

Petrogenesis of the Moosehorn Igneous Complex, Maine

by

Joseph B. Jurinski

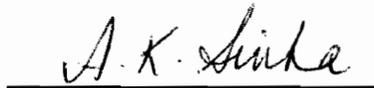
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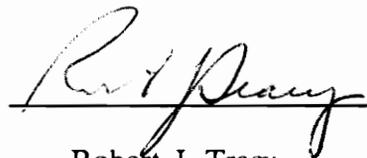
APPROVED:



A. Krishna Sinha



Allan Ludman



Robert J. Tracy

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Blacksburg, Virginia

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Joseph B. Jurinski

A. Krishna Sinha, Chairman

(ABSTRACT)

New radiometric ages and field relations within the Coastal Maine Magmatic Province suggest a bimodal distribution of igneous rocks in both space and time. The earlier magmatic event is represented by the development of large igneous complexes which occur along a magmatic axis extending from Calais to Penobscot Bay, Maine. These complexes are dominated by mafic magmatism ranging in composition from olivine norite through quartz diorite and granodiorite. Partially crystallized mafic magmas are often intruded by slightly peraluminous biotite \pm hornblende granites as demonstrated by the occurrence of a wide range of enclave-host relationships. The igneous complexes are commonly cut by younger voluminous biotite \pm hornblende granites and represent the development of a new tectonothermal perturbation of the crust.

New radiometric data on igneous rocks from the Moosehorn Igneous Complex (MIC) near Calais, Maine indicate that the earlier magmatic event occurred during the interval of 440-420 m.y. This magmatic event in the MIC is marked by the emplacement of a large, complex assemblage of olivine norite, hypersthene gabbro, gabbro, biotite \pm hornblende diorite, quartz diorite, and granodiorite. Compositional layering is present in many mafic bodies, and most commonly strikes northwest and dips gently to the southwest. The Moosehorn complex was intruded by the Baring granite before complete crystallization, resulting in the development of texturally diverse enclave swarms within the granite.

A thermal event that involved such large volumes of mafic magma implies a tensional environment in the coastal belt during Late Ordovician-Silurian times. The detailed radiometric dating within the MIC highlights the tectonothermal evolution of the shallow crust during this time.

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Introduction

Plutonic rocks within the northern Appalachians record a history of magmatism extending from the late Precambrian through the Mesozoic. Areally, the plutonic zone presents an arcuate outcrop pattern that stretches 1000 km from the Long Island Sound to the Maine - New Brunswick international border (figure 1). Plutons extend into southern New Brunswick, but this study will focus on those within the United States. The tract of plutonic rocks has an average width of 270 km, and extends from the Atlantic Ocean to the south and east to the Taconic allochthons to the northwest. Plutons of the northern Appalachians show a wide variation in size from small, stock-like bodies such as the Union ultramafic body (Maine) to large batholith sized intrusions such as the Katahdin granite (Maine), Deblois granite (Maine), and White Mountain Magma Series (New Hampshire)(Harrison et al., 1983; Osberg et al, 1985). Compositional variation of magmas within the region is also equally diverse (Hogan and Sinha, 1989, Harrison et al, 1983). Plutons exhibit compositions ranging from granitic to ultramafic, with a host of intermediate compositions including syenite, monzonite, granodiorite, diorite, gabbro, and alkali granite and gabbro.

The formation of the northern Appalachians is thought to have resulted from periods of magmatism and deformation associated with the assemblage of discrete crustal blocks (Osberg, 1978, Zen, 1983, Boone and Boudette, 1989). Five major lithotectonic zones have been proposed for the northern Appalachian chain (Williams and Hatcher, 1982), including the Piedmont, Dunnage, Gander, Avalon, and Meguma terranes. Defining the boundaries

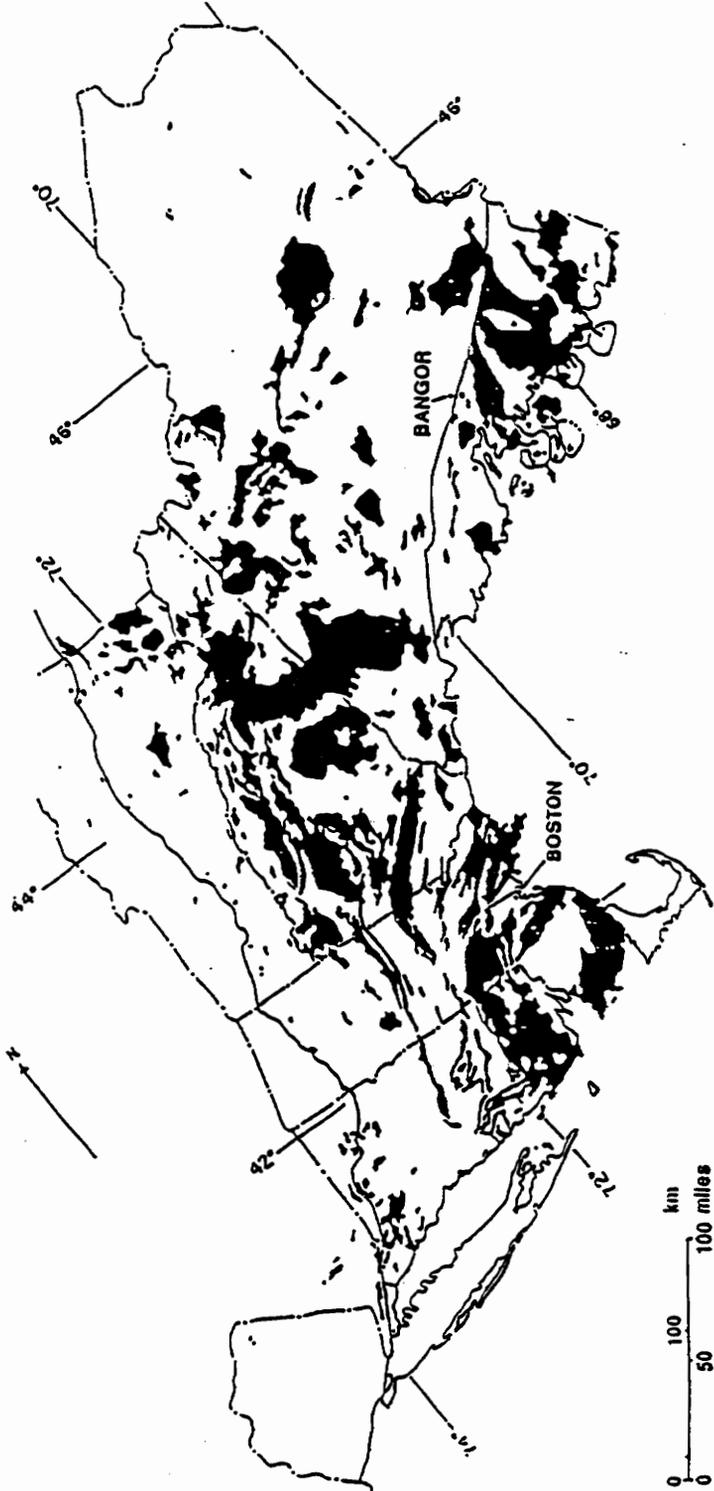


Figure 1: Distribution of plutonic rocks of the Late Precambrian to Mesozoic age in the northern U. S. Caledonides. Modified from Sinha (1988).

of these crustal segments as well as the timing of their accretion remains an active area of research.

Distinct crustal blocks may be defined on the basis of differing igneous, metamorphic, or deformational histories, or may host varying sedimentary packages. Several techniques may be employed in determining timing of terrane accretion. Stratigraphers can determine a minimum age of assemblage through documentation of a common overlap sequence covering two suspected crustal blocks. Similarly, the accretion of two disparate terranes may be marked by the convergence of distinct faunal assemblages (Neumann, 1984). The approach employed here uses the magmatic perspective to unravel the history of the northern Appalachian belt. Information assembled from the study of plutonic rocks permits three dimensional modelling of the crust, as these plutons may be used as "probes" of the deep crust.

There are several advantages in the use of plutonic rocks to document terrane histories. Isotopic studies allow characterization of pluton source regions through initial isotopic signatures (Ayuso, 1986; Hogan and Sinha, 1989). Absolute age determinations of plutons yield precise time frames for dating thermal perturbations of the crust. Documentation of phase relations within the plutons allows assessment of crustal conditions during crystallization of the pluton and partial melting of the source region, and can yield such information as water content of the magma and temperatures and pressures of crystallization (Maaloe and Wyllie, 1975, Naney, 1983). Finally, associations of certain plutonic rock suites may be used to document ancient tectonic settings through correlation with modern tectonic analogs.

Recent isotopic investigations of plutons within the northern Appalachians have revealed a significant period of magmatic activity which occurred throughout the Late Ordovician-Silurian (DNAG time scale--Palmer, 1983; Zartman and Naylor, 1984; Bevier, 1988; this study). This activity resulted in the development of two contemporaneous plutonic belts containing different lithologies. The belts are separated from one another today by an average distance of 150 km. The western belt extends 920 km from eastern Connecticut through central Massachusetts and western New Hampshire, across central Maine and into New Brunswick, Canada, and is composed mainly of monzonites, syenite, diorites, and tonalites. The coastal belt stretches 560 km from eastern Massachusetts through the Penobscot Bay region of Maine into southern New Brunswick, and is characterized by the presence of igneous complexes containing a bimodal granite-gabbro assemblage. Much of the record of this earlier magmatic event was eliminated by emplacement of large volumes of magma into the crust during Devonian times.

The northern portion of the coastal belt is contained within the Coastal Maine Magmatic Province (CMMP) (Hogan and Sinha, 1989). The CMMP is characterized by the presence of large volumes of magma emplaced into the Coastal Lithotectonic Block (CLB). Mafic rocks are exposed over 8 % of the 14,600 km² CMMP, while felsic rocks cover 37 % of the area. The CLB consists of a series of four northeasterly trending fault-bounded crustal segments, each of which hosts a distinct lithologic package (figure 2). From northwest to southeast, the blocks include the Bucksport-Flume Ridge block, the Passagassawaukeag block, the Penobscot-Cookson block, and the Coastal Volcanic block (Osberg et al., 1985). The Bucksport-Flume Ridge block includes finely laminated calcareous siltstones accompanied by small amounts of sulfidic pelite (Ludman, 1981) and

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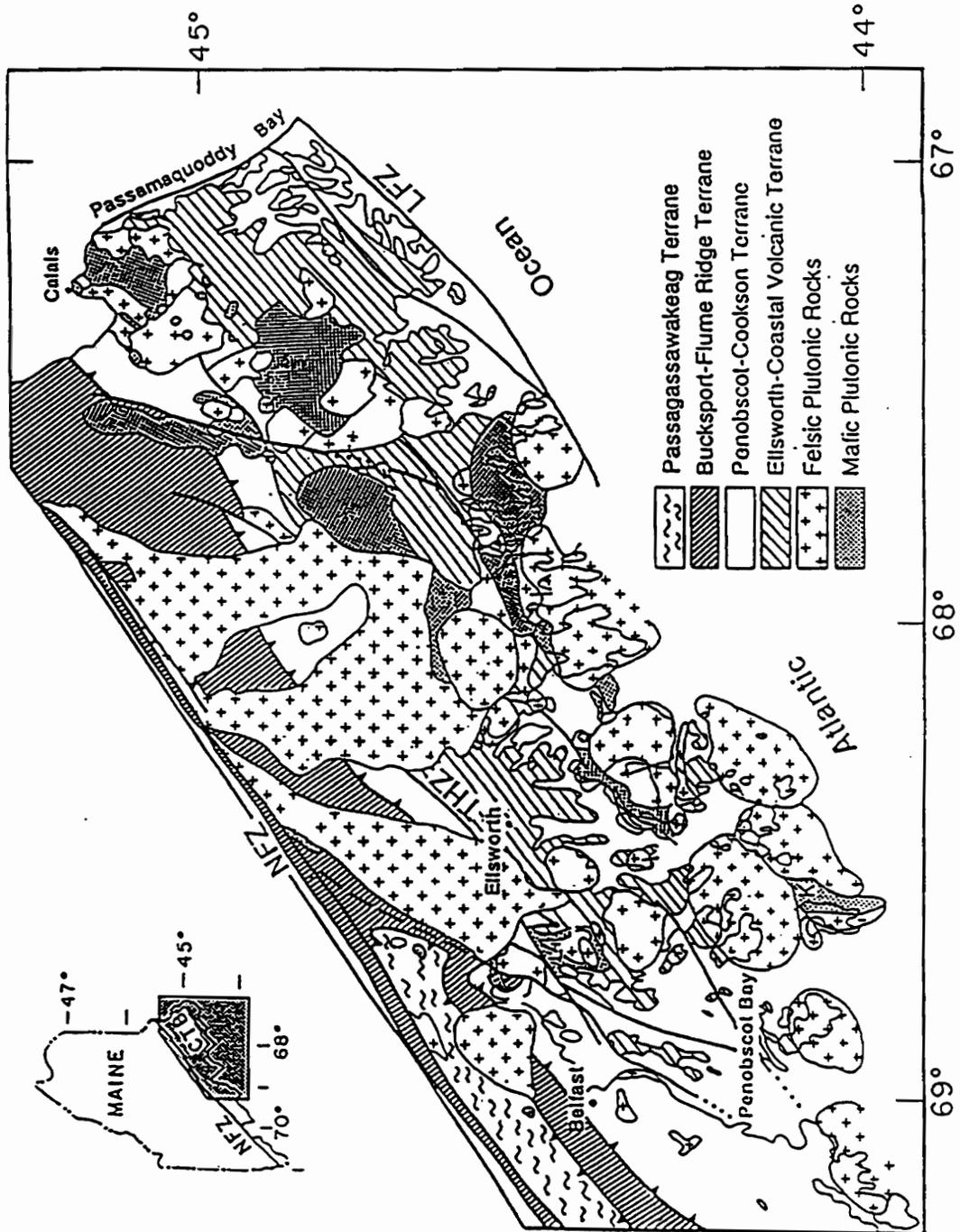


Figure 2: Proposed terranes of the Coastal Lithotectonic Belt (CLB). Modified from Hogan and Sinha (1989).

is the most northwesterly segment of the CLB. The Passagassawaukeag block is inferred to be in fault contact with the Bucksport-Flume Ridge block to the southeast. The Passagassawaukeag terrane consists of migmatitic, complexly deformed metavolcanic rocks, calc-silicate rocks, and quartzofeldspathic gneisses overlain by Cambro-Ordovician pelitic schists, siltstones, and quartzites. The block is extensively intruded by granitoid dikes, sills and stocks (Stewart and Wones, 1974; Hogan and Sinha, 1989). The Penobscot-Cookson block, in fault contact with the Bucksport-Flume Ridge terrane to the north, includes graphitic, sulfidic pelite, siltstone, quartzite, greywacke, metabasalt, slate and schist (Stewart and Wones, 1974, Ludman, 1981). The Penobscot block is separated by the Turtle Head Fault Zone from the Ellsworth-Coastal terrane to the southeast. The Ellsworth-Coastal block consists of polydeformed greenstones and quartzofeldspathic chlorite schists unconformably overlain by bimodal mafic and felsic volcanic rocks of Silurian age which are interbedded with varying amounts of breccia, calcareous siltstones, limestones, shales, and conglomerates (Stewart and Wones, 1974, Gates and Moench, 1981).

The Moosehorn Igneous Complex (MIC) near Calais, Maine serves as the type example for the style of pluton occurrence in the coastal belt during the late Ordovician-Silurian period. The MIC is a roughly circular group of intrusions cropping out along the US-Canadian border and is composed of the Baring granite, Calais Diorite-Gabbro complex, the layered to massive Staples Mountain and St. Stephen gabbros, and several unnamed, isolated gabbro-diorite bodies. The igneous complex was later pervasively intruded by the younger Charlotte, Meddybemps, and Red Beach granites.

Detailed field mapping, undertaken during the summer of 1987, coupled with isotopic and petrographic examination of samples collected from the area, permits definition of the

units contained within the MIC. The petrogenesis of the complex will be outlined from radiometric age determinations (U/Pb zircon and Rb/Sr whole rock) on plutons of the area combined with detailed field observations and petrographic examination of rock samples. Finally, the tectonic significance of igneous complexes in the coastal belt will be highlighted in light of recent geologic investigations within the region, and the tectonothermal evolution of the crust in the coastal belt will be discussed.

Previous Work

The first comprehensive overview of the coastal Maine plutons was presented by Chapman (1962), who defined the Bays-of-Maine Igneous Complex as comprising granitic and gabbroic phases. He also defined a group of younger plutons which were subdivided into biotite granites, hornblende granites, and coarse porphyritic granites. The Baring, Charlotte, and Meddybemps granites were included among the biotite granites of the younger group, while the Red Beach granite was grouped with the granites of the older Bays-of-Maine complex. Rocks now mapped as the St. Stephen gabbro, Staples Mountain gabbro, and Calais Diorite-Gabbro complex were all included within the gabbroic phase of the Bays-of-Maine Complex.

Hogan and Sinha (1989) presented a classification scheme for plutons of the CMMP based on modal, chemical, and isotopic data. The model considered a potential genetic relationship between spatially and possibly temporally associated mafic and felsic magmas, and predicted four types of occurrence related to the amount of observed interaction between felsic and mafic materials. The MIC was shown to contain the full range of pluton types from Type I (uncontaminated granite) to Type IV (uncontaminated gabbro). Types

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II and III also occur within the MIC and represent varying degrees of interaction between mafic and felsic rock types.

The first detailed description of the rock units of the Moosehorn Igneous Complex was presented by Amos (1958, 1963). As a doctoral student under Chapman, Amos detailed the geology of the Calais and Robbinston 15' quadrangles. Field relations among the granites and country rocks were reported, and petrographic descriptions of all rock types within the area were presented.

Several studies have been undertaken on the mafic rocks of the MIC. Coughlin (1981,1986) presented information on the Staples Mountain gabbro. The stratigraphy of the intrusion was divided into five units, with petrography and major element analyses of each unit presented with the general conclusion that the pluton represented a slightly differentiated sheet-like intrusion. Work published on the St. Stephen gabbro has been mostly concerned with its economic potential. Paktunk (1986, 1987) reported characteristics of the sulphide-related Cu-Ni mineralization as well as general petrography of the rock units of the St. Stephen gabbro. A generalized geologic map of the intrusion was also included in these reports.

Individual plutons in the Calais, Maine, area have been the focus of more intensive investigations. Abbott (1977) presented a detailed map of the Red Beach granite, as well as a comprehensive study of the pluton. The granite, previously mapped as a two phase body (Amos 1958), was further divided into seven units. The units were thought to be related through fractional crystallization along a liquid line-of-descent from gabbro to biotite granophyre. Emplacement conditions of the granite were modelled from mineral chemistry and textures. Several Maine Geological Survey Open File Reports have been published on

the geology of the Calais quadrangle. In earlier reports (Ludman, 1981, Ludman and Hill, 1986) the stratigraphy and field relationships of the Cookson Group were described and preliminary work on the plutonic rocks presented. Other open file reports on adjacent quadrangles have shown preliminary contact relations between the younger granites and surrounding lithologies (Gates, 1977, 1978).

Stratigraphy of the Northern Coastal Lithotectonic Block

Distinct sedimentary packages of three lithotectonic blocks are exposed in the region surrounding the MIC (Osberg et al, 1985). From northwest to southeast, the blocks exposed include the Fredericton Trough, St. Croix Cambro-Ordovician belt, and the Coastal Volcanic Belt (figure 3). With few exceptions, only the lithologies of the Coastal Volcanic belt are abundantly fossiliferous and readily dated; other lithologic packages have been tentatively dated through correlation with nearby fossiliferous assemblages. Nevertheless, these sediments represent a time period extending from the Late Precambrian (?) through the upper Devonian and place important constraints on the timing of pluton emplacement in the northern Coastal Lithotectonic Block.

Fredericton Trough

Sediments contained within the Fredericton Trough crop out in the northwest corner of the Calais 15' quadrangle. These rocks have been divided into three formations, the Digdeguash, Flume Ridge, and Pocomoonshine Lake (Ruitenbergh, 1967; Ruitenbergh and Ludman, 1978; Ludman, 1981; Ludman, pers. comm.(10/09/89)). The Digdeguash, first described from exposures in Charlotte County, New Brunswick as a sequence of turbiditic slates and greywackes (Ruitenbergh, 1967), was later extended into the Big Lake 15' quadrangle by Ludman (1974). The unit is in conformable contact with the overlying Flume Ridge Formation and in fault contact with sediments of the Cookson Group to the east. The formation consists of a package of generally well graded, buff-weathering, grey, polymictic granule conglomerates and lithic wackes interbedded with grey slates (Ludman,

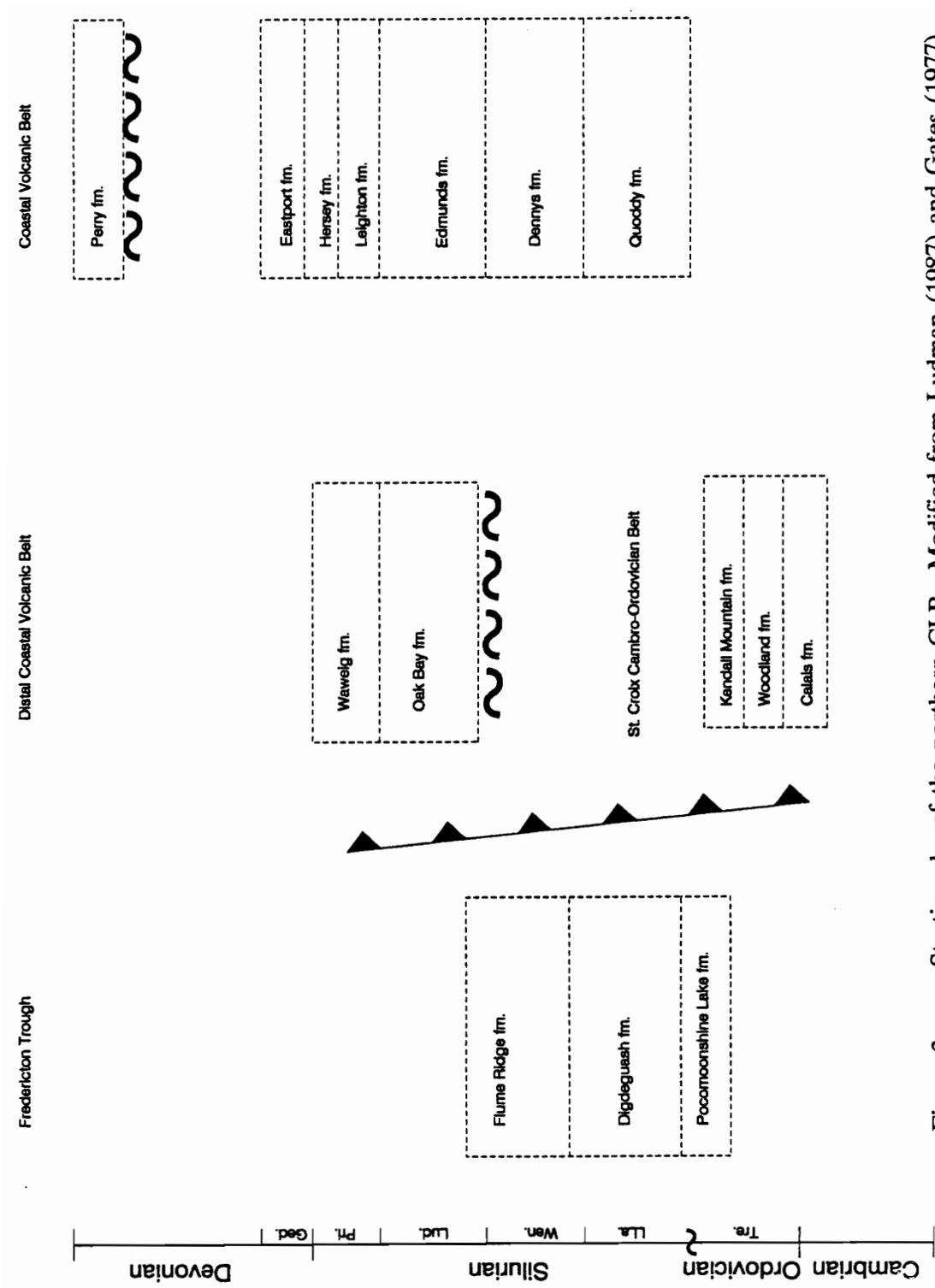


Figure 3: Stratigraphy of the northern CLB. Modified from Ludman (1987) and Gates (1977).

1981). The unit as a whole is generally non-calcareous and consists of two main lithic types, psammite and pelite. These occur in beds of randomly variable thickness, grain size, proportions of sandstone to pelite. Lithic fragments within the formation contain plagioclase, quartz, perthite, and muscovite and are accompanied by rare fragments of muscovite-chlorite-quartz-plagioclase schist indicating an igneous/metamorphic source region for this unit (Ludman, 1981).

Since the Digdeguash is faulted against Cookson group sediments to the east, its true thickness is unknown. Ludman (1981) estimates a minimum thickness of 1000 m from unraveling of isoclinal folds within the unit. As mentioned previously, the Digdeguash Formation is unfossiliferous and has proven difficult to date. Ruitenbergh (1967) suggested the Digdeguash is interfingered with the Waweig Formation, a distal unit of the Coastal Volcanic Belt which contains a well established Pridolian (latest Silurian) fossil assemblage. However, folded Digdeguash beds have been intruded by the Pocomoonshine gabbro which has yielded K-Ar hornblende ages of 414 and 424 my (Westerman, 1972), indicating the unit is as least as old as the middle Silurian.

The Flume Ridge Formation is the most areally extensive unit of the Fredericton Trough in eastern Maine. The formation, first described by Ruitenbergh (1967) in southwestern New Brunswick, was extended into eastern Maine by Ludman (1974). In general, the unit is composed of calcareous quartzofeldspathic wackes interbedded with calcareous and non-calcareous siltstone and non-calcareous shales. Ludman (1981) reported two distinct bedding styles within the unit. Near the contact with the Digdeguash, thick (0.4 to 2 m) beds of calcareous sandstone crop out. The beds are laminated near their tops and exhibit a fairly uniform grain size. This portion of the Flume Ridge Formation contains

little pelite, although the proportion of pelite increases to the northwest concomitant with a decrease in bed thickness and development of primary sedimentary features within the unit. The second mode of occurrence, evident north of Big Lake, is characterized by thinner (2 to 10 cm) beds showing equal proportions of pelite and sandstone.

Ludman (1981) estimated the thickness of the Flume Ridge Formation at several thousand meters, although he admitted it is difficult to judge the number of times the sequence is repeated across the 35 km belt of exposure. As with the Digdeguash, the Flume Ridge is unfossiliferous and difficult to date. However, Ruitenbergh (1967) established that the Flume Ridge is in conformable contact with the underlying Digdeguash Formation.

The Pocomoonshine Lake Formation has only recently been considered as part of the Fredericton Trough, having previously been included among the sediments of the Cookson group. The unit has been reassigned by Ludman (pers. comm.) based on a similar structural history as the Fredericton Trough rocks. The bulk of the unit consists of carbonaceous slates with occasional interbedded siltstones and very fine grained sandstones. Lithologically, the sandstones and siltstones are composed of quartz and feldspar with minor muscovite, graphite, and pyrite. Ludman and Hill (1986) reported that the Pocomoonshine Lake Formation exhibits a sharp to gradational contact with the overlying Kendall Mountain Formation. Ludman and Hill (1986) noted that the shale beds in the lower portion of the Pocomoonshine Lake Formation were locally intensely deformed, but did not relate this to a tectonic break in the section. Currently, Ludman (pers. comm. (04/28/90)) favors a fault contact between the Pocomoonshine Lake and Kendall Mountain Formations.

