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Bedrock Geology of the Calais 15' Quadrangle, Eastern Maine

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INTRODUCTION

The Calais 15' quadrangle (45°00' - 45°15'N; 67°15'-67°30'W) is located in easternmost Washington County at the U.S./Canada border. It lies within the coastal lithotectonic belt (Osberg et al., 1985), a collage of several disparate lithostratigraphic tracts. The quadrangle contains parts of three of these tracts (Fig. 1) — the Fredericton trough, St. Croix belt, and coastal volcanic belt—and also contains a wide variety of plutonic rocks ranging from gabbro-norite through granite. The geologic history recorded in these rocks is complex, and is believed to span at least Cambrian through Devonian times. This interval was one of extensive tectonic activity in the Northern Appalachians, and knowledge of Calais area geology is vital to regional orogenic synthesis.

Physiography and Culture

The study area consists of low, rounded hills that generally stand only 200-300 feet above swampy lowlands and lakes. The highest elevation is at Breakneck Mountain in the southwestern corner of the quadrangle (660+'), and the lowest is in the north-east corner where the St. Croix River leaves the quadrangle at Calais (15' above sea level). Although total relief is thus approximately 650', local relief is generally far less.

Topography is controlled by a combination of glacial depositional features and resistant bedrock knobs, although the correlation between lithology and elevation is often tenuous. For example, Breakneck, Pineo, and Chapman Mountains are underlain by very high grade hornfels, whereas Staples (gabbro-norite) and Magurrewock (granite) Mountains are supported by plutons. Similar plutonic rocks occupy lowlands between these hills and most of the basin filled now by

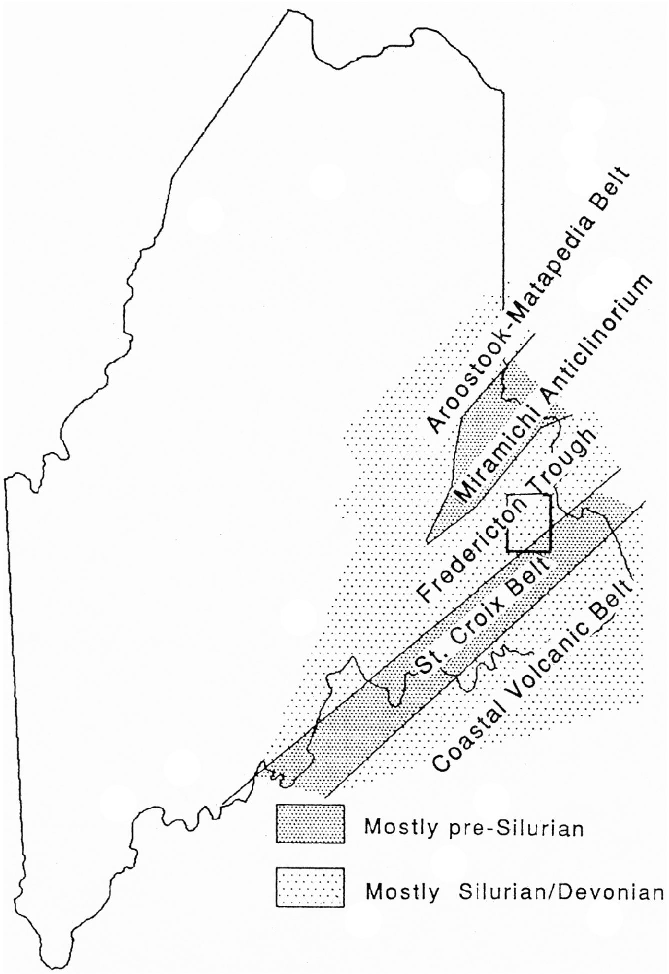

Figure 1. Regional tectonic setting of the Calais quadrangle.

Meddybemps Lake and Heath. Some of the hills display the classic stoss-and-lee form of glaciated bedrock, but others have their steepest slopes facing north (up-glacier) and thick till deposits on their gentle south slopes. The ice-advance direction is reflected by the elongate nature of Meddybemps Lake, and by the southeast course of the St. Croix River through most of the quadrangle.

Glacial deposits include a blanket of till covering most of the area, eskers, and kame-like deposits northwest of Woodland. A coarse, limonite-cemented tillite composed mostly of locally derived boulders of the Calais Formation is exposed in the St. Croix River between Steamboat Street and the Country Club in Calais.

These extensive deposits mask bedrock in most places, but outcrops are abundant locally. The St. Croix River contains extensive exposures in the Milltown-Calais area and at the Woodland and Baring dams. Most of the smaller streams are cut into glacial deposits, but Dead Stream in the southwest corner of the quadrangle flows in bedrock for more than a mile. Most hilltops expose bedrock, particularly in areas underlain by plutonic or high grade metamorphic rocks. Lakeshores vary widely in the amount of bedrock present: Pleasant and Round Lakes are devoid of outcrops, whereas parts of Meddybemps and Bearce Lakes contain abundant exposures. Bedrock exposure is estimated to be approximately 1% of the total area of the Calais quadrangle.

The vast majority of people in the quadrangle live in Calais (pop. 4,254) and Woodland (2,165), with smaller concentrations in Alexander (383), Baring (308), Charlotte (295), and Meddybemps (110). The chief industry in the region is lumbering, and the Georgia-Pacific Corporation operates paper, stud, and particle board mills in Woodland. Washington County is nationally known for its wild blueberry crop, and blueberry fields cover many of the hills in the southern part of the quadrangle. Calais is a major border crossing and supports a number of border brokerage houses, as well as tourist accommodations.

Access is excellent, primarily through a network of paved highways including U.S. Rte. 1, Maine routes 9, 191, and 214, and several unnumbered county and town roads. Lumber roads in the southern and northwestern parts of the quadrangle provide access to areas hitherto reachable only by woods traverses, and also create new outcrops. Large portions of the study area are best visited by boat or canoe, including the numerous lakes and the St. Croix River. Railroad tracks between Woodland and Princeton were removed several years ago, and the right-of-way has been maintained as a good quality dirt road.

Previous Works

Alcock (1946) mapped in Charlotte County, N.B., immediately east of the Calais quadrangle, and divided the stratified rocks there into the "Pale and Dark Argillite Divisions of the Charlotte Group." Amos (1963) extended this nomenclature into the Calais quadrangle, and compiled the first study of the area's plutonic rocks. He mapped complex relationships among granitic, dioritic, and gabbroic bodies in the eastern part of the quadrangle, recognized the Baring, Charlotte, and Meddybemps granites as separate entities, and proposed that the gabbros were emplaced prior to the granites. Larrabee (1964) extended Alcock's stratigraphy into the adjacent Big Lake quadrangle but proposed the name "Kellyland Formation" as a substitute for "Pale Argillite." Ruitenberg (1967) revised the stratigraphy in New Brunswick, recognizing three units where Alcock had mapped two, and subsequent work showed that this threefold division was also applicable in the Calais area (Ludman, 1975; Ruitenberg and Ludman, 1978). Two of these units were assigned to the Fredericton trough, the third to the St. Croix belt. Later work by Senz (1978) and Ludman (1978, 1981, 1985a, b) suggested that further subdivision was necessary, and Ludman (1987) recognized four formations within the St. Croix belt. Recent fossil discoveries in New Brunswick (Fyffe, pers. commun., 1989) have led me to invert the proposed St. Croix sequence and to reassign one of the formations to the Fredericton trough (see Ludman, 1990).

Plutonic rocks of the area have received attention from several workers in addition to Amos. Houston (1956) described the St. Stephen pluton and its possible pyrrhotite deposits, and Coughlin (1981, 1982) suggested a differentiation model for the layered gabbros of the Staples Mountain Complex. Westerman (1972, 1981) mapped variations in the Pocomoonshine gabbro-diorite of the Big Lake quadrangle and explained them by magmatic differentiation. Abbott (1977, 1978) described the lithologies and petrogenesis of the Red Beach granite in the Robbinston quadrangle, and David Wones began a study of the plutons of the Calais quadrangle in 1984. Hill and Abbott (1989) described magma mixing in the Calais-Red Beach area, and Jurinski (in preparation) has examined relationships between the Baring granite and its host rocks. Hogan (in preparation) has worked on the tectonic significance of all the plutonic rocks in the coastal lithotectonic belt.

Acknowledgments

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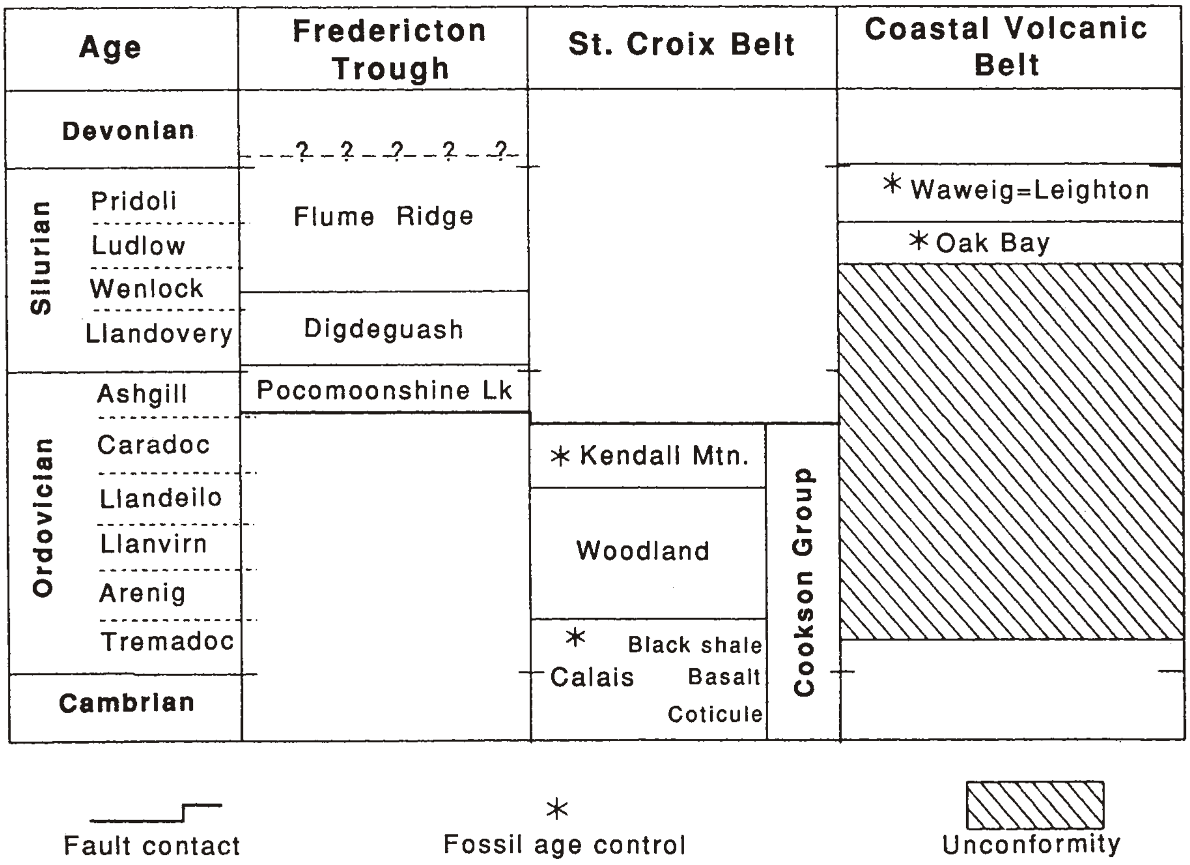

Figure 2. Stratigraphy of the Calais quadrangle.

worked in and around the Calais area, and wish to thank Arthur Ruitenberg, Peter Stringer, George Pajari, Ron Pickerill, Steve McCutcheon, Les Fyffe, Olcott Gates, Richard Gilman, David Westerman, Krishna Sinha, John Hogan, and Joe Jurinski for their advice, suggestions, and arguments. We also wish to acknowledge the contribution made to this project by David Wones during the summer of 1984. Special thanks go to Marc Loiselle for his support and interest in the project, and to Mr. and Mrs. Brydon for making the work in eastern Maine so pleasant.

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STRATIGRAPHY

Each of the three lithotectonic tracts exposed in the Calais quadrangle contains a distinctive stratigraphic package (Fig. 2). The total assemblage contains a wide variety of sedimentary and volcanic rocks, and records important tectonic events in the history of Iapetus, the Early Paleozoic proto-Atlantic Ocean. Metamorphic grade in the quadrangle ranges from chlorite zone in the Fredericton trough to the northwest to anatectic migmatites of the St. Croix belt in the southwest, but primary sedimentary and volcanic features are well preserved in all except the most migmatized zones. Part of the coastal volcanic belt in the southeast corner is highly fossiliferous, and graptolites in New Brunswick date two of the three formations of the St. Croix belt. Rocks of the Fredericton trough are unfossiliferous, however. The St. Croix belt is of Cambro-Ordovician age, and the coastal volcanic belt is clearly Silurian through Early Devonian. The age of the Fredericton trough strata is controversial and will be discussed in detail below.

Cambro-Ordovician Rocks of the St. Croix Belt

Rocks of the St. Croix belt are assigned to the Cookson Group (see Ludman, 1987, 1990), and divided into three formations as shown in Figure 2. These rocks were first mapped as the Dark Argillite Division of the Charlotte Group (Alcock, 1946; Amos, 1963; Larrabee, 1964) and later as members of the Cookson Formation (Ruitenberg, 1967; Ruitenberg and Ludman, 1978). With elevation of the Cookson Formation to group status, these members have been renamed as formations (Ludman, 1987; 1990). All three formations—Kendall Mountain, Woodland, and Calais—are sulfidic and rusty weathering to some extent, contain at least minor amounts of carbonaceous pelite, and were presumably deposited in anoxic conditions.

Calais Formation (OCc). With the elevation of the Cookson Formation to group status, rocks that lie between the Woodland Formation and conglomerates of the Oak Bay Formation have been renamed the Calais Formation. These rocks are on strike and continuous with the former Cookson Island type locality. A superb section through the Calais Formation is exposed in the St. Croix River in Calais and extends downstream into the adjacent Devil's Head 7.5' quadrangle. The westernmost outcrops in this belt can be traced continuously to the fossiliferous rocks on Cookson Island, where the sooty slates are unconformably overlain by the conglomerates of the Oak Bay Formation. In the St. Croix River, a sequence of pillow basalts, massive basalts, and coticule separates what had been called typical "Cookson Formation" and the Oak Bay Formation (Senz, 1978; Senz and Ludman, 1978). These are now mapped as members of the Calais Formation.

The contact between the Woodland and Calais Formations is sharp and apparently conformable, and can be located to within 5 m in the St. Croix River just downstream from the parking area at the foot of Steamboat Street in Calais. The contact between the Calais and Oak Bay Formations is not exposed. Flattening of clasts in the Oak Bay Formation and disruption of layers in the coticule member of the Calais Formation suggests a fault contact rather than an unconformity as at Cookson Island.

The Calais Formation is subdivided into three members. The lowest, separated by a covered interval about 100 m wide from the Oak Bay Formation, is a section composed of siltstone and coticule. This member is exposed only along the St. Croix River in the Devil's Head quadrangle just southeast of the eastern margin of the Calais quadrangle. The coticule consists of quartz-garnet lenses, pods, and layers in a hornfelsed biotite-bearing quartzofeldspathic siltstone. The coticule layers are folded tightly and disrupted, and dismembered fragments of the layers are commonly flattened and rotated.

The middle member of the Calais Formation consists of pillow basalts and massive basalts interbedded with black slates. The basalts are thermally metamorphosed to plagioclase-actinolite rocks, yet still preserve signs of original compositional zoning and both radial and concentric pillow structure. Similar metabasalts in the southwest corner of the Calais quadrangle are assigned to the Calais Formation and are associated with mafic tuff. The basalts are tholeiites, as shown in Table 1.

The uppermost member of the Calais Formation is a homogeneous sequence of rusty weathering, highly carbonaceous black slate/phyllite with very rare beds of quartzwacke. The psammites are 5-10 cm thick and are more resistant to erosion than the pelite. Pelites of the Pocomoonshine Lake Formation are similar to those of the Calais Formation, but are generally parts of well-graded beds, are less carbonaceous, and have more intercalated sandstone. New lumber roads in the southwest corner of the Calais quadrangle have created small outcrops of andalusite-bearing, highly carbonaceous pelite that are thought to be a continuation of the Calais Formation. Cyclically twinned cordierite and prismatic andalusite are abundant in the formation, but are also typical of most pelites of the Cookson Group.

Age and Correlation of the Calais Formation. Graptolites found on Cookson Island by Cumming (1965) have been assigned a Tremadocian age by John Riva (see Ruitenberg and Ludman, 1978), thus establishing an earliest Ordovician age for the youngest part of the Calais Formation. There is no faunal or radiometric evidence for the age of the other members, but their inferred position beneath the black shales suggests a Tremadocian or perhaps latest Cambrian age.

Rocks now assigned to the Calais Formation have been traced into the Wesley quadrangle to the southwest (Gilman, 1974; Westerman, 1978). Similar lithologies crop out further southwest, but are separated by plutons from the type locality at Calais (Osberg et al., 1985). At Penobscot Bay, the Penobscot Formation as described by Stewart and Wones (1974) appears to be largely equivalent to the Calais Formation, although rocks similar to the lithologies of the Kendall Mountain and Woodland Formations occur there as well (Wones, pers. commun., 1984). The Gushee Member of the Penobscot Formation is a tholeiitic basalt that is nearly identical chemically to the middle member of the Calais Formation (Fyffe et al., 1988).

Woodland Formation (Ow). Interbedded metasandstones and metapelites of the Woodland Formation comprise most of the St. Croix belt in the Calais quadrangle and are well exposed

TABLE 1: COMPOSITIONS OF VOLCANIC ROCK FROM THE COOKSON GROUP
(X-ray fluorescence analyses by X-Ray Assay Laboratories)

Oxide	Specimen					
	1	2	3	4	5	6
SiO_2	49.0	50.0	47.3	49.7	77.3	82.4
TiO_2	1.94	1.35	3.18	3.30	0.43	0.17
Al_2O_3	18.1	18.1	15.1	16.2	12.3	9.56
CaO	6.71	9.68	6.57	5.94	0.44	0.17
MgO	6.48	5.49	7.10	6.39	0.56	0.20
Fe_2O_3*	7.93	10.1	14.1	12.0	1.29	1.06
Na_2O	4.37	4.64	3.51	4.12	7.30	6.05
K_2O	0.63	0.83	1.27	0.82	0.10	0.05
MnO	0.14	0.12	0.22	0.18	0.02	0.03
P_2O_5	0.22	0.25	0.46	0.47	0.05	0.03
Loss on ignition	1.31	1.31	1.00	0.39	0.47	0.47
TOTAL	100.1	100.2	99.81	99.51	100.3	99.72

1. Calais Formation, pillow basalt member. Core of pillow from St. Croix River, Calais.
2. Calais Formation, pillow basalt member. Rim of same pillow as #1.
3. Calais Formation, pillow basalt member. Pillow center, St. Croix River, Calais.
4. Calais Formation, pillow basalt member. Pillow from St. Croix River, Calais.

5,6. Felsite from Kendall Mountain Formation, just west of Woodland.

throughout the area. The formation is named for superb outcrops at the Georgia-Pacific dam in Woodland where metamorphic grade is relatively "low"—cordierite zone. Other excellent exposures are found along the powerline southeast of the dam, near the Woodland town dump, on Robb Hill, and in the St. Croix River at Calais. Extensive exposures occur in the southwestern part of the quadrangle on hills such as Breakneck Mountain and in the lowlands as well. These have been thermally metamorphosed to sillimanite-potassic feldspar grade and many have undergone anatexis. Bedding is generally well preserved in all except the anatectic migmatite zones, and graded bedding is typical of the formation.

