the abundance of irregularly shaped alkali-feldspar phenocrysts within the microcline-hornblende-gabbro increases as contacts with granitic rocks are approached (Amos, 1963).

The anomalous nature of the Parks Pond pluton with respect to other plutons in the coastal Maine magmatic province is immediately apparent in comparitive diagrams of whole rock chemical analyses. The pluton is alkalic (Fig. 3), and with the available analyses from the coastal Maine magmatic province, is the only intermediate pluton with a SiO_2 range of 55.5-57.8 wt% (Eriksson and Wones, 1983; Eriksson, 1985). The pluton has Rb (228-319 ppm) and K_2O (5.09-6.08 wt%) contents similar to that of the felsic magmas, but is enriched in Sr (410-565 ppm) and Ba (1420-1790 ppm) and lower in mean Na_2O (1.52±0.20 wt%) than the granitic rocks (Fig. 4). Rb/Sr ratios are similar to type III intrusions and the K/Rb ratio straddles the main trend for plutonic rocks (Fig. 4). A mantle origin has been suggested for the Parks Pond magma based on the Cr-rich nature of the whole rocks (400-500 ppm) and of the magnetite compositions, up to 7.5 wt% Cr_2O_3, but an initial Sr^{87}/Sr^{86} ratio of 0.7099±.0.0012 (2 s.d.) suggests a complex magmatic history for the pluton (Eriksson, 1985).

DISCUSSION

Plutons in the coastal Maine magmatic province appear to have been intruded by a combination of dilation, doming, fracturing, and stoping of the country rocks. The mode of emplacement for many of the plutons may have been by ring dike intrusion and cauldron subsidence (Chapman, 1968). This style of intrusion, as well as the presence of contact breccias, low pressure contact aureoles superimposed on lower greenschist facies regional metamorphic assemblages, chill margins, roof pendants, and miarolitic cavities, attests to the high level, epizonal nature of these plutons. Several granites, such as the Sedgwick pluton, possibly intrude their own volcanics (Brookins et al., 1973), and the presence of granophyric textures, as described for the Red Beach pluton (Abbott, 1978), are consistent with a subvolcanic environment. Mineral composition and phase equilibria studies suggested that the majority of the Lucerne pluton crystallized at temperatures between 650°C and 700°C at 1.0 to 2.0 kb (Wones, 1980a). Such data are consistent with field observations that suggest a shallow level of emplacement for plutons of the coastal Maine magmatic province.

Several observations suggest that fractional crystallization of magmas in the coastal Maine magmatic province occurred at this shallow emplacement level. The well developed magmatic layering and orderly progression of rock types from cumulate troctolite inwards toward quartz-biotite-horndblende-diorite in type I plutons is compatible with fractional crystallization. Whole rock chemistry from the Pocomoonshine pluton supports a model in which melanocratic-gabbronorite (±olivine) and gabbronorite (±olivine) represent mafic cumulates of a water-rich, high-alumina, tholeiitic, basaltic magma that fractionated to produce hornblende-gabbro (Westerman, 1972, 1981). Type II granitic plutons are rarely texturally homogeneous. They generally consist of several rock types which become more differentiated with increasingly younger relative age. Modal variation towards the alkali-feldspar apex (Fig. 5) within the Lucerne pluton has been interpreted to reflect cumulate processes operative during crystallization of the granite, and segregations of alkali-feldspar phenocrysts on the scale of meters to tens of meters across, observed in road cuts, support this idea (Wones, 1980a). The preservation of magmatic layering, textural variability, chill margins, and cumulates in conjunction with high temperature-low pressure contact aureoles superimposed on low-grade regional metamorphic assemblages implies that these magmas were intruded, with relatively low initial phenocryst content, into shallow levels of the crust before significant fractional crystallization took place. The rapid ascent necessary for crystallization at these shallow emplacement levels may have been facilitated by fractures.

Compositional variation produced by the accumulation of varying proportions of minerals as the result of fractional crystallization can be observed in major and trace element plots (Figs. 3 and 4). In general, for the type III Mount Waldo pluton, Rb increases and Ba decreases with increasing SiO_2, defining a trend that parallels the distribution of Rb vs. Ba analyses of type II plutons. This suggests that the negative correlation between Rb and Ba observed for pluton types may reflect compositional variation within individual plutons produced by selective crystal accumulation. Similarly, the positive correlation between FeO*+MgO against TiO_2 that exists for pluton types may, in part, reflect varying modal abundances of mafic minerals such as biotite in early vs. later crystallizing textural varieties within a pluton. A negative correlation of Rb and Sr for the Lucerne pluton has previously been suggested as the result of fractional crystallization (Loiselle and Ayuso, 1980).

Comparative Chemistry of Pluton Types

Compositional variation within plutons and within pluton types may, in part, be explained by fractional crystallization. However, distinctions made between pluton types on the basis of field observations are supported by differences in several plots of major and selected trace element chemistry. For example, significant differences in the Rb/Sr ratios for plutons in the Penobscot Bay area have been previously recognized (Carl et al., 1984), and it appears that the Rb/Sr ratio of plutons is an effective discriminator between granitoid intrusive types as defined by this paper (Fig. 4). Type II plutons generally have an Rb/Sr ratio ≥2.0, whereas type III plutons are characterized by Rb/Sr ratios ≤2.0. Pluton types also define separate fields with limited overlap in plots of Rb vs. Ba and Sr vs. Ba. However, type IIa and IIb plutons commonly do not define separate fields that adequately distinguish between pluton types in several plots. Differences between types III, IIa, and IIb are more subtle in plots of Na_2O vs. K_2O, FeO*+MgO vs. TiO_2, and K_2O vs. Rb where significant overlap between pluton types can occur.

Several possibilities exist that may explain the overlap of some analyses in plots that appear for the most part to discriminate between pluton types. Type III granitoids have the largest range of Rb/Sr ratios and several type III analyses plot within the field of type II plutons (Fig. 4). One of the analyses is from the Mount Waldo granite. This sample is significantly lower in MgO, FeO*, CaO, Ba and significantly higher in SiO_2, K_2O, and MnO than the rest of the analyses of that granite, suggesting that it represents a late stage fractionate. The rest of the type III analyses which overlap the type II field are from the Red Beach pluton near Calais, Maine. The data on whole rock samples are from Spooner and Fairbairn (1970), and information on rock type or sample location within the Red Beach pluton was not reported. The Red Beach pluton is a mineralogically and texturally composite hornblende, biotite-hornblende, biotite-granite (Amos, 1963; Abbott, 1977) associated with the Moosehorn Igneous Complex. Chemical and modal variation expressed by several phases of the pluton, including spatially associated gabbro and diorite, have been interpreted to represent an igneous series formed as the result of crystal fractionation (Abbott, 1977, 1978). Whole rock strontium isotopic analyses from the Red Beach pluton (Spooner and Fairbairn, 1970) do not define an isochron. The presence of internal intrusive contacts between different phases of the Red Beach pluton (Amos, 1963; Abbott, 1977, 1978) in conjunction with the scatter in the isotopic data suggests that this may be a composite intrusion comprised of multiple magmas rather than a consanguineous fractionation suite. A second possible explanation is that the original magma has been inhomogeneously modified to varying degrees by mixing with a mafic magma. The presence of more than one magma or modification through magma mixing is suggested by the plot of Rb/Sr ratios which places samples from the Red Beach pluton in both the type II and III fields.