St Croix Cambro-Ordovician Belt

A discrete package of sedimentary and volcanic rocks is exposed in the St. Croix Cambro-Ordovician Belt and is contained within the Cookson Group of Ludman (1987). From oldest to youngest, the group is comprised of the Calais Formation, the Woodland Formation, and the Kendall Mountain Formation. Both the Calais and Kendall Mountain Formations have yielded fossils which constrain the period of deposition for the group between the Middle Caradocian (458-448 m.y., Palmer, 1983)(Kendall Mountain Formation--graptolites) and Tremadocian (505-488 m.y., Palmer, 1983)(Calais Formation--graptolites) ages. Areally, the sediments crop out in a northeasterly trending belt lying to the northwest of the MIC. A small section of Cookson group metasediments is exposed in the vicinity of Calais, Maine, cropping out between the Baring granite, St. Stephen gabbro, and Calais Diorite-Gabbro unit.

The oldest of the Cookson group units, the Calais Formation, has been divided into three members as discussed by Ludman and Hill (1986). The formation consists of a characteristic basal coticule layer which is overlain by pillowed basalts. These pillow basalts are interbedded with phyllite, massive basalt, and chert. The upper member of the Calais Formation consists of carbonaceous, rusty weathering, black shales intercalated with thin sandstone beds.

The contact between the Calais Formation and the overlying Woodland Formation is reportedly both sharp and conformable (Ludman and Hill, 1986). The Woodland Formation, as described by Ludman and Hill (1986), consists mainly of rusty weathering, interbedded quartzofeldspathic wacke, pelite, carbonaceous and non-carbonaceous slates, and phyllites. These lithologies generally occur in graded beds, with nearly equal proportions

of sandstone and phyllite in the thinner beds. Thicker beds attain sandstone to pelite ratios of up to 4:1. Two distinct minor lithologies occur within the Woodland Formation. The first rock type occurs throughout the formation and consists of a dense quartz, biotite, plagioclase granofels which crops out in thick (15-50 cm) cross-bedded layers. The second characteristic lithology within the Woodland Formation occurs exclusively toward the center of the unit and includes a calc-silicate granofels composed of alternating layers of a lithology consisting of calcite-diopside-actinolite +/- garnet and biotite-quartz granofels.

Variable lithologies of the Kendall Mountain Formation overlie the sulfidic rocks of the Woodland Formation. Ludman and Hill (1986) reported that the Kendall Mountain Formation includes quartz arenite, quartzofeldspathic and lithic arenite, wacke, granule conglomerate, siltstone, carbonaceous pelite, volcanic sediments including felsic tuff, and basalt. The bulk of the unit is made of thick bedded metasandstones cropping out in massive, non-graded, 0.2-1.5 m beds. Thinner interbedded carbonaceous slates and siltstones are common near the top and bottom of the formation. Compositionally, most sandstones within the unit are best characterized as quartzofeldspathic or arenitic, however zones of pure quartzite, lithic wacke, and arenite are also observed within the formation. The lower portion of the Kendall Mountain Formation contains thick (2.0 m), massive beds of coarse granule conglomerate. The conglomerate contains generally well rounded clasts which include quartzite, mafic and felsic volcanic fragments, and occasional phyllite and schist fragments which Ludman and Hill (1986) have identified as having originated from Eocambrian or Precambrian rocks in the vicinity of St. John, New Brunswick. The volcanic component, unique to the Kendall Mountain Formation, is restricted to one horizon near the base of the unit. The rock is composed of densely welded, thinly (1-5 cm) banded,

massive felsic tuff. Ludman and Hill (1986) describe the rock as a very fine grained cryptocrystalline matrix of quartz and feldspar hosting rare microphenocrysts of feldspar. They attribute the banding to compaction of pumice lapilli. The fine grained volcanic component is interbedded among volcanoclastic arenites and wackes. Fine grained, sulfidic, plagioclase-actinolite metabasalts are interbedded with the felsic component. Ludman and Hill (1986) list three characteristic features of the Kendall Mountain Formation which distinguish it from other units of the Cookson group. Specifically: 1) the Kendall Mountain Formation is the only unit with no appreciable amount of pelite (< 5% of the formation), 2) no biotite was produced in the rock at high grades, and 3) the Kendall Mountain Formation is the only unit with a felsic volcanic component.

The Coastal Volcanic Belt

The Coastal Volcanic Belt hosts a thick (7000 m (Gates, 1984)) package of volcanic, volcanoclastic, and clastic sediments. These lithologies were deposited into an increasingly shallow basin, indicated by the change from anoxic through subareal deposition and subsequent development of an erosional unconformity. Volcanic rocks within the package show a history of chemically bimodal, explosive volcanism throughout the region. The formations within the coastal belt are abundantly fossiliferous, permitting accurate assessment of their ages, and show that the sediments were deposited during a period extending from the earliest Silurian (late Llandoveryan) through the Upper Devonian. The tight age control on this sedimentary package provides important constraints on the timing of pluton emplacement throughout the region.

The oldest unit exposed within the Coastal Volcanic Belt is the Quoddy Formation of Bastin and Williams (1914). The unit crops out only within fault-bounded blocks in Maine, but has been shown to unconformably overlie sedimentary and volcanic rocks of the Coldbrook Group in adjacent New Brunswick. The lower portion of the Quoddy Formation consists of dark grey and black, rusty weathering, sulfidic shales and siltstones cropping out in thin (< 2.5 cm) graded beds. Sporadic interbedded feldspathic laminations have been interpreted as ash falls (Gates, 1977). Amos (1958) reported that the Quoddy shales have been deformed and partially recrystallized, citing the occurrence of undulose extinction in quartz, secondary overgrowths, and preferred orientation of some phases within the rock. The percentage of volcanic material increases towards the top of the formation. Gates (1977) reported the occurrence of tuff breccias, lapilli tuffs, porphyritic, siliceous vitrophyres and basalts, some of which were pillowed, within the Quoddy Formation. The felsic volcanics of the unit have been intensely recrystallized with feldspars altered to sericite, epidote, and calcite, and mafic phases altered to chlorite (Amos, 1958). Several species of *Monograptus* have been found in the shales of the Quoddy, giving the unit a late Llandoveryan (438-428 m.y., Palmer, 1983) age (Gates, 1977, Berry and Boucot, 1970). As the upper and lower contacts of the formation are cut by faults, the true thickness of the unit is unknown. However, Bastin and Williams (1914) suggested the unit may be several thousand feet thick.

The Dennys Formation (Bastin and Williams, 1914) overlies the Quoddy Formation. The contact with the Quoddy Formation is a fault, although Gates (1977) reports the base of the Dennys Formation is exposed to the west in the adjacent Gardner Lake 15' quadrangle. The Dennys Formation grades upward into the younger Edmunds Formation,

the boundary being drawn where tuffs and siltstones of the Edmunds Formation overlie basalt pyroclasts assigned to the Dennys Formation (Gates, 1977). The Dennys Formation has been split into five members. These include devitrified vitrophyre, tuff and flow breccia, flow basalt, basaltic agglomerate and lapilli tuff, and a fossiliferous unit containing bedded tuffs, lapilli tuffs, conglomerates, shales, and cherts (Gates, 1977). The devitrified vitrophyre is characterized by white to pink, massive to flow banded, aphanitic to porphyritic rocks which crop out in distinct belts. These are accompanied by localized lenses of autobreccia, leading Gates (1977) to infer that the lithologies resulted from development of a series of rhyolite domes on the sea floor. The rhyolite consists of plagioclase phenocrysts in a devitrified groundmass of quartz, plagioclase feldspar, and chlorite.

The bulk of the Dennys Formation rocks are basaltic in composition. These include massive to thick bedded basaltic agglomerates, tuff breccias, and lapilli tuffs interbedded with pebble conglomerates, coarse sandstones, and thinly bedded basaltic tuffs, siltstone, and chert. A few thin basalt flows occur throughout the formation. These are associated with lenses of tuff breccia composed of angular rhyolite fragments in a matrix of plagioclase, vitrophyre fragments, and chlorite. The chemical composition of the Dennys lithologies, coupled with the fragmented and brecciated nature of many of the rocks, has led to the interpretation that the formation represents rocks deposited along the flanks of an explosive basaltic volcano (Gates, 1977). The sedimentary units of the Dennys Formation contain a fossil assemblage consisting of brachiopods, trilobites, corals, and pelecypods. Berry and Boucot (1970) have assigned a late Llandoveryan (438-428 m.y., Palmer, 1983) to Wenlockian (428-421 m.y., Palmer, 1983) age to this collection.

The Edmunds Formation, first named by Bastin and Williams (1914), unconformably overlies the basaltic volcanics of the Dennys Formation in the nose of the Cobscook anticline, but lies along strike with Dennys rocks through a zone of rhyolite domes on the north flank of the structure. Gates (1977) draws the contact with the Dennys Formation approximately 800' above the one cited by Bastin and Williams (1914). The upper contact of the Edmunds Formation is drawn on the basis of paleontological evidence (Bastin and Williams (1914). In contrast to the Dennys Formation volcanics, rocks of the Edmunds Formation are primarily rhyolitic in composition. Six units have been defined for the formation by Gates (1977). These include a coarse breccia and agglomerate, devitrified vitrophyre and autobreccia, basalt flow unit, tuff breccia with rhyolite and dacite, tuff breccia and mudstone unit, and a fossiliferous clastic sediment unit. The tuff breccia and rhyolite/dacite unit was interpreted as a pyroclastic deposit. The rocks consist of angular blocks of porphyritic devitrified rhyolite to dacite in a matrix of broken, albitized plagioclase, broken quartz, and lithic fragments of basalt, vitrophyre, siltstone, and chert. The unit occurs in discrete bodies which thicken to the north and interfinger with marine sediments to the south. Gates (1977) interpreted these as debris flow deposits. A compositionally similar unit occurs within the Edmunds formation, but consists of tuffs and tuff breccias which have been reworked in a subaqueous environment. The tuff and tuff breccia unit is well-bedded, well-sorted, and exhibits cross bedding, cut-and-fill channels, sub-rounded clasts, and lacks fine grained matrix. Basalt flows occur within the Edmunds formation, but do not constitute a large percentage of the unit. Most basalts are hydrothermally altered labradorite-augite basalts, although Gates (1977) has identified a single olivine-bearing flow within the formation. Several isolated vitrophyre bodies occur

throughout the Edmunds Formation. These consist of pink flow-banded porphyritic devitrified rhyolite vitrophyre, locally brecciated, leading to the interpretation that these represent shallow intrusions or domes (Gates, 1977). The fossiliferous clastic sediments (Ses) of the formation include grey to black tuffaceous siltstones, argillites, and cherts.

Fossils collected from the Edmunds Formation contain abundant brachiopods, trilobites, corals, ostracodes, and *Orthocerids*. The assemblage had been assigned a Ludlovian (421-414 m.y., Palmer, 1983) age by Berry and Boucot (1970). Bastin and Williams (1914) have estimated the thickness of the formation at 2500-3000'.

The Leighton Formation was first mapped as the Leighton grey shale member of Bastin and Williams's (1914) Pembroke Formation but has since been assigned a formation ranking (Gates, 1977). The unit consists of a mixture of shales and compositionally diverse volcanic rocks which has been divided into five members including basalt flows, rhyolite vitrophyre and autobreccia, basaltic block and lapilli tuff, rhyolite/dacite lapilli tuff and breccia, and a fossiliferous clastic sedimentary unit. Most of the Leighton Formation is composed of calcareous grey siltstones and shales interbedded with irregular lenses of limestone. The fossiliferous clastics of the Leighton interfinger with tongues of volcanic material. Localized lenses of tuff breccia have been construed to represent sea floor basalt flows. These are occasionally topped by thin basalt flows (Gates, 1977). Small submarine pyroclastic flows occur within the Leighton Formation and consist of broken quartz, albitized plagioclase, pumice lapilli, and shale fragments.

The Leighton Formation has yielded a distinct shallow water fossil assemblage containing *Rhychonellid* brachiopods, abundant gastropods, pelecypods, ostracodes, trilobites, and members of the characteristic brachiopod genus *Salopina*. Berry and Boucot (1970)

have assigned a Pridolian (414-408 m.y., Palmer, 1983) age to this fossil assemblage. The estimated thickness of the Leighton Formation is 3300' (Bastin and Williams, 1914).

The Hersey Formation conformably overlies the Leighton Formation. The contact is drawn where characteristic maroon mudstones of the Hersey overlie porphyritic tuffs of the Leighton. The Hersey was first mapped as the red shale member of the Pembroke Formation (Bastin and William, 1914) but has since been reassigned a Formation rank by Gates (1977). The Hersey grades laterally into the overlying Eastport Formation through interfingering maroon siltstones, grey shale, and basaltic volcanics (Gates, 1977). Lithologically, the Hersey consists of dark maroon siltstones and mudstones with localized lenses of grey shale. Thin irregular beds of pink limestone occur near the top of the formation. Hersey shales have yielded a fossil assemblage of pelecypods, gastropods, and ostracodes. Ostracodes present within the formation indicate the unit may straddle the Silurian-Devonian boundary (408 m.y., Palmer, 1983)(Berdan, 1971). The Hersey has an estimated thickness of 2700' (Bastin and Williams, 1914).

The Eastport Formation was first named by Bastin and Williams (1914). The lowest section of the unit is stratigraphically equivalent to the Hersey Formation; the upper contact is marked by a fault. The Eastport consists of an assemblage of fossiliferous clastic rocks and limestones intercalated with bimodal volcanic flows, tuffs, and breccias. Upper sections of the Eastport Formation were deposited subaerially, while other portions were deposited in exclusively marine environments (Gates, 1977). Six units have been defined within the Eastport. These include a basaltic andesite member, rhyolite vitrophyre and breccia, basaltic tuff breccia member, fossiliferous limestone member, rhyolite lithic, vitric tuff member, and a fossiliferous siltstone and shale member (Gates, 1977).

Thin andesite flows and thick-bedded basaltic tuff breccias are interbedded with maroon mudstones in the lower part of the formation. These same andesite flows intermingle with fossiliferous siltstones of the Eastport Formation along the shores of Cobscook Bay (Gates, 1977). Basaltic andesite occurs in two other horizons within the formation. A thick sequence of flows overlies the basal series and another group of lavas occurs near the top of the section. The basaltic andesites consist of ophitic intergrowths of augite and plagioclase (An₆₅-An₇₅) with occasional phenocrysts of labradorite (Abbott, 1986, Gates, 1977). The flows are commonly vesiculated, especially near their tops, and locally exhibit red-colored weathering horizons along their upper surfaces. The middle of the formation consists of rhyolitic, lithic, vitric tuffs. These contain pink to maroon ash flows incorporating pieces of vitrophyre, pumice, and devitrified fragments.

The upper Eastport Formation consists of a fossiliferous assemblage of well-bedded shales, siltstones, and breccias. These sedimentary rocks are well cross-bedded, and display ripple marks, cut-and-fill channels, and mudcracks (Gates, 1977). The fossil assemblage collected from the formation contains *Lingulids*, pelecypods, gastropods, ostracodes, and has been assigned a Gedinnian (408-401, Palmer, 1983) age (Berry and Boucot, 1970). Amos (1958) estimates the thickness of the Eastport Formation at 7900 feet based on the average thickness and attitude of its members.

The Perry Formation is the youngest unit observed within the Coastal Volcanic Belt. This fluvial deposit was first studied by Smith and White (1905), and included in Bastin and Williams's (1914) study of the Eastport Quadrangle. The unit rests unconformably on the Eastport, Hersey, and Leighton formations and upon the Red Beach granite. Gates (1977) has mapped three members of the Perry Formation. The bulk of the formation is

composed of a maroon to red colored boulder-pebble conglomerate which includes clasts from the underlying volcanics, as well as clasts from the Red Beach granite upon which it rests. The conglomerates are interbedded with fossiliferous arkosic sandstones, siltstones, and mudstones containing plant fragments. Gates (1977) describes one hydrothermally altered, amygdaloidal, labradorite-augite basalt flow within the formation. Several lines of evidence have been cited suggesting the Perry Formation is a terrestrial fluvial deposit. Alluvial fan, overbank, and lacustrine deposits have been described within the Perry Formation (Schluger, 1973). The Perry Formation has yielded plant fragments, indicating an Upper Devonian age for the formation (Smith and White, 1905).

Distal Coastal Volcanic Belt

A small section of Silurian strata crops out in the vicinity of Calais, Maine. These units (The Oak Bay and Waweig Formations) are considered to be distal equivalents of the Coastal Volcanic Belt through fossil correlation (Ludman and Hill, 1986). The oldest formation within the stratigraphy is the Oak Bay Formation of Ruitenberg, (1967). This polymict conglomerate contains well rounded clasts of tonalite, granite, volcanic rocks, quartzite, and limestone in a matrix of dark-brown pelite deposited upon an erosional unconformity above the Tremadocian (505-488 m.y., Palmer, 1983) Calais Formation (Ludman, 1981, Amos, 1958, Abbott, 1986). The Oak Bay has been intruded and locally metamorphosed by dikes of both felsic and dioritic compositions (Amos, 1958, Ludman, pers. comm.). Neither the upper or lower contact of the unit is exposed; estimates of the thickness range from 320' to 1300' (Amos, 1958).

The Oak Bay Formation grades rapidly upward into the overlying Waweig Formation. The Waweig is composed of calcareous and non-calcareous feldspathic and lithic

greywackes, siltstones, and mudstones with locally abundant volcanoclastic deposits (Gates, 1984, Ludman, 1981). A shallow water *Salopina* fauna, characteristic of the Leighton Formation, has been identified, leading to the correlation of these two units (Pickerill, 1976).

Stratigraphic control on the ages of pluton emplacement

The sedimentary units of the Calais, Maine area provide important control on the ages of intrusion of plutons within the region. Each pluton intrudes at least one formation, constraining a maximum age of emplacement for the body. Only the Red Beach granite has complete stratigraphic control on its age, having both intruded and contributed detritus to sedimentary units.

The Baring granite, situated on the northwest margin of the MIC, intrudes the Woodland Formation of the Cambro-Ordovician Cookson Group. The Woodland Formation has been assigned an age between Tremadocian (505-488, Palmer, 1983) and Middle Caradocian (458-448, Palmer, 1983) based on fossil control and stratigraphic position (Ludman, pers. comm.) The Calais Gabbro-Diorite also intrudes the small portion of Cookson group sediments near the town of Calais, where partial melting of the country rock is evident.

The Charlotte, Meddybemps, and Red Beach granites intrude the Leighton Formation of the Coastal Volcanic Belt. The Leighton Formation has been assigned a Pridolian age based on its well documented fossil assemblage consisting of *Salopina* brachiopods, pelecypods, gastropods, and trilobites (Berry and Boucot, 1970). The Red Beach granite also intrudes the Gedinnian (408-401, Palmer, 1983) aged Eastport Formation, further

constraining its age of emplacement. As previously stated, the Red Beach granite has contributed sediment to the Upper Devonian Perry Formation, resulting in complete stratigraphic control on the age of emplacement for this pluton.

Further constraint is placed upon the ages of emplacement for plutons which have intruded sediments of the Coastal Volcanic Belt. The complete sedimentary package within the Coastal Volcanic Belt has been folded after deposition of the Gedinnian Eastport Formation (Ludman pers. comm. (04/28/90)). Any plutonic rock intruding any part of this sedimentary sequence must be younger than the Gedinnian ($401 \pm 18 - 408 \pm 12$ Ma, Palmer, 1983). Cookson Group rocks within the Penobscot-Cookson terrane and intruded by the Baring granite, are also folded. However, the timing of this folding is not well constrained, and correlation of the folding event within the Penobscot-Cookson terrane with the folding in the Coastal Volcanic Belt is suspect.

Geology of the Igneous Rocks of the Calais Area

The Calais area hosts a variety of igneous rocks exhibiting widely disparate compositions, textures, and field relations. Collectively, the plutons cover an area of approximately 415 km², with felsic rocks making up 68% of the present exposure. However, detailed radiometric dating of plutonic rocks from this region (discussed in a later section) has shown that these plutons were emplaced in two distinct magmatic cycles and cannot be considered as one plutonic episode, regardless of their spatial associations. Based on age determinations, field relations, and isotopic characteristics, the plutonic rocks have been divided into two broad groups. Lithologies associated with the older magmatic event are contained within the Moosehorn Igneous Complex and are characterized by mafic-dominated bimodal magmatism. The other plutons are grouped into younger granites and consist of a compositional assemblage dominated by granites.

Igneous complexes highlight a distinctive style of magmatism observed within the coastal belt during the Late Ordovician-Silurian magmatic event. The complexes are distinguished by a spatial and temporal association of both mafic and felsic rocks, exhibiting a wide range of rock textures. These igneous complexes may be intruded by later plutons, generated during completely independent tectonothermal events. In order to better understand the tectonic significance of these igneous complexes and the processes responsible for their formation, a detailed study of the Moosehorn Igneous Complex, as type example, was undertaken. Although field studies focused on the Baring granite (see geologic map), reconnaissance mapping and sampling was done on the other igneous bodies to provide a basis for areal distribution and petrographic comparison.

Geology of the Moosehorn Igneous Complex

The Moosehorn Igneous Complex (MIC) crops out over an area of 200 km² and straddles the US-Canadian border at Calais, Maine (Figure 4). The complex consists of five units: the Baring granite, Calais Diorite-Gabbro complex, St. Stephen gabbro, Staples Mountain gabbro, and several unnamed gabbro and diorite bodies (SDd and SDga on geologic map). Mafic rocks account for approximately 70 % of the exposure at the present erosional level. The complex was intruded into the Cambro-Ordovician metasediments of the Cookson Group exposed to the northwest and is bounded by younger granite plutons to the south and east.

Baring Granite

The Baring pluton lies to the southwest of Calais, Maine. The granite crops out over an area of nearly 55 km² and is roughly elliptical in outline with a northeasterly trending major axis. Several small (< 3 km²) outliers of the granite occur outside the contact of the main body, most notably the body of granite adjacent to the Meddybemps pluton south of Bearce Lake (Little Lake on geologic map). Baring granite intrudes metasediments of the Cookson Group on the western margin of the pluton with a fairly sharp contact. The contact style is best observed across U. S. Route 1, 3.3 km ESE of Woodland, although a narrow screen of diorite lies along the contact here. The granite intrudes St. Stephen gabbro along the northern contact of the pluton in New Brunswick, Canada (Ludman and Hill, 1986). A small section of Cookson Group metasediments is intruded by the Baring granite in the vicinity of Calais along the eastern margin of the pluton with a very irregular contact. The contact is different from the western contact with the metasediments in that

it is characterized by variable amounts of granite invading the metasediments in dikes ranging in thickness from several centimeters up to several meters wide. Zones of brecciated country rock occur along the contact in several areas. Garnet porphyroblasts are observed in the metasedimentary rocks immediately adjacent to the granite contact, and garnet xenocrysts (?) occasionally are entrained in the adjacent granite, suggesting a degree of reaction and assimilation at the margins of the granite. Samples for isotopic study were not collected from such areas. Intrusive relations along this contact are best observed in a small quarry to the east of U. S. Route 1 just north of Milltown, while the development of garnet along the contact may be observed in exposures along U.S. Route 1 in the northern end of Milltown.

Baring granite intrudes the mafic lithologies of the Calais Diorite-Gabbro unit along a fairly narrow contact. The granite displays a grain size reduction (6-7 mm potassium feldspar average in clean granite, 2-3 mm average in contact facies) towards the mafic unit and locally develops a porphyritic texture. A foliation (average orientation 333° 45-65° NE) of mafic minerals parallel to the contact is developed in the granite in a 250 m wide zone along portions of the contact. The contact facies is best observed in the Moosehorn Wildlife refuge to the west of the old Headquarters road (on geologic map-solid line contact due east of Conic Lake). The grain size reduction and flow fabric suggest emplacement of the granite into a cooler country rock. The small outlier of Baring granite south of Bearce lake is in fault contact with the Meddybemps granite. This contact is best exposed along the northern edge of the peninsula leading to Hardwood island in Meddybemps Lake. Baring granite also intrudes the Staples Mountain gabbro on the southeastern edge of the pluton. Dikes of the granite cut and enclose angular blocks of

the gabbro along the margin. This contact is most easily observed 0.3 km south of the eastern end of Staples Cove at the northern end of Meddybemps Lake.

The Baring granite is divided into three units based on field observations. The bulk of the pluton crops out as a "clean" granite phase (SDb on geologic map). This unit is characterized by outcrops which are relatively free of metasedimentary or igneous xenoliths. The rocks exhibit a chalky white color in hand samples and show slight variations in texture across the pluton in relation to proximity of contacts. Rare miarolitic cavities occur along the northeast contact with the Cookson Group metasediment and in the enclave zones. Aplite dikes intrude locally throughout the pluton but are never abundant. No pegmatite dikes were observed within the Baring granite.

A contact facies of Baring granite has been mapped along the eastern margin of the pluton adjacent to the Calais Gabbro-Diorite unit and Cookson Group metasediments (SDbc on geologic map). This unit occurs in a narrow zone (approximately 250 m wide) against the diorite and is distinguished by a porphyritic to sub-porphyritic texture, finer grain size, grey color, and prominent foliation (average orientation 333° 45-65° NE). This unit is not well exposed along its length. The best exposures of the contact facies lie within the Moosehorn Wildlife Refuge 1.3 km to the east of Conic Lake and to the west of the old Headquarters road within the wilderness area. The contact zone between the granite and Cookson Group metasediments has been defined along the contact in the vicinity of Calais north and east of Magurrewock Mountain. The zone varies in width from tens of meters wide to a maximum of 0.6 km wide on Magurrewock Mountain. Within the zone, dikes of the granite ranging in thickness from several centimeters to meters wide cut and enclose blocks of the metasediment. Garnet porphyroblasts are present in the metasediment

adjacent to Baring granite dikes, and locally, garnet xenocrysts (?) are entrained in the granite.

The third unit of the Baring granite is defined by zones of mafic enclaves within the granite along contacts with mafic bodies (SDbm on geologic map). The largest such zone surrounds a mass of diorite and gabbro extending from the shore of Meddybemps Lake near Staples Mountain northeast towards US Route 1. This facies is best observed in a series of outcrops exposed along US route 1 between routes 191 and 9. Mafic enclave zones are characterized by rounded to angular, intermediate to ultramafic (?) enclaves ranging in size from 1 - 2 centimeters to 1 - 2 meters across. The enclave zones are defined as containing between 10-90% mafic material in association with felsic material in the field. The zones also contain disrupted dikes of mafic material. Granite textures and compositions within these areas are highly variable.

As enclave zones are approached in the field, the modal abundance of mafic material increases. Enclaves within the Baring granite exhibit a large range in shape, size and apparent composition (Jurinski, 1987). There seems to be no preferred orientation to the enclaves; rather, they have a completely random distribution. Within exposures, the abundance of the enclaves varies. The enclaves may cover from 0 to nearly 50 percent of an outcrop surface. Zones with many enclaves are found within 5-10 meters of areas which are relatively free of enclaves. Enclave size ranges from 2.0 cm to 100.0 cm, with an average size of approximately 25.0 cm. There is no apparent relation between size and composition or shape.