The Woodland Formation consists almost entirely of rhythmically interbedded quartzofeldspathic wacke and pelite, with both carbonaceous and non-carbonaceous slate occurring in most outcrops. All rocks are at least slightly sulfidic and weather rusty. Beds range from 2 mm to 50 cm thick, but most are between 2 and 20 cm. Most beds are graded couplets of sandstone passing into slate or phyllite, and the psammite:pelite ratio varies according to bed thickness. Roughly equal amounts are typical of the thinner bedded varieties, but the sandstones dominate thicker beds by as much as 4:1. Fine laminae defined by biotite concentrations parallel to bedding are abundant, as are cross-beds. Soft-sediment slump structures are visible in the larger exposures, particularly on the north slope of Robb Hill. Discoid concretions composed of almost pure calcite are present in a few of the thickest beds and are as large as 50 cm in diameter and 15 cm thick. Ellipsoidal calcareous concretions 25 cm long are found with the discoid masses, but both are rare.

Sandstones of the Woodland Formation are less varied than those of the Kendall Mountain Formation and are uniformly biotite-bearing quartzofeldspathic wackes with minor muscovite. Grains in these sandstones are remarkably constant in size (in the fine sand range). Even in the graded beds, the lower sandy parts show little grain size variation; grading is shown by increasing argillaceous content upward. The Woodland Formation lacks the quartzite, felsite, and lithic fragments of the Kendall Mountain Formation, but contains far more pelite—nearly 50% as compared to about 10% for the Kendall Mountain Formation. Abundant biotite produces a purplish color in the Woodland Formation that contrasts with the typical gray color of Kendall Mountain Formation (non-biotitic) arenite and wacke.

Pelites of the Woodland Formation are mineralogically similar to those of the Kendall Mountain and Pocomoonshine Lake Formations. In much of the northern part of its outcrop area, the Woodland Formation contains abundant cordierite and andalusite porphyroblasts. Cordierite commonly occurs as round grains 1-2 mm in diameter, and where retrograded it pits out on rock surfaces. Andalusite porphyroblasts, in contrast, are the size and shape of large rice grains, and stand up slightly above weathered surfaces. These habits yield a distinctive appearance that permits recognition of the formation even in the highest grades when relict porphyroblasts are preserved.

Two subordinate rock types are locally intercalated with the wackes and slates and combined amount to less than 1% of the formation. The more abundant is a dense quartz-biotite-plagioclase granofels that occurs throughout the formation in thick beds (15-50 cm) within the thinner wacke/pelite graded sets. This sandstone contains less muscovite and plagioclase than that of the graded beds and is commonly cross-bedded. The second is a thinly banded calc-silicate granofels that forms a horizon approximately 7.5 m thick near the center of the Woodland Formation. It is composed of 2.5 cm thick layers of calcite-diopside-actinolite garnet granofels that alternate with biotite-quartz-plagioclase granofels. This horizon was briefly exposed in 1981 in a road metal quarry at the Woodland dump, but has since been consumed by the quarrying. Identical rocks have been exposed just across the St. Croix River in another quarry (Fyffe, pers. commun., 1989).

Wackes of the Woodland Formation have undergone partial melting where they are in contact with gabbro, including that in the Woodland dump. In the southwestern ninth of the Calais quadrangle, even though there is little mafic rock exposed at the surface, nearly all of the exposures are of migmatites. There, quartzofeldspathic mobilizate engulfs rafts of sillimanite-rich restite, or thin gneissic bands of quartz and feldspar occur in swirls with paper thin sillimanite-biotite muscovite "schist." The migmatite crops out very well and yields the most continuous bedrock exposures in the region. It forms the tops of Breakneck and Pineo mountains, and crops out in the valley of Dead Stream, particularly north of where that stream is crossed by the road from the now-abandoned North Union School.

Leucosomes of the migmatite are coarse aggregates of chalky weathering quartz, plagioclase, and potassic feldspar with small amounts of muscovite. Melanosome rafts and laminae are medium gray, coarse assemblages of muscovite, biotite, potassic feldspar and sillimanite, with relict cordierite and/or andalusite. Sillimanite occurs as fibrolite, commonly intergrown with biotite, and as faintly green prisms. Most migmatite outcrops exhibit a swirling foliation that hinders structural interpretation, but some are massive.

<u>*Age and Correlation of the Woodland Formation.*</u> The Woodland Formation has thus far proved unfossiliferous, but its position between the Tremadocian black shale member of the Calais Formation and the Middle Caradocian rocks of the Kendall Mountain Formation indicates an Early Ordovician (Arenigian through Llandeillian) age for the formation. Rhythmically bedded rocks similar to those of the Woodland Formation are present within what has been mapped as the Penobscot Formation (Wones, pers. commun., 1984), but have not been described as a separate unit.

Kendall Mountain Formation (Ok). The Kendall Mountain Formation is named for extensive exposures along the northwest flank of that hill near the western edge of the Calais quadrangle. It is also exposed in the St. Croix River north of Woodland, north of the Woodland-South Princeton Road, and on both sides of Route 1 near the western margin of the St. Croix belt. It is also present in bedrock cores drilled north of Woodland near the St. Croix River. The formation crops out extensively in the Big Lake quadrangle between Pocomoonshine Lake and the Princeton-Alexander road.

The Kendall Mountain Formation contains a varied lithologic assemblage, including quartz arenites; quartzofeldspathic and lithic arenites, wackes, and granule conglomerates; lesser amounts of thinly interbedded siltstone and carbonaceous pelite; and an apparently unique horizon of felsic tuff. Very fine-grained basalt exposed in isolated outcrops on Kendall Mountain may have been flows associated with the felsites, but alternatively may be small dikes (see below). The formation is readily distinguished from all others in the region in that (1) it is the only unit in which pelitic rocks are so sparse (less than 10%); (2) many of its psammites are true arenites, with very little argillaceous matrix. As a result, they fail to produce biotite with elevated metamorphic grade and remain gray, in contrast to the purplish color of biotite-rich metasandstones of other formations; and (3) it is the only unit in which felsic volcanic material is present.

Most of the Kendall Mountain Formation is composed of thick bedded metasandstones, commonly in massive, non-graded beds 20 cm to over 1.5 m thick. Thinner sandstone beds (10-20 cm) intercalated with thin (5 mm-2.0 cm) rusty carbonaceous slate and siltstone layers characterize both the lower and upper contact zones of the formations, and the sandstones of these horizons display well developed convolute bedding not found in the middle part of the formation. Most of the rest of the formation consists of featureless, massive sandstone beds and sparse pelite. In the type locality, for example, most of the beds are of massive sandstone greater than 1 m thick, and pelite occurs as one or two isolated beds of carbonaceous slate 20 cm-50 cm thick.

Several types of sandstone occur in the formation, but poor outcrop control makes it difficult to accurately estimate their proportions. Many are buff to pale gray, chalky weathering, quartzofeldspathic wackes, with a sparse matrix of small white mica flakes. Quartzofeldspathic arenites with very little argillaceous matrix are also abundant, and a few true quartzite beds have been found which contain as much as 90% quartz. These lack the chalky weathering of the feldspathic rocks and are bluish gray on both fresh and weathered surfaces. One of the quartzite horizons had been mapped as a separate member of the Cookson Formation (Ruitenberg, 1967; Ludman, 1978), but new exposures and cores near Woodland indicate that the quartzites are intercalated with more typical sandstones and cannot be mapped separately. A few lithic wackes and lithic arenites are also present and contain clasts of cryptocrystalline felsic volcanic rocks as well as of quartz and feldspar. Most clasts in these rocks range from 0.25 to 0.75 mm, and individual beds tend to be homogeneous. Primary features such as cross-, graded, and convolute bedding are restricted to the upper and lower parts of the formation. Most beds are massive and featureless.

Granule conglomerates occur in thick beds near the (tectonic) contact with the Pocomoonshine Lake Formation. They contain clasts ranging from 1 to 5 mm in most instances. In addition to felsite, fragments of quartzite, mafic volcanic rock, and dark gray phyllite/slate have been identified in these grits. These clasts commonly exhibit cataclastic fabrics and may have been derived from Eocambrian and/or Precambrian sequences now exposed only in the St. John area of New Brunswick (McCutcheon and Ruitenberg, 1984). Very coarse beds with 5 mm-2.5 cm clasts have been observed in float blocks, but have not yet been found in place. Most clasts are well rounded although tectonic flattening is common in fault zones. The conglomerates occur as massive beds up to 2 m thick, as graded units 25 cm - 1 m thick, and as the bases of the best graded sequences in the formation.

The volcanic component of the Kendall Mountain Formation appears to be restricted to a single horizon near the contact with the Woodland Formation. It has been found in a few small outcrops 0.1 mile north of the Woodland-South Princeton Road, 0.6 miles west of Route 1; in a field east of Route 1, 1.65 miles northwest of Woodland; and on Kendall Mountain. The rocks are thinly banded (1-5 cm) to more massive (15 cm), chalky white weathering, light to medium gray felsic tuffs. Most are very fine-grained to cryptocrystalline and fracture conchoidally. In thin section, these rocks are sutured aggregates of quartz and feldspar grains approximately 10 microns in diameter, with rare feldspar micro-phenocrysts up to 0.25 mm long. Small (0.5 mm) slightly elongate white spots are pumice lapilli, and light/dark interdigitations are similar to those in modern pumice flows. Chemical analyses show that these rocks are rhyolites and rhyodacites (Table 1).

Fine grained volcaniclastic arenites and wackes containing felsite clasts are interbedded with these volcanic rocks on Kendall Mountain and east of Route 1. Massive, well jointed diabase and basalt of the Baileyville dike (see below) are in apparently conformable contact with the tuffs, but cross-cut siltstones of the Kendall Mountain Formation in other places. They are therefore considered to be younger than the Kendall Mountain Formation. Fine grained metabasalts on Kendall Mountain, however, seem to be interbedded with the tuffs. These rocks are composed of plagioclase, small sprays of actinolite needles, and accessory pyrite, and are very similar mineralogically and texturally to finer grained portions of the Baileyville dike. It is possible that the dike was emplaced in a thin bimodal volcanic sequence close to the time of eruption (i.e. the dike is not much younger than the rocks that it intrudes), and may have been a sub-volcanic sill-like body or a feeder to the volcanic pile.

Age and Correlation of the Kendall Mountain Formation. Graptolites have been discovered in a black shale bed sandwiched between quartzites in New Brunswick, on strike and continuous with the type locality of the Kendall Mountain Formation (Fyffe, pers. commun., 1989). The faunal assemblage has been examined by Dr. John Riva and assigned to the Middle Caradocian.

Highly quartzose rocks similar to those of the Kendall Mountain Formation crop out on the west shore of Penobscot Bay, where they have been described as the Megunticook Formation (Berry, 1986). Berry considers the Megunticook to lie beneath the Penobscot Formation (Calais Formation equivalent), and until Fyffe discovered the graptolites in the Kendall Mountain Formation I had placed it below the Calais Formation and correlated it with the Megunticook Formation (Ludman, 1987). The new fossil control requires reappraisal of this correlation.

Thickness of the Cookson Group. The Cookson Group has been multiply folded, faulted, and intruded by several plutons, so that it is difficult to estimate its thickness. Further, neither the bottom nor top of the group have been observed, so that only minimum thicknesses can be given. Based on the exposed outcrop widths and interpreted structural history, the Kendall Mountain Formation is between 500 and 700 m thick, the Woodland Formation approximately 800 to 1000 m, and the Calais Formation a minimum of 1,000 m. Total exposed thickness for the group is thus about 2,700 m.

Regional Significance of the Cookson Group. On-strike correlatives of the formations of the Cookson Group have been discussed above. Cross-strike correlations to the east and northwest are more dificult. The nearest potential correlative to the east is the Cambro-Ordovician Saint John Group of southern New Brunswick, recently redescribed by Pickerill and Tanoli (1985). I had argued earlier (Ludman, 1987) for correlation of the Cookson Group with the Late Cambrian and earliest Ordovician parts of the Saint John Group in southern New Brunswick. The Caradocian age of the Kendall Mountain Formation precludes this equivalence and indicates that most of the Cookson Group is younger than the Saint John.

The nearest correlatives to the northwest belong to the Cambro-Ordovician Miramichi anticlinorium (Fig. 1). Rocks of appropriate age are well known in the Miramichi (Fyffe et al., 1983), but the Middle Ordovician section there is a bimodal volcanic suite quite unlike the mature quartzite and black shale of the Kendall Mountain Formation. It is apparent that the St. Croix belt is not a perfect match for either tract.

The relationship of the St. Croix belt rocks to the neighboring pre-Silurian tracts is critical, however, to regional accretion models. Williams' (1978, 1979) zonation of the Appalachian orogen places the Saint John and Miramichi belts in two different tectonic zones—Avalon and Gander, respectively. Avalon is thought to represent an Early Paleozoic continent separated from ancestral North America by the Iapetus Ocean; the Gander Zone is believed to represent deposits in Iapetus, including island arc and back-arc volcanic rocks. Location of the suture between Avalon and the former oceanic rocks to the west depends on what the paleogeographic setting of the Cookson Group was.

The maturity of arenites in the Kendall Mountain Formation suggests affinity to the Saint John Group—the shelf sediments of the Avalon continent—and I had previously suggested that the Cookson Group was deposited on the west-facing continental slope of Avalon (Ludman, 1987). In identifying the graptolites from the Kendall Mountain Formation, Riva stated that they "were species rarely found in North America," implying a European or Baltic affinity. This supports my earlier tectonic interpretation, and makes association with the Miramichi anticlinorium section highly unlikely. If this paleogeographic reconstruction is correct, the Cookson Group contains the westernmost rocks of the Avalon block in Maine. The suture between the Avalon and Gander zones is either the South Princeton-Crawford fault or is buried beneath the Fredericton trough.

Silurian and Devonian Rocks

The two tracts that flank the St. Croix belt contain very different lithologic suites. The coastal volcanic belt consists of a thick bimodal volcanic section with intercalated highly fossiliferous shallow-water sedimentary rocks (Gates, 1977). The fossils define a span of Early Silurian through Early Devonian time for eruption and deposition of these rocks. In contrast, the Fredericton trough lacks volcanic rocks and is almost entirely non-fossiliferous in eastern Maine. It is a thick sequence of non-calcareous turbidites and calcareous quartzofeldspathic wackes.

Fredericton Trough. The Fredericton Trough in Maine crops out in a band nearly 50 km wide, and contains three formations, the Pocomoonshine Lake, Digdeguash and Flume Ridge Formations (Ludman, 1990). None are extensively exposed in the Calais quadrangle. The Digdeguash Formation crops out widely in the Big Lake quadrangle (Ludman, in press), but forms only a few outcrops on the west side of the fault contact with the St. Croix Group. The Flume Ridge Formation is areally far more important, but also crops out only sparsely in the northwestern part of the quadrangle. The Pocomoonshine Lake Formation does not actually crop out in the Calais quadrangle. Brief descriptions of these rocks will be presented here; for more complete discussions, see Ludman (1990).

Pocomoonshine Lake Formation (SOp). The Pocomoonshine Lake Formation does not crop out in the Calais quadrangle, but is thought to extend into the northwest part of the quadrangle (in a region of no bedrock exposures) from its type locality in the Big Lake quadrangle (Ludman, 1987, 1990). Rocks of this formation are pyritiferous, rusty weathering carbonaceous slates, thinly interbedded with sulfidic siltstones, sandstones, and non-carbonaceous slates.

Dark gray to gray-black, slightly to very carbonaceous slates comprise most of the formation. They are strongly cleaved and generally contain both primary (anhedral, flattened) and secondary (cubic) pyrite. The more carbonaceous types are black and slightly sooty, whereas the less carbonaceous pelites are medium gray, muscovite-rich, and exhibit a phyllitic sheen. Thin beds of siltstone or very fine-grained sandstone ranging from 5 mm to 10 cm in thickness are intercalated with the pelites. Most are at the lower end of the indicated thickness range. In many instances, these rocks occur as bases of thin graded sets with the carbonaceous pelite at the tops. The psammites do not cleave well and are more resistant to weathering than the fissile pelite beds. As a result, they stand out as ribs above the slates in most outcrops. The sandstones and siltstones are faintly buff weathering, dark gray on the fresh surface, and are composed of quartz and feldspar grains with only small amounts of interstitial muscovite, carbon, and pyrite.

I had originally included the Pocomoonshine Lake Formation with the Cookson Group because of its carbonaceous pelite and minor psammites and because it seemed to be in conformable contact with the Kendall Mountain Formation. (Ludman, 1987). Re-evaluation of contact relationships based on structural style suggested a different interpretation (Ludman, 1990). The Cookson Group appears to have been intensely polydeformed, whereas the Pocomoonshine Lake, Digdeguash, and Flume Ridge Formations have been deformed penetratively only once. The contact between complexly and simply deformed rocks coincides with that between the Kendall Mountain and Pocomoonshine Lake Formations, and is now thought to be a thrust fault (see below).

Age of the Pocomoonshine Lake Formation. If the structural interpretation mentioned above is correct, an episode of folding followed Middle Caradocian deposition of the Kendall Mountain Formation, and preceded deposition of the Pocomoonshine Lake Formation. Inferred relationships with the Digdeguash and Flume Ridge Formations suggest a Late Ordovician (Ashgillian) age for the Pocomoonshine Lake Formation, but this cannot be proven.

Digdeguash Formation (SOd). The Digdeguash Formation consists of variably bedded, but generally well graded polymictic granule conglomerate, lithic wacke, and medium gray slate. Beds range in thickness from a few centimeters to more than 1.5 meters, and partial to complete Bouma sequences are common. With the exception of a few beds near the contact with the Flume Ridge Formation, the Digdeguash Formation is non-calcareous. At elevated metamorphic grade, the Digdeguash Formation pelites develop large (up to 15 cm), typically chiastolitic andalusite porphyroblasts whose habit contrasts sharply with that of andalusite in the Cookson Group. Some of the coarser rocks resemble lithic arenites of the Kendall Mountain Formation, but the Digdeguash Formation lacks the quartzites, arenites, and carbonaceous pelites of that unit.

The contact with the Flume Ridge Formation is not exposed, but can be located to within 50 m at the Calais-Big Lake border and at two places in the Big Lake quadrangle. In these areas, the contact appears to be a rapid gradation. Beds with typical Digdeguash Formation lithology and bedding style have slightly calcareous bases, and beds of Digdeguash-like pelite are intercalated with typical wackes of the Flume Ridge Formation near the contact. Facing at the contact is not certain in the study area. Ruitenberg (1967) stated that the Flume Ridge Formation is younger than the Digdeguash Formation, and assigned a Silurian age to the latter. More recent interpretations of these age relationships are described in detail elsewhere (Ludman, 1990).

Flume Ridge Formation (DSf). Although outcrops are sparse, the Flume Ridge Formation apparently underlies almost all of the ground in the Calais quadrangle west of the South Princeton-Crawford fault zone. Small outcrops are found along the former railroad between Woodland and Princeton, along and west of Route 1 near the fault, and in heavily glaciated terrain west of the Anderson Brook esker.

On and northeast of Route 1, the Flume Ridge Formation is in the chlorite zone and is an orange-buff weathering, pale to medium gray calcareous quartzofeldspathic wacke with very subordinate, non-calcareous, darker gray siltstone and slate. Weathering of ankerite and pyrite produces the typical weathering rind, and commonly makes it difficult to collect fresh samples. Large detrital muscovite flakes are abundant in the wackes; they, along with the calcareous nature of the sandstones and the combination of weathered/fresh color make the formation readily identifiable. Bed thickness varies from 2 cm to 2 m throughout the large outcrop area of the Flume Ridge Formation, but those in the Calais exposures range only from 5-25 cm. Beds of pelite are rare, and most slate or phyllite occurs as thin partings between sandstone or siltstone layers.