Several similarities between type II and type III plutons in conjunction with subtle differences in modal mineralogy and major and trace element chemistry suggest that type III plutons have been derived from similar source regions as type II plutons, but have had their original chemical characteristics modified by interaction with a mafic magma. Type III plutons with similar accessory mineralogies as type IIa or type IIb plutons have higher plagioclase to alkali-feldspar ratios and are shifted out of the granite field towards granodiorite or quartz-monzonite compositions (Figs. 5 and 6). These differences are also reflected in

major and selected trace element chemistries. Type III plutons have higher $CaO/(Na_2O+K_2O)$ ratios, lower Rb/Sr ratios, and higher concentrations of FeO^*+MgO, and TiO_2 (Figs. 3 and 4). Biotite-muscovite±garnet-bearing type III plutons also have consistently lower mean SiO_2 contents than their type IIa counterparts. These differences are compatible with the addition of small amounts of mafic magma to the crystallizing felsic pluton through processes such as magma mixing to produce the type III plutons. Modification of the original chemical composition of the felsic magma in a similar manner by magma mixing combined with fractional crystallization has been documented for the granitoid rocks of the South Penobscot Intrusive Suite (Stewart et al., 1988).

An antipathetic modal relationship between alkali-feldspar and color index is displayed, to varying degrees, by type III plutons which are also characterized by a larger range in their plagioclase/alkali-feldspar ratio than type II plutons. The Oak Point phase of the Deer Isle pluton, a hornblende-biotite-granite, has a modally higher plagioclase content and color index than the spatially associated Stonington biotite-granite. Brookins and Spooner (1970), on the basis of strontium isotopic analyses, suggested that these two phases of the Deer Isle pluton were consanguineous. The lower color index and presence of alkali-feldspar segregations, which contain minor amounts of plagioclase and quartz, suggest that a similar mechanism of fractional crystallization as proposed by Wones (1980a) for the Lucerne granite operated in the Deer Isle pluton to produce the observed compositional variability. The Oak Point phase is, however, characterized by the presence of abundant mafic enclaves which are uncommon to rare in the Stonington granite. The effects of possible mixing with a basaltic magma may be reflected by the higher plagioclase content and the presence of hornblende in the Oak Point pluton. It is likely that the observed compositional variability in this type III pluton is the result of several processes which may include fractional crystallization as well as magma mixing.

Magmatism within the Moosehorn Igneous Complex is representative of the entire coastal Maine magmatic province. Modal variation within this igneous complex can be represented as four groups which roughly correspond to the four pluton types defined for the coastal Maine magmatic province (Fig. 7). The stratiform, layered mafic sill at Staples Mountain may represent a portion of the original mafic magma which crystallized earlier near the margin of the pluton, but isolated from interaction with felsic magma. The modal mineralogy of these rocks plots at the plagioclase apex, along the plagioclase-mafic join, and at the mafic apex in the quartz-mafic-alkali-feldspar ternary system. The suggestion that the isolated occurrences of gabbroic rocks in the Moosehorn Igneous Complex, such as the Staples Mountain pluton, are remnants of a larger stratiform mafic body (similar to type I plutons) that has been disrupted by later intrusion of felsic magmas (Amos, 1963) is supported by the strong similarities in modal mineralogy and mineral and whole rock chemistry of type I plutons and gabbroic rocks from this complex. Hornblende- and biotite-hornblende granite occur as volumetrically minor facies associated with the dominantly biotite-granite plutons of the Moosehorn Igneous Complex (Amos, 1963). Within the interior of this complex, large areas of biotite-granite devoid of mafic enclaves exist (Jurinski, pers. commun., 1987). These plutons are modally very similar to type II plutons in that they are compositionally restricted and plot within the granite field. These data suggest the presence of domains of felsic magmas which crystallized in isolation from interaction with mafic magma(s). These domains may be similar to type II plutons.

The formation of hybrid rock types within these igneous complexes can then be considered as a model for the formation of type III and IV plutons within the coastal Maine magmatic province. Modal analyses of rocks from contact zones between granitic and gabbroic rocks reveal two distinct groups of modified magmas representing type III and IV plutons. Modified mafic magma or type IV plutons were formerly gabbro and now contain alkali-feldspar, quartz, and possibly biotite as the result of interaction with felsic magma to form hybrid quartz-monzodiorite, quartz-monzogabbro, quartz-gabbro, quartz-diorite, and tonalite. Type III plutons are represented by quartz-monzonite and granodiorite, which are modally higher in plagioclase and mafic minerals than the associated granite as the result of hybridization with mafic melts. This shift in quartz content and alkali-feldspar/plagioclase ratio for hybrid rock types in the Moosehorn Igneous Complex is similar to the variation observed between type II plutons and their type III counterparts.

Aspects of mafic and felsic magma interaction as a function of composition, initial crystallinity, water content, initial temperatures, and mass fraction of the end members has been examined by Frost and Mahood (1987). Their findings suggest that under most circumstances the basaltic end member quenches in the felsic magma to form enclaves and that hybridization to form magmas of intermediate composition, tonalite or mafic granodiorite, can occur only when the compositional difference is less than 10.0 wt% SiO_2 or the mass fraction of the mafic magma is greater than 0.5. Their observations potentially explain (1) the restriction of hybrid intermediate magmas to narrow, intervening zones between the contacts of gabbro and granite within igneous complexes (where the mass fraction of the mafic magma remains high), (2) the paucity of intermediate rock types at a regional scale within the coastal Maine magmatic province, and (3) the presence of mafic enclaves as the dominant field evidence that type III plutons may have interacted with a limited amount of mafic magma.

Intrusive Style in the Coastal Maine Magmatic Province

Contacts of plutons are generally sharp and discordant, and crosscut the regional fabric and folds (Fig. 1). Several large plutons intrude major fault zones that juxtapose distinct lithologies without significant offset along their contacts (Fig.

1). However, prominent faults also crosscut and/or truncate contacts of some plutons (Wallamatogus, Great Wass Island, Lucerne, Deblois, South Penobscot Intrusive Suite), and many plutons show evidence of localized post-emplacement deformation related to faulting (Wones, 1980a; Ludman, 1981b; Loiselle and Wones, 1979a; Stewart et al., 1988). The majority of plutons in the coastal Maine magmatic province, with the exception of a few small intrusions in the Passagassawakeag terrane, are considered to be post-tectonic, post-regional metamorphic, and to have intruded after assembly of the various lithotectonic terranes.

In general, smaller plutons such as Vinalhaven, Long Island, and Great Wass Island tend to be roughly circular or elliptical in shape. Larger intrusions such as the Lucerne and Deblois plutons are angular, elongated batholiths that often transect several lithotectonic terranes (Fig. 1). The bases of plutons in the Penobscot Bay area, as determined by geophysical methods, occur at depths of six to ten kilometers, entirely within the Paleozoic cover sequence (Hodge et al., 1982; Stewart et al., 1985, 1986). It is suggested, based on this observation, that granitic magmas have spread out laterally into their present shape only after the magma reached the upper crustal lithologies above the underlying Precambrian(?) basement rocks (Stewart et al., 1986).