The enclaves show considerable variation in shape (Jurinski, 1987). Some exhibit straight angular margins while others possess rounded edges (Photos 1 and 2). Certain



Photo 1: Enclaves showing straight, angular margins with the enclosing granite.

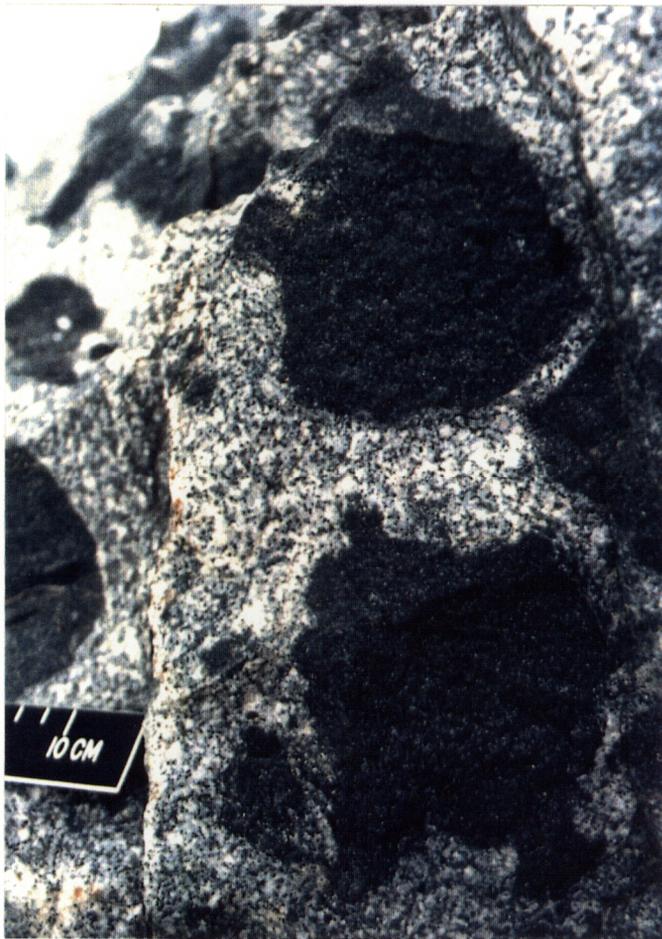


Photo 2: Enclaves showing rounded margins with the enclosing granite.

enclaves exhibit cusped margins possibly indicating a liquid-liquid interaction during formation of liquids with varying viscosities (Photo 3) (Vernon, 1984). Angular enclaves tend to be slightly larger, on average, than the rounded enclaves, although rounded enclaves up to 60 cm have been observed. Groups of enclaves with the same shape tend to occur together, that is there are zones of rounded and zones of angular enclaves (Photo 4).

Compositional variation among enclaves is common (Jurinski, 1989). Along the granite-Cookson Group contacts, metasedimentary xenoliths are often abundant. These tend to have a larger grain size and lower color index than the enclaves of dioritic (mafic) composition. Mafic enclaves vary from very dark blocks to very diffuse patches barely distinguishable from the host granite. Melanocratic enclaves are mostly biotite-rich while more diffuse enclaves contain plagioclase and less commonly potassium feldspars. Porphyritic enclaves with plagioclase phenocrysts have been observed, usually among the melanocratic enclaves.

The margins of some enclaves show distinct contacts with the enclosing granite in thin section. The margins are marked by large discrepancies in grain size between coarse granite and fine grained enclave. This is accompanied by a marked decrease in biotite and plagioclase abundances within the granite. The mafic enclaves locally contain relict pyroxene crystals mantled by either amphibole or feldspar. The margins may occasionally be marked by an increase in biotite seen in dark 1 to 2 mm bands along the enclave margin.

Rare, late-stage diabase dikes (330° steep dip) cut the Baring granite. The dikes are composed of fine grained diabase in 1-2 m wide dikes with well defined, straight contacts with the enclosing granite. These dikes are most abundant along U. S. Route 1 and Maine



Photo 3: Enclaves showing cusped margins.

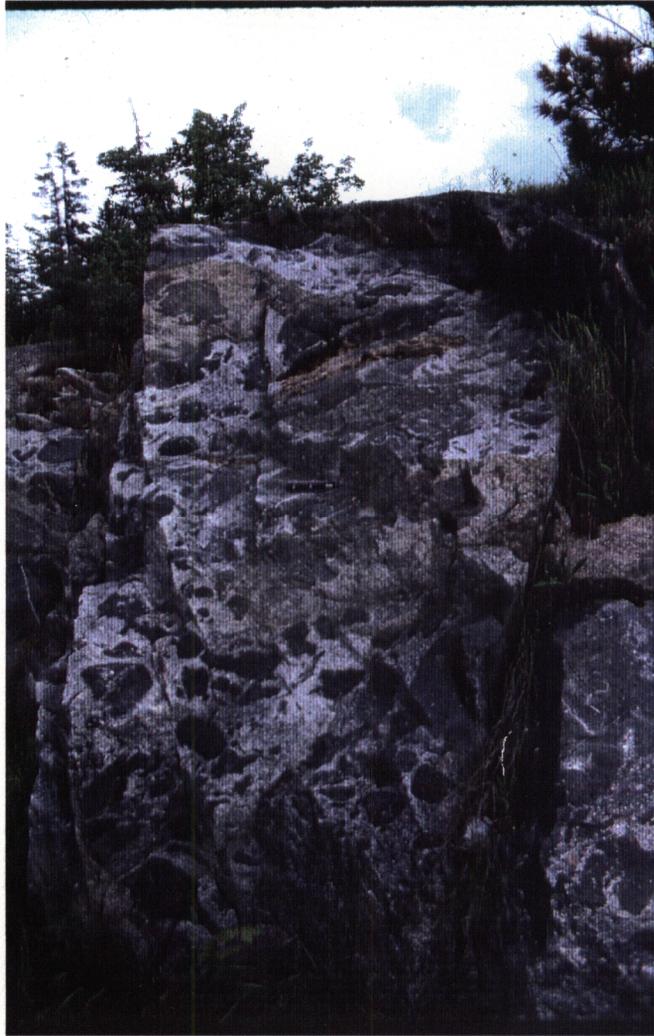


Photo 4: Enclaves in swarms within the
Baring granite

Route 191 near the intersection of these two roads.

Staples Mountain Gabbro

The Staples Mountain gabbro crops out along the northeastern shore of Meddybemps Lake in an unusual outcrop pattern (SDsmg on geologic map). The body appears to be composed of two lobes separated by a fault (Amos, 1958, 1963, Coughlin, 1986). Staples Mountain gabbro is also fault-bounded to the southwest (Amos, 1958, 1963, Coughlin, 1986). The contact between the gabbro and Baring granite to the northeast is marked by granite dikes intruding the upper portion of the gabbro, and locally enclosing xenoliths of the mafic rock (Coughlin, 1986). Contacts between the gabbro and diorite to the north are obscured by Meddybemps Lake, hence intrusive relationships remain unclear.

The Staples Mountain gabbro has been divided into five units based on major and trace phase mineralogy as well as the presence or absence of layering (Coughlin, 1986). The stratigraphy, from bottom to top, consists of a basal unit of layered olivine gabbro, non-layered augite gabbro, layered anorthosite and norite, non-layered augite gabbro, and an upper unit of non-layered gabbros. These were designated by Coughlin as units I, II, III, IV, and V. Contacts between the units strike 330° and dip 15° SW on average.

Unit I is 134 m thick and occurs along the southwest margin of the gabbro body. This is a minimum thickness estimate since the unit is cut by a fault at its base. The basal unit is coarse grained and layered, with layers ranging in thickness from 1 to 30 cm. The rock is composed of labradorite, hypersthene, augite, pigeonite, olivine, magnetite and ilmenite with varying amounts of trace apatite, biotite, pyrite, and chalcopyrite. On average, olivine constitutes 5 modal percent of the rock, but locally occurs in lenses up to 1 m thick in

which 25 % of the rock is olivine.

Non-layered augite gabbros constitute the second unit. Unit II is composed of olivine, augite, pigeonite, hypersthene, labradorite, hornblende, magnetite, ilmenite, and trace amounts of apatite and biotite. A well developed foliation parallel to the contact with unit one was reported. Unit II is 113 m thick.

Unit III contains layered norite and anorthosite and is 40 m thick. Modal plagioclase abundance varies from 55 % in norite layers to a high of 94 % in the anorthosite layers. The rock also contains hypersthene, augite, hornblende, magnetite, ilmenite, apatite, and biotite. No olivine was observed in this unit. Layer thickness varies from 1 cm to 1 m with no gradation in grain size noted between the layers.

A second section of non-layered augite gabbro makes up the fourth unit. The rock is similar in appearance to Unit II, and also shows a foliation parallel to the contacts between the units. The rock is composed of augite, pigeonite, labradorite, hornblende, magnetite, ilmenite, hypersthene, and up to 5 % olivine. The rock is more olivine-rich near the top of the unit. The unit has a reported thickness of 144 m.

The upper unit of the Staples Mountain gabbro consists of non-layered gabbros. The unit is similar to the augite gabbros of unit IV, except that unit V rocks contain a greater abundance of hypersthene and lack olivine. The upper unit has a thickness of 64 m and is intruded by the Baring granite.

St. Stephen Gabbro

The St. Stephen gabbro lies to the north of the Baring pluton and underlies a roughly circular area of approximately 24 km² (SDsga on geologic map). The pluton intrudes

Cambro-Ordovician metasediments of the Cookson Group to the north, west, and east and is in turn intruded by the Baring granite to the south (Paktunk, 1986; Ludman and Hill, 1986). A narrow screen of Cookson Group metasediments surrounds the exposures of the St. Stephen gabbro in the U. S. in the town of Calais. Metasediments in this zone have been highly metamorphosed, possibly to the point of melting. The melt zone is exposed in the town of Calais in exposures located on the southeast edge of the parking lot of the Ames department store (Photo 5).

Four map units have been defined for the intrusion based on petrography and appear to define a zoned pluton (Paktunk, 1986). The outer unit is composed of gabbro and anorthositic gabbro, while the middle unit contains troctolite, olivine gabbro, olivine norite, and anorthosite. The core of the intrusion consists of peridotite (Figure 5). Several small quartz diorite dikes (average width 20 cm) cut the middle member of the intrusion (Paktunk, 1986). Contacts between the units are gradational and are drawn arbitrarily on Figure 5.

Calais Diorite-Gabbro Unit

The Calais Diorite-Gabbro unit is the largest component of the MIC covering an area of 105 km² (SDcdg on geologic map). The unit is best characterized by its high degree of variability. It has been the subject of three detailed studies, each of which has resulted in a different set of map units (Amos, 1958, Abbott, 1977, Ludman and Hill, 1986). Rock types range from olivine gabbro through quartz diorite to granite, while contacts between the lithologies vary from gradational to sharp.

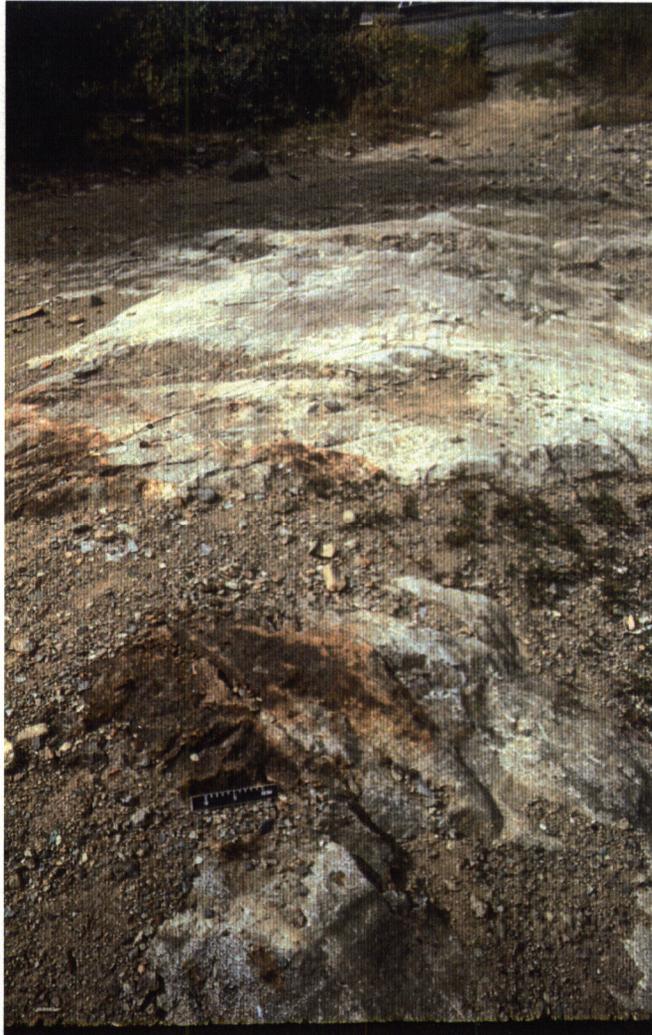
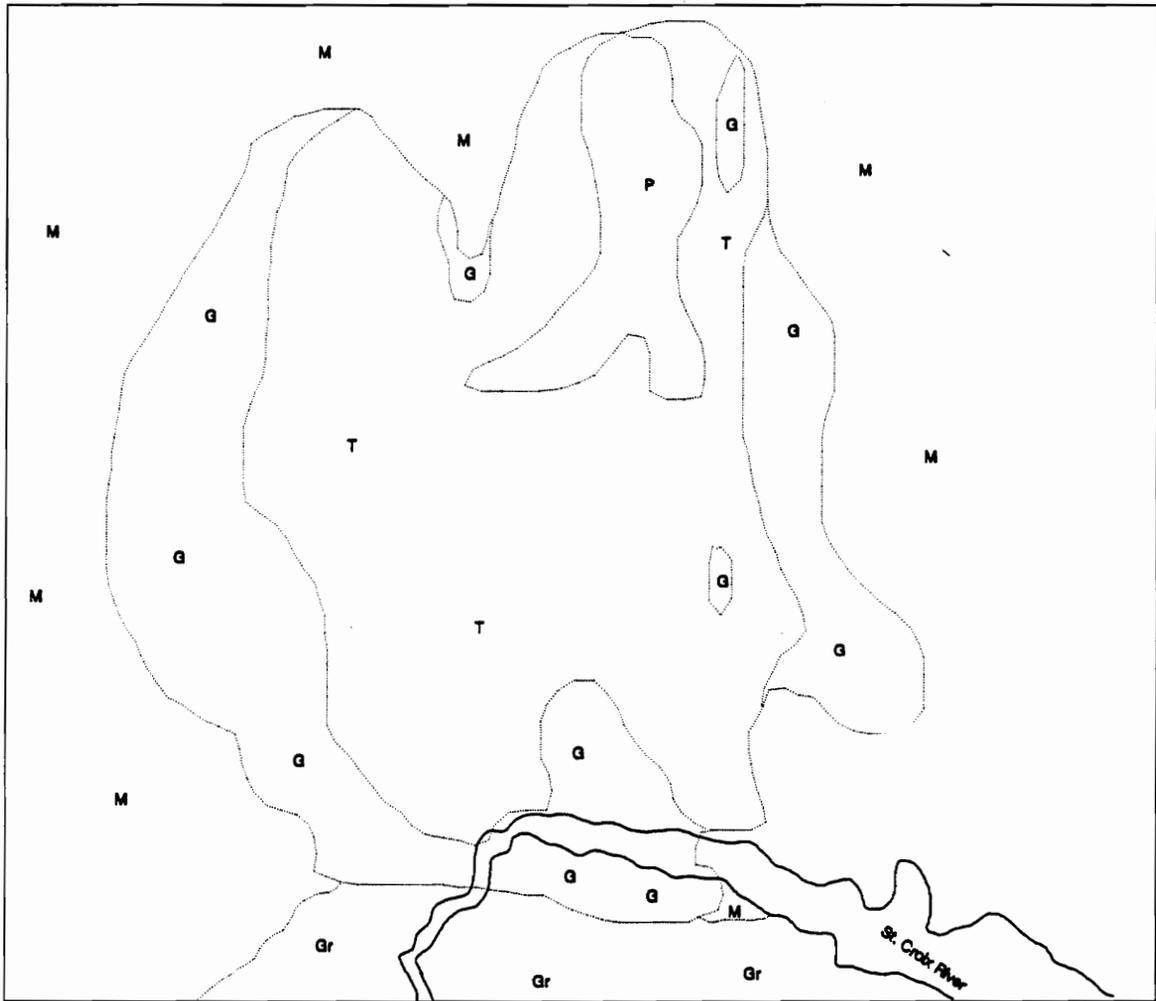


Photo 5: Melt zone between the St. Stephen gabbro and Cookson Group metasedimentary rocks.



St. Stephen Gabbro

G: Gabbro, Anorthositic Gabbro

T: Troctolite, Olivine Gabbro, Olivine Norite, Anorthosite

P: Peridotite

Gr: Granitic Rocks (Baring granite)

M: Metasedimentary rocks (Cookson Group)

Figure 5: Schematic map of the St. Stephen gabbro. Modified from Paktunk (1987).

The earliest detailed investigation on the mafic rocks of the Calais unit was conducted by Amos (1958, 1963) who recognized that the more mafic compositions (gabbros and norites) were intruded by intermediate mafic rocks (diorites of variable composition). The most mafic compositions include olivine norite, norite, hornblende norite, hypersthene gabbro, gabbro, pyroxenite, anorthosite, and harzburgite and are reported as being pre-Silurian in age (Amos, 1958). These rocks were grouped according to internal structure into banded rocks, non-banded rocks, and contact rocks. Banded rocks were inferred to underlie the non-banded variety and considered to be slightly older. More intermediate compositions described in Amos (1958) included biotite quartz diorite, biotite diorite, biotite hornblende diorite, and granodiorite, and were interpreted as having a post-Silurian age. The gradational nature of the contacts between the varieties of intermediate rocks, coupled with the scarcity of outcrop within the unit, prevented distinction of contacts between the various lithologies.

Three Maine Geological Survey open file reports described lithologies contained within the Calais Diorite-Gabbro unit. Mafic rocks within the Calais 15' quadrangle were divided into mafic and intermediate compositions (Ludman and Hill, 1986). Mafic rocks included unnamed gabbros, St. Stephen gabbro, Staples Mountain gabbro, and the Woodland Dump gabbro. Intermediate lithologies were divided into the Mt. Tom andesite and into unnamed diorites. Mafic rocks of the Calais diorite-gabbro unit in the adjoining Devil's Head, Robbinston, and Red Beach 7.5' were examined by Abbott (1986). Four units were defined for the diorite gabbro complex in this area. Mafic and intermediate plutonic rocks were divided into gabbros, granodiorite, mixed rocks, and pillow diabase. Most of what Amos (1958, 1963) mapped as gabbro and diorite was included in the gabbro unit of Abbott.

Granodiorite occurs as mappable bodies intruding the gabbro, and is relatively homogenous in appearance across the area. However, the unit exhibits a large variation in modal abundance of minerals and overlaps the quartz diorite and diorite fields in the CIPW classification scheme (after Streckeisen, 1973) (Abbott, 1986). Abbott's mixed rock unit is very similar to the aforementioned Baring granite mafic enclave zones and contains angular fragments of mafic material in a dioritic to granitic matrix with associated diabase pillows. Abbott reports two modes of occurrence for this unit. The first is a contact facies between gabbro and granodiorite units, the second as isolated patches within the gabbro.

The pillow diabase unit is distinguished by variably shaped pillows of diabase in a felsic matrix. Pillow shapes vary from well-rounded to angular, while the percentage of matrix varies from almost 100 % to 10 %. Pillowed diabase in its host matrix occur as dikes within the gabbro unit. Hill and Abbott (1989) focused on the interaction of felsic and mafic lithologies in the Calais diorite-gabbro unit. The gabbro-diorite unit was divided along the lines of Abbott (1986), although a diorite unit defined as having plagioclase compositions $< An_{50}$ was added.

Geology of the Younger Granites

The southern and eastern margins of the MIC are intruded by large biotite \pm hornblende granites (figure 6). These include the Red Beach granite to the east, the Charlotte granite to the south, and the Meddybemps granite to the southeast. All younger granites intrude the Siluro-Devonian volcanic sequence to the southeast. The Meddybemps also intrudes Cambro-Ordovician Cookson Group metasediments to the northwest. Only

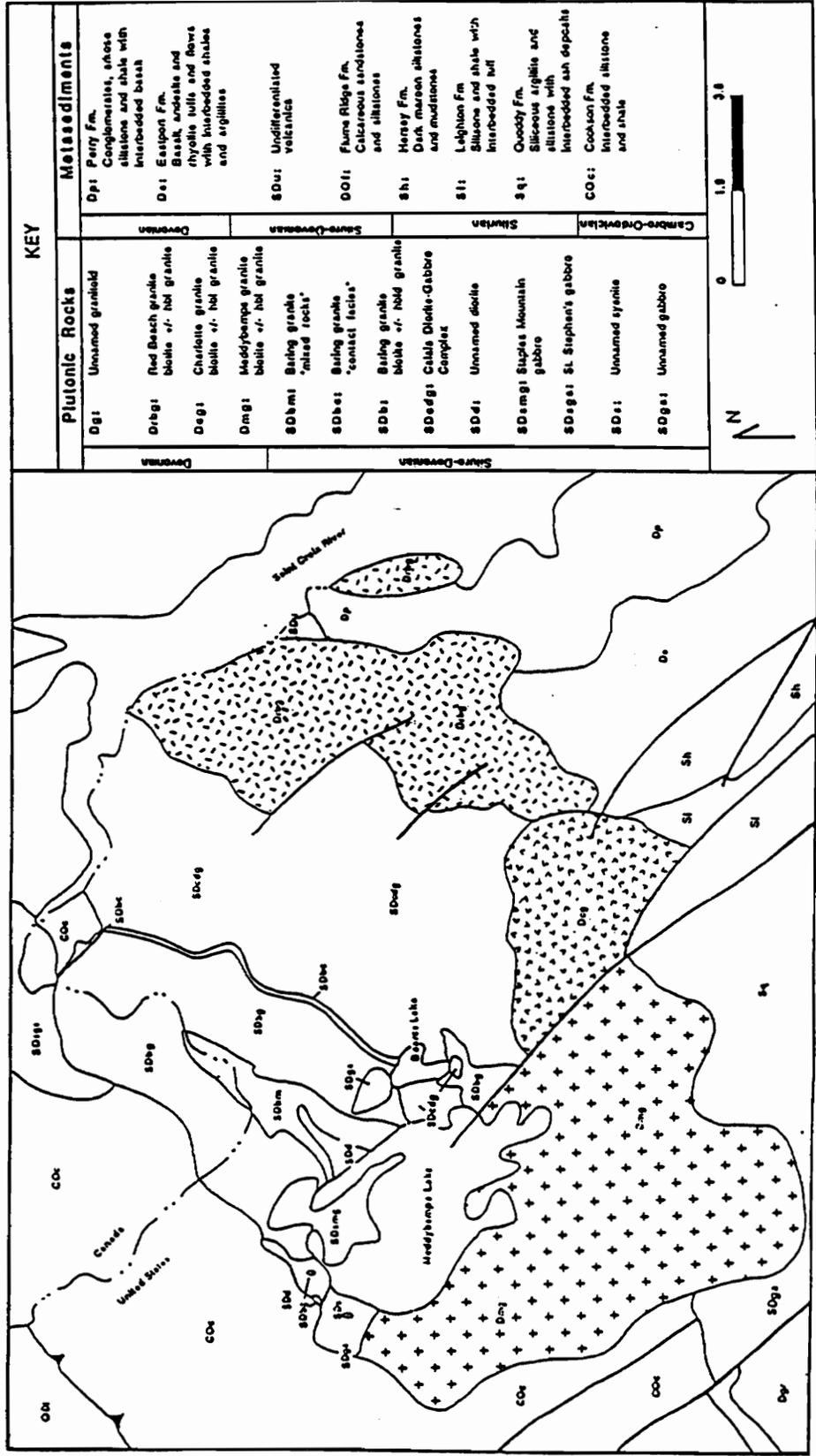


Figure 6: Geology of the Calais, Maine area. Younger granites are shown in stippled patterns. Modified from Osberg et al. (1985).

the Red Beach granite has complete stratigraphic control on its age, having contributed detritus to the overlying Upper Devonian Perry Formation. While not studied in great detail as part of this project, descriptions of these bodies are included to provide a comparison with felsic members of the MIC.

Meddybemps Granite

The Meddybemps granite (Dmg) is the largest of the younger plutons, cropping out over the central portion of the Calais 15' quadrangle and the northern half of the Gardner Lake 15' quadrangle to the south (Amos, 1958, Gates, 1978). The granite covers an area of approximately 126 km² and is the single largest plutonic body within the Calais region. Unfortunately, the pluton does not crop out well; its best exposures are located near the village of Meddybemps on Green Hill.

The granite is a massive, medium grained, rock throughout most of its exposure, and presents a salmon-pink to grey color on fresh surfaces. Major minerals found within the Meddybemps include microcline perthite, quartz, plagioclase, biotite, and occasional hornblende. These are accompanied by trace amounts of apatite, zircon, magnetite, and allanite (Amos, 1958, Ludman and Hill, 1986).

Charlotte Granite

The Charlotte granite (SDcg) crops out in the southeastern corner of the Calais 15' quadrangle and extends eastward into the adjacent Robbinston 7.5' quadrangle, covering an area of approximately 36 km². The granite intrudes the Leighton shale to the southeast, and diorite along its northern margin. A contact facies has been defined for the pluton

characterized by a grain size reduction, change in mineral chemistry, and occasional development of a sub-porphyritic texture (Amos, 1958, Abbott, 1986). Scattered aplite dikes occur throughout the pluton, but are not abundant. Similarly, mafic enclaves within the pluton are rare, occurring only as small elliptical blebs (Ludman and Hill, 1986).

The bulk of the Charlotte granite crops out as a mass of light tan to salmon colored, chalky white weathering, seriate, biotite \pm hornblende granite. Major minerals within the rock include quartz, plagioclase, perthite, biotite, and locally hornblende; trace phases observed include zircon, apatite, hematite, and magnetite (Amos, 1963, Ludman and Hill, 1986).

Red Beach Granite

The Red Beach granite crops out along the eastern margin of the MIC in exposures covering an area of 62 km² contained within the Robbinston, Red Beach and Devil's Head 7.5' quadrangles. The body extends several kilometers northeastward into New Brunswick (Amos, 1958). Red Beach granite intrudes the Eastport and Leighton Formations, as well as diorite of the MIC, indicating a maximum age of intrusion no greater than Gedinnian age (Gates, 1977, Amos, 1958, Abbott, 1986). Constraints on the upper age of intrusion are provided by the Upper Devonian Perry Formation to which the Red Beach granite contributed detritus (Kelley and Gates, 1987, Amos, 1958, Abbott, 1986).

The first detailed mapping of the pluton resulted in its division into two phases: a biotite and hornblende-bearing phase and a biotite-bearing phase (Amos, 1958). However, recent investigation of the Red Beach granite has resulted in the definition of seven distinct phases within the pluton, as well as a group of miscellaneous biotite granites (Abbott, 1977, 1986). From oldest to youngest these include quartz-poor granophyre, quartz-rich

granophyre, hornblende granophyre, fine-grained biotite granite, coarse-grained biotite granite, and fine-grained biotite granite.