The wackes are finer grained and much better sorted than those of the other formations in the area. Clasts are mostly quartz and plagioclase, with few rock fragments. A few of the coarsest rocks, however, do contain lithic clasts, including quartzite and fine-grained felsite fragments. The matrix is a fine-grained assemblage of quartz, feldspar, muscovite, and calcite, with chlorite locally abundant.

South and west of Route 1, the Flume Ridge Formation crops out in the biotite zone, and is converted to a dense buff weathering, purplish quartz-plagioclase-biotite granofels with minor calcite or calc-silicate minerals. Actinolite is the dominant calc-silicate in the Calais quadrangle outcrops, but diopside, garnet, and wollastonite occur at higher grades in the Big Lake quadrangle. Detrital mica and the typical low-grade weathering rind are absent from these exposures due to comsumption of the muscovite and ankerite during biotite-producing reactions.

Thickness, Age, and Correlation of the Fredericton Trough Strata. Tight folding, poor exposure, and the absence of either the top or bottom of the Fredericton trough section make thickness estimates difficult. The exposed Pocomoonshine Lake Formation is about 300 m thick, the Digdeguash Formation on the order of 1 km thick, and the Flume Ridge Formation easily two to three times that.

No fossils have been found in situ in these units, but specimens of *Tentaculites* were collected in float blocks that display the mineralogy and weathering of the Flume Ridge Formation. These suggest a Siluro-Devonian age for that formation. A search for microfossils revealed an assemblage of fungal spores and primitive vascular plant tissue (tracheids) from two localities of the Flume Ridge Formation in the Waite quadrangle, again suggesting a Silurian-Devonian age.

The Flume Ridge Formation has been traced through the Wesley (Westerman,1978) and Lead Mountain (Gilman, 1974) quadrangles to the southwest, and appears to be nearly continuous with higher grade equivalents in the Bucksport Formation at Penobscot Bay. Exposures in the Waite and Scraggly Lake quadrangles are on strike with, and seemingly equivalent to, similar rocks of the Vassalboro Formation of the central Maine sequence (Osberg, 1980; see Osberg et al., 1985). It is important to note that the Norumbega fault zone, a major suture in many tectonic models, is entirely intraformational within the Flume Ridge Formation in eastern Maine.

The Digdeguash Formation cannot be traced as well to the southwest. Coarse conglomerates and grits in the Wesley quadrangle were assigned to the Digdeguash Formation (Westerman, 1978), but in the Penobscot Bay area, only a few small outcrops of graded beds similar to those of the Digdeguash Formation have been found north of Ellsworth (Gilman, pers. commun., 1975).

Coastal Volcanic Belt. The coastal volcanic belt is represented by outcrops in the extreme southeastern corner of the Calais quadrangle, on hills and in fields southeast of Round Lake. Similar rocks crop out just east of the Calais Formation in the St. Croix River, in the Devil's Head 7.5 quadrangle, and will be described here. The contact with the St. Croix belt is not exposed; a small gap in otherwise continuous St. Croix River section probably indicates that it is a fault in the northeast part of the quadrangle, while the Meddybemps and Charlotte granites fill the contact zone in the southeast. Two map units are recognized near Blanchard Corner in the southeast corner of the quadrangle, and both are assigned to the Leighton Formation of Gates (1977).

Leighton Formation (Sl). The Leighton Formation is represented in the Calais area by two members, one dominantly fine-grained siltstones and mudstones with minor calcareous horizons (Sls), the other fine grained basalt (Slb). Both are exposed in the contact aureoles surrounding the Moosehorn Igneous Complex and the granitic rocks to the west, but despite metamorphism many primary features are preserved.

Basalt Member (Slb). Basalts of the Leighton Formation are exposed on the unnamed hill 0.5 miles south of Round Lake, and in fields on both sides of Route 214 at the extreme southeastern corner of the quadrangle. These are very fine-grained, medium to dark gray basalts with a thin, slightly rusty to buff weathering rind. Textural variations in these rocks include microporphyries with visible phagioclase phenocrysts, and vesicular basalts with vesicles and vugs filled with epidote. Original layering is very difficult to identify in most of the smaller field exposures, but grain size and textural differences define bedding more clearly in larger hillside outcrops. Close-spaced jointing is present in nearly every outcrop.

Thin sections show that most of the rocks are composed of a very fine grained (0.4-0.75 mm) felted groundmass of slender plagioclase laths. In some samples these crystals are strongly aligned in a primary flow fabric, whereas in others they are randomly oriented. Larger, stubbier plagioclase microphenocrysts range up to 2.5 mm and are generally highly saussuritized, whereas the groundmass feldspars are typically unaltered. Primary pyroxenes are replaced by actinolite and chlorite. Most of these secondary minerals occur in anhedral patches in the groundmass, but a few pseudomorphs up to 2.0 mm long probably represent pyroxene phenocrysts. Opaque minerals are abundant in most of the basalts, and comprise as much as 5% of some samples. Pyrite, chalcopyrite, and magnetite have been identified, and seem to be most abundant along Route 214.

Small ovoid vesicles 1.0-2.5 mm in diameter and larger vugs up to 2.5 cm across are present in some basalts. Both are filled and most of the fillings are well zoned. Extremely fine-grained plagioclase laths surround each vesicle, followed by an outer lining of interlocking epidote crystals and successive zones of epidote+actinolite, coarse actinolite, and coarse sulfide an isotopic mineral as yet unidentified.

The basalts are probably flows, and are the most abundant volcanic rocks in the limited Calais outcrops of the Leighton Formation. Basaltic tuffs are also present, but are much less abundant. These consist of cryptocrystalline sutured feldspar grains that pass into fine-grained (0.1-0.25 mm) acicular plagioclase crystals. Chlorite and actinolite replace what may have been a volcanic glass rich in ferromagnesian minerals. Sparse siltstone fragments in a few of these rocks suggest an origin as pyroclastic flows. One unusually "coarse" diabasic rock has been observed, consisting of 2.0 mm plagioclase crystals in an ophitic texture with interstices filled with slightly smaller pseudomorphs of actinolite after pyroxene. This may have been part of a thick flow, or a dike or sill emplaced into the volcanic pile.

Siltstone-Mudstone Member (Sls). Siltstones and mudstones assigned to the Leighton Formation crop out east and south of Blanchard Corner in fields and in small roadcuts. They are fine to very fine grained, buff weathering, very dense hornfelses that are deep purple on the fresh surface because of abundant biotite. Bedding is obscured in many places by joints, and is difficult to recognize in many places because of the homogeneous grain size and lack of bedding features. Bedding is most clearly recognized where thin (1.5 cm) calcareous layers are intercalated with the noncalcareous silt and mudstone. Metamorphic production of actinolite in these layers makes them readily visible. Several are highly fossiliferous and seem to have been shell hash beds. Fossils, generally pyritized brachiopods, have also been found in mudstone horizons.

Thin sections reveal very fine-grained aggregates of quartz and feldspar and tiny but very abundant biotite flakes. A few of the siltstones contain small euhedral to subhedral feldspar crystals; these, along with the buff weathering, suggest a tuffaceous component for the siltstones, but most have only rounded to subangular grains of ambiguous provenance.

Thickness. From its limited exposures, it appears that the siltstone member lies beneath the basalt member. Neither the upper contact of the basalt nor the lower contact of the siltstone is observed. Minimum thicknesses on the order of a few hundred meters are suggested for each member by their attitudes and outcrop patterns.

Age and Correlation. Several fossil localities are now known in the Blanchard Corner area (see geologic map), but most contain only a few fauna. Typical mudstones, for example, yield a few fragmental brachiopods or, in some cases, complete valves. An extensive bedding plane pavement exposure on the southeast side of the road 0.35 miles southwest of Blanchard Corner, however, contains a diverse population including brachiopods, cephalopods, trilobites, bryozoans, corals, and ostracods. Pickerill (1976) studied this suite, along with other Leighton Formation fauna, and reported a Pridoli age (latest Silurian) for the formation. He also suggested that the *Salopina* brachiopod assemblage was indicative of extremely shallow water.

Similar fauna are found in the Leighton Formation in the adjacent Eastport quadrangle, and even though small faults separate the Calais exposures from the main portion of the Leighton Formation (Osberg et al., 1985; Gates, 1977), there is little doubt as to their identity. The lithology, faunal assemblage, and depositional environment of the Waweig Formation of New Brunswick are identical to those reported here and by Gates (1977) for the Leighton Formation, and the two are undoubtedly correlative.

Oak Bay and Waweig Formations. Conglomerates continuous with those of the Oak Bay Formation crop out just east of the Calais quadrangle in the St. Croix River, and probably continue on strike into the quadrangle before being truncated by the plutonic complex just south of Route 1. These pass eastward into very fine-grained siltstones/mudstones comparable to those of the Waweig Formation, in a manner similar to that on Cookson Island, 4 miles to the northeast. The Oak Bay Formation consists of pebble to cobble conglomerates that, in the St. Croix exposures, exhibit strongly flattened clasts. These clasts are dominantly of fine-grained volcanic and sedimentary rock typical of the coastal volcanic belt; none seem to have been derived from the adjacent Cookson Group.

The Oak Bay Formation passes gradually into fine-grained siltsones of the Waweig Formation with the disappearance of the coarse clasts. In the St. Croix River section, this occurs at the contact with diorite and granodiorite, so that the rocks are highly metamorphosed and occur partially as xenoliths.

Brachiopods from a clast in the Oak Bay Formation were assigned a Silurian age (Cumming, 1965), and Waweig Formation fauna point to a Pridolian age (latest Silurian; Pickerill, 1976). The Oak Bay Formation is interpreted as a basal conglomerate to the Waweig Formation, and both are thought to be distal components of the coastal volcanic belt. Tuffaceous rocks become abundant in the Waweig Formation to the east and southeast, but are absent from the small exposures of the study area.

STRUCTURAL GEOLOGY

The deformational history of the area is complex, and its interpretation is hindered by a combination of poor bedrock exposure, extensive plutonism that locally complicates structural relationships, and metamorphism that obliterates critical data in many areas. For example, high-grade contact metamorphism adjacent to mafic plutons has produced migmatite with a swirling, non-systematic foliation. Most of the southwest ninth of the quadrangle has been thus affected, and is nearly useless for structural interpretation despite the fact that it contains some of the best bedrock control in the entire region.

The domainal nature of many structures in the Calais and adjacent Big Lake quadrangles further hinders interpretation of local deformational history. Regional NE and ENE structural trends in and west of the Big Lake quadrangle are replaced at the Calais/Big Lake boundary by north-trending beds, cleavage, and minor folds within the South Princeton-Crawford fault zone. NE trends are re-established east of this zone, but near-vertical cleavages alternate with sub-horizontal cleavages over a broad area between South Princeton and Calais.

Outside the migmatized areas, several structural elements are readily observed and have been used to unravel the deformation history. Bedding is recognizable in all but the highest metamorphic grades, and primary facing evidence is abundant in the form of graded bedding, cross-bedding, and scour-and-fill features. Cleavages are well developed in the low-grade pelitic rocks, are less recognizable in massive sandstones such as those of the Kendall Mountain Formation, and have been destroyed by recrystallization of even the pelitic rocks in the inner parts of contact aureoles. Outcrop scale folding is not common, but enough fold and cleavage data are available to interpret a multi-stage folding history for the area. Evidence of faulting is widespread throughout the quadrangle, both in the stratified rocks and the plutons that intrude them. The sequence of folding and faulting that is now interpreted for the study area (Table 2) is far more complex than that suggested by previous workers (Larrabee, 1964; Amos, 1963).

Six separate episodes of deformation are recognized in rocks of the Calais quadrangle, and are designated as D_1 through D_6 in order of decreasing age (Table 2). The first three events were mostly ductile and produced folds of different attitudes and styles, whereas the last three were more brittle and resulted in faults of various attitudes and displacements.

Folding

Rocks of the Cookson Group appear to have experienced a more complex folding history than those of the Fredericton trough or coastal volcanic belt as shown by a plot comparing

TABLE 2: DEFORMATION HISTORY OF THE CALAIS AREA

Event #	Description	Age
D_1	Isoclinal folding (F_1) and formation of S_1 cleavage in pelites of the Cookson Group	Post-Caradocian, but before Silurian strata
D_2	Isoclinal to open folding (F_2) of all rocks of the coastal volcanic, St. Croix, and Fredericton trough belts	Post-Eastport Fm. (Early Devonian); pre-gabbro, granite (Early Devonian)
D_3	F_3 recumbent folding related to SE-over-NW thrusting of the St. Croix belt over the Fredericton trough	After F_2; before Early Devonian granites
D_4	North-trending normal faults; local development of small-scale F_4 folds and cleavage	Synchronous with emplacement of gabbros
D_5	NE and N-trending strike-slip faults; mostly dextral, but some sinistral offset	Post-gabbro and granite. Related to Norumbega fault zone
D_6	NW-trending sinistral strike-slip faults; sinistral kinks	Postdates all other structures

poles to bedding (Figs. 3a,b) and to cleavages (Figs. 3c,d) from the different tracts. The data from both pre-Silurian and Siluro-Devonian rocks define girdles indicative of gently plunging, northeast to east-northeast trending upright folds, but poles from the pre-Silurian section are more widely scattered. Several cleavages are recognized in pelitic rocks of the Cookson Group, one of which is axial planar to the dominant NE-trending upright folds. Both earlier and later generations of cleavage have been observed in the Cookson Group strata. In contrast, a single cleavage, axial planar to the NE-trending folds, dominates pelites of the Fredericton trough. There are local examples of later cleavage development, but nothing suggests widespread deformation of the Fredericton trough prior to the upright folding. The implication is that the Cookson Group was deformed in post-Middle Caradocian times before deposition of the younger strata that flank it.

The second event, D_2, is pervasive, whereas the others appear to be domainal. D_2 structures have been used as markers for interpreting the structural history of the Calais area; assignment of other structures to earlier or later events is based on their relationship to the readily identified features of D_2. It is therefore most appropriate to discuss D_2 first.

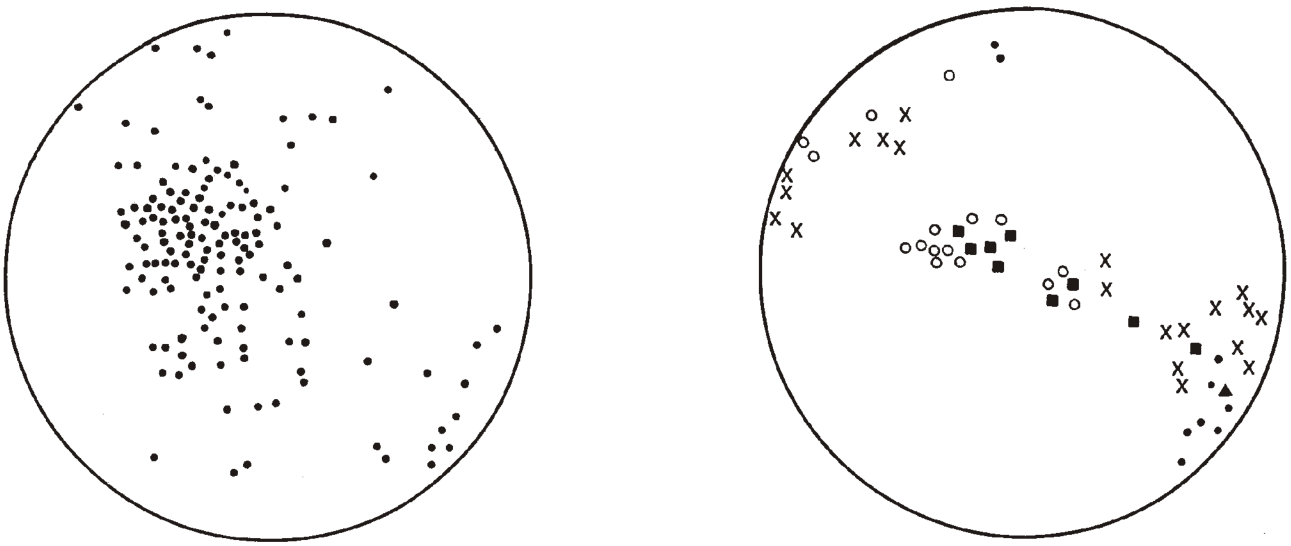
D_2 Deformation. D_2 was an episode of upright folding (F_2) recognized throughout eastern Maine and adjacent New Brunswick. Small-scale folds trend ENE to NE and plunge gently to the southwest or, less commonly, to the northeast. In some areas, notably in the Woodland Formation between Woodland and Kendall Mountain, F_2 and F_3 folds are nearly coaxial, but F_2 hinge surfaces are nearly vertical and those of F_3 generally dip gently to the southeast.

F_2 fold style depends on the rock type involved. Folds in thin-bedded sandstones and slates of the Digdeguash and Flume Ridge Formations are tight to nearly isoclinal, with small interlimb angles and sharp hinges. Most are similar folds. In thicker bedded, more massive granule conglomerates and sandstones of these units, folds are more open, hinges more rounded, and the style more concentric. Abundant facing reversals in the Fredericton trough indicate many mesoscopic folds with wavelengths on the order of 0.4-0.5 km. These are parasitic to regional scale folds such as those shown on Section B-B' of the new geologic map of Maine (Osberg et al., 1985). The Huntley Ridge anticline in the Big Lake quadrangle is the largest F_2 fold in the area (Ludman, 1986).

Outcrop-scale folds were not observed in the Leighton Formation in the Calais quadrangle, but a weakly developed spaced cleavage in the basalts and mudstones parallels F_2 folds in both the St. Croix and Fredericton tracts. The absence of facing evidence from the Leighton Formation, and the small area in which it crops out in the Calais quadrangle make it difficult to identify the mesoscopic features. The map pattern, however, suggests relatively broad, open folding comparable to the larger features of the Fredericton trough. F_2 folds have been identified in all formations of the Cookson Group. Thick-bedded sandstones of the Kendall Mountain Formation and wackes of the Woodland Formation exhibit open, concentric folds similar to those of comparably bedded strata of the Digdeguash and Flume Ridge Formations.

An upright, ENE-trending spaced cleavage associated with these folds is designated as S_2. It is close-spaced in most of the pelitic rocks (a few mm to a few cm), but is much more widely spaced in the sandstones (several cm). Only a very poor foliation accompanies S_2, and is defined by small muscovite and chlorite flakes in the low-grade exposures. This foliation is obscured by contact metamorphism, and in many instances the cleavage is obliterated as well.

<u>Age of F_2 folding.</u> Structures comparable to F_2 folds have been mapped in rocks as young as the Early Devonian Eastport Formation in the Eastport area to the southeast (Gates, 1977), indicating that this deformation must be later than Early Devonian. Radiometric dating of plutons that cut these folds (see below) suggests that the folding cannot be much later, however. Early Devonian ages are measured or inferred for the granites and gabbros that truncate F_2 features in the Calais quadrangle, so that F_2 is bracketed tightly within the Early Devonian. This event appears to be the major expression of the Acadian orogeny in southeastern Maine.