Fault-controlled emplacement has been suggested for both felsic and mafic plutons (Chapman, 1968; Sweeney, 1976; Biggi and Hodge, 1982; Hodge et al., 1982). Gravity modeling over several plutons indicates a strong spatial correlation between the projected location of prominent faults and the subsurface distribution of the majority of the mass of these plutons (Hodge et al., 1982). These data strongly suggest that preexisting faults may have controlled the location and shape of many of the intrusions in the coastal Maine magmatic province (Biggi and Hodge, 1982; Hodge et al., 1982; Sweeney, 1976). The intrusion of elliptical stocks in eastern coastal Maine may have occurred at the intersection of two sets of steep crustal fracture zones (Chapman, 1968). While plutons appear to be related to the regional structure in that they are intruded along fault zones, observed faults do not necessarily correspond with Chapman's (1968) proposed grids (Wones, 1976a).

Pluton Emplacement within a Transcurrent Fault Zone

It is likely that the orientation and shape of some intrusions within the coastal Maine magmatic province are controlled by the presence of a preexisting fault system. Juxtaposition of lithotectonic terranes along prominent N60°E fault boundaries (e.g. Turtle Head fault zone) as well as apparent dextral offset of these linear belts along N20-30°E faults can be seen in several places along the strike of the Penobscot-Cookson terrane (Fig. 1) and must have occurred prior to emplacement of plutons such as the Mount Waldo, Lucerne, Deblois, and Pocomoonshine. The long axes of the Lucerne pluton, the Lead Mountain and Cranberry Lakes facies of the Deblois pluton, and the Pocomoonshine pluton are at high angles to the regional strike of the major fault systems and the lithotectonic terranes. The axes of these batholiths coincide with the N20-30°E fault system that links several of the major N60°E-trending dextral fault zones of eastern coastal Maine.

Depending on the relative geometry and movement of associated transcurrent fault zones, intervening regions can be areas of extension or compression and are referred to as either transtensional or transpressional fault zones (Aydin and Page, 1984). Relative motions along major N60°E fault zones within the coastal Maine magmatic province (Norumbega fault zone, Turtle Head fault zone, Lubec fault zone, Fig. 1) indicate that this area was a region of dextral shear (Stewart, 1974; Wones and Stewart, 1976; Johnson and Wones, 1984; Ludman, 1986). An en-echelon system of dextral shear zones with sinistral step-over geometry, which appears to be the case for eastern coastal Maine, can be characterized by high-angle reverse faults within the shear zone (Aydin and Page, 1984). Such high-angle reverse faults are present within the N20-30°E fault system that coincides with Penobscot Bay (Osberg et al., 1985), suggesting that these faults may have formed as a part of the dextral shear zone which is so prominent in this area. The geometry of step-over faults within this dextral shear zone is compatible with a transpressional regime. The orientation of the larger batholiths coincides with the N20-N30°E step-over fault system, suggesting that these large plutons exploited the existence of this fault system and intruded after initiation of this transpressional tectonic regime.

Tectonic Setting of the Coastal Maine Magmatic Province

Unique assemblages of Mesozoic and Cenozoic plutonic rocks have been correlated with specific tectonic settings; this correlation has been found to extend to Paleozoic rocks as well (Pitcher, 1982). Plutonic rocks from different tectonic settings have been characterized by their mineralogy, mode, aluminum saturation index, enclave types, duration of plutonism, and intrusive style. Similarly, a series of mineralogical and chemical criteria have been used to successfully distinguish between Mesozoic and Cenozoic plutonic rocks generated at compressional vs. extensional plate boundaries (Martin and Piniwinskii, 1972; Petro et al., 1979). Compositional intrusive sequences are also characteristic of tectonic setting. Repetitive intrusion of the compositional series ±gabbro, quartz diorite, tonalite, granodiorite, and granite that is characteristic of plutonic arcs, has been attributed to constant replenishment of similar source material to the site of melting by subduction processes (Bateman et al., 1963; Bateman, 1983). Incremental melting of a static source region to first produce low-temperature, hydrous, peraluminous magmas followed by higher temperature, drier, metaluminous magmas and finally by high-temperature, anhydrous peralkaline plutons (Brown and Fyfe, 1970) is more compatible with a rift related tectonic setting where underplating of mantle-derived magmas can provide the heat to melt the overlying source region (Wones and Sinha, 1988). In magmatic

provinces where the tectonic setting is poorly known, characterization of plutonic rocks in terms of physical, petrographic, and chemical characteristics, as well as intrusive sequences, can be used to develop tectonic models compatible with the associated plutonism (Wones, 1980b). Using this approach, we will attempt to identify tectonic settings and develop a model for magma genesis consistent with mineralogical and chemical characteristics and intrusive style of plutonism in the coastal Maine magmatic province.

Type I plutons have mineral and chemical characteristics suggestive of crystallization from magmas with affinities transitional between alkalic and tholeiitic basalts. Chemical analyses of mafic rocks, including samples associated with the igneous complexes (Fig. 3), straddle the alkalic/tholeiitic boundary as proposed by Macdonald and Katsura (1964). They are suggestive of having been in equilibrium with magmas that had dominantly high alumina to alkalic affinities as proposed by Kuno (1966). Nepheline and quartz normative samples are present in the Pocomoonshine pluton (Westerman, pers. commun., 1985) although primary minerals, indicative of a strongly alkalic nature such as nepheline or alkali-feldspar, have not been reported from type I plutons (Bickford, 1963; Westerman, 1972). In the AFM ternary diagram (Fig. 3), type IV plutons appear to be iron- and alkali-enriched with respect to type I plutons. However, the two groups do overlap and together they display an overall minor alkali- and iron-enrichment trend. The type IV Parks Pond pluton plots alone in the alkalic field of the AFM ternary diagram, reinforcing its unique character with respect to plutonism in the coastal Maine magmatic province.

Peraluminous and metaluminous granitoid plutons can occur in both compressional and extensional tectonic environments, however, peralkaline compositions appear to be restricted to regions of extension (Petro et al., 1979). The high alumina to alkali, type II granitoid plutons of the coastal Maine magmatic province can be subdivided into at least two suites, each characterized by its own chemical and mineralogical signature. The high silica, weak to strongly peraluminous, type IIa plutons are characterized by aluminous biotite, ±muscovite, ±garnet. The lower silica, higher CaO contents and metaluminous to weakly peraluminous nature of type IIb plutons is reflected by the presence of aluminous biotite ±hornblende. Both suites of type II plutons are modally dominated by monzogranite. However, the type IIb Deblois pluton also contains alkali-feldspar granite (Fig. 5). The Deblois pluton has been inferred to have crystallized from a relatively anhydrous magma with an intrinsically low oxygen fugacity, suggestive of potential affinity with granite generated in anorogenic settings (Andrews et al., 1983; Loiselle and Wones, 1979a, 1979b; Loiselle et al., 1983; Collins et al., 1982). Hypersolvus, aegirine-augite, riebeckite, alkali-feldspar granite of alkaline affinity is represented in the coastal Maine magmatic province by the type III Tunk Lake and Cadillac Mountain plutons (Fig. 6).

The calc-alkaline index (the value of SiO_2 where $CaO/(Na_2O+K_2O)=1$), a variation of the Peacock Index (Peacock, 1931), has been successful in discriminating between extensional and compressional tectonic settings for igneous provinces (Petro et al., 1979). The calc-alkaline index for the coastal Maine magmatic province falls in the alkali-calcic range (51-56% SiO_2), and although displaying considerable scatter at low silica values (Fig. 3), it is comparable to plutonic rock suites generated in extensional tectonic settings.