The Granite of Magurrewock Lakes

Amos (1958) defined a group of numerous, small, isolated bodies of biotite granite, which cropped out in a northeasterly trending belt, as the granites of Magurrewock Lakes. The isolated bodies are small, never exceeding 3 km² in areal exposure, and average several hundred meters in diameter (Amos, 1958). The granites are white to pink in color and consist of anhedral, granular aggregates of microcline, quartz, plagioclase and biotite (Amos, 1958). Accessory phases observed within the granite include apatite, rutile, zircon, and magnetite (Amos, 1958).

The Magurrewock Lakes granites were thought to be related to the Charlotte granite, coarse-grained Red Beach granite, and medium-grained Red Beach granite through modal and textural similarities to the latter units (Abbott, 1986). However, the Magurrewock Lakes granites are isotopically distinct from the Red Beach and Charlotte granites, possessing differing strontium initial ratios, a possible inherited lead component, and a distinctly younger U/Pb zircon age (see isotope geochemistry section).

Petrography of the MIC Units

Baring Granite

Samples of representative Baring granite consist of a medium grained, seriate aggregate of quartz, plagioclase, potassium feldspar, biotite, and occasional amphibole. Trace phases include zircon, apatite, magnetite, monazite, and allanite. The rock is light grey on fresh surfaces, weathering to a chalky white color. The average color index of hand samples collected from across the pluton is 6.2, although color index varies greatly as contacts with adjacent lithologies are approached.

Quartz occurs in polycrystalline aggregates up to 6.0 mm long composed of anhedral grains 0.1 to 1.0 mm in diameter. Plagioclase (An_{20-40}), compositions measured by the Michel-Levy method, exists as subhedral 1.0-5.0 mm laths dispersed throughout the rock. Crystals of plagioclase are locally zoned and often sericitized in weathered samples. Large (up to 9.0 mm) crystals of perthite occur in all thin sections examined and are commonly sericitized in weathered specimens. Microcline is found in several samples randomly dispersed through the rock.

Biotite appears to have formed in two distinct phases. An earlier phase, composed of subhedral 1.5 mm crystals dispersed evenly through the samples, is followed by a later phase composed of anhedral 0.1 to 0.25 mm grains interstitial to other phases within the rock. Most biotites exhibit a poikilitic texture with inclusions of zircon and magnetite. Dark brown to tan pleochroism is prevalent in biotites of the Baring granite.

Amphibole is dispersed through the granite and is not present in every sample studied. The mineral is visible in hand sample in only a few locations, including exposures adjacent

to the Baring airport and in the enclave zones along U.S. Route 1. The presence or absence of amphibole from thin sections may be a result of the sampling procedure if amphibole is rare and evenly distributed through the pluton. Thin sections of selected specimens may not "sample" enough rock to detect the presence of this phase. However, preparation of 50-75 kg of sample for mineral separation inevitably produces appreciable amounts of amphibole. In thin section, the amphibole appears olive green to brown in color and occurs in subhedral to anhedral, 0.1 to 1.0 mm crystals. These are commonly embayed with intergrowths of quartz. Allanite is observed as an accessory phase in samples with amphibole.

Crystallization Sequence

The earliest forming phases in the Baring granite are zircon and magnetite (See figure 7). They occur as small (<0.1mm) anhedral grains dispersed throughout the rock. They are commonly included in flakes of biotite. Biotite began crystallization next, possibly preceded by amphibole. The biotite appears to have a complex crystallization history as represented by two distinct morphological populations of this phase. The earlier phase consists of larger (1.5 cm) biotites evenly scattered throughout the rock while the second population contains smaller grains (0.1 to 0.25 cm) which occur interstitially to other phases. Both populations contain inclusions of zircons and magnetite and exhibit the same range of pleochroism (light tan to dark brown).

Amphibole occurs in only a few samples of the Baring granite. It appears either in clusters or evenly dispersed throughout the rock. It is often embayed by quartz and is occasionally surrounded (mantled?) by biotite. Crystallization of plagioclase appears

CRYSTALLIZATION SEQUENCE OF THE BARING GRANITE

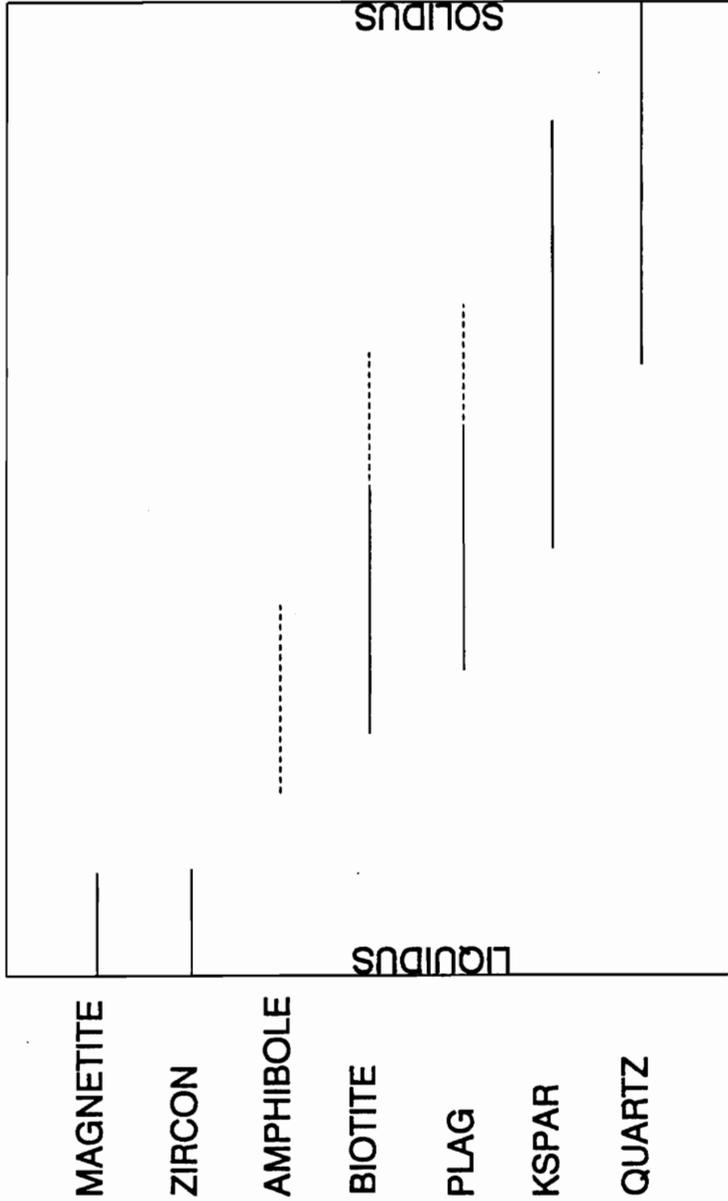


Figure 7: Crystallization sequence of the Baring granite.

contemporaneous with the formation of biotite and amphibole. No inclusions of the feldspar are contained in these phases. Some plagioclase exhibit zoning, with rounded cores often overgrown by euhedral plagioclase. Cores of plagioclases are often completely sericitized.

Potassium feldspar occurs in blocky anhedral grains up to 9.0 mm in size. These grains locally contain inclusions of plagioclase and occur with quartz. Perthitic feldspars as well as microcline occur. Myrmekite is found in a few specimens.

Quartz appears to be the latest crystallizing phase and generally occurs in polycrystalline aggregates throughout the rock. Individual grains are evenly distributed throughout the rock. The aggregates typically surround earlier forming phases such as biotite. Undulose extinction is not commonly observed and the crystals appear strain free.

Modal Analyses of the Baring Granite

Modal analyses of slabs of Baring granite stained for potassium feldspar were conducted on representative samples from across the pluton (Figure 8). The data are listed in Table 1; the locations of slabs are shown on a map in Appendix 4. The bulk of the samples analyzed fell in the plagioclase-rich portion of the granite field (plag / plag + quartz + ksp = 23-39%) (after Streckeisen, 1973), although two samples plotted in the granodiorite field. No variation in color index in relation to other phases was noted (Jurinski, 1987).

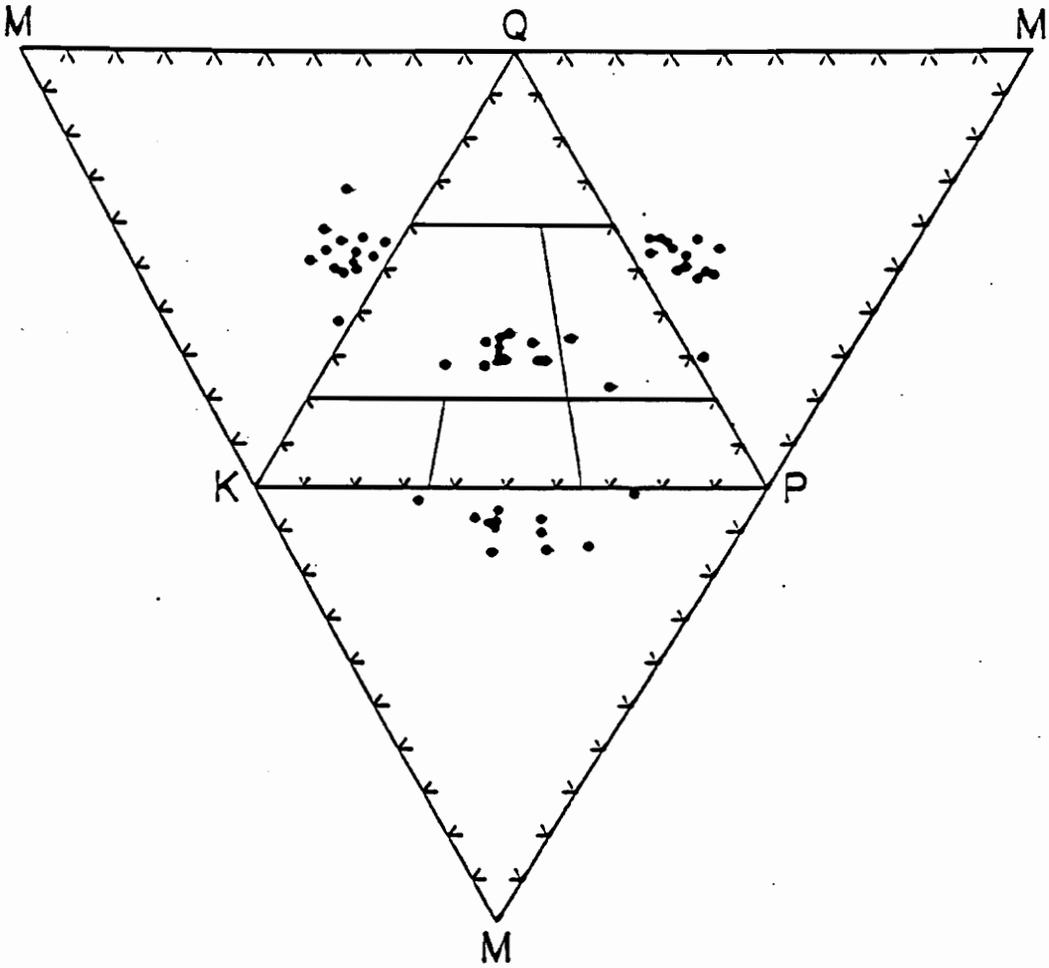


Figure 8: Modal data plotted from the Baring granite, this study.

Table 1: Modal data for the Baring granite. One count of 1000 points was made for each sample.

| <u>Sample #</u> | <u>Quartz</u> | <u>Kspar</u> | <u>Plag</u> | <u>Mafic</u> |
|-----------------|---------------|--------------|-------------|--------------|
| JJ-12-85 | 283 | 348 | 308 | 67 |
| JJ-15-85 | 254 | 337 | 297 | 113 |
| JJ-54-85 | 272 | 276 | 378 | 67 |
| JJ-55A-85 | 316 | 365 | 275 | 44 |
| JJ-55B-85 | 278 | 347 | 321 | 58 |
| CL-132 | 312 | 277 | 363 | 49 |
| CL-133 | 306 | 342 | 297 | 55 |
| JJ-5-85 | 272 | 266 | 391 | 103 |
| JJ-19-85 | 323 | 329 | 298 | 56 |
| JJ-24-85 | 280 | 496 | 232 | 22 |
| JJ-45A-85 | 311 | 193 | 418 | 100 |
| JJ-49-85 | 339 | 326 | 312 | 33 |
| JJ-49-85 | 339 | 195 | 577 | 13 |

St. Stephen Gabbro

The petrography of the St. Stephen intrusion has been briefly described by Paktunk (1986, 1987) in assessments of the Ni-Cu mineralization associated with the gabbro. Four units were defined in the gabbro on the basis of limited field mapping and core sampling. These include a marginal gabbro unit, a unit consisting troctolite, olivine gabbro, olivine norite, and anorthosite, a core facies of peridotite, and isolated dikes of quartz diorite.

The gabbros consist of plagioclase cumulates and are restricted to a marginal facies of the intrusion (Paktunk, 1987). The central facies, composed of troctolite and gabbro, hosts a range of cumulate textures. Both rock types contain plagioclase and olivine cumulus minerals accompanied by intercumulus clinopyroxene (Paktunk, 1987). The rocks of the central facies are medium grained and locally exhibit thin layering. Minor amounts of anorthosite, olivine norite, and norite accompany the troctolite and olivine gabbro and consist of varying amounts of cumulus plagioclase, olivine, and orthopyroxene.

The central core facies of peridotite is characterized by poorly layered to massive lithologies consisting of olivine cumulates. Clinopyroxene occurs in the peridotites as oikocrysts, whereas plagioclase and sulfide minerals are observed as intercumulus phases (Paktunk, 1987)

Calais Diorite-Gabbro Unit

The Calais Diorite-Gabbro unit contains a wide variety of basic and intermediate lithologies. The mineralogy of this unit has been described extensively by Amos (1958, 1963). A brief description of the mineralogy of major phases from the unit is included here. For detailed petrographic descriptions of all mafic units of the MIC, the reader is referred to Amos (1958).

Amos divided non-granitic rocks of the Calais area into two broad groups, mafic and intermediate rocks. The mafic rocks comprise norites, gabbros, pyroxenites, anorthosites, harzburgite, and syenite. Norites consist of light to dark grey, mottled, coarse to medium grained rocks of uniform grain size. Major minerals include plagioclase, orthopyroxene, and clinopyroxene, while trace minerals include olivine, hornblende, pyrrhotite, and magnetite. Amos also recognized zones of hornblende norite, characterized by brown hornblende replacing plagioclase and pyroxene as a major phase. In the norites, plagioclase occurs as subhedral grains, rarely zoned, with compositions ranging from An_{57} to An_{73} . Orthopyroxenes are weakly pleochroic, euhedral to subhedral, and have compositions ranging from En_{67} - En_{80} . Augite occurs in variable amounts through the unit and is interstitial to plagioclase (Amos, 1958).

Gabbro is the most common rock type of the mafic lithologies within the Calais Diorite-Gabbro complex. It occurs as a grey to mottled, medium grained lithology and consists primarily of plagioclase and clinopyroxene. Accessory phases include chalcopyrite, pyrrhotite, ilmenite, orthopyroxene, apatite, biotite, and hornblende. Plagioclase occurs as subhedral, rarely zoned crystals with compositions ranging between An_{54} and An_{78} . Augite shows a range in both texture and composition. Crystals range from euhedral to anhedral and are equant in coarser rocks, lath-shaped in finer grained rocks. Amos defined a hypersthene gabbro, distinguished from the other gabbros by containing appreciable amounts of orthopyroxene in addition to clinopyroxene and plagioclase.

Lithologies of intermediate composition reported by Amos in the Calais area include biotite quartz diorite, biotite diorite, biotite hornblende diorite, hornblende diorite, and granodiorite. The diorites consist of the same major mineralogy, with variations in the

abundance of certain major minerals. All diorite described include plagioclase, with compositions averaging An_{25-50} . Other major minerals, varying from among the assorted lithologies, include biotite, hornblende, and quartz. Accessory minerals often include zircon, apatite, pyrite, magnetite, hornblende, sphene, microcline, and augite (Amos, 1958).

Granodiorite occurs in localized bodies within the Calais Diorite-Gabbro unit. The rock consists of a medium to fine grained seriate aggregate of plagioclase, microcline, quartz, and biotite. Accessory minerals noted in the granodiorite include hornblende, apatite, magnetite, sphene, and zircon.

Chemistry of the Moosehorn Igneous Complex

Chemical description of igneous rocks may provide useful insight into the characteristics of source regions from which melts were generated, as chemical suites of magma have been inferred to relate to source region geochemistry (Chappell and White, 1974, Loiselle and Wones, 1979b). The chemistry and emplacement conditions of melts have a direct bearing on the resultant phase relations and mineralogy of the igneous rocks. When combined with modal and petrographic data, a comprehensive picture of the petrogenesis of the igneous bodies can be constructed.

Partial chemical analyses of samples of the Baring granite and Staples Mountain gabbro are shown in Table 2 (analytical techniques are listed in Appendix 1). CL- and JJ- series samples are from this study; SC- and Avg- samples were reported by Coughlin (1986). Elemental composition data coupled with textures and modal data observed in the rock suites of the MIC (see petrography section) can be used to model source region characteristics as well as emplacement conditions of the bodies (Naney, 1983, Maaloe and White, 1975, Loiselle and Wones, 1979b, Chappell and White, 1974). Modal data collected from the MIC are shown schematically in Figure 9 (Hogan and Sinha, 1989 (after Streckeisen, 1973)).

The Baring granite is weakly peraluminous to peraluminous after the classification scheme of Shand (1955). Calculated ANCK (mol % $\text{Al}_2\text{O}_3 / (\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$) ratios averaged $1.08 \pm .02$. The modal mineralogy reflects the high alumina saturation index through the presence of early biotite and amphibole. However, no muscovite, garnet, or other highly aluminous minerals were observed in the Baring granite, except immediately

Table 2: Partial chemical analyses from the Baring granite and associated mafic rocks. Data from this study and Coughlin (1986).

| | JJ-47-85 | JJ-55B-85 | CL-134-84 | JJ-29B-85 | Cl-133A-84 | JJ-49-85 | CL-132-84 | JJ-54-85 | JJ-52-85 |
|--------------------------------|-----------|-----------|-----------|-----------|------------|----------|-----------|-------------|-----------|
| SiO ₂ | 72.28 | 71.84 | 72.68 | 70.65 | 72.27 | 72.72 | 71.70 | 71.05 | 70.77 |
| Al ₂ O ₃ | 14.66 | 14.25 | 14.29 | 14.57 | 14.33 | 14.36 | 14.66 | 14.30 | 16.88 |
| CaO | 1.49 | 1.51 | 1.46 | 1.92 | 1.76 | 1.44 | 1.89 | 1.96 | 3.46 |
| Na ₂ O | 3.73 | 3.15 | 3.30 | 3.43 | 2.97 | 3.27 | 3.69 | 2.85 | 4.00 |
| K ₂ O | 4.29 | 4.57 | 4.40 | 4.14 | 4.31 | 4.54 | 3.87 | 4.10 | 2.88 |
| | CL-137-84 | JJ-51-87 | JJ-50-87 | SC-A | SC-B | SC-C | SC-D | Avg. gabbro | Mix. rock |
| SiO ₂ | 50.49 | 53.39 | 59.00 | 71.10 | 71.80 | 73.90 | 72.10 | 42.80 | 46.20 |
| Al ₂ O ₃ | 16.73 | 18.36 | 18.10 | 13.40 | 13.10 | 13.60 | 14.00 | 14.10 | 16.00 |
| CaO | 8.51 | 7.84 | 6.59 | 1.44 | 1.71 | 1.49 | 1.88 | 11.10 | 10.90 |
| Na ₂ O | 2.52 | 2.84 | 3.02 | 3.62 | 3.50 | 3.78 | 4.08 | 2.07 | 1.98 |
| K ₂ O | 1.32 | 1.81 | 1.66 | 3.90 | 3.86 | 3.25 | 3.43 | 0.18 | 0.61 |
| P ₂ O ₅ | 0.31 | 0.19 | 0.18 | 0.08 | 0.08 | 0.08 | 0.08 | 0.20 | 1.95 |

MOOSEHORN IGNEOUS COMPLEX

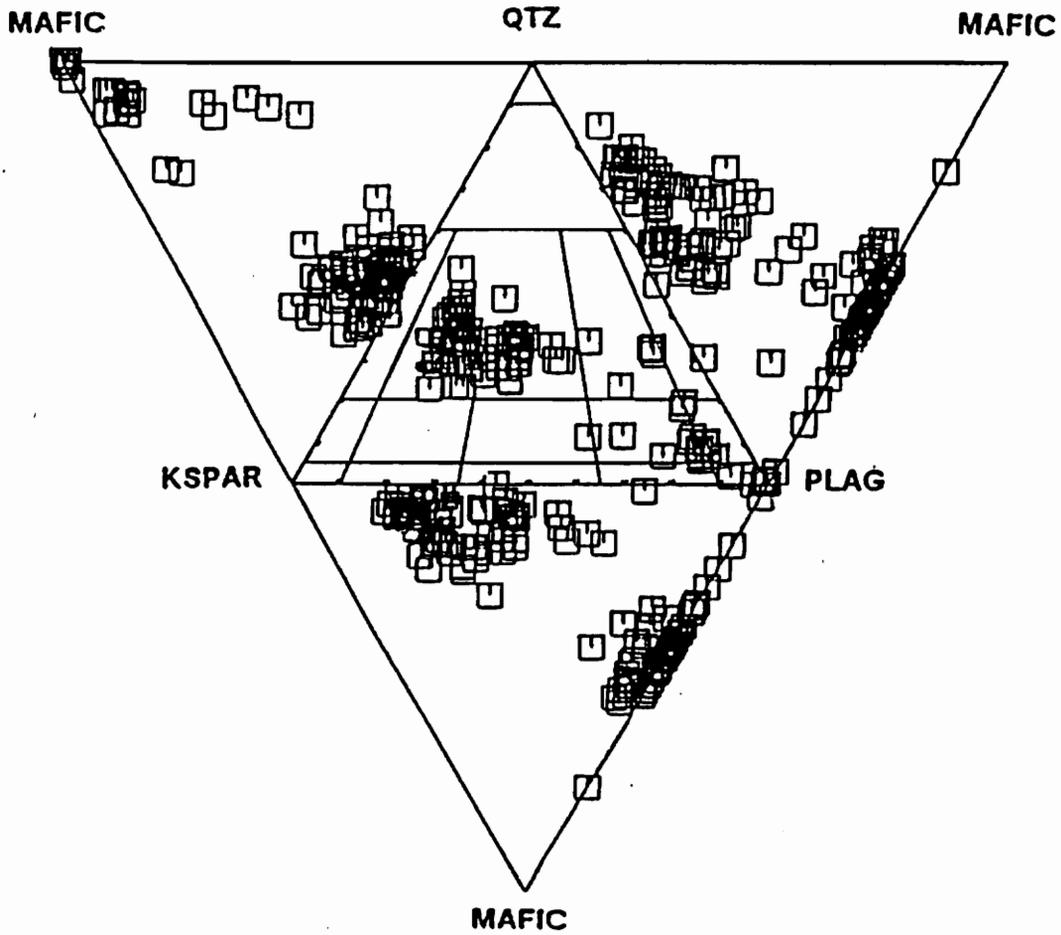


Figure 9: Modal data compiled from the MIC. Figure adapted from Hogan and Sinha (1989).

adjacent to pelitic sediments of the Cookson Group where local occurrences of tourmaline and garnet were noted.

Modal data compiled from the MIC show a pattern of distribution characteristic of a calcalkaline igneous suite (Hogan and Sinha, 1989, Barker, 1983) The MIC exhibits a predominantly bimodal distribution of compositions with the bulk of the rocks falling in the granite and diorite/gabbro fields. Other compositions observed within the igneous complex include granodiorite, tonalite, quartz monzodiorite, quartz monzonite, and quartz diorite.

Trace element data may also be employed to discriminate among the felsic rocks of the Calais area. The rubidium versus strontium variation diagram shown in Figure 10 plots data from the Calais plutons. Concentration data are tabulated in the isotope geochemistry section. Lithologies from the MIC are shown as filled in symbols. Samples from the Baring granite have lower Rb / Sr ratios, on average, than the other felsic plutons of the area, and are fairly tightly clustered in a field bounded by Rb / Sr ratios of between 1 and 2, although their SiO₂ contents show little variation (71-72 wt.% SiO₂ average). Most of the other data cluster around a Rb / Sr ratio of 3.0.

Rubidium versus Strontium

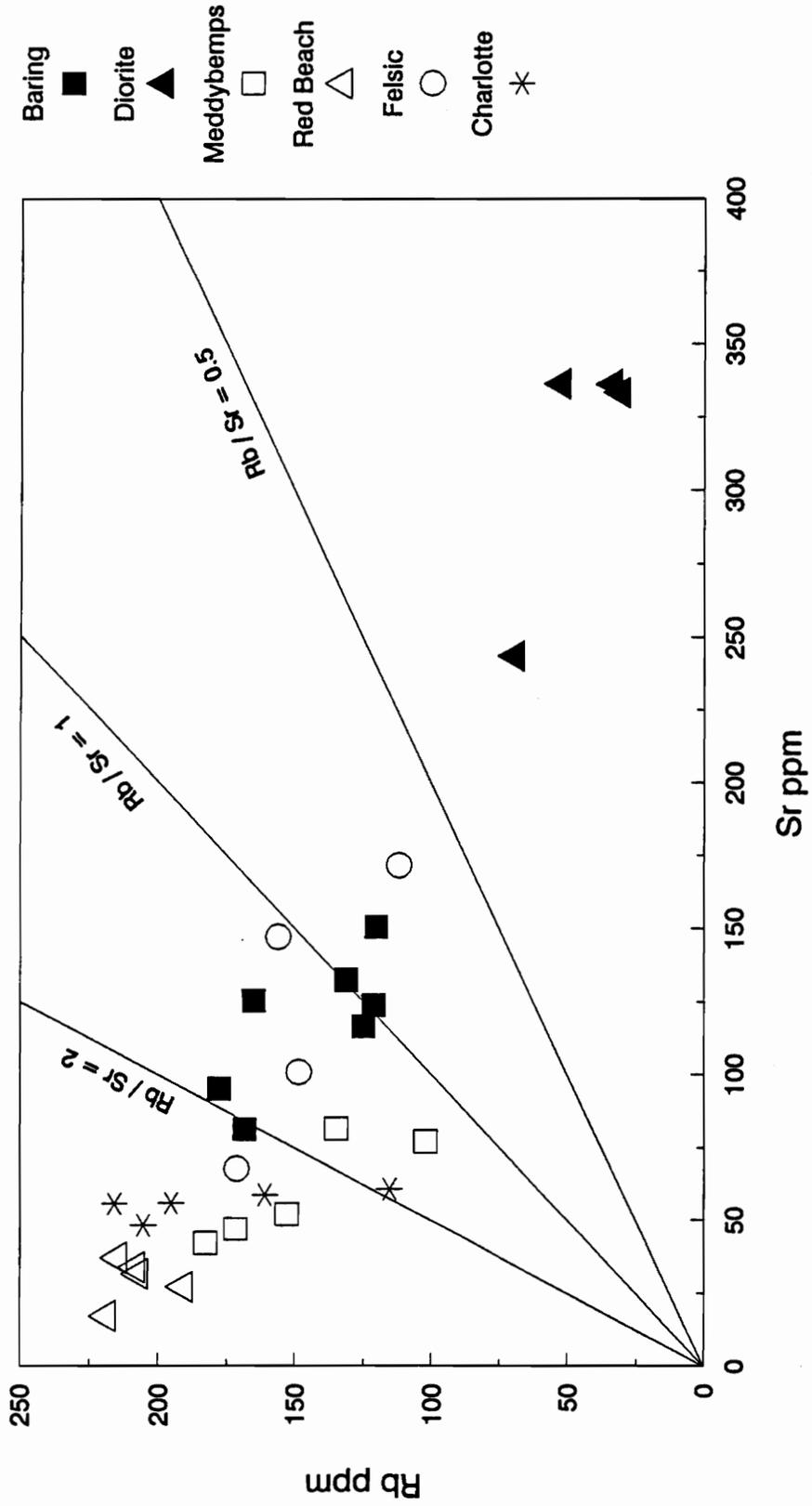


Figure 10: Rubidium versus strontium variation diagram for data from Calais area plutons.