A: Poles to bedding in Pre-Silurian rocks, Calais quadrangle [N=171]

C: Poles to cleavage and hinge surfaces in Pre-Silurian rocks, Calais quadrangle

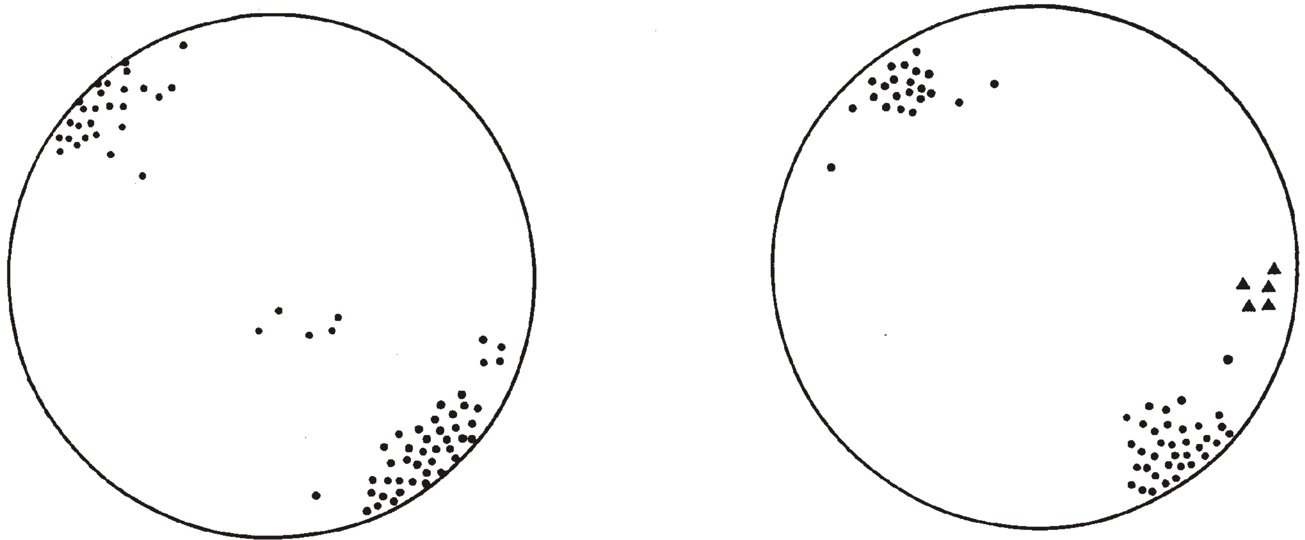
• = F_2 cleavage

■ = F_3 hinge surface

○ = F_3 cleavage

▲ = F_1 hinge surface

x = cleavage, fold episode uncertain



B: Poles to bedding in Flume Ridge and Dideguash formations,+ Leighton mudstone, Calais & Big Lake quadrangles [N=101]

D: Poles to cleavage, Fredericton Trough rocks in Calais & Big Lake quadrangles

• = F_3 [N=71]

▲ = Late cleavage in Crawford fault

Figure 3. Comparison of bedding and cleavage in Siluro-Devonian and Pre-Silurian strata, Calais-Big Lake area.

D_1 Deformation. F_2 folds in the adjacent Big Lake quadrangle deform a cleavage as well as bedding in the Woodland and Kendall Mountain Formations. This cleavage (S_1) is subparallel to bedding and is interpreted as axial planar to an early (F_1) episode of isoclinal folding. Evidence for F_1 is limited to a few exposures because of the lack of cleavage development in thick-bedded Kendall Mountain and Woodland Formation sandstones. Outcrops of actual F_1 folds are even more rare and the best examples are visible just below the dam at Woodland on the Canadian side of the St. Croix River. There, open F_2 folds clearly deform earlier isoclinal folds outlined by thin graded couplets of the Woodland Formation. Similar relationships have been observed in the Kendall Mountain Formation in a field east of Route 1 northwest of Woodland, and in lowlands both west and east of the type locality on Kendall Mountain.

Graded beds in the Woodland and Kendall Mountain Formations show that nearly all folds face upward. The exceptions are located in the western part of the Calais quadrangle and in the adjacent Big Lake quadrangle where F_2 folds in sandstones and pelites of the Kendall Mountain Formation appear to face downward. The Cookson Group is interpreted as lying for the most part on the upright limb of a large recumbent structure, but the limited width of the St. Croix belt and low relief of the area hinder evaluation of this possibility.

Age of D_1. F_1 folds have been identified in the Woodland and Kendall Mountain Formations. The apparently conformable nature of the Woodland/Calais Formation contact suggests that the entire Cookson Group must have experienced D_1 folding. There is no evidence of D_1 in the Pocomoonshine Lake, Digdeguash, or Flume Ridge Formations. D_1 is younger than the Middle Caradocian age of the Kendall Mountain Formation, but its minimum age is poorly constrained because of the lack of firm ages for the Fredericton trough strata. A Caradocian age is considered most likely.

D_3 Deformation. Much of the St. Croix belt north and west of Route 9 is characterized by beds that are subhorizontal or dip gently to the southeast, in contrast to the near-vertical attitude of most strata elsewhere in eastern Maine. The possibility that these anomalously gentle dips might be related to deformation during emplacement of plutons was considered early in analysis of local structure. It has been dismissed because the attitudes are uniform and are as abundant in low-grade rocks far from the plutons as they are in high-grade rocks of the contact aureoles.

An episode of west-vergent recumbent to strongly inclined folding (F_3) is now considered responsible for these attitudes. Several outcrop-scale F_3 folds have been identified in the Calais quadrangle, in rocks of the Kendall Mountain and Woodland Formations. Excellent examples are found on the north slope of Robb Hill in a stream channel, and beneath the powerline running southeast along the ridge next to the St. Croix River, just south of the Georgia-Pacific pulp mill.

Most of the folds are asymmetric, S-folds (counterclockwise) indicating southeast-over-northwest transport. Two perfectly symmetrical isoclinal recumbent folds have been found, however, between the northeast peak of Kendall Mountain and the esker east of that peak. F_3 folds are relatively tight with broad, rounded closures, and hinge surfaces that strike 055-070°, roughly parallel to those of F_2. F_3 hinge surfaces dip very gently, however, generally between 10° and 20° to the southeast, although the full range is between horizontality and 40°. A slaty cleavage (S_3) is commonly well developed in pelitic horizons at chlorite grade, but has been obliterated in higher grade exposures.

Numerous small-scale southeast-over-northwest thrust faults have been observed in the Cookson Group, and several are exposed at the Woodland Dam. We propose that F_3 folds formed during westward thrusting of the Cookson Group over the Fredericton trough, and that there may be thrusts within the St. Croix belt that have not been mapped because of poor outcrop control, particularly between Kendall Mountain and the Woodland-South Princeton Road.

Age of D_3. D_3 thrust faults and associated folds postdate D_1 and D_2, but predate the emplacement of mafic and felsic plutons. Neither recumbent folds nor thrust faults have been mapped in the Fredericton trough, but their absence is thought to be due to D_4 faulting and subsequent erosion. An Early Devonian age is suggested, and D_3 is attributed to a late stage of the Acadian orogeny.

Faulting

It is impossible to find a large outcrop of metasedimentary or igneous rock in the Calais quadrangle that does not contain at least one small-scale fault. Sheared, polished, and slickensided surfaces are found throughout the map area, and the complexity of brittle deformation is revealed by the varied orientations of fault planes and the types of displacement.

Figure 4, a stereonet showing faults and slickenside lineations from outcrops below the Woodland Dam, shows some of the variety present. Steeply dipping NW-trending faults dominate at this exposure, but NE-trending faults are also common and some north-trending shear zones are present. There are a few sub-horizontal shear surfaces as well, and these are attributed to the D_3 event just described. Relationships are complicated by the apparent reactivation of some early faults during later events. Several parallel faults at the dam exhibit either dip-slip or strike-slip slickensides, and one records both: early sub-horizontal slickensides are cross-cut by later dip-slip striations and grooves.

D_4 Deformation. D_4 was an episode of faulting that affected stratified rocks of the Fredericton trough, the St. Croix belt, and the coastal volcanic belt, as well as the plutonic rocks that intrude them. D_4 faults are recognized by the local development of cataclastic fabrics in narrow zones aligned within 10 degrees of north-south; by similarly domainal close-spaced cleavage striking north and dipping steeply to vertically; small-scale north-trending upright folds; and by local disruption of earlier structures. In the adjacent Big Lake quadrangle, D_4

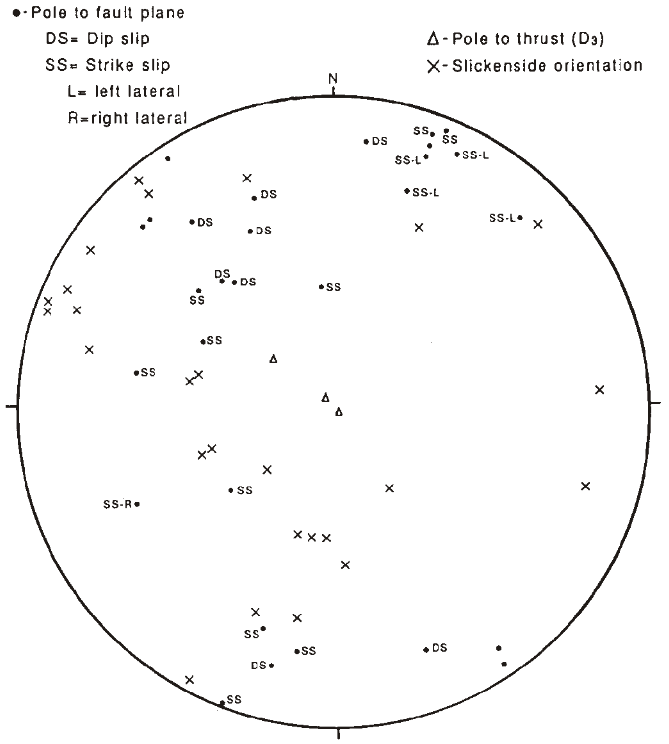


Figure 4. Faults and slickensides in the Woodland Formation at the Woodland Dam exposure.

faults are also located by their topographic expression as valleys and aligned depressions oriented north-south. Some of the faults shown in the western part of the Calais quadrangle are continuations of those structures, including the N-S part of the South Princeton-Crawford fault zone that now forms the boundary between the Fredericton trough and St. Croix belt. It is more difficult to trace structures through the thick glacial deposits north of Kendall Mountain, but additional D_4 faults are inferred there by offset of the contact between the Kendall Mountain and Woodland Formations.

Slickensides in these fault zones indicate both dip-slip and strike-slip separation, but what is here termed D_4 refers only to the dip-slip motion. Horizontal movement is inferred to have taken place during D_5 reactivation of the D_4 faults. D_4 affected all earlier structures, deforming F_3 hinge surfaces and axial plane cleavage into broad anticlines and synclines near the South Princeton-Crawford fault zone, and refolding F_2. Based on the offset of formation contacts and the apparent removal by erosion of the inferred F_3 thrust plate from the Fredericton trough, the west sides of the D_4 faults are thought to be upthrown relative to the east sides. Separations of as much as 300 m are estimated on some faults in the Calais quadrangle. A significant change is indicated from the intense compression associated with F_2 and F_3.

Age of D_4. The age of D_4 faulting is constrained by the youngest rocks affected (Early Devonian gabbro and granite), and by the fact that the faults offset $F_{1\text{-}3}$. Anatectic migmatites in the Digdeguash Formation adjacent to the Pocomoonshine gabbro-diorite in the Big Lake quadrangle are axial planar to small-scale, north-trending folds attributed to D_4. In addition, high-grade Flume Ridge Formation hornfels adjacent to that pluton has experienced extremely ductile folding about north-trending hinge surfaces. These relationships indicate that D_4 occurred during intrusion of the Pocomoonshine pluton. This pluton has at least a two-stage emplacement history (Ludman et al., 1989), and D_4 is thought to have occurred during the second stage. It is possible that the faulting spanned the entire emplacement of the pluton, and may have played a role in controlling its location. An Early Devonian age is suggested (but see below for further discussion of the age of this pluton).

D_5 Deformation. Several northeast-trending high angle faults believed to have formed after D_4 are assigned to D_5. These include the unnamed fault that separates the Waweig and Calais Formations in Calais and the ENE-trending segment of the South Princeton-Crawford fault zone. Cataclastic fabrics and silicified zones are developed in the metasedimentary rocks and granites, chloritized and/or serpentinized zones in mafic rocks. Slickensides generally indicate strike-slip separation, and small drag folds almost always show that this separation was dextral. One important exception, however, is the South Princeton-Crawford fault zone. As mentioned above, its early (D_4) displacement was dominantly dip-slip, but it was reactivated during D_5 as a sinistral strike-slip fault. Evidence for the sinistral nature of offset is clearly seen in drag folds along the southeast shore of Pocomoonshine Lake, and by the larger scale rotation of F_3 folds into a north-south orientation along the northeast part of the shoreline.

Age of D_5. D_5 postdates emplacement of the granites and gabbros of the Calais quadrangle, but there is no constraint on its minimum age. Similar faults in the Big Lake quadrangle are probably part of the Norumbega fault system, and cut Pennsylvanian rocks in New Brunswick (Rast, pers. commun., 1985).

D_6 Deformation. Numerous small asymmetric (sinistral) kinks, folds and warps deform all structural elements in the study area, and are most abundant near NW- and WNW-trending shear zones designated as D_6. There are few places where D_6 faults produce mappable offsets, although pluton contacts are offset in the eastern part of the quadrangle. Shear zones are commonly silicified, one quartz-veined fault standing dramatically above adjacent granites in the eastern part of the quadrangle. Sub-horizontal slickensides and vertically plunging Z-shaped drag folds indicate sinistral strike-slip separation for these faults.

Age of D_6. D_6 is the last deformational event recognized in the Calais quadrangle, and the most poorly constrained in terms of age. It cuts across and displaces all previous structures and rock types, but is itself not truncated by any datable feature.

Faults, folds, and the exotic terrane model. Earlier, the possibility that the St. Croix belt is exotic with respect to adjoining terranes was discarded in favor of a facies transition into the different lithologic suites of the Miramichi and St. John pre-Silurian tracts (Ludman, 1987). Direct contacts do not exist between any of these three belts, but the structures discussed above shed some light on the problem:

(1) Faults do indeed separate the St. Croix belt from adjacent terranes: the western boundary (with the Fredericton trough) is the South Princeton-Crawford fault zone, and the fault at the eastern boundary (with the coastal volcanic belt) is unnamed.

(2) These faults are assigned to D_5 and thus come relatively late in the region's tectonic evolution.

(3) F_2 affects rocks of all three tracts, and mafic and felsic plutons of the Bays-of-Maine Igneous Complex intrude all their strata and structures, suggesting juxtaposition well before D_5. Specifically, the Baring granite and Saint George batholith seal the eastern contact of the St. Croix belt, while the Pocomoonshine gabbro-diorite seals the western contact.

(4) Fault displacement of these plutons and their aureoles seems to be minor.

These faults cannot be sutures responsible for juxtaposing the three terranes present in the Calais quadrangle. Similar evidence indicates that the Miramichi anticlinorium and Fredericton trough were in roughly their present positions by the Early Devonian (Pollock et al., 1988). Since the coastal volcanic belt is widely considered to have erupted on Avalonian crust, it is thus difficult to see how post-Early Devonian faulting could have been responsible for suturing of the three terranes. It is still possible that the St. Croix belt might be exotic with respect to either or both of the Miramichi or Saint John tracts, but if so, their juxtaposition must have been prior to F_2 (i.e., Ordovician).

INTRUSIVE ROCKS

A large part of the Calais quadrangle is underlain by plutonic rocks ranging from layered gabbros through massive gabbros and diorites to several different granites. Some of these granites have been dated radiometrically as Early Devonian, and provide important information concerning the timing of deformational events. Previous workers (Amos, 1963; Westerman, 1972, 1973) interpreted the mafic rocks as the earliest, followed by the diorites and granitoids, and our studies confirm these relationships to a great extent. There is strong evidence, however, that the three are not of greatly different age, and that magmas of all three types commingled (if not mixed).

Pre-Acadian(?) Plutons

Most of the plutonic rocks were emplaced after the dominant regional folding. They are known or thought to be of Early Devonian age, and are an extension of the Bays-of-Maine Igneous complex of Chapman (1962). Two bodies are older, and probably pre-date Acadian folding. One, the Mt. Tom andesite in the southeast corner of the quadrangle, was first described by Bastin and Williams (1914), but the other, the Baileyville Dike, is described here for the first time.

Baileyville Dike (DCb) and Related Rocks. Fine to medium grained metadiabase forms low outcrops along and on both sides of the Woodland-South Princeton road, but are commonly not visible from a car. They are in apparently conformable contact with Kendall Mountain Formation felsic tuffs just north of this road, about 0.62 miles west of Route 1 in Woodland, but clearly cross-cut beds of the Kendall Mountain Formation 1.25 miles further west. Poor outcrop control makes it impossible to know whether these exposures represent more than one intrusive, and they are here mapped as a single dike. Related diabases just north of the main body occur as thin(?) dikes, also intruded into rocks of the Kendall Mountain Formation.

Most outcrops of the Baileyville dike contain orange-brown weathering, medium to dark gray sulfidic metadiabase. Some are massive and relatively featureless, but many are strongly jointed. Grain size varies from 0.4 to over 4.0 mm, but there is no apparent chilling near contacts with the host rocks. Indeed, one of the coarsest varieties is at the dike's southern contact.

The metadiabase consists of fresh plagioclase laths 0.4 to 4.0 mm long that form a subophitic framework with interstitial actinolite, chlorite, and pyrite. Many plagioclase crystals are bent, kinked, or fractured, indicating deformation after emplacement. Primary mafic minerals are replaced in most samples by small blue-green actinolite crystals occurring as individual needles or radiating aggregates, and by smaller amounts of chlorite. In a few specimens, however, pseudomorphs of chlorite and actinolite preserve the shape and size of original pyroxene phenocrysts. Plagioclase:actinolite proportions vary from sample to sample, but lie within the range of 3:2 to 2:3. Although chlorite is generally less abundant than actinolite, it is the only mafic mineral in specimens that have been strongly sheared. In these rocks, aligned chlorite and fractured plagioclase weakly define a foliation that is barely discernible in hand sample. Small pyrite grains are disseminated throughout the rock and produce

Table 3: CHEMICAL COMPOSITION OF THE BAILEYVILLE DIKE

Oxide	Specimen 1	Specimen 2
SiO_2	47.7	46.5
TiO_2	3.17	3.25
Al_2O_3	13.8	14.0
CaO	6.63	7.02
MgO	7.63	7.46
Fe_2O_3*	14.2	15.3
Na_2O	3.61	3.22
K_2O	0.08	0.11
MnO	0.28	0.28
P_2O_5	0.37	0.33
Loss on Ignition	2.23	1.93
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TOTAL	99.8	99.5

1,2: Well jointed metabasalts from small hill north of Woodland - South Princeton Road, 0.6 miles west of junction with Route 1 in Woodland.

tiny rust spots on weathered surfaces. Table 3 gives compositions of 2 representative samples of the Baileyville dike.

Age. There are few constraints on the age of the Baileyville dike, other than the fact that it cuts pelites and sandstones of the Kendall Mountain Formation. The metadiabases are similar mineralogically and texturally to what appear to be thin basaltic flows intercalated with felsic tuffs on Kendall Mountain, and may have been either feeders or shallow sub-volcanic intrusives. They may therefore be as old as the upper parts of the Kendall Mountain Formation, and thus Caradocian in age. There is little control on their minimum age because the metadiabases do not cut other units. The Baileyville dike has been metamorphosed to the same grade as its host rock, and apparently at the same time. This metamorphism is clearly associated with Devonian emplacement of the gabbroic through granitic plutons described below. An age within the span of Late Ordovician through Early Devonian is thus possible for the body.

Mt. Tom Andesite (Dia). A small area at the southeast corner of the quadrangle is underlain by a continuation of an intrusive porphyritic basaltic andesite named the Mt. Tom andesite by Bastin and Williams (1914) and Gates (1977). This body is a small oval stock intruded into the Leighton Formation in the Calais, Eastport, and Gardner Lake quadrangles. It consists of massive porphyry in which abundant gray and greenish gray plagioclase phenocrysts 1-5 mm long are set in a dark gray groundmass. Many of the phenocrysts appear to be deformed, and in thin section all are observed to have undergone extensive saussuritization. The groundmass is also altered and consists of chlorite, epidote, and small plagioclase laths that locally preserve a trachytic texture. Small black phenocrysts prove to be aggregates of chlorite and epidote with minor calcite, and may be pseudomorphs after clinopyroxene. Magnetite is the most abundant accessory mineral.