Plutonism in the coastal Maine magmatic province is best described as being bimodal. The paucity of intermediate plutonic rocks in these analyses from the coastal Maine magmatic province is clearly demonstrated in the plots of K_2O+Na_2O vs. SiO_2 and CaO/K_2O+Na_2O vs. SiO_2 (Fig. 3). The dominant plutonic rock types in the coastal Maine magmatic province consist of high-alumina to alkali gabbro and granite with the intermediate SiO_2 compositions restricted to the type IV Parks Pond pluton and some hybrid plutonic rocks cropping out within the igneous complexes. The bimodal nature of the province is again emphasized in the AFM ternary diagram (Fig. 3) where gabbroic rocks define an iron enrichment trend in contrast to the granitoids which plot along the iron-alkali join. Available intermediate rock analyses are again restricted to the alkalic Parks Pond pluton. The bimodal nature of plutonism in the coastal Maine magmatic province is reflected by the intimate spatial association of mafic and felsic magmatism within the igneous complexes, an intrusive style that is characteristic of the coastal Maine magmatic province.

Plutons in the coastal Maine magmatic province have a variety of geometries and an intrusive style which contrasts sharply with that of plutonic arcs. Plutons occur as individual diapiric or thin sheet-like bodies, dispersed isolated complexes comprised of multiple plutons, and multiple batholiths. Emplacement appears to be influenced by the presence of preexisting crustal fractures. Several plutons expand laterally upon intruding the upper crustal Paleozoic section (Hodge et al., 1982; Stewart et al., 1986), others form ring dikes and appear to have been emplaced by cauldron subsidence (Chapman, 1968). In contrast, magmatism over Cordilleran subduction zones is characterized by great, multiple linear batholiths consisting of arrays of composite cauldrons (Pitcher, 1982) with steeply dipping intrusive contacts and large tabular batholiths oriented parallel to the regional trend (Wones, 1980b). The thin (<2 km) sheet-like plutons that are present in the coastal Maine magmatic province appear to be absent in the Sierra Nevada batholith (Wones, 1980b) and although linear, tabular, plutons do exist in the coastal Maine magmatic province, their orientation is at a high angle to the regional trend, in contrast to those of the Sierra Nevada batholith.

The bimodal nature of plutonism, the iron-enrichment trend in the AFM ternary diagram, the alkali-calcic calc-alkaline index, the overall high-alumina to alkaline nature of the magmas, the presence of granite with alkaline tendencies, as well as the style of intrusion are all characteristics of plutonism generated in an extensional tectonic setting and contrasts sharply with plutonism associated with subduction zone processes. The as-

sociation of a transcurrent fault zone with magmatism that is characteristic of an extensional rifting environment suggests that this fault zone was transtensional during part of its history. Siluro-Devonian bimodal volcanism in the coastal volcanic belt may have been localized by normal block faulting along the margins of an extensional rift graben (Gates and Moench, 1981), a feature that would be compatible with a transtensional fault geometry. Thinning of the lithosphere and upwelling of the underlying mantle may have produced the early mafic magmatism in the coastal Maine magmatic province. However, emplacement of the large, felsic, type IIb, granitoid plutons may have been controlled by a preexisting transcurrent fault system with a transpressional geometry. The significant volume of felsic plutonism in the province during the middle Paleozoic represents a large-scale thermal instability of the underlying crust. Ponding of basaltic magmas at the base of the crust was proposed by Wones (1976b) as a heat source to promote partial melting. A change from an early transtensional fault geometry, which allowed for rapid ascent of basaltic magmas to high levels in the crust, to one of transpression may have restricted the bulk of the mafic magmatism to the base of the crust, triggering the large degree of partial melting represented by these granitic batholiths. This complex history suggests that a long term relationship existed between Middle to Late Paleozoic magmatism of an extensional tectonic affinity with movements along portions of a major transcurrent fault zone.

Tectono-Thermal Evolution of Compositionally Distinct Granitoid Magmas in the Coastal Maine Magmatic Province

The successively higher temperature of intersection of the H_2O-saturated granite solidus with the dehydration reactions for muscovite and quartz, and biotite and quartz in rocks of peraluminous as well as metaluminous bulk compositions, is responsible for the generation of granitic magmas with initially distinct compositions, mineralogies, water contents, and temperatures (Brown and Fyfe, 1970; Clemens and Wall, 1981; Clemens, 1984). Lower temperature granitic magmas formed from incongruent melting of muscovite will have the highest $xH_2O^{(MELT)}$ contents; those formed from Fe-rich biotite will have a moderate $xH_2O^{(MELT)}$ content, and higher temperature melts formed from melting reactions involving Mg-rich biotite will have the lowest $xH_2O^{(MELT)}$ content (Wones, 1981). Melting reactions in source rocks that involve either biotite and feldspar or amphibole and feldspar assemblages should have similar water contents because of the overlap of the stability fields of biotite and amphibole (Wones, 1981). Characteristics of granitic melts would be determined by vapor-absent melting of the appropriate hydrous phases present in the source rocks at various metamorphic grades and levels in the crust.

Thermal decomposition of muscovite in muscovite-quartz-alkali-feldspar assemblages to produce a strongly peraluminous, low temperature hydrous melt at mid-crustal levels occurs at temperatures below 700°C (Thompson and Tracy, 1977). Upon crystallization, these melts, which contain small concentrations of non-minimum melt components such as CaO, TiO_2, MgO, and FeO*, would crystallize some combination of peraluminous phases, such as muscovite, aluminous biotite, garnet, and/or Al_2SiO_5 (Clemens and Wall, 1981). These characteristics are typical of the strongly peraluminous type IIa plutons such as the Wallamatogus, Spruce Mountain, and Indian Lake plutons. The strongly peraluminous type III plutons such as the Spruce Head or Northport plutons may have formed in a similar manner, but were modified at some point in their history by interaction with a mafic magma.

Melts produced from the decomposition of biotite at temperatures above the thermal stability of muscovite and quartz have been recognized as being important in the generation of granitic magmas (Brown and Fyfe, 1970; Clemens and Wall, 1981; Clemens, 1984). The thermal stability of biotite is expanded by compositional substitutions such as $Ti^{VI}O_2 = (FeMg)^{VI}(OH)_2$ and F = OH; melting may occur over a range in temperatures from 750°C to 850°C depending on the composition of biotite and the coexisting mineral assemblage (Clemens and Wall, 1981). Granitic magmas generated by partial melting due to the thermal instability of biotite alone will have significantly lower $xH_2O^{(MELT)}$ than melts derived from source rocks also containing muscovite. Melts generated from aluminous compositions may evolve along reactions such as

$$\text{Bio} + Al_2SiO_5 + \text{Feldspars} \rightarrow \text{Gar} + \text{K-Fld} + \text{Melt} \qquad (1)$$

and produce water-undersaturated, higher temperature melts, with relatively low contents of refractory components such as CaO, TiO_2, and MgO (Clemens and Wall, 1981; Clemens, 1984). The degree of aluminum saturation of granites crystallizing from these melts will depend on the modal percentage of aluminous phases involved in partial melting. Melting by reactions such as this may produce moderately peraluminous, biotite-dominated type IIa plutons such as the Sedgwick or Blue Hill granites and contaminated counterparts such as the type III Sullivan biotite-granite.