Isotope Geochemistry

Stratigraphic age control on the timing of pluton emplacement within the Calais area is extremely limited, with most constraints providing control only on the maximum age of intrusion. Younger limits on emplacement ages are not constrained by cross-cutting relationships with sedimentary units. To model the petrogenesis of the MIC and younger granites accurately, precise radiometric age determinations (both U/Pb zircon and Rb/Sr whole rock) on plutons of the Calais area were undertaken. These age determinations allow discrimination of distinct events only suggested by field relations, permitting accurate modeling of the formation of the igneous complexes and the distinction of two magmatic cycles within the northern CMMP. Deciphering the evolution of the igneous complexes permits the modeling of the tectonothermal evolution of the crust, and an accurate assessment of the tectonic setting of the Late Ordovician-Silurian event.

Both whole rock rubidium / strontium and uranium / lead zircon analyses were conducted on the Baring, Charlotte, Meddybemps, and Red Beach granites, as well as on diorite from the Calais Diorite-Gabbro and the felsic granite intrusive into the Calais Diorite-Gabbro. Results of Rb / Sr analyses are listed in Table 3, while U /Pb information is tabulated in Table 4. Calculated ages for U /Pb analyses are presented in Table 5. Analytical procedures for all work presented are listed in Appendix 1; sample locations are shown in Appendix 4.

Table 3: Rubidium / Strontium data for plutonic rocks of the Calais, Maine area.

| Sample Number | Concentrations in ppm | | 87 Sr / 86 Sr | 87 Rb / 86 Sr |
|---------------------------|-----------------------|----------|---------------|---------------|
| | Rb conc. | Sr. conc | | |
| Baring granite | | | | |
| ----- | | | | |
| JJ-54-85 | 125.0 | 116.8 | 0.72449 | 3.10 |
| CL-132-84 | 120.4 | 150.8 | 0.71932 | 2.31 |
| JJ-558-85 | 177.8 | 95.4 | 0.73848 | 5.41 |
| CL-133A-84 | 168.5 | 81.6 | 0.74225 | 6.00 |
| CL-134-84 | 121.3 | 124.0 | 0.72330 | 2.83 |
| JJ-298-85 | 131.4 | 132.7 | 0.72273 | 2.87 |
| JJ-49-85 | 165.2 | 125.6 | 0.72843 | 3.81 |
| Meddybemps granite | | | | |
| ----- | | | | |
| JJ-96-87 | 152.9 | 52.3 | 0.75303 | 8.50 |
| JJ-377-87 | 171.8 | 47.2 | 0.76410 | 10.59 |
| JJ-378-87 | 102.2 | 77.4 | 0.72757 | 3.83 |
| JJ-379-87 | 182.6 | 42.3 | 0.77353 | 12.57 |
| JJ-380-87 | 134.8 | 81.8 | 0.73341 | 4.78 |
| Charlotte granite | | | | |
| ----- | | | | |
| JJ-162-87 | 161.0 | 59.1 | 0.75052 | 7.92 |
| JJ-163-87 | 115.4 | 61.1 | 0.73508 | 5.48 |
| JJ-169-87 | 216.0 | 56.0 | 0.76968 | 11.23 |
| JJ-170-87 | 195.3 | 56.2 | 0.76411 | 10.11 |
| JJ-181-87 | 205.5 | 48.4 | 0.77349 | 12.36 |
| Red Beach granite | | | | |
| ----- | | | | |
| JJ-307-87 | 190.8 | 27.4 | 0.80025 | 20.17 |
| JJ-308-87 | 208.1 | 34.0 | 0.79142 | 17.84 |
| JJ-309-87 | 207.0 | 31.8 | 0.79888 | 19.03 |
| JJ-310-87 | 214.6 | 37.3 | 0.78854 | 16.78 |
| JJ-311-87 | 218.9 | 17.5 | 0.86635 | 36.75 |
| Calais diorite | | | | |
| ----- | | | | |
| JJ-257-87 | 52.5 | 336.3 | 0.70745 | 0.45 |
| JJ-304-87 | 69.5 | 243.6 | 0.70910 | 0.83 |
| JJ-305-87 | 30.9 | 333.4 | 0.70554 | 0.27 |
| JJ-306-87 | 33.6 | 336.2 | 0.70540 | 0.29 |
| Felsic in diorite | | | | |
| ----- | | | | |
| JJ-166-87 | 112.0 | 172.0 | 0.71747 | 1.89 |
| JJ-64-87 | 171.3 | 68.1 | 0.74470 | 7.30 |
| JJ-61-87 | 148.6 | 101.1 | 0.72790 | 4.26 |
| JJ-59-87 | 156.2 | 147.5 | 0.72637 | 3.07 |

Table 4: Uranium / Lead data for plutonic rocks of the Calais, Maine area.

** PERCENT ERRORS LISTED AS 2 SIGMA ERRORS OF THE MEAN**

CL-133A BARING GRANITE

| SIZE | 206/204 | XERROR | u206/207 | XERROR | u206/208 | XERROR | s206/207 | XERROR | s206/208 | XERROR | s238/235 | XERROR |
|-----------|---------|--------|----------|--------|----------|--------|----------|--------|----------|--------|----------|--------|
| -200/+325 | 4345.39 | 3.56 | 17.00 | 0.052 | 11.35 | 0.079 | 16.315 | 0.047 | 2.138 | 0.022 | 20.901 | 0.27 |
| -150/+200 | 1090.59 | 1.58 | 14.51 | 0.052 | 8.63 | 0.077 | 16.330 | 0.065 | 2.124 | 0.063 | 21.047 | 0.27 |

JJ-181-87 CHARLOTTE GRANITE

| SIZE | 206/204 | XERROR | u206/207 | XERROR | u206/208 | XERROR | s206/207 | XERROR | s206/208 | XERROR | s238/235 | XERROR |
|-----------|---------|--------|----------|--------|----------|--------|----------|--------|----------|--------|----------|--------|
| -325 | 3075 | 0.806 | 16.67 | 0.0306 | 8.19 | 0.056 | 16.79 | 0.038 | 0.490 | 0.027 | 4.868 | 0.13 |
| -325 DUP | 3072 | 0.497 | 16.66 | 0.0286 | 8.17 | 0.024 | | | | | | |
| -200/+325 | 5396 | 1.840 | 17.28 | 0.0297 | 8.62 | 0.036 | 17.20 | 0.026 | 0.971 | 0.021 | 9.442 | 0.12 |
| +200 | 2276 | 0.845 | 16.35 | 0.0341 | 8.85 | 0.043 | 16.09 | 0.020 | 2.500 | 0.0255 | 29.132 | 0.15 |

JJ-307-87 RED BEACH GRANITE

| SIZE | 206/204 | XERROR | u206/207 | XERROR | u206/208 | XERROR | s206/207 | XERROR | s206/208 | XERROR | s238/235 | XERROR |
|----------|---------|--------|----------|--------|----------|--------|----------|--------|----------|--------|----------|--------|
| -200+325 | 973.2 | 0.842 | 14.27 | 0.0193 | 4.81 | 0.0123 | 14.14 | 0.0550 | 1.77 | 0.052 | 22.58 | 0.1300 |
| +200 | 1052.7 | 0.381 | 14.53 | 0.0187 | 5.00 | 0.0165 | 14.67 | 0.0212 | 1.35 | 0.021 | 15.49 | 0.1625 |

JJ-387-87 DIORITE

| SIZE | 206/204 | XERROR | u206/207 | XERROR | u206/208 | XERROR | s206/207 | XERROR | s206/208 | XERROR | s238/235 | XERROR |
|----------|---------|--------|----------|--------|----------|--------|----------|--------|----------|--------|----------|--------|
| -200+325 | 1581 | 0.46 | 15.57 | 0.0169 | 2.38 | 0.016 | 15.42 | 0.0204 | 0.6568 | 0.014 | 7.79 | 0.199 |
| -150+200 | 1270 | 0.6 | 14.92 | 0.0251 | 2.24 | 0.0235 | 14.87 | 0.0206 | 0.6682 | 0.016 | 8.239 | 0.235 |
| -100+150 | 811 | 0.85 | 13.74 | 0.0245 | 2.26 | 0.0373 | 15.55 | 0.0231 | 0.5402 | 0.0154 | 6.192 | 0.118 |

JJ-59-87 FELSIC IN THE DIORITE

| SIZE | 206/204 | XERROR | u206/207 | XERROR | u206/208 | XERROR | s206/207 | XERROR | s206/208 | XERROR | s238/235 | XERROR |
|----------|---------|--------|----------|--------|----------|--------|----------|--------|----------|--------|----------|--------|
| -325 | 4746 | 0.579 | 16.99 | 0.0203 | 12.27 | 0.0177 | 16.92 | 0.0455 | 0.2682 | 0.0154 | 2.57 | 1.221 |
| -200+325 | 10533 | 0.524 | 17.22 | 0.0195 | 14.16 | 0.0183 | 17.21 | 0.0159 | 1.1884 | 0.0184 | 11.07 | 0.166 |
| +200 | 8052 | 0.862 | 17.35 | 0.0332 | 14.23 | 0.0404 | 17.43 | 0.0215 | 1.3641 | 0.0227 | 12.99 | 0.088 |

Table 5: Ages from U/Pb analyses of zircons from this study.

| Pluton | Fraction | Ages | | | U ppm | Pb ppm |
|-----------|----------|----------------------------------|----------------------------------|-----------------------------------|-------|--------|
| | | $^{206}\text{Pb}/^{238}\text{U}$ | $^{207}\text{Pb}/^{235}\text{U}$ | $^{207}\text{Pb}/^{206}\text{Pb}$ | | |
| Baring | -200+325 | 418 | 421 | 433 | 1286 | 86 |
| Baring | +200 | 414 | 417 | 436 | 1075 | 74 |
| Charlotte | -325 | 399 | 403 | 424 | 865 | 56 |
| Charlotte | -200+325 | 418 | 418 | 422 | 1288 | 87 |
| Charlotte | +200 | 367 | 373 | 405 | 3040 | 182 |
| Red Beach | -200+325 | 397 | 400 | 422 | 1609 | 115 |
| Red Beach | +200 | 404 | 406 | 417 | 1720 | 124 |
| Diorite | -200+325 | 422 | 421 | 416 | 833 | 73 |
| Diorite | -150+200 | 416 | 419 | 438 | 1015 | 90 |
| Diorite | -100+150 | 415 | 414 | 408 | 1584 | 141 |
| Felsic | -325 | 406 | 412 | 446 | 632 | 40 |
| Felsic | -200+325 | 418 | 428 | 482 | 815 | 53 |
| Felsic | +200 | 408 | 414 | 448 | 1102 | 70 |

Rb / Sr Whole Rock Analyses, MIC

Baring Granite

Seven samples of Baring granite were run for rubidium / strontium analysis. Rubidium concentrations averaged 144 ppm and ranged from a low of 120 ppm to a high of 178 ppm; strontium concentrations averaged 118 ppm and ranged from 82 to 151 ppm. The seven Baring granite samples yielded an isochron with an age of 430 ± 20 my and a strontium initial ratio of $.705 \pm .001$ (2σ errors--see figure 11). The square root of the mean sum of the residuals squared (MSRS) for the isochron is 1.01. Regressions with the square root of the MSRS less than ≈ 2.5 were considered true isochrons (Brooks et al., 1972).

Calais Diorite-Gabbro Complex

Analysis of diorite samples did not yield an isochron. Diorite samples collected from the northern portion of the Calais Diorite-Gabbro complex showed little variation in strontium concentrations, with one exception. The four-sample average of strontium concentration equals 312 ppm with a spread in values from 244 to 336 ppm. Rubidium concentrations from the diorite ranged from 31 to 70 ppm with an average of 47 ppm. The data array for the diorite is plotted in figure 11.

Rb / Sr Whole Rock Analyses, Younger Granites

Charlotte Granite

Five samples of the Charlotte granite yielded an isochron with an age of 411 ± 16 my with an initial $^{87}\text{Sr} / ^{86}\text{Sr}$ ratio of $0.704 \pm .002$ (2σ errors--see figure 12). Rubidium

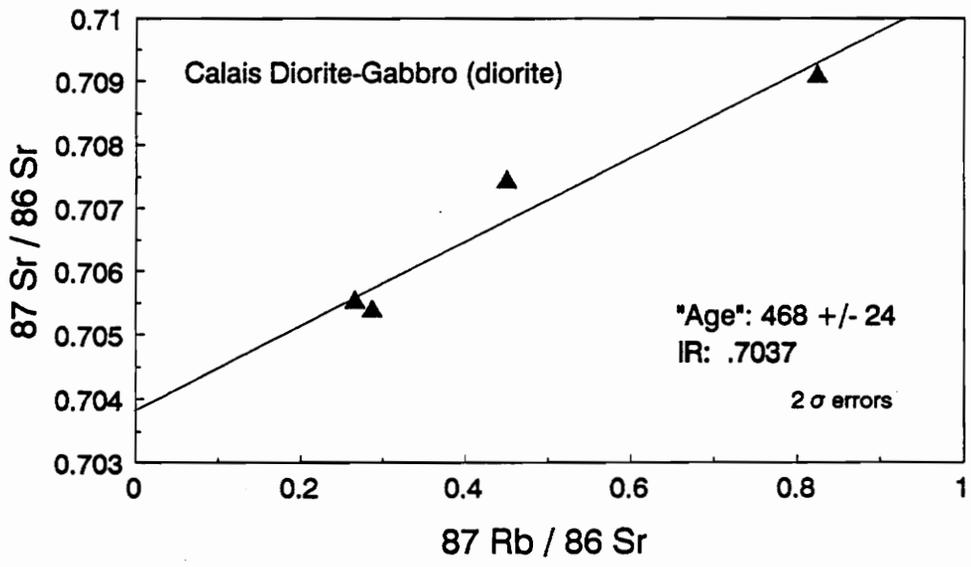
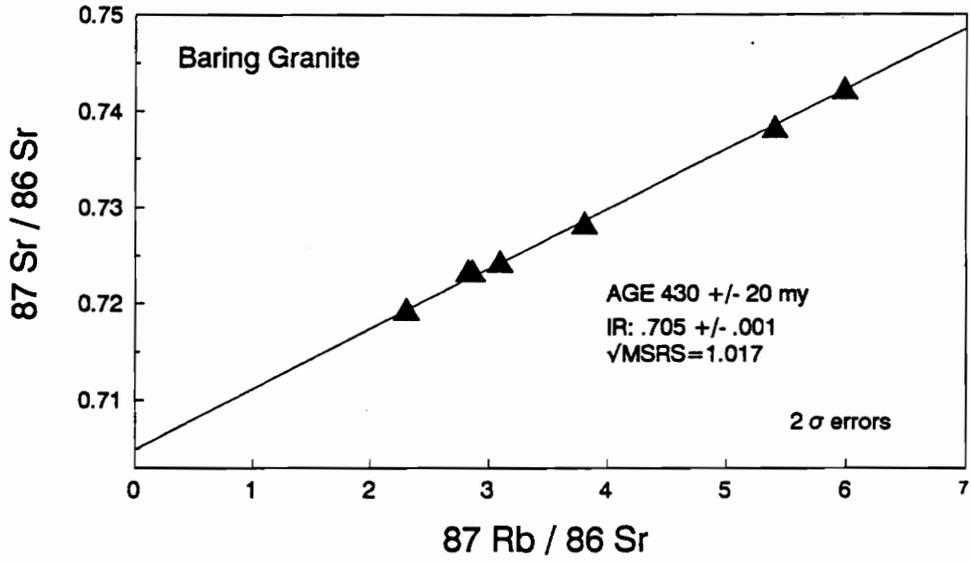


Figure 11: Baring granite isochron and diorite data array.

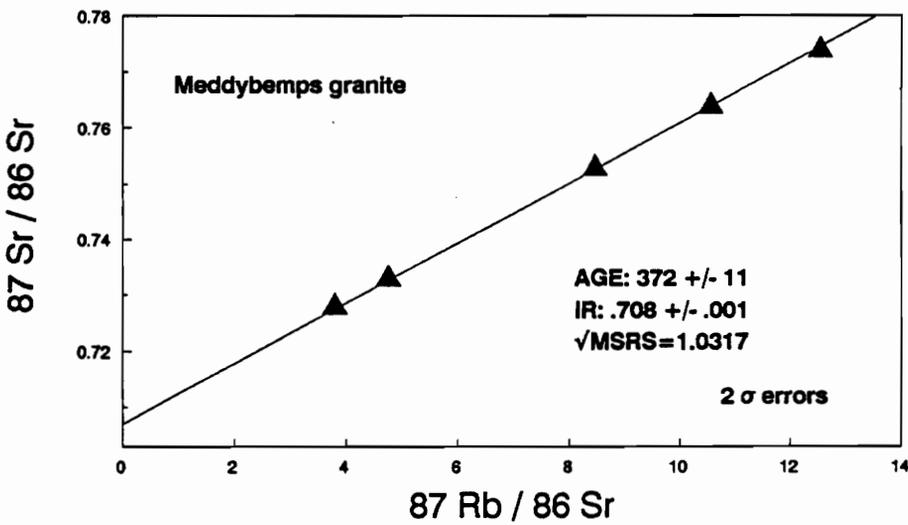
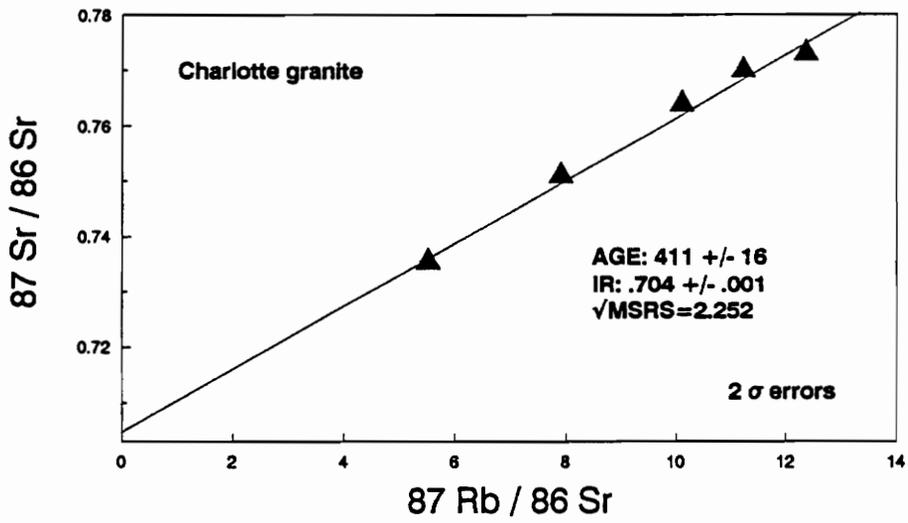


Figure 12: Charlotte and Meddybemps granite isochrons.

concentrations ranged from 115 to 216 ppm and averaged 178 ppm. Strontium concentrations were lower than those measured in the Baring granite, and were fairly uniform within the samples measured. Concentrations ranged from 48 to 61 ppm and averaged 56 ppm. The square root of the MSRS of the Charlotte isochron is 2.25.

Meddybemps Granite

The Meddybemps granite yielded a well defined 5 point isochron with an age of 372 \pm 11 my and an initial $^{87}\text{Sr} / ^{86}\text{Sr}$ ratio of $0.708 \pm .001$. (square root of the MSRS=1.03, 2σ errors, see figure 12). Rubidium concentrations of samples analyzed ranged from 102 to 183 ppm with an average of 149 ppm; strontium concentrations ranged from a low of 42 to a high of 82 ppm and had an average concentration of 60 ppm.

Rubidium / strontium analyses of the other plutonic rocks of the Calais area did not yield isochrons, but resulted in rough data arrays with positive slopes with unacceptably high values for the square root of the MSRS upon regression. $^{87}\text{Sr} / ^{86}\text{Sr}$ versus $^{87}\text{Rb} / ^{86}\text{Sr}$ plots of these data are presented in figure 13. The Red Beach granite has the highest average rubidium concentration of rocks sampled from the Calais plutons at 208 ppm. Measured rubidium concentrations ranged from 191 to 219 ppm. Strontium concentrations for the Red Beach granite were uniformly low, ranging between 18 and 37 ppm, with an average of 30 ppm. Samples analyzed from the felsic granite intrusive into the diorite showed a mean rubidium concentration of 147 ppm with values ranging from 112 to 171 ppm (n=4). Strontium concentrations ranged from 68 to 172 ppm and averaged 122 ppm.

Several factors may affect the ability of the rubidium / strontium system to reflect the true age of the rock. Samples collected need to be fresh and relatively unaffected by

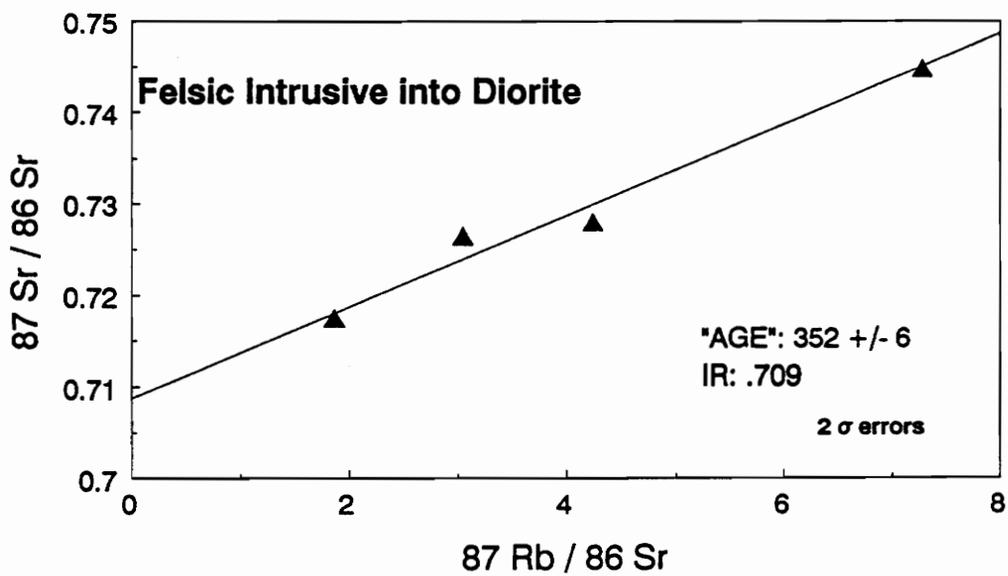
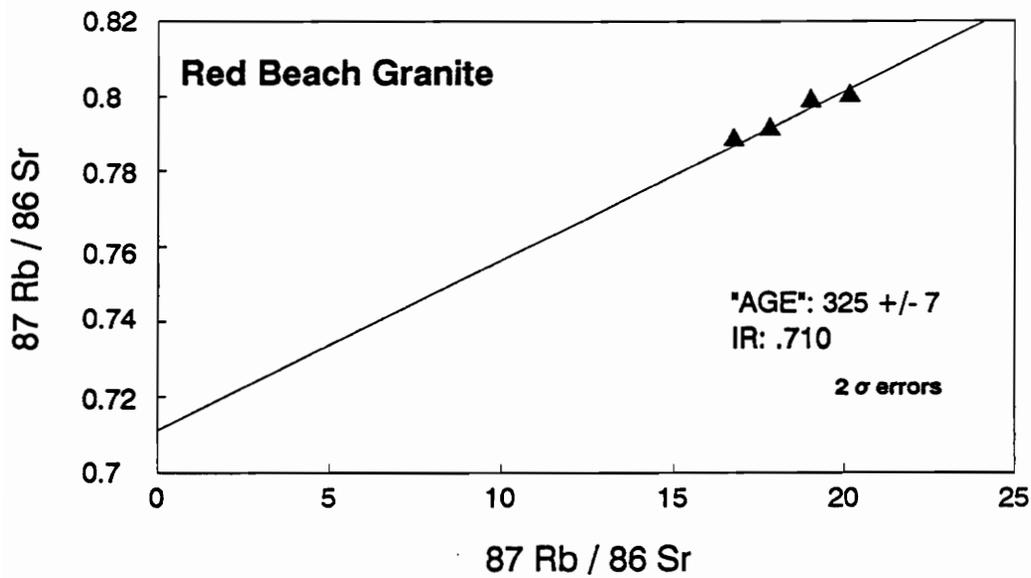


Figure 13: Red Beach granite and Felsic intrusive data arrays. Regression of this data did not yield isochrons.

weathering processes which might alter the concentrations of the rubidium or strontium. The samples collected must be from the same melt, with a homogenized initial strontium isotopic composition. Assimilation of country rock, or mixing of magmas, may result in alteration of the initial strontium ratios for samples, making accurate dating impossible. Mixing of two endmembers with differing element concentrations and isotopic compositions may result in formation of mixing lines whose slopes give meaningless "ages" upon regression.

The samples of felsic granite intruding the diorite were collected from small dikes spread over a relatively wide geographic area. Texturally, the samples showed a wide variation in grain size. The most plausible explanation for the scatter in the data would be that the samples came from different melts and did not have a similar initial strontium ratio. Evidence for this exists in a plot of calculated strontium initial ratio (SIR) versus $1 / ^{86}\text{Sr}$ concentration (see Figure 14). In this plot, SIR's are calculated by assuming an age for the rock and solving for time using the equation for the radioactive decay of ^{87}Rb . Data for the felsic granite scatters over a range of initial SIR's, indicating that individual samples came from different melts, each with a distinctive initial strontium signature. Had they formed from an isotopically homogenized melt, the data should have formed a horizontal data array, with the spread in data relating only to the variation in strontium concentrations.