It is difficult to establish the precise age of the Mt. Tom andesite. In the Eastport quadrangle, it clearly cross-cuts and must be younger than the Pridolian Leighton Formation. Gates and Moench (1981) reported a single chemical analysis of the andesite and indicated that it was similar both lithologically and chemically to basaltic andesites of the Early Devonian Eastport Formation. They suggested that the stock might have been one of the feeders for the extensive Eastport volcanism. If this is correct, the Mt. Tom stock is an Early Devonian, pre-Acadian body.

Acadian (Post-folding) Plutons

Much of the southeastern half of the Calais quadrangle is underlain by an extensive suite of plutonic rocks characterized by complex contact relationships among its mafic, intermediate, and felsic components. Most of the individual mafic bodies within this suite remain unnamed, but three — the St. Stephen, Staples Mountain, and Woodland Dump gabbros — have been singled out in the past for study and named by their researchers. Granitic rocks of the study area have received more attention and are assigned to one of four main masses: Baring, Meddybemps, and Charlotte granites, and the granite of Magurrewock Lakes.

Gabbro. Amos (1963) described several types of mafic to ultramafic plutonic rocks in the Calais quadrangle, including gabbro, norite, pyroxenite, and anorthosite. These range from fine to medium grained, equigranular to seriate (locally porphyritic), and massive to layered. On fresh surfaces the rocks are black to salt-and-pepper colored; weathered surfaces are rusty black. The unnamed bodies will be described first, followed by a brief discussion of the three named above.

In this study, "gabbro" refers to any sample with plagioclase composition An_{50}. Samples with more sodic plagioclase are described below as "diorite." These two rock types have similar color index values: mean = 48% in gabbro, 44% in diorite. All of the diorites contain at least minor amounts of quartz (see Table 4), as do some gabbros. Olivine is present in some gabbros, but has not been observed in any diorite. There is a continuous gradation between gabbro and diorite in the study area, so that it is frequently impossible to name the rock at a given outcrop without thin-section determination of plagioclase composition.

Field Relations. Gabbro intrudes the Woodland Formation north and southwest of Meddybemps Lake and in the St. Croix River at Calais, and a body of gabbro crops out within the outcrop area of the Meddybemps granite (see geologic map). Contact aureoles with broad zones of high grade metamorphism and local anatexis are developed in the Cookson Group adjacent to the mafic rocks. The gabbros are commonly intruded by granitic rocks. For example, small bodies of the granite of Magurrewock Lakes intrude gabbro in the easternmost part of the quadrangle; the mafic pluton 3 km north of Bald Mountain is intruded on the west and northwest by Baring granite. A mappable zone of diorite has developed along the western contact, and is shown on the geologic map as "gabbro-granite intrusive complex." Another gabbro, along the northeast shore of Bearce Lake (shown as "Little Lake" on the topographic map) is in fault contact with the Baring granite. This fault, like other northeast-trending faults in the area, is marked by a prominent free-standing quartz ledge. Contacts between the Meddybemps granite and the gabbro it surrounds were not visible.

Relationships among gabbro, diorite, and Baring granite are complex and suggest broad contemporaneity of emplacement between the Baring granite, the diorite, and at least some of the gabbro. Hill and Abbott (1989) refer to this as magma commingling, following Mitchell's (1986) and Mitchell and Rhodes' (1988, 1989) description of granite/gabbro relationships further south in the Bays-of-Maine Complex on Vinalhaven Island. While some gabbro exposures are sharply crosscut by veins or dikes of Baring granite, other outcrops indicate more or less extensive hybridization between the two rock types. Evidence for local hybridization includes:

(i) Some gabbro occurs as fine-grained (basaltic) amoeboid blebs set in a matrix of either granite or, locally, diorite with very nearly the same color index as the gabbro. These

TABLE 4: MODAL ANALYSES OF PLUTONIC ROCKS FROM THE CALAIS 15' QUADRANGLE (Based on 1,000 or more points per thin section)

4.1: BARING GRANITE

Sample	CORE	3	13	14A	18A	34A	36	37A
Quartz	31.3	35.2	36.1	28.6	29.5	21.9	30.2	28.8
Plagioclase	29.3	27.9	27.4	31.2	28.4	31.7	36.0	32.7
K-feldspar	32.5	25.4	27.5	33.4	34.5	38.8	26.0	32.9
Biotite	6.6	9.3	8.7	5.2	7.0	2.3	7.6	5.1
Amphibole	—	1.7	0.1	0.3	0.3	4.0	0.2	0.2
Opaque	tr	0.2	tr	0.1	tr	tr	tr	0.1
Apatite	0.2	0.3	0.1	tr	tr	tr	tr	tr
Zircon	0.1	tr	tr	tr	0.2	tr	tr	tr
Allanite	tr	—	—	—	0.1	—	—	—

Sample	72C	138B	140	153	159	183B	187A	238A
Quartz	29.7	37.0	32.4	31.8	30.7	31.1	33.2	26.8
Plagioclase	35.7	31.8	28.4	27.1	30.1	31.4	22.6	41.3
K-feldspar	17.3	25.0	36.8	36.0	35.2	30.3	39.1	18.9
Biotite	12.1	4.0	1.8	4.7	3.4	5.9	4.4	12.2
Amphibole	2.8	—	—	—	0.2	0.7	0.2	—
Opaque	1.5	0.7	0.4	0.1	0.1	0.4	0.5	0.3
Apatite	0.5	0.1	0.1	0.1	0.1	0.2	0.1	0.1
Zircon	0.2	0.1	tr	0.1	0.1	tr	0.1	tr
Allanite	0.3	0.3	tr	—	0.1	—	—	—

Sample	249	258	263B	271A	281A	400	871A
Quartz	30.4	35.3	27.2	36.2	33.7	32.3	35.9
Plagioclase	33.2	27.6	27.4	29.3	40.1	34.5	28.8
K-feldspar	28.8	33.1	36.0	29.9	20.6	26.2	29.3
Biotite	5.9	3.1	8.7	3.2	5.3	6.9	4.4
Amphibole	1.0	0.6	0.1	0.1	—	—	0.6
Opaque	0.2	0.1	0.6	tr	0.2	tr	0.1
Apatite	tr	tr	tr	tr	0.1	tr	0.1
Zircon	0.1	tr	0.2	tr	tr	tr	0.2
Allanite	0.1	—	—	0.1	tr	—	0.1
Muscovite	—	0.2	—	—	tr	—	—

4.2: MEDDYBEMPS GRANITE

Sample	10	23	25A	282A	283	285	287
Quartz	29.4	38.0	40.0	40.9	31.8	35.2	35.6
Plagioclase	32.6	27.6	21.8	27.3	28.1	29.0	25.9
K-feldspar	30.7	32.0	34.9	26.6	34.9	32.9	33.6
Biotite	5.5	2.0	1.1	3.0	2.9	2.6	3.2
Amphibole	—	—	1.5	0.1	1.0	—	1.2
Opaque	0.2	0.1	0.6	tr	0.2	tr	0.1
Apatite	tr	tr	tr	tr	0.1	tr	0.1
Zircon	0.1	tr	0.2	tr	tr	tr	0.2
Allanite	0.1	—	—	0.1	tr	—	0.1
Muscovite	—	0.2	—	—	tr	—	—

4.3: CHARLOTTE GRANITE

Sample	8	8A	228B	239	292	471
Quartz	39.5	35.4	32.0	36.1	30.6	27.3
Plagioclase	31.0	28.1	38.5	21.6	30.5	28.6
K-feldspar	26.5	30.3	22.2	39.5	31.8	37.0
Biotite	1.8	5.0	5.9	2.3	5.4	2.7
Amphibole	0.2	0.1	0.8	—	1.5	2.8
Opaque	0.4	0.2	0.2	0.5	0.3	0.5
Apatite	tr	0.1	tr	tr	tr	0.2
Zircon	0.1	0.1	tr	tr	tr	0.1
Allanite	—	—	—	—	—	tr

4.4: GRANITE OF MAGURREWOCK LAKES

Sample	4OD	51	61B	960A
Quartz	32.5	33.7	33.1	32.0
Plagioclase	32.6	37.9	41.7	35.5
K-feldspar	28.5	21.2	17.3	19.8
Biotite	6.0	6.5	6.4	11.7
Amphibole	—	—	0.3	0.2
Opaque	0.1	tr	0.2	0.4
Apatite	0.1	tr	0.1	0.4
Zircon	0.1	tr	tr	tr
Muscovite	0.1	0.3	0.8	—

4.5: GABBRO

Sample	28B	29D	43	58	65	72A	72B	111
Quartz	0.3	3.5	2.5	—	0.7	—	—	—
Plagioclase	46.1	44.9	47.5	48.5	51.1	57.5	50.7	20.5
Augite	7.3	—	11.6	12.5	7.5	11.4	7.5	31.5
Hornblende	34.6	34.2	21.0	25.0	23.3	16.5	27.9	23.3
Biotite	6.7	15.3	13.0	9.0	12.6	9.9	7.4	9.5
Olivine	—	—	—	—	—	—	—	12.5
Opaque	4.1	1.8	3.7	4.4	2.8	3.4	5.0	2.5
Apatite	0.5	0.4	0.6	0.6	2.0	1.0	0.5	0.2
Zircon	0.1	—	—	0.1	tr	0.2	—	—
Sphene	—	—	0.1	—	—	—	—	—

Sample	135	254A	952
Quartz	0.5	0.1	—
Plagioclase	47.9	51.2	69.1
Augite	5.1	16.1	—
Hornblende	35.6	20.1	20.7
Biotite	5.9	6.7	4.8
Olivine	—	3.5	—
Opaque	4.3	1.7	4.1
Apatite	0.5	0.1	1.0
Zircon	—	—	0.2
Sphene	—	—	0.1

4.6: DIORITE, QUARTZ DIORITE, AND TONALITE FROM THE GABBRO-GRANITE INTRUSIVE COMPLEX

Sample	5C	40A	49	50B	69	79	91
Quartz	1.0	16.0	3.3	1.7	9.4	1.4	4.9
Plagioclase	58.7	67.4	46.1	52.9	49.9	50.2	50.7
K-feldspar	—	—	—	—	—	—	2.4
Augite	9.4	—	2.3	6.8	2.2	4.3	0.4
Hornblende	11.4	6.3	37.6	27.2	15.8	31.6	29.7
Biotite	18.7	9.6	7.3	8.4	17.5	9.7	7.1
Opaque	0.3	0.5	1.9	1.8	3.1	2.4	3.1
Apatite	tr	0.2	1.0	1.0	0.9	0.3	tr
Zircon	—	0.1	—	—	tr	tr	tr
Sphene	—	0.2	0.2	0.1	1.2	—	1.0
Epidote	0.4	0.2	—	—	—	—	—
Allanite	—	—	0.2	—	—	—	—

Sample	97	106	115	274	879A
Quartz	1.9	1.6	3.7	6.5	23.3
Plagioclase	45.2	53.5	52.6	29.1	36.3
K-feldspar	—	—	—	tr	3.5
Augite	11.8	1.5	0.2	5.3	4.2
Hornblende	29.6	35.6	27.7	24.9	16.7
Biotite	8.7	5.6	10.9	10.2	15.5
Opaque	1.5	1.5	3.3	2.9	0.4
Apatite	1.0	0.8	1.5	0.9	0.1
Zircon	—	—	—	tr	tr
Sphene	0.3	tr	tr	—	—
Epidote	—	—	0.1	tr	—
Allanite	—	—	—	—	—

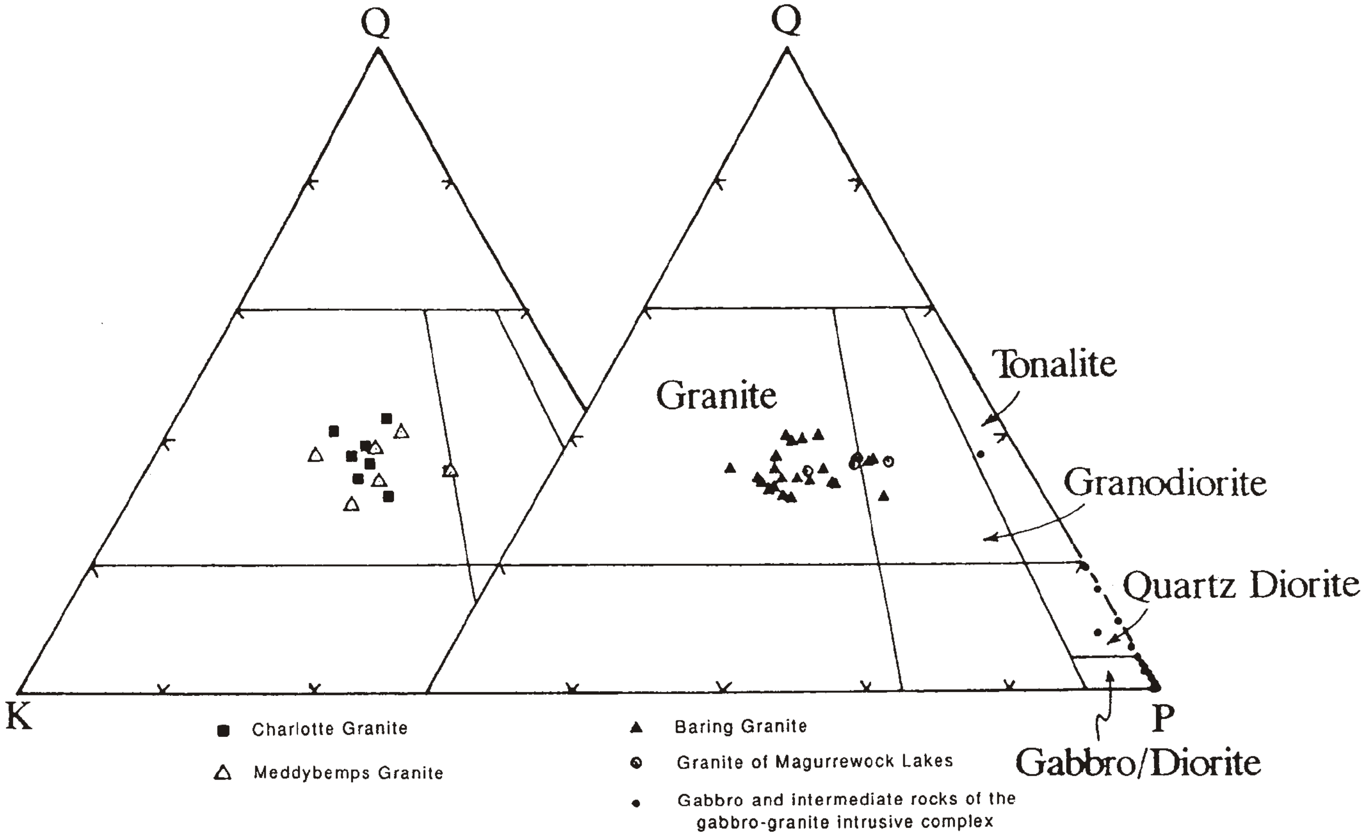

Figure 5. Modal analyses of plutonic rocks from the Calais quadrangle (based on counts of at least 1,000 points per thin section).

amoeboid mafic bodies are interpreted as "pillows" formed by quenching during mixing of magmas with very different temperatures. This intepretation implies that at least some of the gabbro, diorite, and Baring granite magmas were contemporaneous. Similar relationships are commonly observed between quenched diorite pillows in a Baring granite matrix. Hence, it is thought that gabbro, diorite, and the Baring granite were all intruded at about the same time.

(ii) All of the amoeboid, quenched pillows studied in thin section have outer margins dominantly composed of green to brown biotite, whereas the predominant ferromagnesian phase in the pillow interiors is green hornblende with only subordinate biotite. Unless this represents preferential nucleation of biotite rather than of hornblende in the cooler pillow margin, it indicates some chemical interchange (water and alkalies?) across the pillow/matrix interface.

(iii) The Baring granite matrix adjacent to the pillows is in some instances greatly enriched in hornblende compared with the granite far from gabbro contacts. This suggests that the Baring granite has been enriched in mafic components through interaction with gabbro. More commonly, however, the granite at the pillow interface contains anomalously low amounts of ferromagnesian minerals, and in many cases is alaskitic. Again, these relationships suggest mass transfer between pillow and matrix, perhaps preferential loss of water to the pillows. There is much scope for further study on magma commingling processes in these rocks.

Rocks shown as gabbro on the geologic map consist either of massive equigranular or porphyritic lithologies. Outcrops which contain pillows of gabbro in granite matrix, brecciated blocks in granite matrix, or massive gabbro with 10% or more granite veins are shown as "gabbro-granite intrusive complex." This mapped unit also contains all of the diorite, quartz diorite, and tonalite (described below). These intermediate rocks are typically, but not always, associated with pillowed textures or with abundant veins or irregular patches of Baring granite. At the 1:62,500 scale of mapping, it is not practical to subdivide this unit.

Petrography. The most common type of gabbro encountered in this study (Table 4.5) is equigranular and contains zoned plagioclase (An$_{65}$ cores, An$_{30}$ rims), green pleochroic hornblende, brown to red-brown biotite, relict clinopyroxene preserved as cores of hornblende crystals, apatite, zircon, and both oxide and sulfide opaque minerals. The clinopyroxene is not sector-zoned and is not pleochroic; it is probably common augite rather than Ti-augite. Quartz-bearing varieties also occur, and two samples (111 and 254a in Table 4.5) contain olivine. Euhedral to subhedral sphene occurs only in a few quartz-bear-

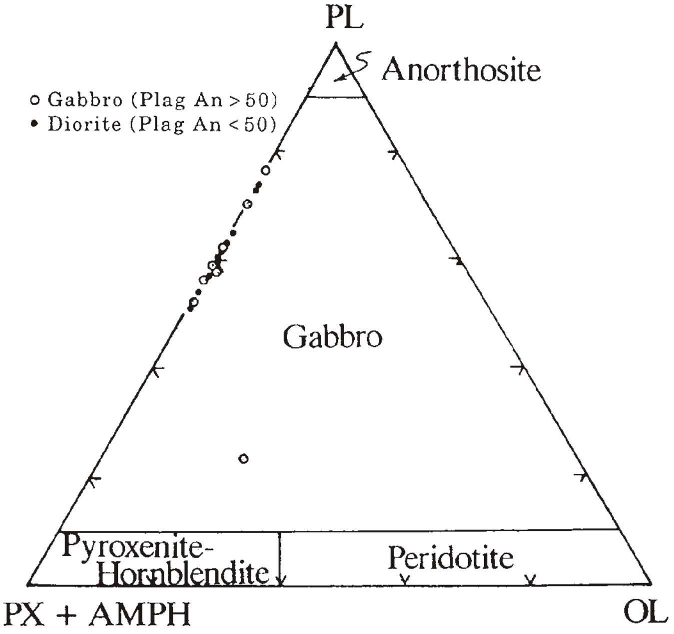

Figure 6. Modal analyses of gabbro, diorite, and quartz diorite from the Calais quadrangle.

ing gabbros, but is much more common in the diorites. The color index of most of the equigranular, massive gabbros ranges from 39-53, but one sample (111) has a color index of 79.

The modal data of Table 4 are summarized graphically in Figures 5 and 6. All samples with plagioclase more calcic than An_{50} plot in the gabbro/diorite field on Figure 5. Figure 6 demonstrates that (a) the Calais area gabbros are dominantly olivine-poor; (b) gabbro and diorite show nearly complete overlap in their plagioclase: pyroxene+amphibole ratios; and (c) except for gabbro sample 952, the plagioclase-porphyritic varieties of gabbro and diorite fall in the same range of modal composition as the more common equigranular varieties.