In weakly peraluminous or metaluminous source rocks, biotite may persist to higher temperatures during high-grade thermal metamorphism. Generation of melt by decomposition of biotite will be of the form

$$\text{Bio} + \text{Qtz} + \text{Fld} \rightarrow \text{Opx} + \text{K-Fld} + \text{Melt} \pm \text{Gar, Cord} \qquad (2)$$

(Clemens 1984). Because partial melting of biotite in the presence of other aluminous phases begins at higher H_2O fugacities and lower temperatures than pure biotite, partial melts derived from peraluminous metasedimentary source rocks will have relatively higher water contents than those derived from metaluminous source rocks (Hoffer and Grant, 1980; Wones, 1981). Depending on the composition of biotite, melts generated by reactions of this type will be strongly water-undersaturated, metaluminous to weakly peraluminous, and will have relatively

low SiO_2 content and be slightly enriched in refractory components such as Ca, Ti, Fe, and Mg (Clemens and Wall, 1981). Granitic magmas in the coastal Maine magmatic province that appear to have formed as a result of incongruent melting of biotite are the type IIb plutons such as the Lucerne and Deblois granites. The lower activity of H_2O, lower K/Rb ratios and higher absolute K_2O and Rb contents in comparison to type IIa plutons reflect the decomposition of biotite during partial melting of the source. A potassium-rich quartz-plagioclase-biotite gneiss, depleted in muscovite and H_2O by an earlier metamorphic event, has been suggested as a likely source for the Lucerne magma (Wones, 1980a). The type III Mount Waldo pluton is possibly a modified counterpart of the type IIb Lucerne pluton.

Several plutons in the coastal Maine magmatic province are characterized by the presence of hypersolvus, alkali-feldspar granite, high Na_2O+K_2O content, and late-crystallizing sodic amphiboles and closely resemble the high temperature, relatively anhydrous, fluorine-rich, A-type granites of Loiselle and Wones (1979b), Collins et al. (1982), and Whalen et al. (1987). These characteristics are suggested to have been inherited from the partial melting of source region material that has been metamorphosed to granulite facies conditions (Collins et al., 1982; Clemens et al., 1986). The production of granitic magmas from granulites in quantities sufficent enough to allow migration of the melt from the source region at geologically reasonable temperatures is limited by the availabilty of a volatile component (Collins et al., 1982). The increased thermal stability of fluorobiotite and fluoro-amphibole to granulite facies conditions suggests that thermal decomposition of these phases may provide the necessary volatile component to induce vapor-absent partial melting of a granulite source (Collins et al., 1982; Clemens et al., 1986). At elevated temperatures (>830°C), reactions of the type

$$\text{F-rich (Bio,Hbl)} + \text{Qtz} + \text{Fld} \rightarrow \text{(Opx,Cpx)} + \text{K-Fld} + \text{Melt} \quad (3)$$

have been suggested for the formation of granitic melts from rocks at granulite facies conditions (Clemens et al., 1986; Collins et al., 1982). High temperature, vapor-absent partial melting of granulite source regions by reactions of this type could form the small volume of relatively anhydrous, high temperature, fluorine-rich, granitic magmas due to the dehydrated, low H_2O nature of the source region as well as the presence of additional volatile species such as fluorine during partial melting (Clemens et al., 1986). High Na_2O+K_2O content of these magmas may be attributed to the thermal decomposition of biotite, amphibole, and the albite component, and reflect the relatively refractory nature of calcic plagioclase (Clemens et al., 1986).

Melting of lower crustal granulite facies source regions by vapor-absent partial melting along reactions similar to reaction 3 may have produced magmas which crystallized to form the type III Cadillac Mountain and Tunk Lake plutons. Intrusion of basaltic magma has been suggested as an extracrustal heat source that could produce the high crustal temperatures necessary for melting to take place along reactions of this type (Clemens et al., 1986) and may explain the close spatial association of mafic magmas with type III plutons of alkaline affinity in the coastal Maine magmatic province.

A general chronological pattern of intrusion has been proposed for the province, where the earliest magmas intruded are gabbroic (type I) followed by peraluminous plutons (type IIa) then by biotite, biotite-hornblende metaluminous granite (type IIb) with the youngest intrusions being of an alkaline affinity (Wones and Sinha, 1988). This chronological sequence for emplacement of granitic magmas from early intrusion of low-temperature, hydrous, peraluminous magmas, to sequentially higher temperature, metaluminous magmas to progressively more anhydrous magmas is predicted by Brown and Fyfe (1970) for incremental melting of an initially hydrous source rock on the basis of the progressive increase in temperature required to obtain thermal instability of first muscovite, then biotite, and finally hornblende for vapor-absent melting. Peraluminous magmas such as the type IIa Wallamatogus pluton would be produced first. Successive melting of the same source region would produce the metaluminous, H_2O-undersaturated Lucerne granite (type IIb) leaving behind a relatively anhydrous residuum, which upon additional melting might produce the drier magmas such as represented by the Tunk Lake pluton.

However, deviations from this idealized compositional intrusive sequence can be found within the coastal Maine magmatic province and neighboring regions. Recent geochronological investigations have established a Silurian age for the Cadillac Mountain pluton (D. Lux, pers. commun., 1986). Peralkaline granitic plutonism of similar age has been identified south of the magmatic province within the Gulf of Maine and in the Avalonian terranes of southeastern New England where both Middle to Late Ordovician and Middle to Late Devonian peralkaline plutonism is present (Hermes et al., 1978; Hermes and Zartman, 1985). In southern New Brunswick, Canada, granites with A-type affinities span a range of ages from the Siluro-Devonian to the Carboniferous (Payette and Martin, 1987; Whalen, 1986) and may also precede intrusion of peraluminous to metaluminous granitic magmas.

Extraction of a peraluminous to metaluminous partial melt from the source region has been proposed as a dehydration mechanism to produce anhydrous granulite facies assemblages prior to generation of granitic magmas with A-type affinities (Collins et al., 1982; Clemens et al., 1986). However, granulite facies assemblages can also be formed by mineral dehydration reactions alone, liberating H_2O without the removal of a melt fraction (Nesbitt, 1980), resulting in a potential source region for granitic magmas with A-type affinities. The presence of rift-related, bimodal Siluro-Devonian volcanic rocks extending from approximately Passamaquoddy Bay to Penobscot Bay (Gates and Moench, 1981; Pinette, 1983) indicates that this area was a region of high heat-flow prior to intrusion of the majority of plutons in the coastal Maine magmatic province. Efficient convection of heat away from the base of the crust during incipient

rifting by the liberation of volatiles during mineral dehydration reactions may have supressed the role of partial melting in the formation of anhydrous granulite facies assemblages in the lower crust beneath the magmatic province. After dehydration of the lower crust occurs, continued underplating of mantle-derived magmas results in additional heat that can no longer be rapidly transferred from the base of the crust by migration of a volatile component. Initial melting of the anhydrous lower crust during the early stages of rifting could form the early granitic magmas of A-type affinity.