Scatter in the Red Beach data may be best explained by weathering of the samples. All the samples of granite collected for analysis bore the characteristic brick red color of exposures close to the Devonian unconformity, and were probably affected by this weathering event. When plotted on a SIR versus $1 / ^{86}\text{Sr}$ diagram, the analyses form an array with a negative slope. SIR values calculated for the samples based on the age derived

SIR versus $1 / 86\text{Sr}$

Calais area plutons and South Penobscot

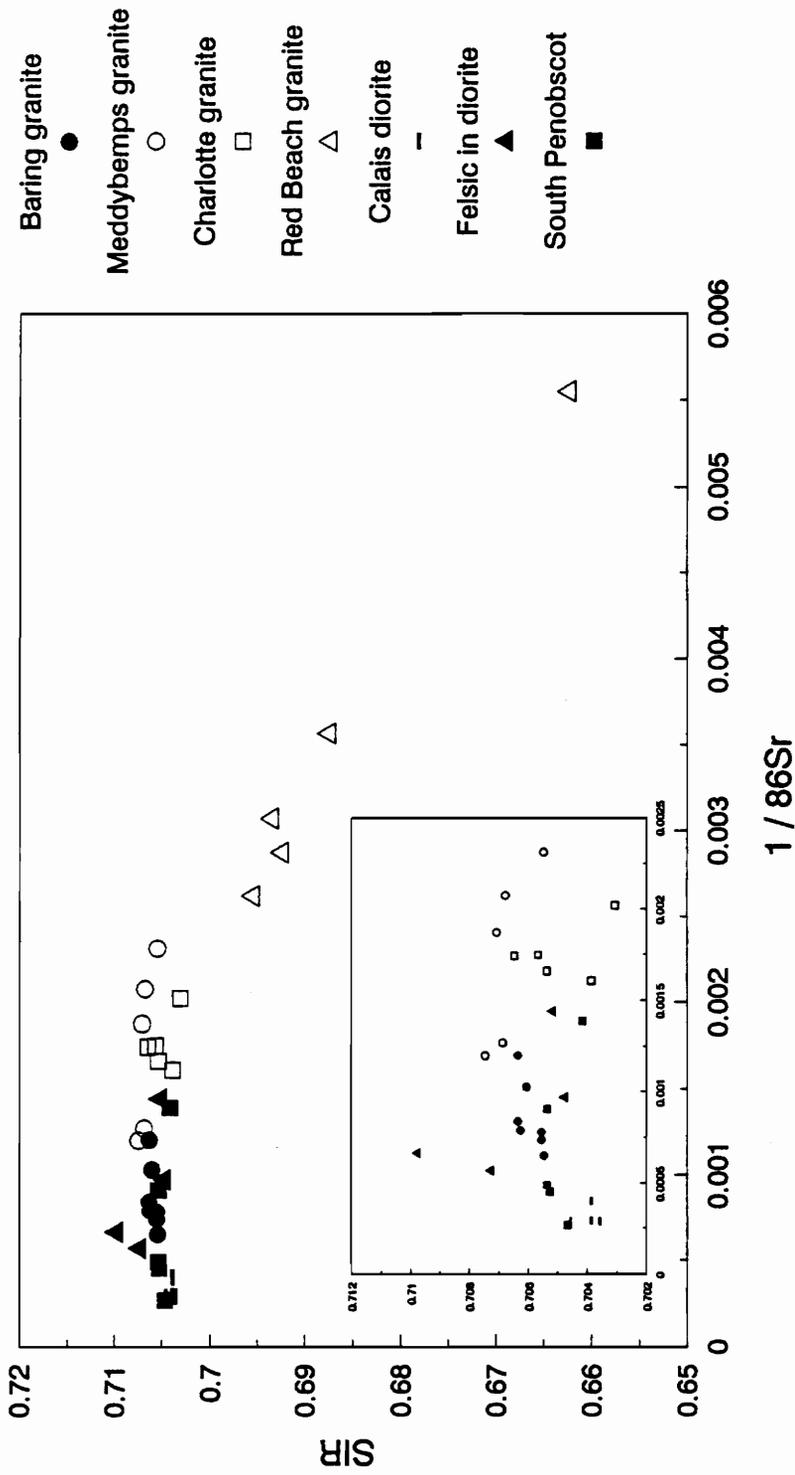


Figure 14: SIR versus $1 / 86\text{Sr}$ variation diagram for the Calais area plutons and the South Penobscot Intrusive Series. Inset shows the data rescaled without the Red Beach granite.

from zircon analyses (see U / Pb discussion, this section) give ratios with values lower than the most primitive strontium isotopic composition possible (Faure, 1986). The scatter in the array is probably related to a change in concentration of strontium due to weathering.

Discrepancies in the diorite analyses are more difficult to explain given the small amount of data. All samples analyzed were from a very restricted geographic area (two large outcrops along U.S. Route 1) and showed moderate textural variation in the field. Upon analysis, however, the samples showed very little variation in concentrations of strontium, and to some extent, rubidium. The data points do not form a line within analytical errors. The scatter may have been induced by a non-uniform assimilation of country rock.

U / Pb Zircon Analyses, MIC Units

Zircon splits from the plutons analyzed for Rb / Sr were run to refine age relations suggested by the Rb / Sr work. Size splits were run for the Baring, Charlotte, Meddybemps, and Red Beach granites, as well as the felsic granite intrusive into the diorite and the diorite itself. Analytical results of all analyses are listed in Table 4 while results of data reduction are listed in Table 5. Raw data from the mass spectrometer were entered into the FORTRAN program PBDAT (Ludwig, 1989). All errors reported are 2σ percent errors of the mean. Lead initial isotope ratios of the Baring, Charlotte, and Red Beach granites were provided by Hogan (pers. comm.) and are: Baring $^{206}\text{Pb} / ^{204}\text{Pb} = 18.908$, $^{207}\text{Pb} / ^{204}\text{Pb} = 15.709$; Charlotte $^{206}\text{Pb} / ^{204}\text{Pb} = 18.284$, $^{207}\text{Pb} / ^{204}\text{Pb} = 15.642$; Red Beach $^{206}\text{Pb} / ^{204}\text{Pb} = 19.172$, $^{207}\text{Pb} / ^{204}\text{Pb} = 15.606$. Initial lead isotope ages for the diorite and felsic material were calculated from a model lead age of 450 m. y. (Stacey and

Kramers, 1975). York regressions of zircon analyses were calculated using the program CONCORDI of Ludwig (1980). Upper intercept ages were calculated using a forced fit through a lower intercept age of 1 my (Krogh, 1988).

Baring Granite

Two non-magnetic size splits of zircons were analyzed from sample Cl-133A of the Baring granite. Size splits included fractions with sizes between 150 and 200 mesh and between 200 and 325 mesh. Zircons from the smaller size fraction were slightly elongate, with aspect ratios averaging between 3-5:1. Crystals were subhedral to euhedral and prismatic with slightly rounded facets. Colors observed were gradational between clear and honey brown. The zircons contained very few inclusions, although some grains were fractured. The smallest fraction of Baring granite zircons contained stubby to elongate crystals with aspect ratios between 2-5:1. The size fraction was composed to subhedral to euhedral, clear to brown grains with rare inclusions. Larger grains were, on average, darker brown, cracked, and hosted more inclusions.

Concentrations of uranium and lead were uniformly high in the Baring granite zircons. Uranium concentrations ranged from 1078 to 1286 ppm and averaged 1182 ppm. Lead concentrations ranged from 74 to 86 ppm. Regression of the two size fractions of zircons yields an upper intercept age of 434 ± 9 my (2σ errors). The lower intercept was fixed by a 1 m. y. concordant point added into the regression (Figure 15).

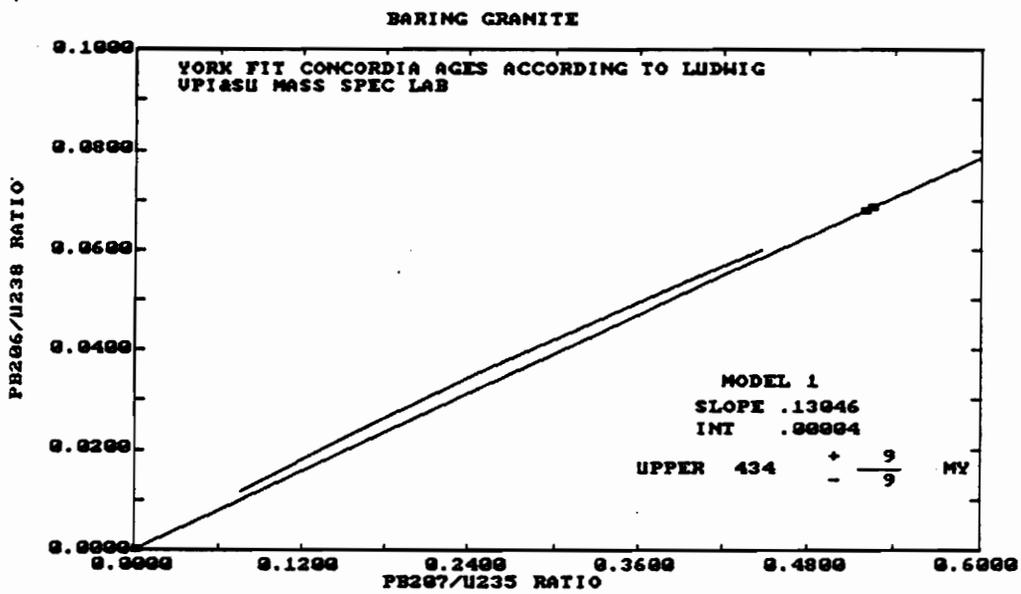


Figure 15: York regression of Baring granite data. Output from CONCORDI program of Ludwig, 1980.

Diorite of the Calais Gabbro-Diorite Unit

Three non-magnetic size fractions of zircon from diorite of the northern portion of the Calais Diorite-Gabbro unit were separated from sample number JJ-387-87 for uranium and lead isotopic analysis. Size splits included -100+150 mesh, 150+200 mesh, and -200+325 mesh. The largest fraction of zircons analyzed contained stubby crystals with aspect ratios averaging 3:1. The crystals were very anhedral to subhedral, honey brown in color, and contained rare inclusions. Zircons in the middle size range consisted of stubby, anhedral crystals (aspect ratios 2-3:1) with very irregular facets. The zircons are honey brown and contained rare inclusions. The largest fraction of zircons from the diorite consisted of stubby crystals with aspect ratios averaging 1-4:1. The subhedral to anhedral, rounded grains are often broken. The zircons are honey brown in color, cloudy, and contain very rare opaque inclusions.

Concentrations of uranium and lead are lower than observed in the Baring granite. Uranium concentrations varied from a low of 833 ppm to a maximum of 1584 ppm; lead concentrations ranged from 73 to 141 ppm. Regression of the three size fractions of zircon yields an upper intercept age of 420 ± 40 my (2σ errors). The lower intercept is fixed by a point of 1.0 my added to the regression. Data for the diorite are plotted in Figure 16.

U / Pb Zircon Analyses, Younger Granites

Red Beach Granite

Two size fractions of zircon from the Red Beach granite, including +200 mesh and -200+325 mesh, were analyzed for uranium and lead. Zircons from the smaller size fraction

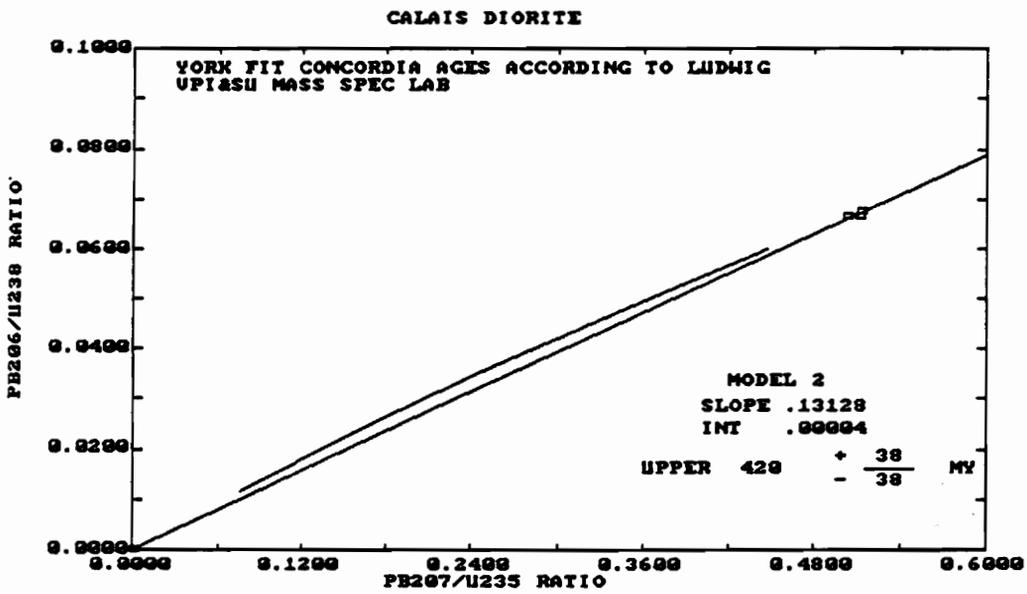


Figure 16: York regression of diorite from the Calais Diorite-Gabbro unit. Output from CONCORDI program of Ludwig, 1980.

are stubby, with aspect ratios averaging 1-3:1. The crystals are subhedral to euhedral, occasionally broken, and are dark red in color, probably from an iron oxide coating. The zircons contain very rare inclusions. The largest zircon fraction consists of very stubby (1.5 to 5:1 aspect ratio) subhedral to euhedral, prismatic crystals with occasional broken prism tips. The crystals are dark brown to red in color, cloudy, and contain rare opaque inclusions.

Uranium concentrations were extremely high in these zircons, ranging from a low of 1609 ppm to a high of 1720 ppm. Lead concentrations also ran high, varying from 115 to 124 ppm. Regression of the two size fractions of Red Beach zircons, with a point added in for recent lead loss at 1.0 my yields an upper intercept age of 415 ± 6 my (Figure 17).

Charlotte Granite

Three size fractions of zircon from sample JJ-181-87 of the Charlotte granite were analyzed for uranium and lead. Size splits included +200 mesh, -200+325 mesh, and -325 mesh. The -325 fraction of zircons from the Charlotte granite consists of stubby grains with aspect ratios averaging 2-4:1. The fraction is characterized by subhedral to euhedral, complete prisms of clear to very slightly honey brown colored zircons. Inclusions within the crystals are extremely rare, and the population as a whole is exceedingly uniform. The middle size fraction of Charlotte granite consists of stubby to slightly elongate (3-5:1 aspect ratio), subhedral to euhedral, rounded prisms. The crystals are clear to light brown in color and contain very rare opaque inclusions and few cracked, cloudy, grains. The largest zircon fraction from the Charlotte granite is composed of stubby to elongate (aspect ratio averages 2-5:1), anhedral to euhedral zircons, rarely exhibiting sharp terminations. The zircons

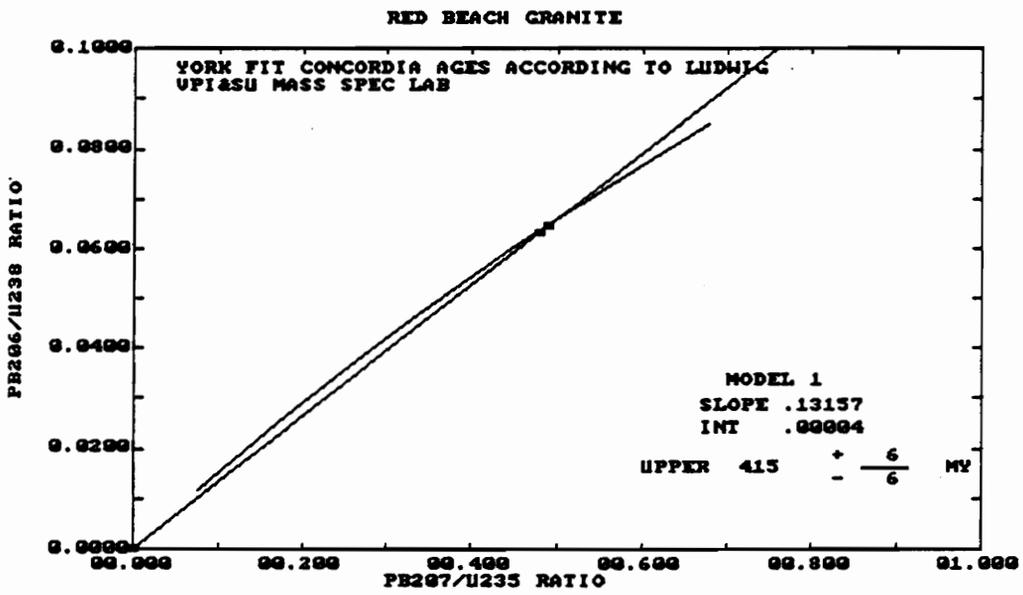


Figure 17: Regression of Red Beach zircon analyses. Output from CONCORDIA program of Ludwig, 1980

display an even brown to light brown color and rarely enclose opaque inclusions. Most grains of this fraction are extremely cloudy.

Concentrations of uranium varied widely in the analyzed splits from a low of 865 ppm to a high of 3040 ppm. Lead concentrations were also similarly scattered, ranging from 56 to 182 ppm. Regression of the three size splits of zircons from the Charlotte granite, with the lower intercept offset by 1.0 my, yields an upper intercept age of 421 ± 30 my (Figure 18).

Felsic Intrusive

Three size splits of zircons were analyzed from the felsic material intrusive into the diorite in the southern portion of the Calais Diorite-Gabbro complex. Size ranges included splits of +200 mesh, -200+325 mesh, and -325 mesh. The smallest fraction of zircons from the felsic intrusive are characterized by their extremely elongate to acicular habit. Aspect ratios vary from a low of 3:1 to a maximum of approximately 10:1. The zircons are subhedral to euhedral with rare terminations, clear in color, and contain extremely rare opaque inclusions. Zircons from the -200+325 split are stubby to elongate crystals, not as acicular, on average, as the smaller fraction (aspect ratios vary from 3:1 to 10:1). The zircons are subhedral to euhedral, with the less-elongated crystals exhibiting a more euhedral habit. The grains are clear to tan in color and contain extremely rare opaque inclusions. The largest fraction of zircons contains stubby to elongate (aspect ratio 3-6:1), subhedral crystals and rare complete prisms. The crystals are tan to light brown, cloudy, and contain rare inclusions.

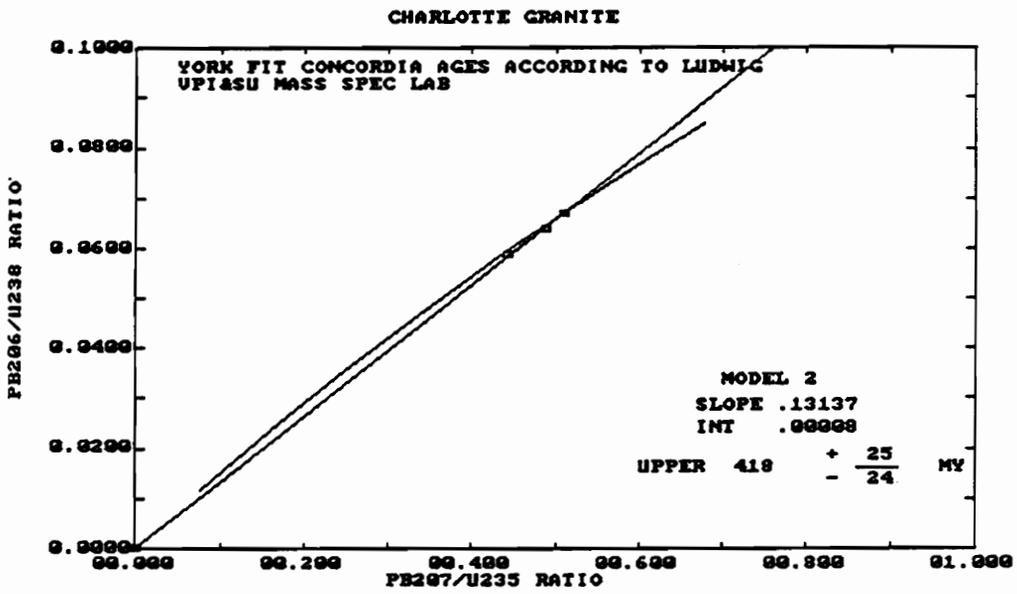


Figure 18: Regression of Charlotte granite zircon data. Output from CONCORDI program of Ludwig, 1980

Concentrations of uranium and lead from these zircons were fairly restricted; uranium concentrations ranged from 632 to 1102 ppm while lead concentrations varied from 40 to 70 ppm. Regression of the zircon fractions yielded an upper intercept age of $1150 \pm 450/-376$ m. y., and a lower intercept of $390 \pm 10/-27$ m. y. (Figure 19).

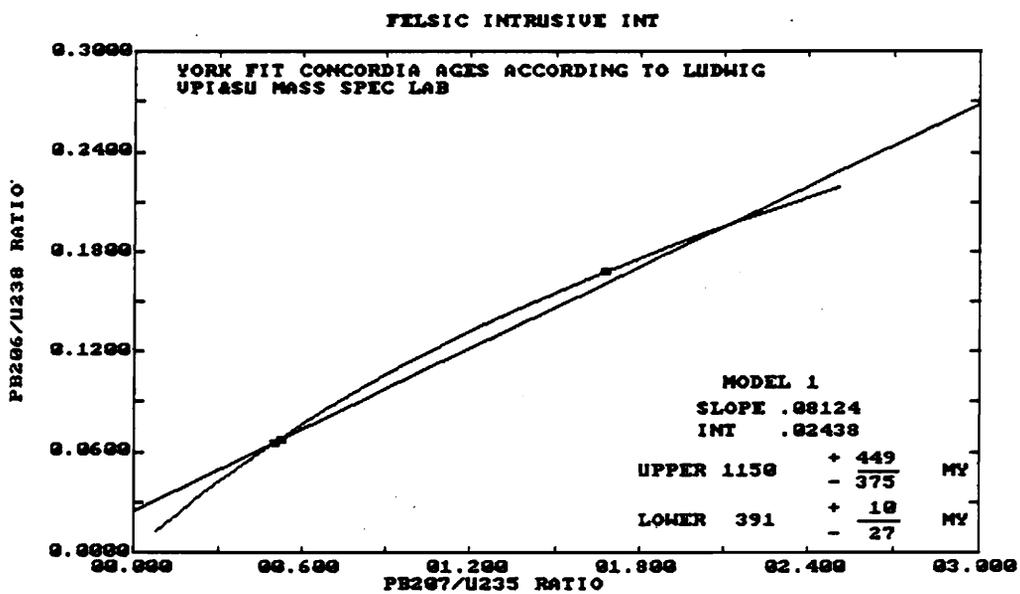


Figure 19: Regression of Zircon data from felsic material intrusive into the diorite. Output from CONCORDI program of Ludwig, 1980.

Discussion

The northern Appalachians presents a complex array of plutons of varying age and composition. Interpretation of this assemblage is facilitated if the effects of later plutonism and deformation can be removed to examine earlier igneous episodes. This is particularly relevant in the CMMP where Devonian plutonism resulted in emplacement of large volumes of magma into the crust, wiping out much of the earlier geologic record. Examination of discrete time slices through the Ordovician to Devonian periods allows reconstruction of the earlier geologic history of the region and delineation of the tectonothermal evolution of the coastal belt.

Decades of research in the northern Appalachians have generated a large database of reliable radiometric age determinations which have been compiled by several workers in regional studies of the Appalachian chain. Most recently, Sinha (1988) has compiled a list of ages and lithologies of plutons of the US Appalachians. Ages listed in this collection have been used to model the thermal evolution of the northern Appalachians, concentrating on the development of the Late Ordovician to Silurian magmatic event. Published radiometric ages used in compiling the data on the two belts are tabulated in Appendix 3.

Ages of northern Appalachian plutons were plotted against the area of exposure (used as an approximation of volume) to determine volumetrically significant periods of magmatism (Figure 20). The age groups were broken into 10 my intervals in an attempt to discriminate true volume peaks. Two distinct pulses of magmatism are evident; one occurs during the interval between 445-415 m.y. (Late Ordovician-Silurian), the other between 400-360 m.y. (Devonian).

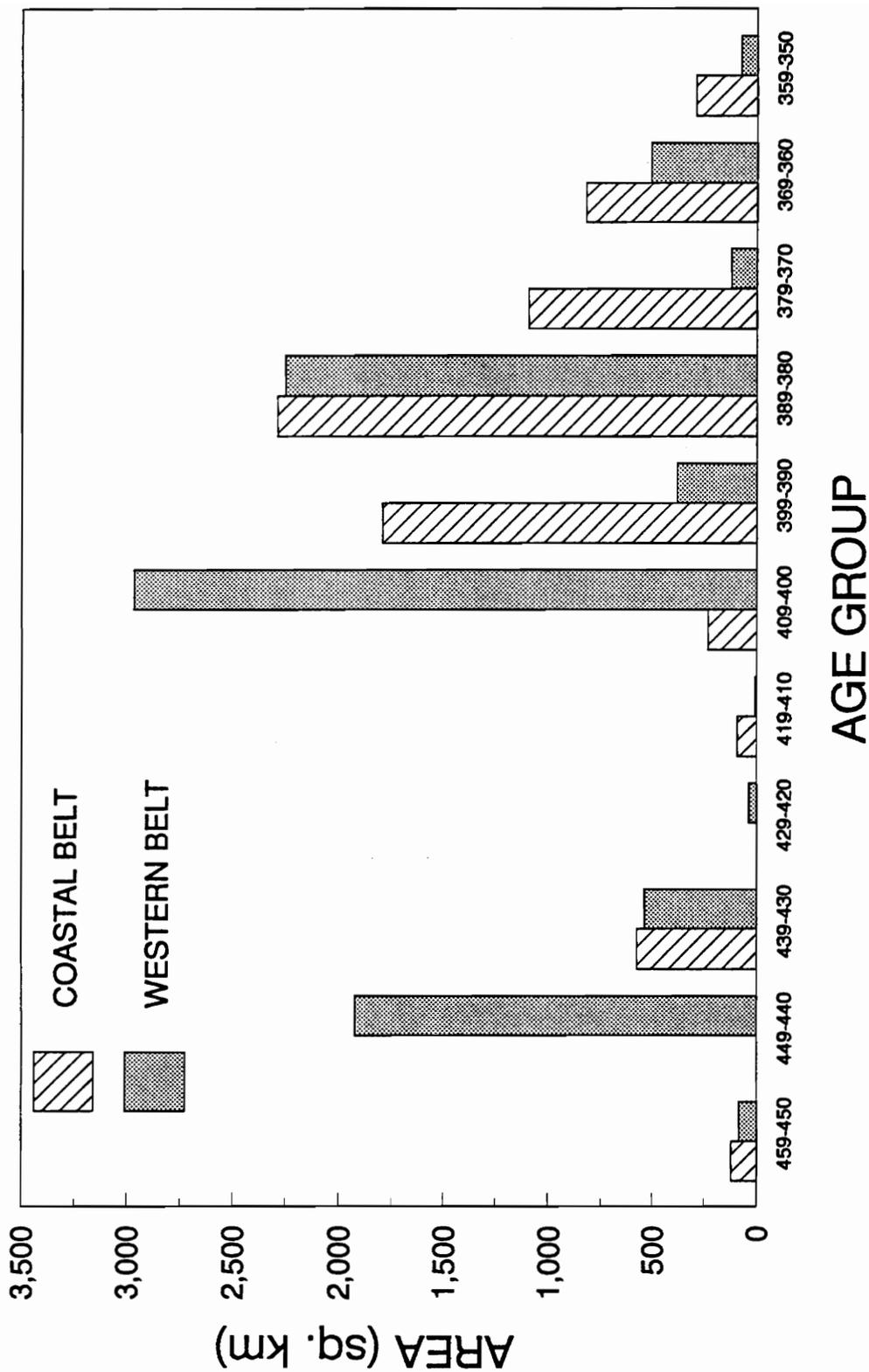


Figure 20: Distribution of age versus area for plutons of the northern Appalachians. Ages sampled range between 460-350 Ma.