Although it is not difficult to find "reasonably" unaltered rock for thin section or geochemical analysis, all samples show some alteration of the igneous minerals. In some samples, the primary grain textures are all but obliterated. Typically, cores of plagioclase are preferentially altered to sericite in varying degrees; olivine is partially replaced with chlorite or serpentine; biotite may be altered to chlorite; and hornblende is replaced by chlorite or, less commonly, a secondary amphibole. Clinopyroxene is the most resistant of the primary igneous minerals, but in the most altered samples even this phase may be replaced by fibrous amphiboles (distinctly different from the primary green hornblende surrounding ragged clinopyroxene cores).

Porphyritic gabbro is less abundant than the equigranular variety, but is relatively common (#43 and 952 in Table 4.5). This type contains large (3-4 cm) phenocrysts of plagioclase in a medium-grained equigranular groundmass similar to that of the massive gabbros described above. The phenocrysts range from An_{54} in sample #43 to An_{38-27} in #952. The color index of #43 is 49, well within the range of values for the equigranular gabbros. Sample 952, however, has a color index of 30, although that is probably an artifact of determining color index from a point count in thin section rather than from a rock slab or outcrop surface. This sample does not have a positive europium anomaly (see below) and has thus not experienced feldspar accumulation.

St. Stephen Gabbro. The St. Stephen gabbro is exposed most widely in New Brunswick, in and north of the city of St. Stephen. It also underlies most of the northern part of the city of Calais. Houston (1956) studied the St. Stephen gabbro as part of a project designed to evaluate possible pyrrhotite-bearing plutons, and the Maine portion of the body was also examined by Amos (1963). A variety of mafic and ultramafic lithologies is present in this pluton, including peridotite north of St. Stephen, and olivine norite, norite, gabbro, and hornblende gabbro in St. Stephen and Calais. Phase layering is weakly developed throughout the pluton, particularly in the gabbro and norite. This layering is not very distinct, tends to pinch out over distances of only a few meters, and has not been shown to vary systematically. Similarly, it has not been possible to define compositional zonation within the St. Stephen gabbro.

The St. Stephen gabbro intrudes the Woodland and Calais Formations of the Cookson Group, and is itself intruded by the Baring granite. It truncates folds assigned to the Acadian orogeny, and its age is thus bracketed firmly within the Early Devonian.

Staples Mountain Complex. The mafic rocks at Staples Mountain were first described by Amos (1963), and investigated in detail by Coughlin (1983). Although it is much smaller than the St. Stephen pluton, Coughlin was able to show that it is a well differentiated body composed of sub-horizontal lithologic zones, some of which display well-developed phase layering. She demonstrated that the lowest exposed zones are the most mafic, consisting of norites and olivine gabbros. One of the lowest zones contains a unique horizon in which discontinuous lenses composed almost entirely of olivine (with only very minor plagioclase) are included within the norite. Above this zone are a variety of augite gabbros, and the center of the body is composed of superbly interlayered anorthosite and hornblende gabbro. Layering in this zone is on the scale of a few centimeters to a few meters, and several layers exhibit "graded bedding" and basal scour features. Quarry cuts near the top of Staples Mountain reveal excellent cross-laminations defined by aligned amphibole crystals. The highest stratigraphic position in the body is occupied by augite gabbros and very sparse olivine gabbros, suggesting that the pluton is roughly symmetrical.

Coughlin (1983) interpreted the complex as a differentiated sheet-like mass which cooled symmetrically from top and bottom. The pluton intrudes rocks of the Woodland Formation, but is itself intruded on the north and west by the Baring granite and on the northwest by unnamed diorite. Extensive hybridization along the contact of the Baring granite is particularly well

TABLE 5: MAJOR AND TRACE ELEMENT COMPOSITIONS OF PLUTONIC ROCKS

5.1—GRANITES

	Baring Granite			Meddybemps Granite		Charlotte Granite				Granite of Magurrewock Lakes		
Sample	36	258	138B	23	285	8A	292	471	228B	40D	61B	59
SiO_2		76.06		76.68			72.95			72.36	73.32	72.57
TiO_2		0.15		0.10			0.28			0.26	0.21	0.20
Al_2O_3		23.83		12.95			13.78			14.12	14.50	13.30
Fe_2O_3*	2.73	1.28	2.10	0.95	1.31	1.86	2.47	2.48	2.52	1.97	1.64	1.40
MnO		0.03		0.04			0.05			0.05	0.06	0.03
MgO		0.78		0.79			1.08			1.12	1.12	0.97
CaO		0.48		0.27			1.27			1.48	1.48	0.80
Na_2O	3.57	4.47	3.27	3.71	3.20	3.19	4.02	3.92	3.36	4.13	4.13	3.64
K_2O		4.57		4.56			4.38			3.83	3.83	4.88
P_2O_5		0.03		0.02			0.06			0.08	0.08	0.20
LOI		0.30		0.50			0.20			0.60	0.60	0.20
TOTAL		100.98		100.57			100.54			100.00	100.97	98.03
Sc	11.40	3.71	9.56	4.25	4.19	8.04	9.64	5.41	9.67	5.80	4.15	4.74
V		16.		10.			23.			17.	3.	7.
Cr	4.6	1.7	5.8	6.	1.9	2.6	5.0	2.1	5.7	6.0	4.6	3.0
Co	2.67	0.82	2.91	0.61	1.20	1.47	2.73	1.47	3.42	2.74	2.22	1.66
Ni		6.		3.			8.					
Cu		nd		nd			5.					
Zn		31.		20.			57.					
Ga		17		17			17.					
Rb		204.		462.			199.					
Sr		25.		11.			82.					
Y		71.		142.			63.					
Zr		134.		118.			164.					
Nb		14.		37.			10.					
Cs	4.66	1.47	2.53	6.4	2.80	8.22	10.8	0.96	4.71	8.9	10.0	11.3
Ba		160.		34.			510.			392.	352.	354.
La	45.1	32.2	50.0	29.8	33.2	42.8	54.4	42.1	48.4	34.1	25.6	36.4
Ce	97.5	78.0	105.6	69.8	51.0	96.3	100.7	93.1	103.1	73.3	53.8	75.6
Nd	46.8	40.2	48.6	33.7	29.2	46.1	54.6	46.3	49.6	31.1	23.2	28.7
Sm	8.76	8.46	9.09	10.78	5.30	9.56	10.48	9.29	9.77	6.42	4.57	5.71
Eu	1.15	0.390	0.856	0.170	0.844	0.732	1.02	1.27	0.911	0.844	0.797	
	0.601											
Tb	1.46	1.76	1.56	3.44	0.593	1.80	1.76	1.25	1.71	1.35	0.96	1.49
Yb	4.78	7.13	4.94	16.3	2.44	6.69	5.27	5.23	5.90	4.13	2.59	3.78
Lu	0.77	1.01	0.74	2.34	0.363	1.01	0.77	0.79	0.88	0.66	0.387	0.58
Hf	7.27	5.36	6.24	6.73	5.29	6.07	6.33	10.47	6.84	5.04	4.01	4.51
Ta	1.18	1.04	1.36	8.4	0.94	1.41	1.26	0.97	1.26	1.39	1.53	1.66
Th	14.76	19.0	16.42	46.8	18.6	18.84	16.9	7.13	18.72	17.7	13.6	22.6
U	3.0	4.91	2.7	25.6	2.8	7.5	6.2	1.6	4.3	3.1	3.2	3.3
Pb		12.		38.			20.			25.	20.	30.

Major elements in weight %; trace elements in ppm
Fe_2O_3*: Total iron as Fe_2O_3 nd: not detected
LOI: % Weight loss on ignition

exposed on two hills northeast of Ryan Lake. An age comparable to that of the St. Stephen gabbro is inferred for the Staples Mountain Complex.

Woodland Dump Gabbro. This unromantically named plug occupies a few tens of thousands of square feet at the south end of the Woodland town dump, and underlies small hills in the adjacent water treatment plant. During excavations for that plant, gabbro was seen to underlie much of the area now occupied by the settling lagoon.

Most of the Woodland Dump gabbro consists of dark gray, medium to coarse-grained olivine norite composed of plagioclase feldspar (An_{70}), hypersthene, augite, olivine, biotite,

TABLE 5: CONTINUED.

	5.2—GABBRO						
Sample	58	111	231	72A	72B	454B	952
SiO_2	48.06	46.12	47.91	49.05	48.38		
TiO_2	2.26	0.97	0.91	2.05	2.28		
Al_2O_3	15.65	11.40	18.68	16.56	15.52		
Fe_2O_3*	11.93	13.13	8.24	11.00	12.04	10.26	8.76
MnO	0.18	0.20	0.13	0.17	0.19		
MgO	6.69	17.31	8.92	6.14	6.20		
CaO	8.82	6.09	10.47	8.95	9.10		
Na_2O	3.84	1.50	3.16	4.58	4.39	2.89	3.68
K_2O	1.12	0.78	0.48	0.93	1.21		
P_2O_5	0.37	0.17	0.14	0.36	0.40		
LOI	0.90	0.90	0.90	1.00	1.00		
TOTAL	99.82	98.57	99.94	100.79	100.72		
Sc	31.7	19.58	21.24	29.4	34.5	30.55	19.20
V	268.	164.	131.	245.	297.		
Cr	93.	1131.	350.	81.3	102.4	106.4	57.4
Co	44.1	81.8	43.5	39.7	43.9	37.89	28.5
Ni	69.	321.	98.	64.	64.		
Cu	41.	30.	21.	54.	64.		
Zn	102.	96.	66.	98.	111.		
Ga	21.	12.	14.	18.	19.		
Rb	36.	26.	10.	27.	36.		
Sr	349.	217.	383.	394.	363.		
Y	35.	20.	19.	33.	39.		
Zr	200.	101.	86.	184.	196.		
Nb	20.	8.	5.	16.	16.		
Cs	3.5	3.2	2.34	1.50	1.64	0.87	1.44
Ba	224.	149.	109.	210.	219.		
La	20.24	10.82	11.70	20.94	22.68	16.67	16.70
Ce	47.3	27.7	27.4	48.7	52.5	39.6	38.4
Nd	29.9	13.9	17.3	28.7	31.9	20.9	22.9
Sm	6.47	3.10	3.34	6.21	6.73	5.25	4.79
Eu	2.13	1.02	1.17	2.06	2.24	1.72	1.63
Tb	0.85	0.364	0.45	0.84	0.78	0.63	0.60
Yb	3.24	1.75	1.83	3.17	3.36	2.61	2.42
Lu	0.506	0.269	0.229	0.489	0.536	0.44	0.38
Hf	5.11	2.38	2.33	4.74	5.08	3.80	3.66
Ta	1.35	0.47	0.32	1.30	1.30	0.87	0.98
Th	1.51	1.76	1.17	2.70	2.82	1.76	1.37
U	nd	0.53	nd	1.2	0.5	nd	nd
Pb	nd	nd	nd	nd	nd	nd	nd

and abundant pyrite and magnetite. The rock weathers with a typical nubbly, cauliflower-like surface, and limonite spots mark concentrations of the opaque minerals. Thin, irregular, pale gray lenses of plagioclase-rich gabbro and local coarsening of grain size define a very inconspicuous layering. Some of these rocks are similar to basal norites of the Staples Mountain Complex just a few miles to the south, but preliminary studies suggest that initial $Sr^{87/86}$ ratios of the two bodies may be significantly different.

The Woodland Dump gabbro intrudes the Woodland Formation, and is intruded on its south side by the Baring granite. Its age is thought to be comparable to that of the Staples Mountain and St. Stephen gabbros—Early Devonian. Rb/Sr and Nd/Sm whole-rock and mineral dating are currently in progress, and will hopefully provide better evidence for the age of the body.

TABLE 6: CIPW NORMS FOR PLUTONIC ROCKS, CALAIS QUADRANGLE

	6.1—GABBRO				
Sample	58	111	72A	72B	231
Orthoclase	6.62	4.61	5.50	7.15	2.84
Albite	30.47	12.69	31.88	28.73	25.08
Anorthite	22.16	22.07	21.88	19.07	35.37
Nepheline	1.10	—-	3.72	4.56	0.90
Diopside	15.46	4.64	16.25	18.95	12.51
Hypersthene	—-	22.86	—-	—-	—-
Olivine	11.70	22.92	9.94	9.69	16.22
Magnetite	5.45	3.58	5.15	5.48	3.49
Ilmenite	4.29	1.84	3.89	4.33	1.73
Apatite	0.86	0.39	0.83	0.93	0.323

	6.2—GRANITE					
Sample	258	23	292	40D	59	61B
Quartz	30.23	35.63	27.88	28.47	29.27	29.51
Orthoclase	27.01	26.95	25.88	22.63	28.84	22.63
Albite	37.82	31.39	34.02	32.95	30.80	34.95
Anorthite	1.45	1.21	5.91	6.82	3.71	6.82
Corundum	—	1.47	0.26	0.68	0.67	1.06
Diopside	0.60	—	—	—	—	—
Hypersthene	2.52	2.66	4.36	4.08	3.30	3.91
Magnetite	0.62	0.46	1.19	0.95	0.68	0.79
Ilmenite	0.28	0.19	0.53	0.49	0.38	0.40
Apatite	0.07	0.05	0.14	0.19	0.09	0.19

258: Baring granite
23: Meddybemps granite
292: Charlotte granite
40D, 59, 61B: Granite of Magurrewock Lakes

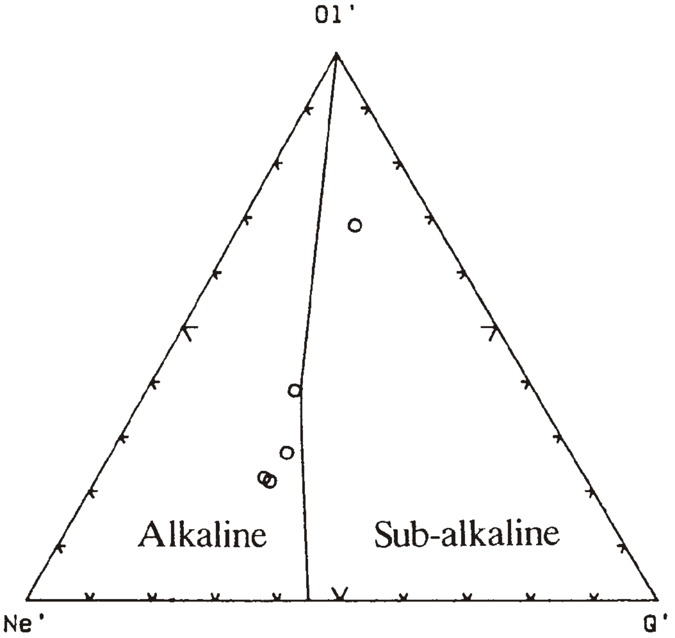

Figure 7. Plot of normative olivine, nepheline, and quartz in alkaline gabbros (open circles) of the Calais quadrangle. Boundary between Alkaline/Subalkaline fields from Irvine and Baragar (1971).

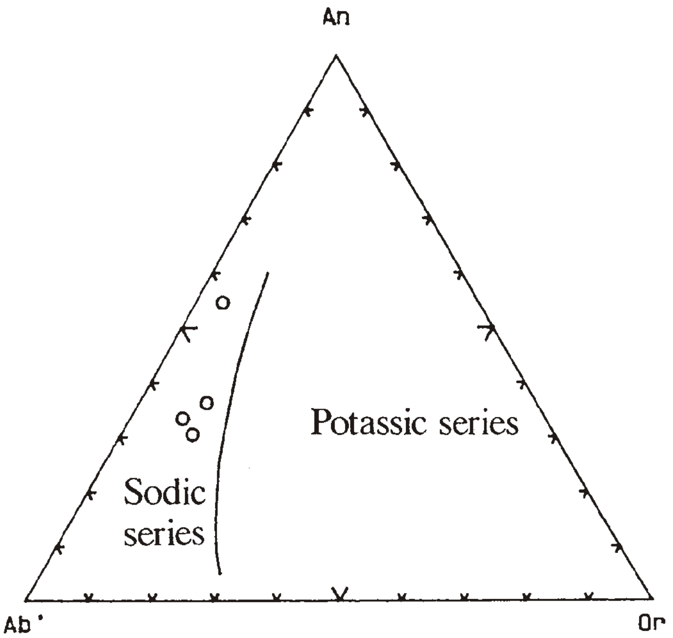

Figure 8. Plot of normative anorthite, albite, and orthoclase in alkaline gabbros from the Calais quadrangle. Boundary between sodic and potassic series after Irvine and Baragar (1971).

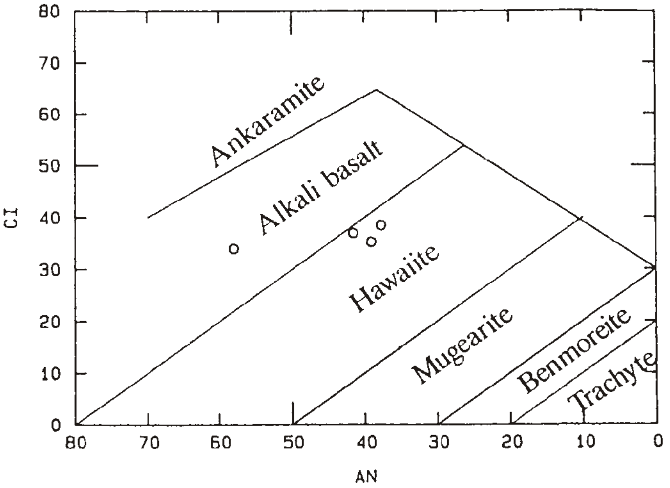

Figure 9. Crystallization Index plotted against normative anorthite for alkaline gabbros. Crystalline Index (C.I.)= normative anorthite + magnesian diopside + forsterite + enstatite. Field boundaries from Irvine and Baragar (1971).

Geochemistry of Gabbroic Rocks. Chemical analyses were carried out on several gabbro samples by x-ray fluorescence and instrumental neutron activation methods, and are reported in Table 5. CIPW normative minerals calculated from the major element analyses are listed in Table 6. Note that four of the five gabbros analyzed for major elements contain normative nepheline, suggesting an alkaline affinity. The fifth, #111, is olivine- and hypersthene-normative, and is unusual texturally as well as mineralogically (compare its modal analysis with those of more typical types in Table 4.5). Following the classification scheme of Irvine and Baragar (1971), Figure 7 demonstrates that the same four gabbros fall on the alkaline side of the boundary separating alkaline from subalkaline mafic suites. This is in contrast to the subalkaline compositions reported by Mitchell and Rhodes (1988, 1989) for gabbros further south in the Bays-of-Maine Igneous Complex. Figure 8 suggests that the four alkaline gabbros are sodic rather than potassic, and Figure 9 suggests that their compositions are most similar to the alkaline magmas termed "hawaiite."

Rare earth element data are shown in Figure 10. All samples analyzed are moderately enriched in the light rare earth elements (La=30-70X chondrite values) compared with the heavy rare earth elements (Lu=6.6-22X chondritic). The rare earth data are compatible with the mildly alkaline nature of the gabbros. The patterns suggest slight europium enrichment in these gabbros as a group, but the sample with the highest plagioclase content (#952) does not show a more pronounced europium anomaly than the other samples. While Sample #111 may have formed via crystal accumulation, there is little evidence for cumulate textures in thin sections of the more common equigranular or porphyritic gabbros, and our discussion of the chemistry of these dominant rocks assumes that they approximate the compositions of the original magmas.

The contents of other trace elements (including Rb, Sr, Ba, Zr, Nb, Hf, Ta, and Th) are moderate for basaltic compositions, and can also be reconciled with the mildly alkalic nature of the original magma as inferred from the major element data. The contents of these elements in strongly alkalic magmas would be much higher; the contents of Rb, Sr, and Ba, in particular, would be somewhat lower in typical depleted tholeiitic basalt of the sea floors. Although the data have been plotted on a variety of tectonic discrimination diagrams, no clear consensus emerges and none of these diagrams is shown.