During the early stages of rifting, the high heat-flow from the mantle may have produced a vertical metamorphic gradient in the crust. The anhydrous granulites of the lower crust would give way to progressively more hydrous lower amphibolite to greenschist facies assemblages at successively shallower levels. The initial extensional environment created by the transtensional fault geometry may have facilitated access of mantle-derived magmas to higher levels in the crust. This rapid transfer of heat to low-grade, biotite-muscovite-bearing hydrous source regions could trigger partial melting of these source regions to form the type IIa plutons. In some instances crustal partial melts and their heat source, the mantle-derived high-temperature mafic magmas, interacted to varying degrees to form the type III and IV plutons as well as the igneous complexes that are characteristic of the magmatic province.

Intrusion of the large metaluminous type IIb batholiths and younger plutons with alkaline affinities occurred after this transcurrent fault zone became transpressional. Restriction of mafic magmas to the lower crust in a transpressional environment would result in partial melting of the more dehydrated source regions, such as a quartzo-feldspathic biotite-hornblende gneiss to produce the type IIb plutons and the anhydrous granulites of the lower crust for the source region of the younger granites of alkaline affinity.

The relationship between tectonic setting, pluton type, and thermal history of the crust in eastern coastal Maine is summarized in Figure 8, an idealized schematic cross section of the coastal Maine magmatic province. Transfer of heat from the mantle to the overlying crust is accomplished by ascent of mantle-derived magmas. These magmas may become trapped at various levels in the overlying crust. Mantle-derived magmas trapped at the lithologic boundary between the lower crust and mantle may provide the heat necessary to melt relatively anhydrous source materials to generate crustal magmas with A-type affinities, whereas those that intrude higher levels in the crust may induce partial melting of progressively less dehydrated source regions to form either type IIa or IIb plutons. Mantle-derived magmas, facilitated by the presence of crustal fractures, may ascend to near surface levels in the crust where they crystallize to form the type I layered mafic plutons or are subsequently intruded by crustal-derived magmas to form the bimodal igneous complexes that are characteristic of the province. Interaction between the crustal magmas and their heat source, the mantle-derived magmas, results in formation of the compositional hybrid type III granitic plutons and/or the type IV intermediate to mafic plutons of the coastal Maine magmatic province.

CONCLUSIONS

Proposed Models for Terrane Accretion in Coastal Maine

Juxtaposition of disparate lithologies of varying structural complexity and metamorphic grade along fault boundaries in the Penobscot Bay region has led to the suggestion that these lithotectonic belts of eastern Maine are best represented as suspect terranes (Stewart and Wones, 1974; Wones and Stewart, 1976; Osberg, 1974, 1978; Bickel, 1976; Zen, 1983). Plate tectonic models proposed to explain the juxtaposition and amalgamation of these terranes in the Early- to Mid-Paleozoic differ considerably on the role of subduction. One model proposed telescoping of a complex continental margin, comprised of a series of small ocean basins separating microcontinental blocks, through subduction of the intervening oceanic crust along consuming plate margins (Osberg, 1978; McKerrow and Ziegler, 1971; Rast and Stringer, 1975; Dewey and Kidd, 1974; Ruitenberg and Ludman, 1978; Poole, 1976). Subduction terminated with successive accretion of each outboard terrane onto the North American margin along thrust faults. Volcanic and plutonic rocks of eastern coastal Maine are proposed to represent remnants of a former volcanic arc overlying a subduction zone (Osberg, 1978; McKerrow and Ziegler, 1971; Dewey and Kidd, 1974; Ruitenberg and Ludman, 1978; Poole, 1976; Gates et al., 1984).

Alternative models for terrane accretion suggest that subduction of oceanic crust played a minor role in the assembly of the different terranes (Wones and Stewart, 1976; Wones, 1976b, 1980b; Andrews et al., 1983; Ayuso, 1986). Amalgamation of these terranes is believed to have occurred through lateral transport of distinct structural/stratigraphic crustal blocks over large distances along major dextral transcurrent faults during the Acadian compressional event (Wones and Stewart, 1976). Geochemical and isotopic characteristics of the source regions of plutons intruding these terranes cannot be correlated across proposed terrane boundaries, suggesting that observed discontinuities between terranes at the surface persist at depth, maintaining the integrity of these terranes into the lower crust. These data are suggested to be consistent with the assembly of distinct crustal blocks along transcurrent faults (Andrews et al., 1983; Ayuso, 1986).

Characteristics of Siluro-Devonian to Carboniferous plutonism in the coastal Maine magmatic province appears to be more compatible with magmatism related to an extensional plate tectonic environment. Plutonism postdated terrane assembly in eastern coastal Maine and the strong structural control of dextral transcurrent faults on the emplacement of plutons suggests that intrusion of magmas into the overlying crust was facilitated by the presence of a preexisting transcurrent fault system. Changes