Late Ordovician-Silurian plutons form two distinct belts (Figure 21). A western belt extends from the Long Island sound northwards through Connecticut, Massachusetts, New Hampshire and across Maine into New Brunswick and contains plutons covering 1870 km². The coastal belt stretches from Massachusetts through the Maine coast into New Brunswick and is represented by plutons covering a present surface area of 705 km². Each belt contains a distinct suite of lithologies and both belts can be modelled as a coherent package.

Before a possible genetic relationship between the two belts may be discussed, they must be shown to have been spatially associated during the time interval of pluton emplacement. If the lithotectonic blocks bearing the plutons were spatially separated during the Late Ordovician-Silurian period, discussion of a common genetic relationship between the two igneous belts would be meaningless. Documentation of crustal continuity during the Ordovician-Silurian periods is difficult at best. Several methods have been explored in an attempt to document the accretionary history of the North American margin, including geochemical and isotopic studies, geophysical investigations including gravity and seismic modeling, documentation of structural and metamorphic histories, and description of faunal provinces (Neumann, 1984; Ayuso, 1986; Ludman, 1981, 1986a, 1986b; Hogan and Sinha, 1989; Boone and Boudette, 1989; Foland and Loiselle, 1981; Lyons et al, 1986; Zartman and Naylor, 1984; Zartman and Leo, 1985). All of these techniques have been applied in the northern Appalachians and have led to differing conclusions. Geochemical and geophysical evidence points to the existence of multiple terranes between the western and coastal plutonic belts (Ayuso, 1986; Hogan and Sinha, 1989). Faunal province studies suggest the crustal blocks had accreted by the Ordovician (Neumann, 1984). Ludman

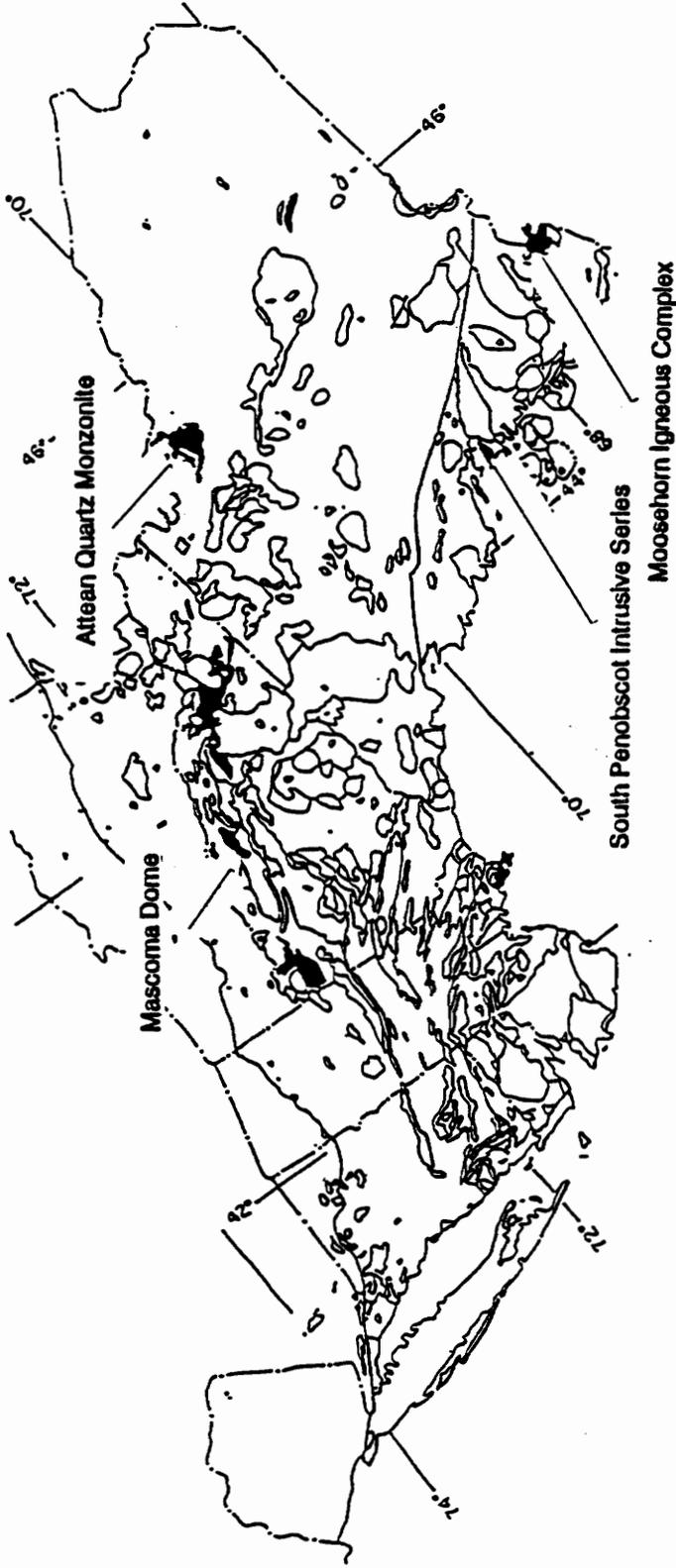


Figure 21: Distribution of Late Ordovician to Silurian aged plutons in the northern U.S. Caledonides. Note the definition of the two parallel plutonic belts. Type localities discussed in the text are labeled in this figure.

(1986a, 1986b) addresses this problem in suggesting that formerly exotic blocks had joined in time for deposition of the Siluro-Devonian cover sequence. This interpretation, based on lithologic and stratigraphic correlations across fault zones, may be suspect (Fyffe and Pickerill, 1986).

Geophysical and geochemical source region studies do not provide narrow time estimates of terrane accretion; they merely delimit proposed terrane boundaries. Stratigraphic and paleontologic evidence from Maine seems to favor assemblage of all terranes by at least the Silurian and possibly as early as the Ordovician. In the absence of direct evidence against early assemblage of terranes (such as tight time constraints imposed by terrane-suturing plutons), it will be accepted that the bulk of terrane accretion was completed by the Silurian, and any later terrane movement was restricted to minor re-shuffling along fault boundaries.

The Late Ordovician-Silurian plutonic belts each host a different, yet characteristic lithologic package. The differences in lithologies contained within the two belts will be highlighted by comparing type pluton occurrences from each belt. Associations of rock types from each belt will then be discussed in an attempt to establish the tectonic environment of the two ancient belts. The Attean Quartz Monzonite and Mascoma Dome are chosen as examples to represent the western belt plutons, while the MIC and South Penobscot Intrusive Suite will be used to characterize the coastal belt plutons. Furthermore, the development of the CMMP will be shown to reflect the distinct tectonothermal evolution of the crust during the Late Ordovician through Devonian periods.

The Western Belt

Plutons of the western belt are intruded along the axis of the Bronson Hill anticline and contained within the Oliverian and Highlandcroft plutonic suites (Naylor, 1969; Foland and Loiselle, 1981; Zartman and Leo, 1985; Lyons et al., 1986; Tucker and Robinson, in press). These two magmatic suites were shown to be coeval by Lyons et al., 1986. The domes of the western belt incorporate a range of lithologies, including gabbro, diorites, tonalites, granodiorites, granites, monzonites, and syenites, all of which have been intruded into the Late Ordovician Ammonoosuc Volcanics (Lyons et al., 1986, Tucker and Robinson, in press).

Attean Quartz Monzonite

The Attean Quartz Monzonite crops out across the Attean quadrangle as well as parts of the Skinner, Long Pond, Pierce Pond, and Spencer Lake quadrangles of Maine, covering an area of approximately 435 square kilometers. Dikes of the quartz monzonite intrude the quartzofeldspathic basement rocks of the Chain Lakes Massif, as well as small isolated bodies of dioritic material. Enclaves of diorite as well as metasedimentary rock occur near the margin of the pluton (Albee and Boudette, 1972). The quartz monzonite is unconformably overlain by fossiliferous Upper Silurian conglomerates containing clasts petrographically identical to the Attean pluton as well as a time-equivalent unnamed limestone and slate unit (Albee and Boudette, 1972). These units are conformably overlain by fossiliferous slates of the Devonian Seboomook Formation.

The Attean quartz monzonite, as described by Albee and Boudette (1972), consists of a mottled pink and green medium to coarse-grained porphyritic quartz monzonite. Modally,

the rock consists of 25-30% quartz, 30-35% potassium feldspar, 35-40% plagioclase feldspar, and exhibits a color index of 5-10. Mafic phases include biotite, hornblende, tremolite, sphene, ilmenite, magnetite, as well as chlorite, epidote, muscovite, and calcite.

Mascoma Dome

The Mascoma dome is located on the crest of the Bronson Hill Anticlinorium in western central New Hampshire. The dome, as reported by Naylor (1969), may be divided into a stratified core unit which interfingers with the overlying Ammonoosuc volcanics, and a non-stratified core unit. The stratified core rocks occur in thinly laminated layers three to ten feet thick and are composed of medium grained plagioclase-quartz-biotite-epidote gneiss. The unstratified core unit includes porphyritic quartz monzonite and granite with localized occurrences of fine grained granite, quartz diorite, and pegmatite.

The monzonite contains large microcline crystals up to one centimeter long in a matrix of quartz and plagioclase. Mafic phases include biotite, epidote, magnetite and garnet. The quartz monzonite exhibits gradational contacts with the granite of the unstratified core unit. Quartz diorite consists of plagioclase, quartz, biotite, and hornblende and is similar in composition to the stratified core rocks.

The Coastal Belt

Several igneous complexes were emplaced into the Coastal Belt during the Late Ordovician-Silurian period. These include the MIC (Maine), South Penobscot Intrusive Series (Maine), Cadillac Mountain granite and associated mafic material (Maine), and the Northport granite (Maine). The MIC has been discussed in previous sections. A brief

description of the South Penobscot Intrusive Series is presented to reinforce the characteristics of plutonism associated with emplacement of the igneous complexes.

South Penobscot Intrusive Series

The South Penobscot Intrusive Series crops out over an area of approximately 84 km² along the shores of Northern Bay near the town of South Penobscot, Hancock County, Maine. The intrusive series has been separated into four units based on field investigations (Stewart et al., 1988). From oldest to youngest, these include a border zone of rocks of mixed compositions, the granite of Camp Stream, the granite of Grey Ridge, and a porphyritic variant of the Grey Ridge granite. The South Penobscot series forms a roughly zoned pluton with marginal mafic and mixed phases surrounding a granite core.

The mixed zone occurs along the margins of the intrusive suite and consists of a host of rock types including quartz diorite, granodiorite, and tonalite accompanied by minor amounts of hornblende gabbro. The variety of textures observed in the border zone of the South Penobscot rocks parallels those documented in the MIC and ranges from anastomosing dikes of granite within the gabbro to zones of mafic igneous breccia in the granite. Mafic enclaves within the granite phase often exhibit thick biotite-rich rims indicative of reaction with the granite. Zones of rock with compositions intermediate to gabbro and granite are locally developed in the border zone and are postulated to have formed from hybridization of the two liquids (Stewart et al., 1988).

Several isolated bodies of hornblende gabbro occur in the border zone. These are locally layered, with compositional layering dipping 60°-90° towards the center of the intrusive suite. Layer thickness averages between 2-10 cm, although layers may attain

thicknesses of up to 1 m (Stewart et al., 1988).

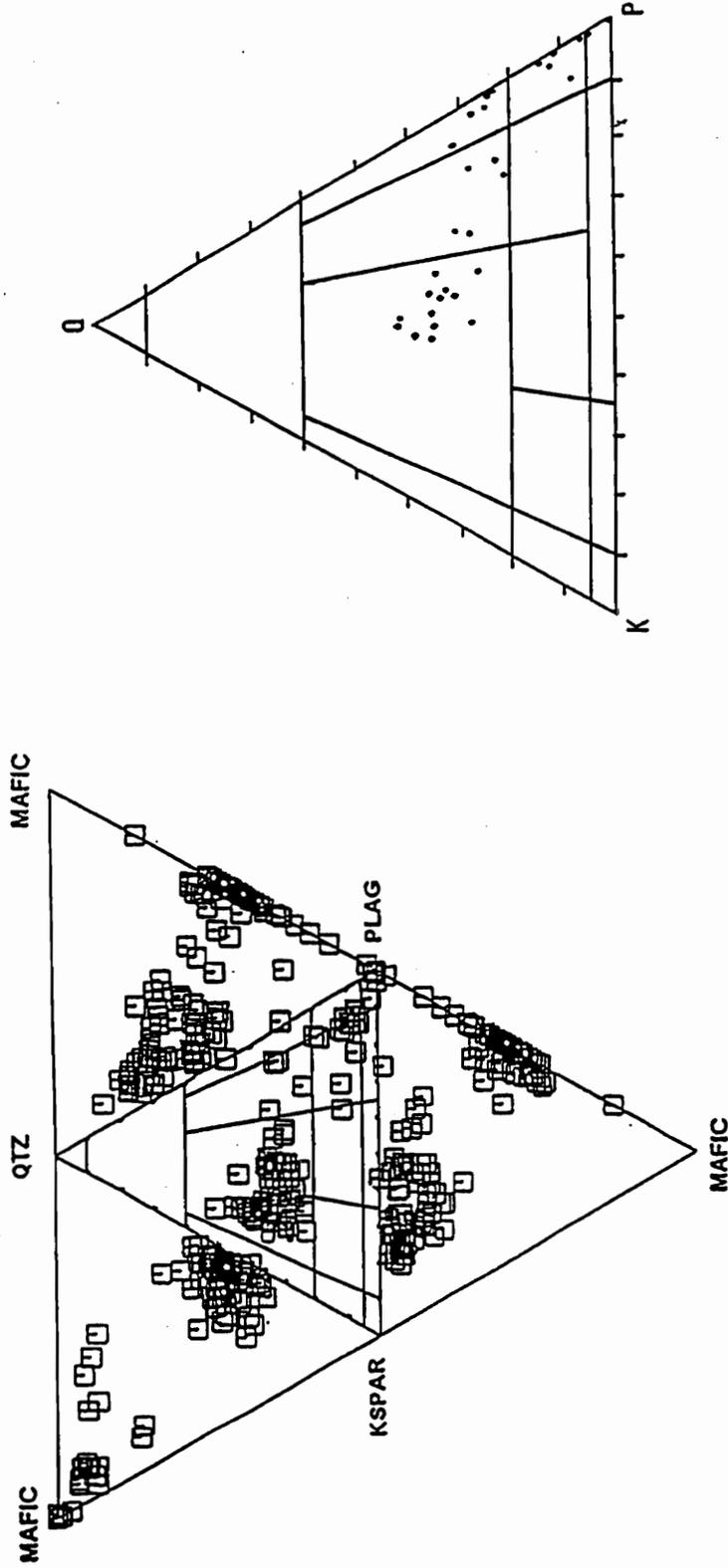
The Grey Ridge granite lies within the center of the igneous series and occurs in fine to medium grained, hypidiomorphic-granular to weakly porphyritic exposures (Stewart et al., 1988). The granite becomes strongly porphyritic to the south. A smaller granite body (Camp Stream granite) occurs outside the border zone to the southeast and consists of fine to medium grained, hypidiomorphic-equigranular granite. Late stage quartz diorite dikes cut the center granite within the South Penobscot, indicating mafic that magmatism continued through emplacement of the igneous series.

The range of rock types observed within the South Penobscot Intrusive series closely parallels those observed in the MIC. Comparisons of modal data are shown in Figure 22. Both igneous complexes contain compositions ranging from granite to gabbro and include minor components of granodiorite, tonalite, quartz diorite, and diorite (after Streckeisen, 1973). Field relations preserved in the South Penobscot series are almost identical to the range in textures observed in the Moosehorn suite. Both examples point to the early emplacement of mafic material, with mafic magmatism continuing through the complete igneous event. The resulting textures, including dikes of the granite into mafic material, development of mafic igneous breccias, and possible hybridization of mafic and felsic magmas, may be found in both igneous complexes.

Isotope Data, South Penobscot Intrusive Series

Stewart et al.,(1988) included preliminary isotopic data on their study of the South Penobscot Intrusive Series. The data from their study has been included in Table 6. Both

IGNEOUS COMPLEX MODAL DATA



MOOSEHORN IGNEOUS COMPLEX SOUTH PENOBSCOT

Figure 22: Comparison of MIC and South Penobscot Intrusive Series modal data. South Penobscot data reported by Stewart et al. (1988)

Table 6: Isotopic data reported for the South Penobscot Intrusive Series by Stewart et al. (1988)

| Sample # | Concentration (ppm) | | Atomic Ratios | | Ages in m.y. | | | | |
|----------|---------------------|-------------------|---|---|--|--|---|---|--|
| | <u>Rb</u> | <u>Sr</u> | $\frac{^{87}\text{Rb}}{^{86}\text{Sr}}$ | $\frac{^{87}\text{Sr}}{^{86}\text{Sr}}$ | $\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$ | $\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$ | $\frac{^{238}\text{U}}{^{206}\text{Pb}}$ | $\frac{^{235}\text{U}}{^{207}\text{Pb}}$ | $\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$ |
| S70-49B | 14.3 | 362.8 | 0.1141 | 0.70540 | | | | | |
| S70-66 | 103.5 | 199.6 | 1.501 | 0.71462 | | | | | |
| S70-89 | 246.5 | 70.5 | 10.17 | 0.7665 | | | | | |
| S70-100 | 87.2 | 215.6 | 1.172 | 0.71244 | | | | | |
| S70-103 | 187.1 | 108.0 | 5.023 | 0.73618 | | | | | |
| S-70-89 | <u>Pb</u> 175.7 | <u>U</u> 279.8 | | | $\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$ 0.06004 | $\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$ 308.2 | $\frac{^{238}\text{U}}{^{206}\text{Pb}}$ 399.5 | $\frac{^{235}\text{U}}{^{207}\text{Pb}}$ 403.2 | $\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$ 424.4 |

whole-rock Rb/Sr analyses as well as U/Pb analysis of one zircon fraction were presented. The authors reported a Rb / Sr whole rock age of 436 ± 9 Ma. (1σ error) and a $^{207}\text{Pb} / ^{206}\text{Pb}$ age of $424.4 \pm \approx 6$ Ma. Stewart et al. posed two possible interpretations for the data. The first scenario assumed the two ages were valid within analytical uncertainties and reflected an age of intrusion of 430 ± 10 Ma. The second model, favored by the authors, proposed that the ages were in error, and that the intrusions were Devonian in age. The authors cited the possibility of mixing magmas of differing strontium initial ratios to discredit their Rb / Sr isochron, and pointed out the possibility that the zircon had an inherited lead component, resulting in an older apparent age.

Data reported by Stewart et al. were plotted on an SIR versus $1 / ^{86}\text{Sr}$ diagram to test their mixing hypothesis (Figure 23). Initial ratios were calculated based on an age of 430 Ma. Three samples returned similar initial Sr ratios of 0.7054. These included two samples of granodiorite and one of tonalite. Stewart's quartz diorite and granite sample returned different calculated initial Sr ratios, lower than those of the granodiorite and tonalite. In this sense, the regression, as reported by Stewart et al., does represent a mixing line. However, York model II regression of three samples with similar strontium initial ratios returns an age of 432 ± 17 Ma (2σ errors, square root of the MSRS=0.31) representing an age for the granodiorite-tonalite assemblage which is broadly similar to the $^{207}\text{Pb} / ^{206}\text{Pb}$ zircon age.

Comparison of the MIC and South Penobscot Intrusive Series

The MIC and South Penobscot Intrusive Series share many similar characteristics, from isotopic signatures and range of lithologies to style of pluton emplacement. Both plutons

SIR versus 1/Sr
South Penobscot Intrusive Series

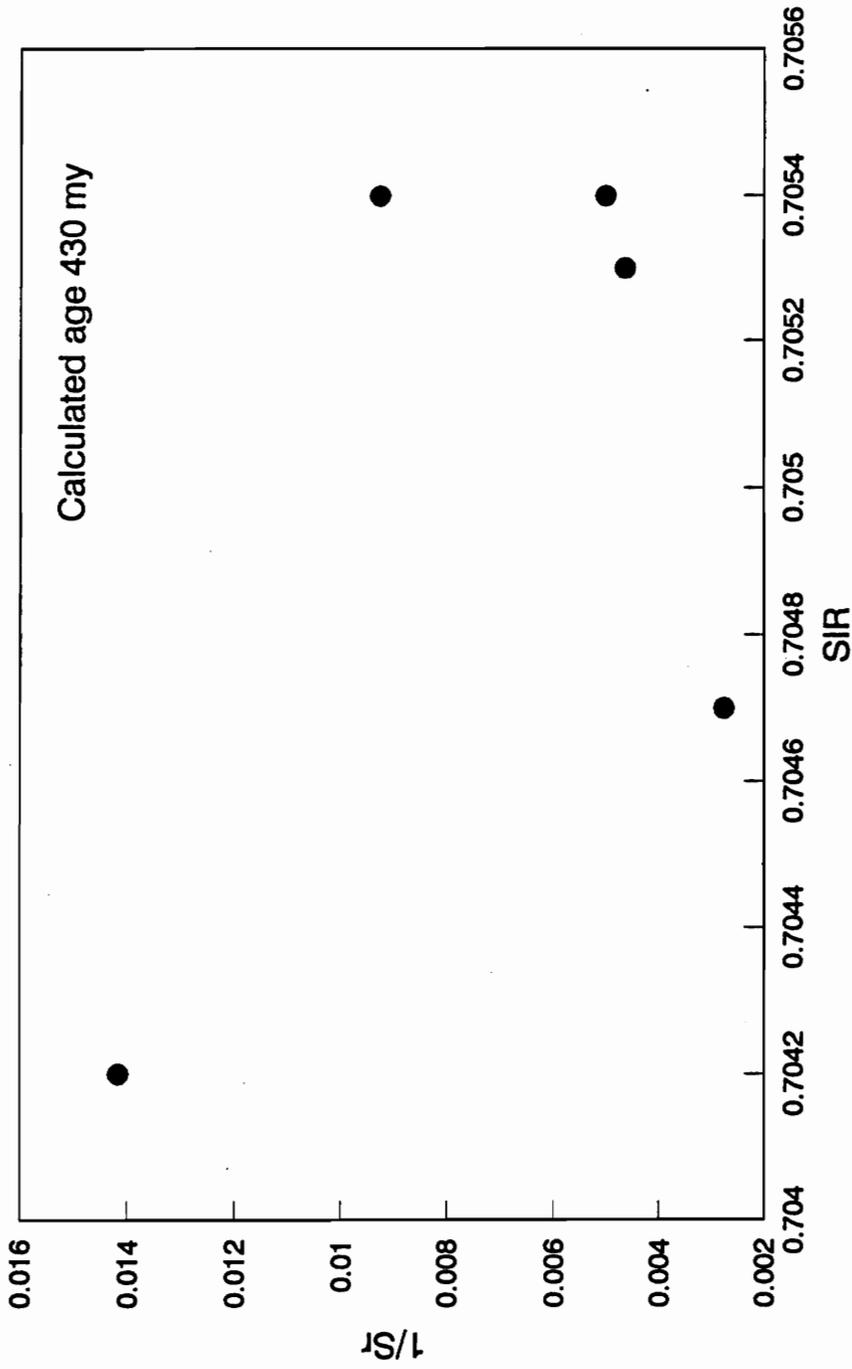


Figure 23: SIR versus $1 / ^{86}\text{Sr}$ variation diagram for data from the South Penobscot Intrusive Series. Data is taken from Stewart et al., 1988.

were intruded during the Early Silurian as indicated by Rb / Sr whole rock analyses (≈ 430 Ma), and carry a similar strontium initial ratio of 0.705. Both plutons yield zircons fractions with $^{207}\text{Pb} / ^{206}\text{Pb}$ upper intercept ages of between 430-435 Ma.

The two complexes contain a similar range of lithologies. Mafic rocks within the complex show a range of compositions from layered gabbros and norites through massive gabbros to diorites. Felsic compositions include granites and granodiorites. Field relations and radiometric age determinations point to an elaborate history of pluton emplacement in the complexes, with early stratiform mafic intrusions cut by later felsic plutons. Mafic magmatism continued throughout emplacement of the igneous complexes, with intrusion of more intermediate compositions. The complete magmatic cycle lasted at least 12-15 m.y. as indicated by the radiometric ages returned from zircons of the early MIC units (Baring granite and Calais Diorite-Gabbro).

Interaction between mafic and felsic units did not result in significant generation of melts with intermediate compositions. Most interaction between mafic and felsic materials is limited to anastomosing dikes of granite invading gabbro, or granite intruding and brecciating the host mafic phase. Local zones of rounded enclaves occur, usually grouped in swarms, and may represent injected, pillowed, mafic melt in a felsic host. True hybridization may occur in the enclave zones, but is extremely rare. Limited chemical data from the Baring granite suggest intermediate compositions are present, but restricted in occurrence.

Tectonic Setting of the Late Ordovician-Silurian Magmatic Cycle

Characteristics of the two plutonic belts result from the tectonic setting into which they were emplaced. Attributes important to deciphering the tectonic setting include the length

and separation of the two belts, the duration, nature, and timing of associated magmatism, and the levels of the crust into which they were emplaced. The Late Ordovician-Silurian magmatic cycle in Maine is represented by two sub-parallel belts averaging 700 km in length and separated by an average distance of 150 km. It should be noted that the separation between the two belts represents an absolute minimum distance for separation of the two magmatic axes due to later crustal shortening during the Devonian period. At present erosional levels, the western belt contains the more areally extensive and compositionally diverse suite, covering 1870 km² and containing an assemblage of diorites, syenites, monzonites, tonalites, and gabbros. The coastal belt is more restricted in both areal extent and lithologies present, covering an area of approximately 700 km² and consisting of gabbro, diorite, granodiorite, tonalite, and granite.

The nature of magmatism during the Late Ordovician-Silurian in the northern Appalachians may best be represented as an arc back-arc system (Naylor, 1969, Foland and Loiselle, 1985, Tucker and Robinson, in press). Plutons of the western belt were emplaced beneath the island arc; the coastal belt plutons intruded into the extensional back arc environment. The Bronson Hill anticlinorium has long been postulated as the locus of an ancient volcanic arc (Naylor, 1969, Foland and Loiselle, 1985). Furthermore, the Late Ordovician Ammonoosuc volcanics, which mantle the domes, have been theorized to have been generated at depth along an eastward-dipping subduction zone underneath the Bronson Hill anticlinorium (Leo, 1985, Drake et al., 1989).

While there seems to be little dispute that the Bronson Hill rocks represent the remnants of an ancient island arc, controversy still abounds as to the nature and duration of subduction. Based on the lithologies present in the coastal belt and the timing of

magmatism as highlighted by radiometric dating, it is possible that the coastal belt plutons were emplaced into an extensional environment in the back-arc region behind the Bronson Hill arc (Jurinski and Sinha, 1989, Hogan et al, 1988, Tucker and Robinson, in press). Several lines of evidence suggest a back arc setting for the coastal belt lithologies. The mafic-dominated, bimodal magmatism of the coastal belt has been observed in other extensional, back arc settings (e. g. the Great Bear magmatic zone of the Wopmay orogen, (Hildebrand et al., 1987)). Initiation of back arc magmatism in both the Wopmay orogen and the CMMP shows an average lag of 5-15 m. y. behind onset of arc magmatism. The bimodal nature of the back arc magmatism in the Wopmay orogen was ascribed to the switch from a compressional to tensional stress regime in the back arc region to which the authors attributed the change in distribution of pluton compositions (Hildebrand et al., 1987).