Figure 11 is a "spidergram" that graphically shows the relationships between elements with a wide range of geochemical properties. The concentrations of the elements in each rock are divided by concentrations in a reference standard (in this case, the average ocean ridge basalt of Pearce, 1983). If the Calais gabbros had compositions similar to this type of sea floor basalt, they would plot as straight, horizontal lines near 1.0 on the concentration axis. Many arc basalts plot as more or less horizontal lines also, sometimes with higher contents of Sr, K, Rb, and Ba, and sometimes with pronounced negative dips in the pattern at Ta-Nb and Zr-Hf. Both tholeiitic and mildly alkaline rocks of the continents and of oceanic islands such as Hawaii typically have patterns most similar to those shown by the Calais gabbros, with maxima at the alkali elements (K, Rb) and a generally smooth drop to the right of the diagram.

Coughlin (1983) cited preliminary values for initial $Sr^{87/86}$ in the Staples Mountain Complex of 0.7041, and a slightly lower value of 0.7037 for the Woodland Dump gabbro. These ratios

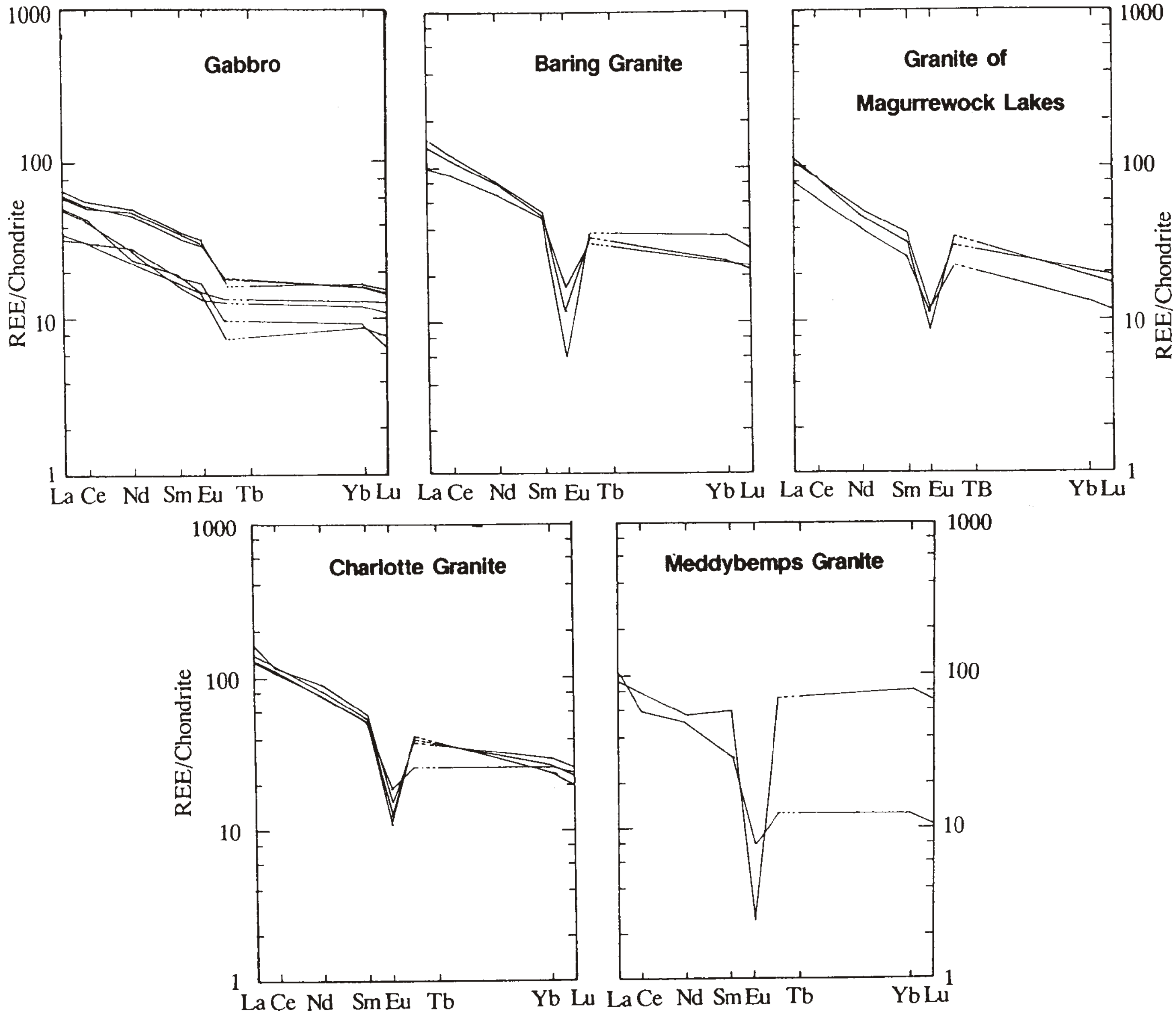

Figure 10. Rare earth element distributions in plutonic rocks of the Calais quadrangle.

are compatible with basaltic magma values. They are consistent with ratios observed in modern mildly alkalic basalts, but are also observed in basalts of several other compositions.

In light of the field evidence for extensive commingling of gabbroic and granitic magmas in the Calais area, it is natural to ask whether the compositional variation within the gabbros might be caused by mixing between the two liquids. Figure 12 suggests that this process, if it has occurred, has not exerted a systematic effect on the compositions of the mafic rocks. Simple mixing of varying amounts of granitic and gabbroic magmas would produce a series of gabbro compositions which should lie on straight lines in Figure 12. Although the concentrations of some oxides (Na_2O) do change systematically with increasing SiO_2, those of most others vary erratically (particularly TiO_2, Fe_2O_3, and K_2O). Field and petrographic studies show that hybridization has clearly occurred in at least some places, but Figure 12 indicates that either there are a number of distinct gabbro parent magmas, or that the mixing process or components were different in different locations, or that both have operated to bring about the observed relationships.

Diorite, Quartz Diorite, and Tonalite. As discussed above, diorite, quartz-diorite, and tonalite crop out where the Baring granite and gabbro are extensively commingled. They form an extremely heterogeneous mixture which, for the purposes of compiling this 15' map, have been combined into a single unit labeled "gabbro-granite intrusive complex." These

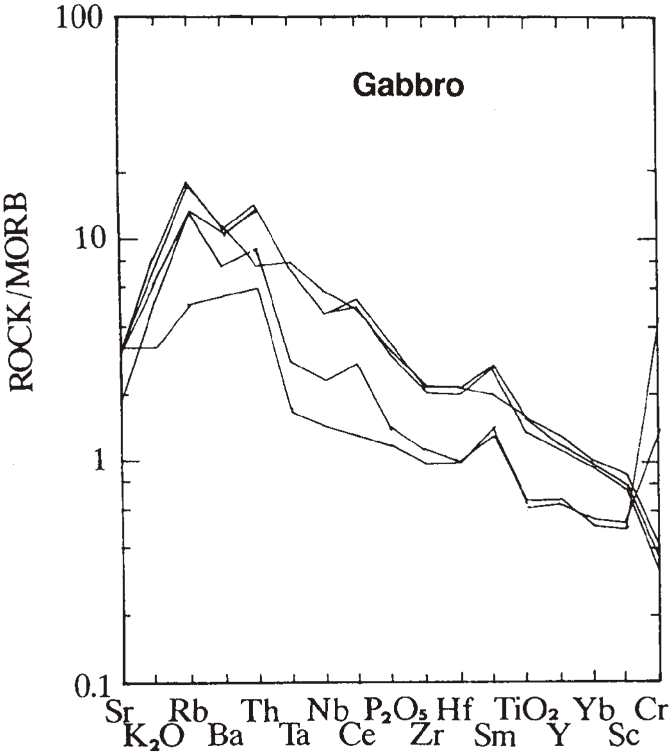

Figure 11. "Spider diagram" for gabbros from the Calais quadrangle. Element concentrations in rock normalized to the MORB average of Pearce (1983).

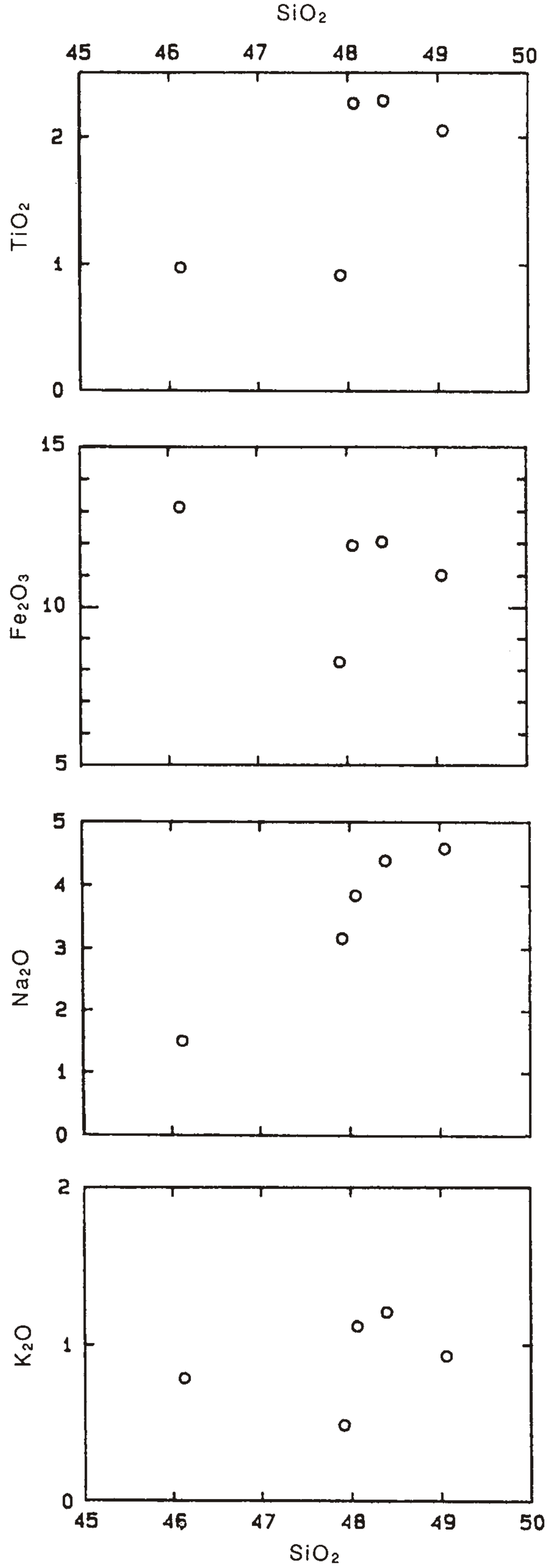

Figure 12. Variation diagrams of TiO_2, Fe_2O_3*, Na_2O, and K_2O vs SiO_2 for gabbros from the Calais area.

rocks range from fine to medium grained and are usually equigranular. Rare porphyritic varieties with large feldspar phenocrysts up to 3 cm long occur locally. Most outcrops are massive with no sense of preferential mineral alignment or concentration. At four locations, however, strongly foliated diorite occurs, with long axes of feldspars, mica, and amphibole aligned, and streaks of mafic and felsic minerals. Thin section study shows that this is a primary igneous foliation, rather than the result of metamorphism or cataclasis.

Field Relationships. "Gabbro-granite intrusive complex" occurs at Baring granite/ gabbro contacts, but is itself cut by the granite of Magurrewock Lakes and by northwest-trending faults that are marked by prominent free-standing quartz ledges. Relationships among diorite, gabbro, and Baring granite are complex and suggest that the three units were emplaced simultaneously. In some locations, diorite is crosscut by veins of Baring granite or by biotite-granite pegmatite dikes attributed to the Baring granite. Angular diorite blocks from a few centimeters to a few meters in size are common within a Baring granite matrix, as are more rounded "pillows" of fine-grained (quenched) diorite. The amoeboid pillows commonly occur in the same outcrop as the angular, brecciated blocks. The pillows demonstrate that granite and diorite magma coexisted; the pillows formed by quenching of the hotter diorite magma during mixing with cooler granitic magma. Similar relationships were described earlier between gabbro pillows and diorite matrix.

Although outcrops exist with only angular blocks of diorite set in a Baring granite matrix, others clearly show a two-stage history: formation of an amoeboid diorite pillow followed by pillow fracturing and filling of the fractures with a granitic material identical to that which forms the host material for the pillow. This suggests that brittle fracture is possible within a recently-quenched mafic component in an active commingling zone, and does not necessarily indicate a substantial age difference between mafic and felsic components in outcrops which contain only brittlely fractured fragments of the former.

The foliated diorite crops out in the center of Meddybemps Lake (on a small island east of Pierce Island), and in the region between Meddybemps and Bearce Lakes. The foliation does not display consistent orientation. In Meddybemps Lake, the foliated diorite is intruded by Meddybemps granite, and, where contacts are observed at the other localities, it is intruded by equigranular diorite. Similar relationships are developed in a small outcrop area of Meddybemps granite, on the steep hill 2 km west of Blanchard Corner. There, well-developed cliff exposures show that Meddybemps granite and gabbro commingled to produce the same kines of amoeboid pillows, etc., developed by interaction of Baring granite and gabbro.

The gabbro-granite intrusive complex is intruded by the Charlotte granite southeast of Meddybemps Lake, between Route 191 and the Charlotte Road. Good outcrop makes this contact easy to map; close to the contact, the Charlotte granite is finer grained than at exposures within the center of the body. The Charlotte granite is thus thought to be younger than the diorites of the intrusive complex.

We interpret the gabbro-granite intrusive complex as a variable, gradational unit developed by commingling between the Baring granite and one or more gabbroic magmas. This follows the interpretation of Amos (1963) and is clearly required by the map pattern showing a thin rind of intrusive complex (diorite) at the contact of Baring granite and gabbro 2 km southeast of the town of Baring. This interpretation implies that the gabbro and all diorites of the intrusive complex are approximately coeval. However, because accurate delineation of gabbro vs diorite essentially requires a thin section from most outcrops, we cannot be absolutely certain that there are no gabbros that predate or postdate the intermediate rocks of the intrusive complex.

Granitic Rocks. The granitic rocks of the Calais quadrangle are assigned to the four major bodies named above, following the early classification of Amos (1963). These can be distinguished from one another by their appearance in the field, and by their mineralogy and chemistry. Each of the four will be described below.

Baring Granite. The Baring granite is composed of medium to coarse-grained, biotite-(hornblende) granite. Most samples have a seriate texture, although a quenched, porphyritic facies with rapakivi mantling and inclusions of quenched basalt blebs occurs locally near the gabbro-granite intrusive complex just described. On fresh surfaces, most samples of the Baring granite are white to gray-white, grading to green in some varieties. Weathered surfaces are chalky white due to surface weathering, or pink in the most pervasively altered specimens.

Pegmatites of simple mineralogy (quartz, feldspar, biotite) and aplite are common. Rapakivi mantling is developed in scattered localities, but is not as common as in the Charlotte granite to the south. Most outcrops are massive with no sense of mineral alignment, but long axes of alkali feldspars define a crude alignment in a small number of exposures.

Field Relationships. The Baring granite occupies a north-south swath approximately 3 km wide from Milltown to Porcupine Mountain. At Magurrewock Mountain, the Baring granite intrudes unspecified, highly metamorphosed sedimentary rocks designated as DCus. Metasedimentary xenoliths are abundant in the granite near its northeastern contact, and there is clear evidence of partial melting of the metasedimentary rocks near the contact. The Baring granite intrudes rocks of the Woodland Formation that had previously been deformed by Acadian folding. The granite also intrudes gabbro and, southeast of Baring, a thin screen of diorite has developed along this contact. Extensive hybridization has occurred along Baring/gabbro and possible Baring/diorite contacts, resulting in the "gabbro-granite intrusive complex" shown on the map. Amos (1963) reported that the Baring granite is intruded by the granite of Magurrewock Lakes, but we were unable to observe this directly in our work (see below). Although the Charlotte granite is shown in contact with the Baring granite south of Porcupine Mountain, that contact has not been observed in the field. The Charlotte granite is younger than the intrusive complex, and is hence inferred to be younger than the Baring granite. Finally, the Baring granite has been cut by northeast-, north-, and northwest-trending faults.

Petrography. Modal analyses of Baring granite obtained from counts of at least 1000 points per thin section are given in Table 4.1 and shown graphically in Figure 5. Most samples analyzed are true granites; a few are granodiorites, generally those in close contact with mafic rocks of the gabbro-granite intrusive complex. The granite contains quartz, plagioclase with minor zoning (An_{26-23} cores, An_{21} rims), perthitic microcline, biotite, hornblende in most samples, apatite, zircon, opaque minerals, and allanite in some samples. The amphibole in most Baring granite thin sections is common green hornblende, but in some cases an alkali amphibole (deep blue-green pleochroism) occurs instead. Myrmekite intergrowths occur in some, but not all samples. No primary muscovite was observed in any of the thin sections studied, although some extensively altered samples contain coarse patches of secondary, ragged mica replacing feldspar. Alteration of the igneous minerals is variable. Some samples are fresh and nearly unaffected by secondary processes, whereas others have been extensively replaced by secondary sericite, chlorite, etc.

Charlotte Granite. The Charlotte granite underlies most of the southeastern part of the quadrangle. It ranges from equigranular to seriate, medium to coarse-grained, biotite-(hornblende) granite. Fresh surfaces are pinkish gray to greenish gray, and weathered surfaces are chalky white. Pervasively altered samples are salmon pink. The granite is massive, with no detectable foliation. No aplites or pegmatite dikes were seen in the few outcrops that have been discovered, but small elliptical mafic inclusions are present in some localities.

Field Relationships. The Charlotte granite is thought to have a chilled margin against the "gabbro-granite intrusive complex" because its contact facies is significantly finer grained than the coarser facies typical of this body away from the contact. The Charlotte granite/gabbro contact along the eastern margin of the quadrangle is inferred from the work of Abbott (1986). Although the Charlotte and Meddybemps granites adjoin over a substantial distance, the area contains little outcrop and no contacts are exposed. This contact may be a simple intrusive one, but it does parallel known northeast-trending faults in the region and could be a fault. Indeed, a fault can be seen in outcrop along the projection of this contact into Meddybemps Lake.

Petrography. Table 4.3 and Figure 5 summarize the results of thin section analysis of the Charlotte granite. The granite contains quartz, weakly zoned plagioclase, perthitic microcline, biotite, hornblende (some samples), alkali amphibole (vivid blue-green pleochroism; most samples), opaque minerals, apatite, and zircon. A single molybdenite flake was found in one sample from the roadcut along the Charlotte Road at the crest of the hill 2 km north of Round Lake. Myrmekite intergrowths are common in most samples, as is rapakivi mantling of white plagioclase around pink microcline phenocrysts. Secondary alteration of varying intensity occurs in most samples. Plagioclase has been altered to sericite, and chlorite replaces biotite. No primary muscovite has been observed in any of the samples of the Charlotte granite.

Meddybemps Granite. The Meddybemps granite underlies an extensive area south of Meddybemps Lake and extends into the adjacent Gardner Lake quadrangle. It is an equigranular to seriate, medium grained, biotite-(hornblende) granite. Fresh surface color ranges from gray to salmon pink, and weathered surfaces are chalky white. As is common for most of the granites of the region, pervasively altered rocks are pink. The granite is massive, with no alignment of its tabular feldspar crystals. Aplites are present, but are much less common than in the Baring granite to the north. A few small, fine-grained elliptical mafic inclusions were noted, but are also much less common than in the inclusion-choked Baring granite.

Field Relationships. On the small island just east of Pierce Island in Meddybemps Lake, Meddybemps granite intrudes foliated diorite. It is thus younger than at least some phases of the gabbro-granite intrusive complex, but a similar type of complex is developed at a Meddybemps granite/gabbro contact on the hill west of Blanchard Corner, complete with amoeboid pillows and related features. Texturally, the granite in this small exposure is quite unlike the Baring granite and is similar to many exposures of the Meddybemps body.