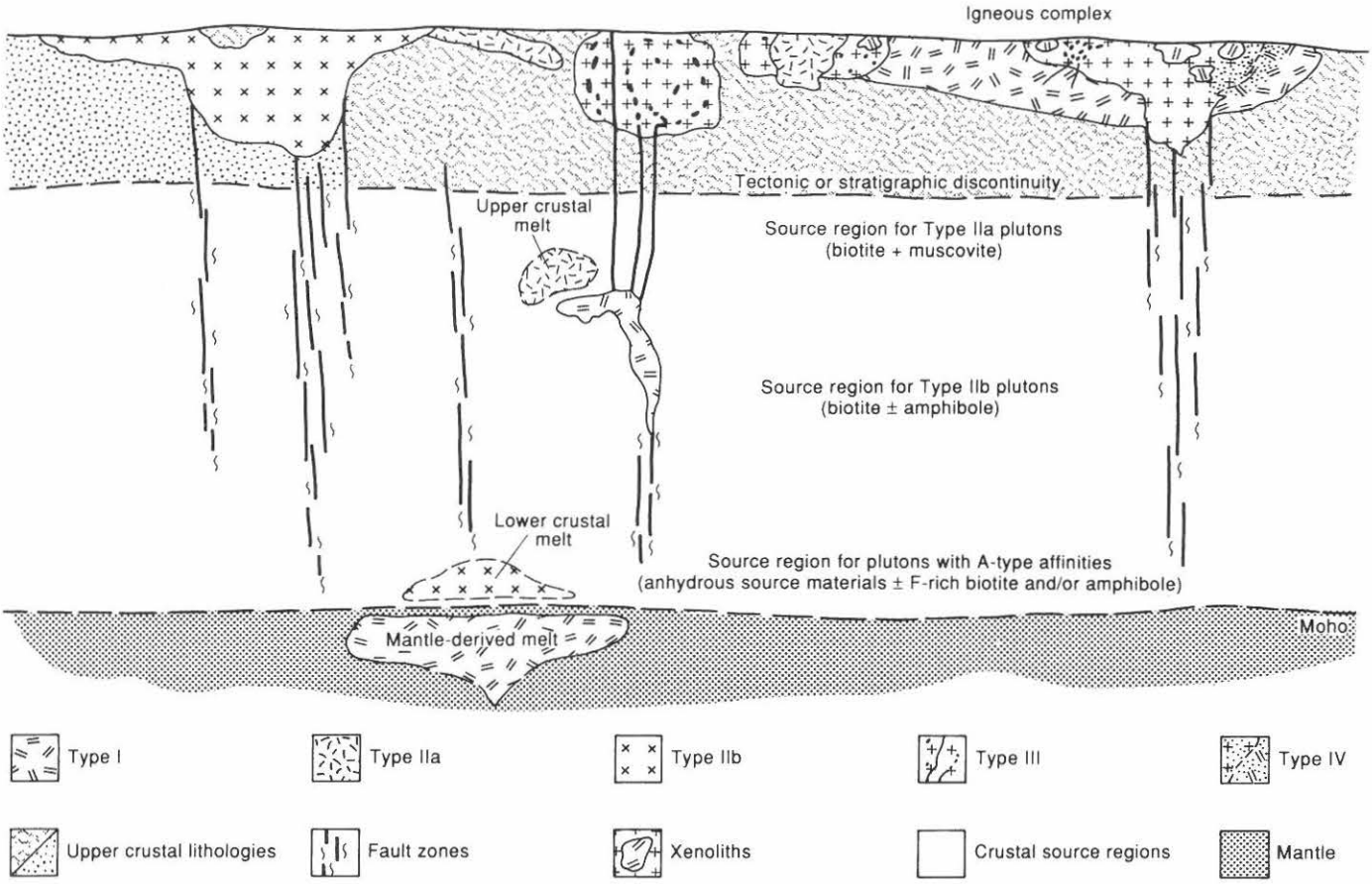

Figure 8. Schematic cross section (not to scale) of the coastal Maine magmatic province. Upper crustal lithologies are in fault contact with each other and may be either autochthonous or allochthonous over the underlying source region(s). Mantle-derived magmas act as the heat source to induce melting of source region(s) and crystallize to form type I intrusions. Melting of different crustal levels produces felsic magmas with unique mineralogical and compositional characteristics which reflect the metamorphic assemblage of the source. These magmas crystallize to form type IIa or IIb plutons. Interaction between crustal melts and their heat source (characterized by the presence of synplutonic mafic dikes, mafic enclaves, or gradational contacts between mafic and felsic rocks) results in the formation of hybrid type III or IV plutons. Close spatial association, but not necessarily a close temporal association, of different pluton types is expressed by the presence of igneous complexes.

in the geometry of this fault system resulted in different periods of intraplating and underplating of mantle-derived magmas resulting in partial melting of crustal source regions at various metamorphic grades which gave rise to compositionally distinct granitoid magmas. Interaction between crustal- and mantle-derived partial melts during crystallization may have resulted in variable degrees of hybridization of felsic and mafic magmas.

Comparison of the Coastal Maine Magmatic Province with Neighboring Regions

In New Brunswick, Canada, Fyffe et al. (1981) subdivided plutons into types A through H on the basis of field relationships, texture, mineralogy, and chemistry. Several features of Siluro-Devonian to Carboniferous plutonism in the southern plutonic belt of New Brunswick, summarized here from Fyffe et al. (1981), suggest that a similar petrogenetic and tectonic setting exists for this region and the coastal Maine magmatic province. Plutonism has been interpreted to be coeval and to also postdate faulting associated with the later stages of the Acadian orogeny. Early mantle-derived mafic magmas (type A ~ type I), intruded along faults, were subsequently intruded by a texturally and compositionally diverse group of felsic granitoids (type B ~ type III), often resulting in the formation of hybrid rocks (type A-B ~ type IV) of intermediate composition. This mafic-felsic association corresponds to the igneous complexes of the Maine province. These intrusions were subsequently followed by water-saturated, peraluminous, muscovite-bearing granites (type D ~ type IIa) and water-undersaturated, metaluminous, megacrystic, biotite±hornblende granites (type F ~ type IIb), and then by equigranular biotite±muscovite granites (type H ~ type IIa). The intrusive sequence of granitoids progressively changes

towards more felsic and potassic compositions (Fyffe et al., 1981). Recent work in this area has also described the occurrence of both Siluro-Devonian and Carboniferous peralkaline magmatism associated with hybrid and basic rocks (Whalen, 1986; Payette and Martin, 1987) that would correspond to the type III Cadillac Mountian and Tunk Lake plutons of the coastal Maine province.

Subduction-related magmatism as an origin for plutonism in southern New Brunswick was ruled out in favor of initially localized melting of the crust by intrusion of mafic magmas followed by widespread melting due to radioactive heating of a continental crust tectonically overthickened during the Taconic orogeny (Fyffe et al., 1981). Alternatively, the association of Siluro-Devonian peralkaline magmatism with graben formation has been interpreted to represent rift-related igneous activity related to extension during the Siluro-Devonian (Payette and Martin, 1987). The presence of Siluro-Devonian ductile, dextral, transcurrent fault zones in this region (Leger and Williams, 1986) as well as the similarity in plutonic styles suggests that Early to Middle Paleozoic plutonism in southern New Brunswick may have also been related to mantle upwelling beneath a transtensional transcurrent fault zone.

Siluro-Devonian plutonism in the Nashoba terrane and Avalonian terranes of southeastern Massachusetts and Rhode Island (Hepburn et al., 1987) is also similar in some respects to plutonism in the coastal Maine magmatic province. The salient characteristics of plutonism in these terranes as summarized by Hepburn et al. (1987) are presented here for comparison. The Avalonian terranes are characterized by a 650 to 600 Ma period of coarse grained, calc-alkaline, hornblende-biotite, tonalite-granodiorite-granite intrusions that has not yet been identified in the coastal Maine magmatic province. Late Ordovician to Devonian plutonism generally exhibits alkaline affinities and can also be associated with contemporaneous gabbroic plutons, suggesting strong similarities with the type III Cadillac Mountain and Tunk Lake plutons of the Maine province. Carboniferous plutonism in the Avalonian terranes is represented by the peraluminous Narragansett Pier granite. The Nashoba terrane experienced widespread bimodal plutonism commencing possibly as early as the Middle to Late Ordovician and waning in the Early Devonian. The oldest intrusion is represented by the 446±32 Ma peraluminous, foliated, and non-foliated Andover pluton. Mafic to intermediate magmas consisting of gabbroic cumulates (possible type I plutons?), tonalite, and hornblende-biotite-diorite were intruded during the Silurian and Early Devonian. Granitic crustal partial melts coexisted with mafic magmas associated with the 430±5 Ma Sharpners Pond diorite, suggesting that intermediate compositions may be the result of magma mixing and could possibly have an origin similar to that of type IV plutons. Some of the igneous complexes present in the Maine province have a similar age and association of magma compositions as the Sharpners Pond diorite.

Although the character of plutonism in the coastal Maine magmatic province can be readily extended into southern New Brunswick, correlation with similar age plutonism in southeastern New England remains tenuous at present. Plutonism in the Nashoba terrane may have resulted through subduction related processes during the Siluro-Devonian, whereas Late Ordovician to Devonian plutonism in the Avalonian terrane is more characteristic of anorogenic magmatism on a stable cratonic platform (Hepburn et al., 1987). Juxtaposition of these distinct plutonic regimes may reflect accretion along transcurrent faults during the Mid-Paleozoic (Hepburn et al., 1987). However, similarities with temporally equivalent plutonism in the coastal Maine magmatic province suggest that a similar thermal disturbance triggered partial melting of the crust beneath both regions. If this is the case, then compositional differences of granitoid plutons across terrane boundaries may reflect partial melting of distinct source regions juxtaposed by transcurrent faulting prior to plutonism, suggesting that southeastern New Brunswick, Canada, eastern coastal Maine, southeastern Massachusetts, and Rhode Island shared a common Middle Ordovician to Siluro-Devonian tectonic history. However, it is clear that several problems remain to be resolved before the relationship between plutonism in the coastal Maine magmatic province and southern New England is fully understood.