Tectonothermal Evolution of the Coastal Maine Magmatic Province

Plutonism within the CMMP reflects the complex tectonothermal evolution of the upper crust during the Late Silurian through Devonian periods. Discrete peaks in distribution of ages reflect thermal perturbations of the crust, which are distinctly characteristic with respect to lithologic associations.

Field relationships, enhanced by detailed isotopic investigations of plutons within the MIC, have allowed resolution of two thermal peaks in the northern portion of the coastal belt from the Late Ordovician through the Devonian. An earlier event, centered around 430 Ma, is characterized by predominantly mafic magmatism associated with minor felsic (granitic to granodioritic) plutonism. The units of the MIC were emplaced in conjunction

with this earlier thermal perturbation. A second thermal peak occurred around 380 Ma and resulted in the emplacement of the voluminous felsic Devonian plutons. A third magmatic cycle is possible around 360 Ma and is characterized by a distinctly bimodal granite-gabbro assemblage. At the present time, the two earliest thermal perturbations appear to be separated by a 20 my break in magmatism. However, this apparent break may be an artifact of sampling of dated plutons, and not representative of a true lag in magma generation. Continued dating of plutons within the CMMP may reveal plutons emplaced during this period.

Close examination of the plutons of the MIC permits dissection of the earlier magmatic pulse through examination of the field relations and magmatic stratigraphy of the complex as outlined by the radiometric age determinations. The 430 Ma event is characterized by extensive and complex mafic magmatism, accompanied by minor granitic to granodioritic magmatism. In the MIC, mafic magmatism preceded emplacement of the felsic to intermediate composition magmas (Amos, 1958, Coughlin, 1987, this study). The earliest units emplaced in the MIC included the layered mafic gabbro complexes, represented by the Staples Mountain and St. Stephen' gabbros. Field relations demonstrate that the emplacement of the Staples Mountain gabbro preceded that of the Baring granite, because the granite cuts and encloses blocks of the older mafic unit. Baring granite also intrudes diorite of the Calais Diorite-Gabbro unit to the east. Intrusive breccias are also developed along this margin, and the granite appears to have chilled against the more mafic unit. The interaction of Baring granite and the diorite was quite complex, resulting in the development of the highly variable mafic enclave zones within the granite. Mafic magmatism continued in the Calais Diorite-Gabbro unit after intrusion of the Baring

granite. Zircons dated from the northern portion of the Calais Diorite-Gabbro unit suggest large scale mafic magmatism continued at least until 420 Ma.

The large heat flux imposed on the crust from intrusion of the mafic magmas may have triggered local melting of previously untapped source regions. Zircons dated from the Charlotte and Red Beach granites imply this melting response to the thermal perturbation occurred at approximately 420-415 Ma., at least 10 m. y. after the onset of the major mafic magmatic pulse.

The Red Beach age determination has special significance in that the granite intrudes sedimentary units which straddle the Siluro-Devonian boundary. The Red Beach granite intrudes both the Silurian Leighton shale (Pridolian) as well as the Lower Devonian (Gedinnian) Eastport Formation. Age determinations on the two fractions presented for the Red Beach granite imply the boundary between the Silurian and Devonian in the northern coastal Maine region is older than 415 ± 6 m. y. (compared to the published boundary of 408 ± 12). Incorporation of Red Beach detritus in the Upper Devonian Perry Formation highlights the rapid rate of pluton emplacement, uplift, and erosion that the northern CMMP was experiencing at this time. As previously mentioned, data gathered in the Calais area suggest a lag in magmatic activity in the region which began around 410 Ma and continued until the initiation of Devonian magmatism. Zircons recovered from the felsic intrusion into the diorite were dated from a lower intercept age of ≈ 390 Ma. An upper intercept age of ≈ 1100 Ma highlights a probable inherited Grenville component in these zircons. Recent work by Hogan (pers. comm.) has demonstrated a complex history of lead evolution within the source regions of the CMMP. Zircons from the younger intrusives in the Calais area reflect generation from a source region bearing this older

signature. The Meddybemps granite, dated at 372 ± 11 Ma by Rb / Sr whole rock analysis, is included with the younger intrusives of the Calais area.

The change in the style of plutonism among the two thermal events directly reflects a change in stress regime within the upper crust. The 430 Ma event, accompanied by the emplacement of the diverse granite-gabbro-diorite assemblage, occurred in an extensional environment. Extension within this region allowed mafic magmas access to upper levels of the crust. The thermal anomaly associated with the emplacement of the mafic magmas resulted in local melting of previously untapped source regions, recognized in the MIC by the generation of the Charlotte and Red Beach granites. The absence of mafic magmas during the later 380 Ma event suggests a switch to a compressional environment, resulting in ponding of the mafic magmas at the base of the crust. These magmas provided the heat source to melt previously unexploited source regions, resulting in the genesis of voluminous amounts of felsic melt (Hogan and Sinha, 1989).

Conclusions

Plutonic rocks exposed in the Calais, Maine, area provide a well documented history of several cycles of magmatism, evidence which has been obliterated from most of the rest of the CMMP. The reconstructed magmatic history points to emplacement of a mafic-dominated bimodal plutonic suite into an extensional back arc setting. The extensional stress regime allowed mafic magmas access to upper levels of the crust, where localized melting generated the Charlotte and Red Beach granites. A change in stress regime resulted in the ponding of mafic magmas at deeper levels, where a new and distinct source region melted in response to the thermal perturbation, resulting in generation of the

Meddybemps granite and felsic material intrusive into the diorite.

The complex history preserved in the MIC and surrounding units highlights the problems of working in areas with extensive histories of thermal activity. Detailed age dating and source region studies of plutons in these regions are needed to sort out the tectonothermal history before realistic modeling of the geologic history is possible. Plutons cannot be assumed to have resulted from a single magmatic event, regardless of their spatial distribution at present erosional levels.

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Appendix 1: Analytical Techniques

All analyses were performed by the author at the isotope geochemistry lab at Virginia Tech.

Whole Rock Preparation

Samples ranging in weight from 5 to 25 kg (sample size dependant upon grain size) were processed for whole rock analyses. Samples were cleaned of any weathering rinds then jaw crushed. Material from the jaw crusher was reduced to a fine powder by means of a tungsten carbide shatter box. In all cases, cleaning and precontamination techniques were used.

Mineral Preparation

Samples ranging in weight from 50 to 100 kg were jaw crushed and roller milled several times until 90-95 % of the material passed through a 425 micron (40 mesh) screen. Cleaning and precontamination techniques were employed at each step. The material was then passed across a Wilfley table to separate out a heavy fraction. This fraction was further refined with heavy liquids and magnetic separation. Zircons were hand-picked to assure 99 % + purity and then washed in acid solutions before dissolution.

Major Element Analysis

Major element oxide analyses were made on fused glass disks of whole rock powders. Analyses were performed on a Phillips Sequential X-ray Analysis System Model 1450, utilizing the methods of Norrish and Chappell (1977). Fused glass disks were prepared

from homogenized whole rock powders, mixed with a LiNO_3 oxidizer and a La-based flux (Spectroflux). These were fired in Pt crucibles over Meeker burners and cast in aluminum molds.

Calibrations for major element oxides were based on analysis of USGS standard rock powders PCC-1, GSP-1, BCR-1, AVG-1, and G-2 and performed by H. M. T. Pendrak. Errors in calibration imply precisions of 1% for SiO_2 , TiO_2 , Al_2O_3 , FeO , CaO , and K_2O , 3% for MgO , MnO , and Na_2O , and less than 0.01% for P_2O_5 .

Barium, Rubidium, and Strontium Concentrations

Concentration data for Ba, Rb, and Sr was collected on a Phillips Sequential X-ray Analysis System Model 1450 by H. N. T. Pendrak. Pressed pellets of homogenized whole rock powder, bound with fine grained boric acid and mounted in a granular boric acid background, were analyzed according to the methods of Norrish and Chappel (1977). Calibrations were based on analysis of standards including G-2, AGV-1, BCR-1, GSP-1, NBS-607, and PCC-1. Replicate analyses of pellets indicate precisions of better than 1.5% (2σ errors of the mean) for rubidium concentrations greater than 100 ppm and strontium concentrations greater than 50 ppm (Allen, 1989).

Isotope Analyses

Reagent grade HCl , HNO_3 , HBr , HF , and deionized H_2O were cleaned through subboiling distillation in teflon for all isotope work. HCl and H_2O were pre-cleaned in a quartz still prior to teflon distillation. Pre-cleaned Savillex bombs were used for whole rock analyses, while teflon was used for zircon. Samples were collected in polymethylpentene

(PMP) beakers washed overnight in warm 20% HNO₃, rinsed in quartz distilled H₂O, and refluxed with warm teflon distilled 6N HCl.

Isotope ratios were measured on a modified and automated AVCO 35 cm radius, 90° sector, solid source mass spectrometer interfaced to a PDP-11 computer. The magnetic field was switched and controlled by a Varian FR-41 gaussmeter/controller. Ratios were integrated by a HP integrating voltmeter processed in an algorithm following the procedure of Hart and Brooks (1977).

Strontium Isotopic Analysis

0.1 g of rock powder were dissolved in a mixture of 1 part teflon distilled H₂O, 4 parts teflon HF, and 2 parts teflon HNO₃ contained in teflon-refluxed 5 or 10 ml Savillex bombs. Dissolution took 2 to 3 days at 150° C. After the samples were dissolved, the solution was evaporated down, rinsed with a minimum amount of teflon H₂O, and turned to a chloride by addition of 0.5 ml 6N HCl. After evaporation, samples were equilibrated overnight with 1.0 ml 2.5N teflon HCl. The samples were then centrifuged and loaded on to cation exchange columns consisting of 0.5 cm diameter pyrex tubes with fitted blown silica frits filled with 3 ml AG 50w x 8, 200-400 mesh resin with a bed length of approximately 20 cm. The columns had previously been cleaned with teflon distilled HCl, and conditioned with 2.5N HCl. Samples were then eluted with 2.5N HCl.

Strontium isotopic composition determinations were run on the mass spectrometer as phosphates loaded onto previously degassed Re filaments. Filaments were coated with Ta₂O₅ prior to sample loading, then dried and mounted into the machine. ⁸⁷Sr / ⁸⁶Sr ratios were corrected to a ⁸⁶Sr / ⁸⁸Sr ratio of 0.1194 during the run. 50-125 ratios were collected

until a standard error of 0.0001 (2 sigma) had been obtained.

$^{87}\text{Rb} / ^{86}\text{Sr}$ calculations were performed on a spreadsheet after the equation of Faure (1986). Age determinations of plutons were calculated from a FORTRAN program based on a York Model II regression (York, 1966). The decay constant used for $^{87}\text{Rb} = 1.42 \times 10^{-11}$ /yr (Steiger and Jaeger, 1977).

Uranium and Lead Isotopic Analysis

Zircon separates were divided into size fractions by sieving to various mesh sizes. The fractions were then hand picked to assure 99% + purity. The pure fractions were washed in warm HNO_3 and rinsed in teflon H_2O and teflon acetone. Each size fraction was split into two samples, one of which was spiked with a mixed $^{235}\text{U} / ^{208}\text{Pb}$ solution. Samples and spikes were placed into clean teflon bombs with a mixture of 90% teflon distilled 48% HF and 14N HNO_3 . The bombs were loaded into MONEL screw top sleeves and heated in a 220° C oven for 7 days (Krogh, 1973). Samples were then checked for complete dissolution, evaporated, and converted to a chloride by addition of teflon HCl. Uranium and lead were collected by elution on 0.5 cm diameter teflon columns with fitted blown silica frits filled with AG 1-x8 200-400 mesh resin to a bed length of 2 cm. 3.1N teflon distilled HCl was used for the elution (Krogh, 1973).

Three lead blanks averaged 552 pg, and range from a high of 962 pg to a low of 211 pg.

Ages, ratios, concentration, and errors were calculated with the FORTRAN program PBDAT (Ludwig, 1989) using the ratios and standard error of the mass spectrometer data combined with known information on the composition of the spike and the size of the

blank. Common lead correction estimates were provided by Hogan (pers. comm.) or calculated by a two stage lead evolution model (Stacy and Kramers, 1975). Errors on the regression (age) were calculated from errors given in PBDAT on CONCORDI (Ludwig, 1980). Decay constants used for age determinations were $^{238}\text{U} = 1.5525 \times 10^{-10}/\text{yr}$ and $^{235}\text{U} = 9.8485 \times 10^{-10}/\text{yr}$ (Steiger and Jaeger, 1977).

Appendix 2: Road Transect of the MIC

| Mileage | Description |
|---------|---|
| 0.00 | Start of transect 1.35 km SE of Anderson Brook along U. S. Route 1. Transect continues south along Route 1. Outcrop of the Kendall Mountain Formation to the SW. Outcrop is composed of jointed quartzite with no apparent bedding. |
| 2.70 | Interbedded sulfidic sandstones and shales of the Woodland Formation. Bedding averages 075 45° SE. |
| 5.40 | Baring granite-Diorite-Cookson group contact. Folded sediments of the Cookson group crop out at intersection of old Route 1 and new road to the northeast. Traversing southeast along Route 1, one passes through a narrow screen of diorite. The first outcrops of Baring granite lie along the north side of Route 1, adjacent to the small road heading north. |
| 7.20 | First exposure of the enclave zone adjacent to drive-in theater. Approximately 75% mafic material. A large diversity in enclave textures is observed in this exposure. Rounded enclaves appear to predominate. |
| 7.40 | Type locality for the enclave zones. Large variety of enclave in a granite host. Abundant enclave swarms hosting a variety of textures and compositions occur across the outcrop. |
| 7.70 | A small exposure of diorite crops out along the north side of the road. Outcrop contains approximately 90% mafic material. The exposure also contains possible ultramafic xenoliths. |
| 7.80 | Outcrops of "clean" Baring granite to the south of the road. Possible late mafic dikes cut the outcrop. Granite varies from fine to medium grained. |
| 8.10 | Intersection of Routes 1 and 191. Outcrops of enclaves and highly variable granite crop out. Aplite and leucocratic granite dikes cut the outcrop. Enclaves are highly variable in shape and composition. |
| 8.20 | Outcrop on SE side of road. Enclave swarm of approximately 75-80% mafic material crops out. The exposure also contains a large number of late stage felsic veins. |
| 9.30 | Baring Airport exposure. Outcrops of hornblende-bearing granite lie to the south of the road. The exposure contains a few, small, biotite-rich xenoliths. |

- 10.1 Outcrops of clean Baring granite lie to the south of the road. The outcrop contains very few xenoliths or aplite dikes.
- 11.6 Exposures of clean Baring granite crop out at the entrance to the Calais Industrial Park. These are the last exposures of "clean" Baring granite.
- 12.5 Outcrop of Cookson hornfels cut by dikes of Baring granite. Granite cut the metasediments, spalling off blocks. Metasediments contain garnet porphyroblasts, while the granite contains garnet xenocrysts(?).
- 13.5 Ames department store parking lot. Exposures of St. Stephen gabbro and gabbro-Cookson group melt zone. Exposures SW of the parking lot contain xenoliths of metasediment in a gabbro matrix. Abundant felsic dikes in the gabbro are proposed melts of the metasediment. Large exposures of gabbro with minor, narrow, felsic dikes, crop out the the NE of the parking lot.
- 17.0 Across the road from Taylor Furniture store. Outcrops of the Calais Diorite-Gabbro unit. Outcrops consists mainly of diorite with minor occurrences of felsic dikes and enclave swarms. Enclaves exhibit a large range in size and are mostly angular. Large phenocrysts of feldspar, up to 2.5 cm, are developed in the diorite.
- 17.7 Large exposures of diorite intruded by sills of Red Beach granite. Contacts between gabbro and granite are sharp. Granite textures range from coarse grained to fine grained. Dikes of the granite entrain enclaves of the gabbro.
- 18.1 Exposures of microgabbro with pegmatite and aplite dikes crop out along the south side of the road. Contacts between the felsic dikes an enclosing gabbro are sharp. Mafic clots occur in the gabbro as isolated bodies and in swarms. These mafic zones average 2-3 cm in length and are ellipsoidal in shape.
- 18.5 Outcrops of diorite. Diorite exhibits "salt and pepper" texture. The exposure contains a few zones of felsic material (Red Beach granite (?)). Gradational contacts appear between mafic and felsic material through zones of intermediate composition.
- 19.7 Exposures of massive diorite up the hill past Heslin's motel. Diorite shows minor variations in texture through the exposure. This outcrop was sampled for both zircon analysis and for a suite of samples for Rb / Sr whole rock analysis. Samples JJ-304, 3045, 306, 387-87 collected here.
- 20.2 Small exposure of Red Beach-Diorite contact zone.
- 20.6 Red Beach granite contact.

- 20.8 Exposures of Red Beach granite. Sample location for Red Beach zircon sample and one Rb / Sr whole rock sample. Samples JJ-307,308 collected here.
- 21.0 Red Beach outcrop. Sample JJ-309-87 collected here.
- 21.1 Red Beach outcrop. Sample JJ-310-87 collected here.
- 21.6 Red Beach outcrop. Sample JJ-311-87 collected here.

Appendix 3: Late Ordovician-Silurian Plutons

| Pluton | Age | Method | Reference |
|---------------------|------------|--------|--------------------------|
| East Inlet | 430 ± 4 | U/Pb | Lyons et al., 1986 |
| Sharpners Pond | 430 ± 5 | U/Pb | Zartman and Naylor, 1984 |
| Cape Ann | 430 ± 4 | U/Pb | Zartman, 1977 |
| Lebanon | 431 ± 20* | Rb/Sr | Naylor, 1969 |
| Mascoma | 431 ± 45* | Rb/Sr | Naylor, 1969 |
| Ayer | 433 ± 3 | U/Pb | Zartman and Naylor, 1984 |
| Baring | 434 ± 9 | U/Pb | <i>this study</i> |
| Trousers Lake | 434 +29/-6 | U/Pb | Bevier, 1988 |
| Candlewood Lake | 435 ± 12 | Rb/Sr | Mose and Nagel, 1982 |
| South Penobscot | 436 ± 9 | U/Pb | Stewart et al., 1988 |
| Lost Nation | 439 ± 25 | U/Pb | Lyons et al., 1986 |
| Brookfield Center | 440 ± 4 | Rb/Sr | Mose and Nagel, 1982 |
| Monson | 440 ± 10 | U/Pb | Zartman and Naylor, 1984 |
| Attean | 443 ± 4 | U/Pb | Lyons et al., 1986 |
| Jefferson | 444 ± 8 | U/Pb | Zartman and Leo, 1985 |
| (Whitefield gneiss) | | | |
| Keene | 444 ± 8 | U/Pb | Zartman and Leo, 1985 |
| (Swanzy gneiss) | | | |
| Owl's head | 444 ± 8 | U/Pb | Zartman and Leo, 1985 |
| Sugar Hill | 444 ± 8 | U/Pb | Zartman and Leo, 1985 |
| Lincoln | 444 ± 8 | U/Pb | Zartman and Leo, 1985 |

*ages corrected for decay constant of $^{87}\text{Rb} = 1.42 \times 10^{-11} /\text{y}$.

Ages compiled from Sinha (1988)

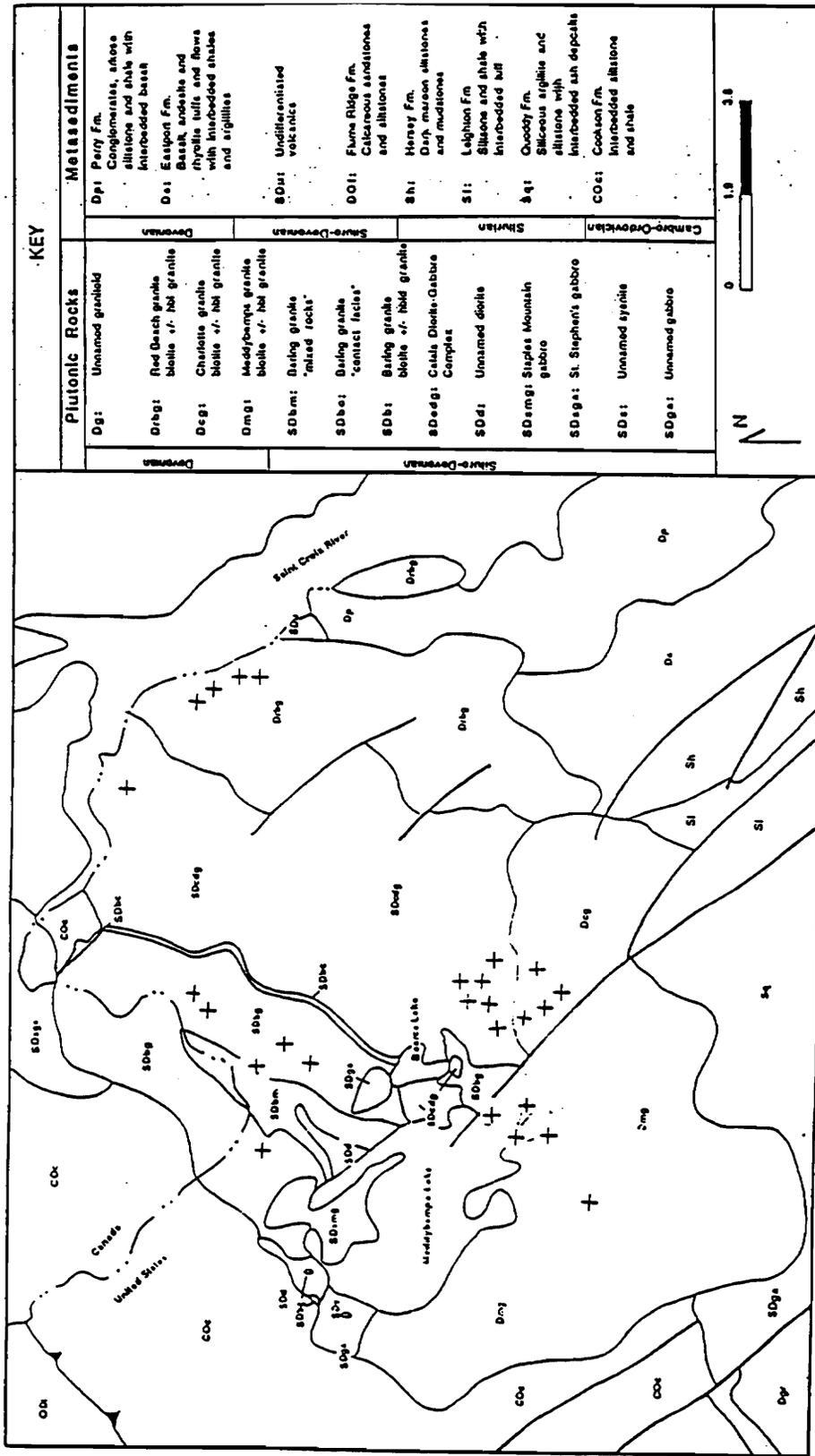
Appendix 4: Sample Location Maps

Map 1: Baring granite modal analyses.

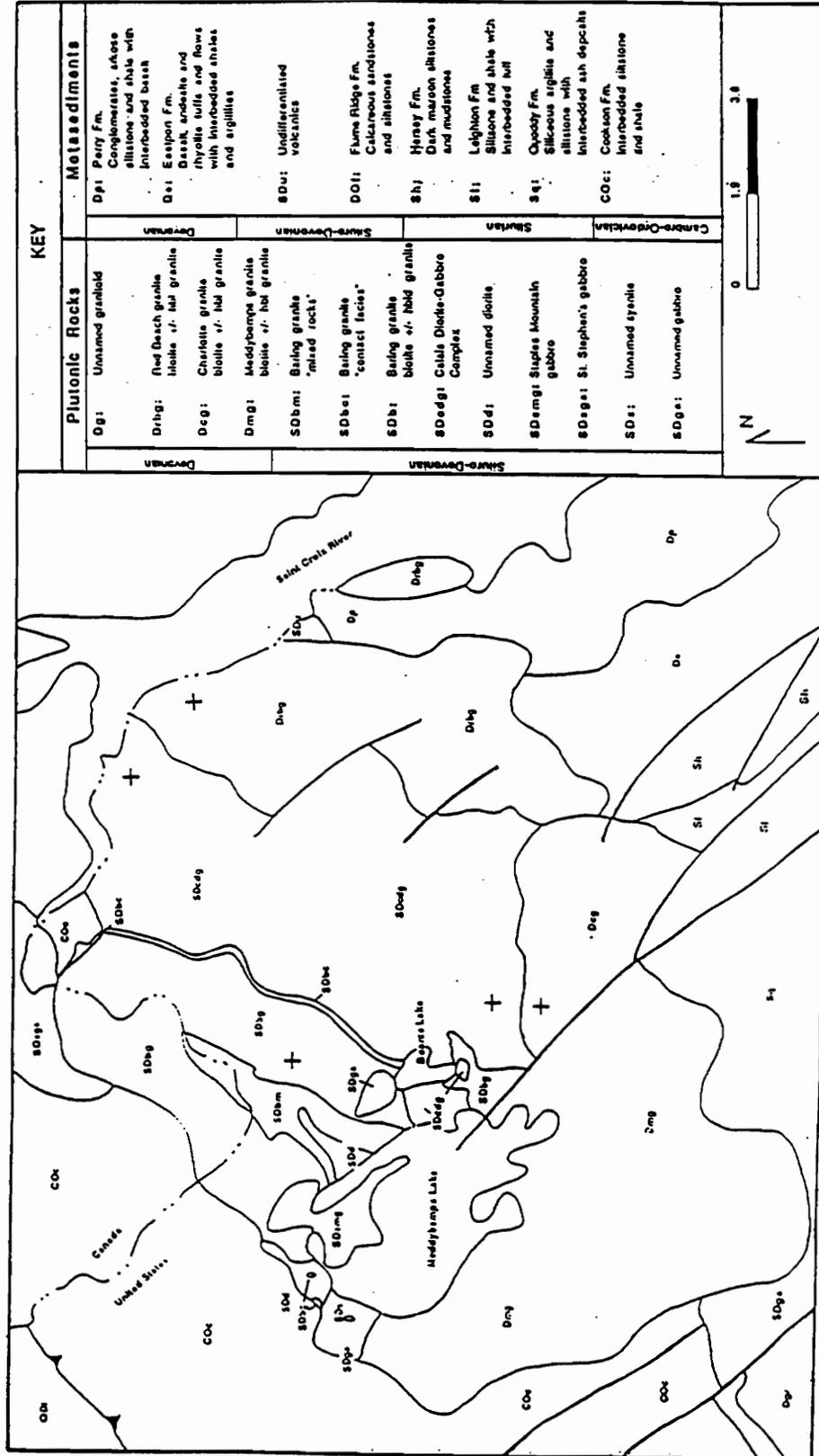
Map 2: Rubidium / Strontium whole rock sample locations.

Map 3: Zircon sample locations

Appendix 4: Sample Location Maps



Rb / Sr sample locations.



Zircon sample locations

Appendix 5: Geologic Map

The geologic map, included as an insert, was compiled on an enlarged copy of the U.S. Geological survey Calais quadrangle 15' sheet. The order of the igneous units listed in the key does not imply their stratigraphic order in the field. Dated plutons are designated as SD (Siluro-Devonian) based on preliminary radiometric age determinations. The ages of the plutons quoted in the text span the Silurian-Devonian boundary within the errors reported for the analyses.

Vita

"Free at last! Free at last! Thank God Almighty we are free at last."

-Martin Luther King, Jr.

Joseph B. Jumper
5/7/90