Tectonic Implications of Possible Crustal Source Region Geometries Beneath the Coastal Maine Magmatic Province

Petrologic and geochemical characteristics of plutonism in Maine have been correlated with unique fault-bounded lithologic crustal domains (Loiselle and Ayuso, 1980; Andrews et al., 1983; Ayuso, 1986). Distinct differences between source region characteristics for granitic plutons intruded into opposing sides of proposed terrane boundaries, such as the Norumbega fault zone, were used to suggest that these discontinuities persist into the lower crust as fundamental tectonic boundaries, reflecting juxtaposition of discrete source regions by transcurrent faulting (Loiselle and Ayuso, 1980; Andrews et al., 1983; Ayuso, 1986). In eastern coastal Maine, southeast of the Norumbega fault zone, the majority of magmatism appears to have postdated assembly of the proposed terranes by transcurrent dextral fault motions. Individual plutons, such as the type IIb Lucerne pluton, may intrude several of the lithotectonic blocks; several examples of a pluton type, such as the type IIa Wallamatogus and Blue Hill plutons, can intrude several different terranes within the coastal Maine magmatic province.

This suggests two possiblities for source region geometries beneath the magmatic province (Fig. 9). The first case (Fig. 9) is one in which vertical packages of unrelated, but compositionally similar, source region lithologies are juxtaposed along transcurrent faults. These distinct source regions become progressively more dehydrated with increasing depth in the crust. Partial melting of source rocks at similar metamorphic grades beneath each terrane is controlled by vapor-absent melting reactions in equivalent mineral assemblages resulting in

formation of compositionally similar types of granitic melts. The granite magmas (type II) intrude upper crustal lithologies that overlie the source region of their respective terrane. Mineralogically and compositionally, these magmas may appear very similar, but if the source region beneath each terrane is sufficently distinct, compositionally similar granites across terrane boundaries should be isotopically distinguishable. Transcurrent faults that juxtapose distinct upper crustal lithologies would maintain their integrity as terrane boundaries in the lower crust. This model is a variant of those proposed by Wones (1976b), Loiselle and Ayuso (1980), Andrews et al. (1983), and Ayuso (1986).

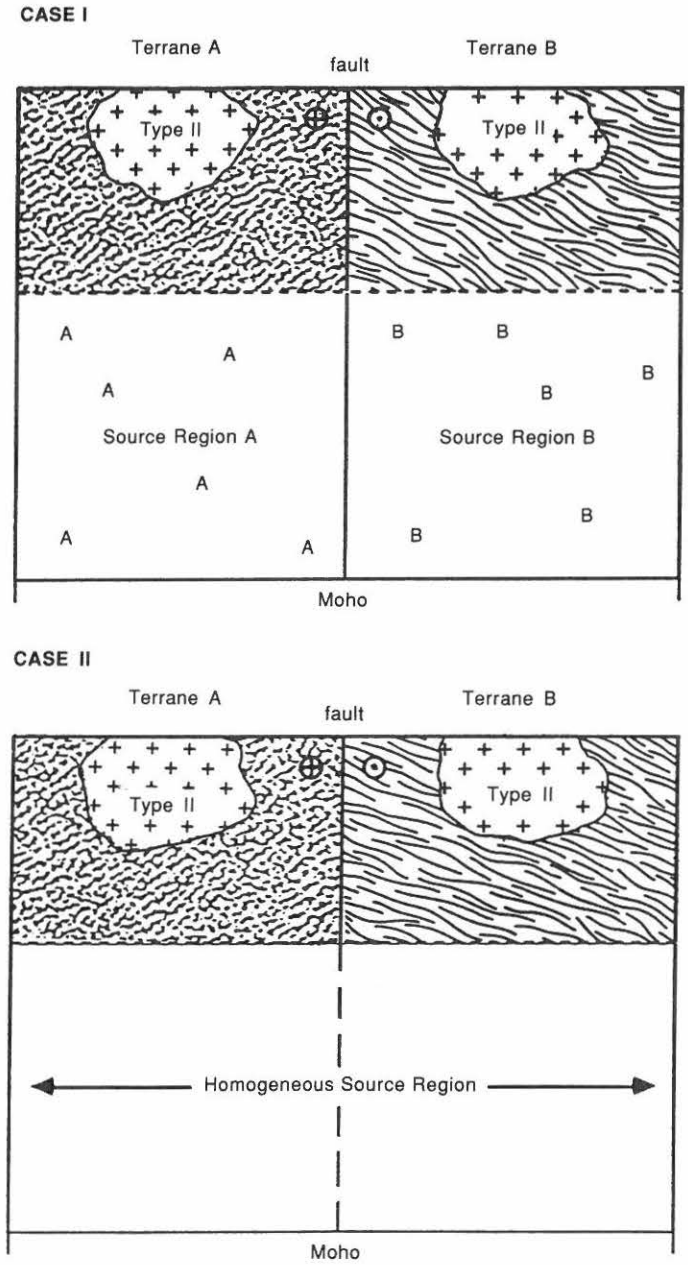

Figure 9. Possible source region geometries in the coastal Maine magmatic province. In case I distinct vertical packages of upper crustal lithologies and their source regions represent separate terranes A and B that have been juxtaposed by transcurrent faulting. In case II, a compositionally and isotopically homogeneous source region underlies both terranes A and B. In case I upper crustal lithologies may be either autochthonous or allochthonous above the underlying source regions, whereas case II is compatible with an allochthonous cover sequence overlying the source region.

A second possibility (case II, Fig. 9) arises if the presence of type II granites in several terranes reflects the presence of a common, laterally extensive, mineralogically and chemically homogeneous source rock that exists beneath several of the proposed terranes. Isotopic characteristics of compositionally similar type II granites cropping out in separate terranes would be similar if they originate by equilibrium partial melting from the same source rock layer that underlies both terranes. Superposition of different pluton types within the same terrane may be due to increasing metamorphic grade of this source rock with depth or the horizontal stacking of chemically and compositionally distinct source regions at different metamorphic grades beneath the terranes. Isotopic characteristics of distinct granite types (types IIa and IIb) within the same terrane should be dissimilar if they form by partial melting of different horizontally stacked source rock layers and similar if they formed by incremental partial melting of the same source rock. In this second case, proposed terrane boundaries between upper crustal lithologies would not represent fundamental tectonic boundaries in the source regions immediately beneath these terranes. In case I upper crustal lithologies may be either autochthonous or allochthonous above the underlying source regions, whereas case II is compatible with an allochthonous cover sequence overlying the source region.

Isotopic studies are presently underway to determine the internal consistency of granitoid types IIa and IIb, distinguished on the basis of mineralogical, major element, and limited trace element chemistry (Hogan and Sinha, in prep.). These data should provide a means to test between successively derived melts from a single source region vs. distinct melts derived from unique, vertically stacked source regions beneath the coastal Maine magmatic province as well as determine the lateral continuity of the source regions beneath proposed terrane boundaries and to evaluate the role of transcurrent faulting in the assembly of terranes in eastern coastal Maine. Determination of the isotopic characteristics of type I gabbros is also in progress to determine the possible role of mantle-derived melts in the formation of hybrid type III and IV plutons in the coastal Maine magmatic province.

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