Petrography. The Meddybemps granite consists of quartz, weakly zoned plagioclase (An_{23-22}), perthitic microcline, biotite, hornblende in some samples, alkali amphibole in most samples, apatite, zircon, opaque minerals, and allanite. A pale yellow pleochroic mineral with a poikilitic texture surrounding quartz grains occurs in some samples and may be a hastingitic amphibole. Myrmekite intergrowths are common. Triangular patches of (late-magmatic?) muscovite with planar contacts against adjacent feldspar crystal faces occur in some, but not all samples of the Meddybemps granite. This muscovite meets some of the petrographic criteria listed by Zen (1988) for a magmatic origin.

Secondary alteration is pervasive but of variable intensity. Plagioclase is altered to sericite and biotite has been partially replaced by chlorite. Reddish-brown alteration minerals along thin fractures in the granite are common in many thin sections. In some samples, biotite has been altered to an intensely pleochroic (emerald green to pale green) mineral with anomalous birefringence colors that may be pumpellyite. This mineral has not been observed in any other igneous unit in the region, and may indicate alteration effects unique to the Meddybemps granite.

According to local residents, molybdenite prospecting has been carried out recently in the Meddybemps pluton in the area around Lake Cathance in the adjacent Gardner Lake quadrangle, just south of Grove. The pervasive alteration effects within the pluton likely correlate with this mineralization. Sample #23, from the top of Cooper Hill (just south of Grove, in the Gardner Lake quadrangle) is located near a copper mine that was active in the late 1800's. It is a texturally unusual variety of Meddybemps granite, with euhedral to subhedral plagioclase, and is one of the rare Meddybemps granite samples to contain muscovite. It is one of the most highly altered samples studied, and contains very high uranium and thorium contents (see Table 5), and extremely high concentrations of the heavy rare earth elements (see below).

Granite of Magurrewock Lakes. Small stocks (up to a few hundred meters across) of this fine to medium grained, porphyritic (pink alkali feldspars to 1 cm) to equigranular biotite granite intrude gabbro and the gabbro-granite intrusive complex in the easternmost part of the quadrangle. On a fresh surface the rock is light gray to pinkish gray; weathered surfaces are chalky white, and pervasively altered samples are salmon pink. The most diagnostic feature of this map unit is a distinctive "quartz droplet" texture in which subhedral, rounded quartz grains are set in tabular pink alkali feldspar crystals.

The granite contains quartz, weakly zoned plagioclase (An_{24-22}), perthitic alkali feldspar, biotite, opaque minerals, apatite, zircon, and secondary muscovite. Both myrmekite (within individual feldspar grains) and micrographic (developed in patches across several grains) textures occur.

Rapakivi mantling of white plagioclase around pink alkali feldspar phenocrysts occurs in some samples. Aplite and pegmatite are common. The granite of Magurrewock Lakes intrudes gabbro, diorite, and Baring granite. An easily accessible site to observe these relationships is at the old dam at the Howard

Mill Flowage in the Moosehorn National Wildlife Refuge. There, a fine-grained, buff-weathering biotite granite intrudes and brecciates a pre-existing gabbro-granite intrusive complex. This complex contains brecciated blocks of coarse-grained hornblende gabbro and quenched gabbro in a matrix of medium grained biotite granite or granodiorite that we assign to the Baring granite. The granite of Magurrewock Lakes thus postdates the gabbro-granite intrusive complex. There is no evidence for commingling of basaltic magma with that of the granite of Magurrewock Lakes. Amos (1963) indicated that this granite is intruded by the Red Beach granite in the adjacent Robbinston 15' quadrangle. There are no radiometric age data for the granite of Magurrewock Lakes.

Chemistry of Granitic Rocks. Chemical data for the four granitic plutons described above are presented in Tables 5 (major and trace element compositions) and 6 (CIPW normative minerals), and Figure 10 (rare element distributions). Table 5 indicates that most of the Calais area granites analyzed are mildly peraluminous (i.e., molecular Al_2O_3 > molecular CaO + Na_2O + K_2O). As a result, they contain small amounts of normative corundum. One sample (#258) from the Baring granite contains normative diopside rather than normative corundum, and is therefore metaluminous. Zen (1988) discussed the origin of peraluminous granites and noted that mildly peraluminous types similar to those of the Calais area can form either by melting of perlauminous source rocks (such as shales and graywackes or older peraluminous granites), or by crystal fractionation involving hornblende from metaluminous magmas. None of the Calais area granites contain any minerals (e.g. cordierite, almandine-rich garnet, or aluminosilicates) which would indicate a strongly peraluminous nature for samples that we did not analyze chemically. Muscovite, when present in the Calais granites as a possibly primary magmatic mineral, is always much subordinate to biotite.

The predominance in the Meddybemps and Charlotte granites of intensely blue-green amphibole (riebeckite or arfvedsonite), instead of hornblende, and its presence in some samples of the Baring granite, suggest that these three bodies are alkali granites. Hill and Abbott (1989) suggest that these may be "A-type" granites, inferred by Loiselle and Wones (1979) to form in an anorogenic tectonic environment. Although some A-type granites are peralkaline (i.e. molecular Na_2O + K_2O > Al_2O_3), none of the Calais granites are peralkaline. Whalen (1986) indicated that A-type granites are widespread in New Brunswick, with a widely varying degree of alkalinity. He also noted that some A-type granites are known to contain muscovite, and that in some places in New Brunswick they are associated with molybdenite mineralization.

The compositions of the Calais granites match those of some A-type granites elsewhere in the world, but not others. For example, the Baring and Charlotte granites have Ba, Zn, Nb, and Sc contents much more similar to the Australian I-type granites than to the A-type granites of the Gabo and Mumbulla suites (Collins et al., 1982), although some other elements form a close match. This is a critical problem as I-type granites are thought to form by melting of dominantly igneous source rocks, typically at convergent plate margins (see Pitcher, 1982). The Charlotte granite agrees well in overall composition with the McGerrigle Complex, a magma commingling suite in the Gaspé Peninsula of Quebec involving alkali gabbro and granite (Whalen and Gariepy, 1986), although the Charlotte granite has more Fe, Mg, Zn, and Sc and less Nb, Ta, and Th than the A-type granites of that complex. It is evident that there is a wide diversity in A-type granite compositions. More detailed work in the Calais quadrangle will permit better comparison with mineralized suites elsewhere, whether of A-, I-, or some other type.

Mitchell and Rhodes (1988, 1989) reported the compositions of another gabbro-granite commingling complex further south in the Bays-of-Maine Igneous Complex, on Vinalhaven Island. They described field relations (pillowed gabbro in a matrix of biotite granite) which are quite similar to those present in the Calais area. Furthermore, the limited geochemical data that we report for gabbro and for the Baring, Charlotte, and Meddybemps granites agree well with the majority of elements from the Vinalhaven suite, except for a higher concentration of alkali elements in the Calais gabbros. The major distinction between our conclusions for the Calais rocks and those of Mitchell and Rhodes (1988) for those of Vinalhaven is that: (1) we interpret the biotite rich gabbros of the Calais area as alkali gabbro while they attribute the enriched alkali contents of Vinalhaven gabbros to shallow-level commingling effects; and (2) they interpret the Vinalhaven granites to be of I-type parentage, whereas we suggest a possible A-type affinity for at least some of the Calais granites.

Inspection of the SiO_2 contents in Table 5 shows that, over the admittedly small number of samples, there is a large gap between gabbroic rocks (46-49%) and granitic samples (72-77%). If our samples are representative, and we have tried to make them so, this indicates a strongly bimodal field association. Although Figure 5 shows that some Baring granite samples of granodiorite composition exist, and that there is a petrographic range from gabbro through diorite to quartz diorite and tonalite, our conclusion based on field observations is that the bimodal nature of the association (at this level of exposure) suggested by the chemical data is real. While some samples will be found which can fill in most of the range between granite and gabbro end members, these are due to local hybridization between coexisting magmas on a small scale. The intermediate compositions do not appear to be volumetrically significant. The gabbro and granite represent separate magmas, perhaps both of alkaline parentage, which commingled at a relatively shallow level in the crust (as inferred from the lack of high grade regional metamorphism in the host rocks —see below). Provisional Sr isotope data cited by Coughlin (1983) contrast sharply with data for the Charlotte and Meddybemps granites (Spooner and Fairbairn, 1970). If both data sets are valid, two distinct sources are clearly required, most reasonably a mantle source for the alkali gabbros and a crustal source for the metaluminous and peraluminous granites (Baring, Magurrewock Lakes) and alkali granites (Meddybemps, Charlotte, and possibly Baring).

Summary of Plutonic Rocks

Field evidence unambiguously indicates that granitic and gabbroic magmas of the Bays-of-Maine Igneous Complex exposed near Calais have commingled over an extensive outcrop area. The Baring granite/gabbro commingling zone underlies the largest mapped area of plutonic rock in the quadrangle. Similar relationships were observed between gabbro and the Meddybemps granite in a smaller outcrop area. We find no evidence for commingling of gabbroic magma and either the Charlotte granite or the granite of Magurrewock Lakes and infer that the Baring and Meddybemps granites were coeval with gabbroic magmatism. The abrupt loss of commingling relationships south of the Meddybemps granite contact suggests that the Meddybemps granite may be slightly younger than the Baring granite. The Charlotte granite appears to postdate the Meddybemps and Baring granites as well as the intrusive complex. The granite of Magurrewock Lakes is definitely younger than the Baring granite/gabbro intrusive complex, but its relationship to the Charlotte granite is uncertain at this time. To the east, the Red Beach granite postdates both the granite of Magurrewock Lakes and the Charlotte granite (Abbott, 1986).

Ages of the Plutonic Rocks (and Deformation Events). Relationships between the plutons and structural elements provide important constraints on the ages of the deformation events described earlier. Unfortunately, although most details of the sequence of intrusion have been worked out, there is some question as to the absolute ages of the various plutons. As a result, there is ambiguity about the timing of deformation.

TABLE 7: RADIOMETRIC AGES OF GRANITIC PLUTONS IN THE CALAIS QUADRANGLE

PLUTON	Faul et al., 1963[1]	Jurinski, pers. comm., 1988[2]
Baring	none reported	430 19 m.y.
Meddybemps	394 m.y.	372 11 m.y.
Charlotte	396 m.y.	383 28 m.y.
Magurrewock Lakes	no radiometric dates available	

1. Potassium/Argon ages recalculated using decay constants of Steiger and Jaeger (1977).
2. Rubidium/Strontium whole-rock preliminary ages.

Table 7 shows the available radiometric data for granitic plutons of the Calais quadrangle and reveals the problem. Early K/Ar dating by Faul et al. (1963) indicated Early Devonian ages for the Meddybemps and Charlotte granites and agreed with the intepretation that the pre-intrusion folding was probably an Acadian event. Preliminary Rb/Sr dating by Jurinski (pers. commun., 1988) suggests that these plutons are younger: the Charlotte granite may be Middle Devonian, the Meddybemps early Late Devonian. These dates are in conflict with our field evidence, which suggests that the Meddybemps granite is older than the Charlotte granite, but are not critical to tectonic interpretation. All they do is loosen some of the constraints on the ages of D_2 and D_3.

The Early Silurian age of the Baring granite reported by Jurinski is much more important. If correct, it requires a major change in our thinking about the tectonic history of eastern Maine, because it indicates that D_2 and D_3 had ended before the Early Silurian. The climactic episode of deformation in eastern Maine is generally considered to have been the Acadian orogeny, and its timing is tightly constrained by fossil-based ages in the coastal volcanic belt. Acadian folding must have occurred after eruption and deposition of the Early Devonian Eastport Formation but before deposition of the unfolded Middle Devonian Perry Formation. If the Baring granite is Early Silurian, the St. Croix belt would have sustained only brittle deformation (D_4) during the Acadian orogeny, D_2 and D_3 would have to be Ordovician, and strata of the Fredericton trough would be much older than the Siluro-Devonian age now proposed.

The problem is not new. Westerman (1972, 1973) reported a Silurian K/Ar age for the post-D_3 Pocomoonshine gabbro-diorite of the Big Lake quadrangle, and recent studies of granitoids of New Brunswick have also revealed some Silurian ages (Bevier and Whalen, 1988). We suggest, however, that the age of the Baring granite proposed by Jurinski is incorrect, for the following reasons:

(1) D_2 folds cut by the Baring granite deform rocks as young as the Gedinnian Eastport Formation in the coastal volcanic belt. Folds correlated with D_2 also affect Late Silurian to Early Devonian strata in the Kearsarge-central Maine synclinorium and Miramichi anticlinorium. Post-Early Devonian folding has thus affected rocks on strike with and on both sides of the study area.

(2) Granite believed to part of the Baring body intrudes the Oak Bay and Waweig Formations in the St. Croix River at Calais. These rocks are of Pridoli age (Latest Silurian) and were folded by D_2 prior to being intruded. The granite that intrudes them cannot be Early Silurian. An Oak Bay xenolith is included within the Baring granite in a pavement outcrop at the junction of Route 1 and South Street in Baring.

(3) Our field data suggest that both the Baring and Meddybemps plutons were locally coeval with what seem to be the same mafic magmas, yet the new ages indicate an almost 60 million year difference in the ages of these granites.

Until the question has been firmly resolved, there must be doubt as to the timing of deformation proposed above. We hope to be able to separate enough zircon from the gabbros (see Table 4.5) to date mafic rocks from the intrusive complex, and are nearly finished with Nd/Sm and Rb/Sr whole-rock and mineral isochron studies of the Staples Mountain and Woodland Dump gabbros (Brueckner and Ludman, in progress).

Economic Potential of the Granitic Rocks. There is a possibility of metal deposits (molybdenum) in the Meddybemps and Charlotte granites. Parts of the Meddybemps granite, particularly on Cooper Hill in the Gardner Lake quadrangle, contain extremely high contents of U, Th, Y, and heavy rare earth elements compared with other granites in the Calais area. Sample #23 from the Cooper Hill site has been analyzed for uranium-series nuclides, including radon by Nancy Davis (M.S. thesis in progress, Department of Geology and Geophysics, Boston College). We suggest that residents of the immediate area who draw water from bedrock wells may wish to have their water analyzed for radon. A detailed study to delimit the extent of the high-uranium zone at Cooper Hill may be of value in both estimating the mineral resource potential of the Meddybemps granite and in outlining the extent of possible radon hazards to local residents.

METAMORPHISM

Rocks of the Calais quadrangle have been subjected to a wide range of metamorphic conditions, from chlorite grade to the northwest (Flume Ridge, Kendall Mountain, and Pocomoonshine Lake Formations) to anatectic migmatite in the southwest (Kendall Mountain and Woodland Formations). Data from the Big Lake quadrangle (Ludman, 1990) suggest that although the Cookson Group has been multiply deformed, the accompanying regional metamorphism never was more intense than chlorite zone conditions. The Fredericton trough, St. Croix belt, and coastal volcanic belt thus record the epizonal history of the Northern Appalachians, and were probably never buried below 2.5 Kbars at the peak of metamorphism (Ludman et al., 1989).

Metamorphic intensity in the Calais quadrangle depends on proximity to intrusive bodies. Isograds showing the progressive contact metamorphism of the pelitic rocks are shown on the geologic map, and Table 8 summarizes the metamorphic assemblages identified in the metasedimentary and metavolcanic rocks of the map area.

Regional Metamorphism

Episodes of regional metamorphism accompanied F_1, F_2, and F_3, and are designated as M_{1-3}. Recrystallization was at very low grade conditions in all three instances, and chlorite and muscovite were the only metamorphic minerals produced. The extent to which the three metamorphic events is exhibited by the rocks depends on their lithology and age. M_2 is present in most rocks of the study area. It is best developed in slates of the Flume

TABLE 8 : METAMORPHIC ASSEMBLAGES IN THE CALAIS QUADRANGLE

A) POCOMOONSHINE LAKE FORMATION (all + pyrite)

muscovite-quartz-plagioclase-carbon
muscovite-quartz-plagioclase-biotite-cordierite

B) KENDALL MOUNTAIN FORMATION

Pelites (all carbon, pyrite)
quartz-plagioclase-muscovite
quartz-plagioclase-biotite-cordierite-andalusite
quartz-muscovite-biotite-andalusite
quartz-plagioclase-muscovite-andalusite-cordierite
quartz-muscovite-biotite-cordierite

Psammite (all + rock fragments)
quartz-plagioclase-muscovite
quartz-plagioclase-potassic feldspar
quartz-plagioclase-clinozoisite-calcite
quartz-plagioclase
quartz-plagioclase-muscovite-chlorite

Felsic volcanic rock
quartz-plagioclase-potassic feldspar
quartz-feldspar-chlorite
quartz-feldspar-chlorite-sericite

C) WOODLAND FORMATION (all + pyrite, carbon, retrograde chlorite)

quartz-plagioclase-biotite
quartz-plagioclase-biotite-musc-cordierite
quartz-plagioclase-biotite-muscovite-Kspar-sillimanite
quartz-plagioclase-muscovite-biotite-andalusite-sillimanite
quartz-plagioclase-biotite-muscovite
quartz-plagioclase-biotite-muscovite-cordierite-andalusite
quartz-plagioclase-muscovite-Kspar-sillimanite
diopside-garnet-actinolite-plagioclase

quartz-muscovite-plagioclase-Kspar-biotite (mobilizate)
quartz-cordierite-muscovite-biotite-sillimanite (restite)

D) CALAIS FORMATION (all pyrite, carbon)

Lower (black shale) Member
muscovite-quartz-plagioclase-cordierite
muscovite-quartz-plagioclase-cordierite-andalusite
muscovite-quartz-biotite-cordierite

Calais Member (Basalt)
plagioclase-chlorite-actinolite
quartz-plagioclase-garnet
plagioclase-actinolite

E) LEIGHTON FORMATION

Basalt (pyrite)
plagioclase-actinolite-chlorite
plagioclase-actinolite-biotite
plagioclase-actinolite-epidote

Siltstone/Mudstone
quartz-plagioclase-biotite
quartz-plagioclase-biotite-calcite
quartz-plagioclase-actinolite

F) FLUME RIDGE FORMATION

quartz-plagioclase-muscovite-calcite ankerite, pyrite
quartz-plagioclase-muscovite
quartz-plagioclase-actinolite calcite

Ridge Formation, and is recognized by the presence of aligned muscovite and chlorite flakes parallel to S_2. M_2 foliation is also present in low-grade pelites of the Cookson Group and Digdeguash Formation, but is not visible in the siltstones and mudstones of the Leighton Formation. Even though the Leighton Formaton has been subjected to the same deformation, subsequent contact metamorphism (M_4, M_{4a}) has obliterated the earlier fabrics.

M_1 is restricted to chlorite-grade outcrops of the Kendall Mountain Formation at the west edge of the quadrangle, and is expressed as a well-developed foliation of muscovite flakes parallel to bedding. A similar foliation is axial planar to F_3 folds, but has been coarsened by later contact metamorphism.

Contact Metamorphism

Throughout most of the St. Croix belt, the Cookson Group is exposed at elevated metamorphic grades, but these resulted from contact metamorphism associated with emplacement of the extensive mafic and felsic plutons described earlier. Thus, the isograds shown on the map and the mineral assemblages listed in Table 8 are mainly the result of thermal metamorphism. The highest grades are recorded adjacent to the mafic rocks, and contact metamorphic anatexis has occurred locally in the innermost parts of aureoles adjacent to the Woodland Dump and St. Stephen gabbros. The entire southwest corner of the Calais quadrangle is a migmatite terrain in which quartzofeldspthic leucosome material is injected into a gray, sillimanite-rich melanosome. Small isolated plugs of mafic rock intrude the migmatite, and a large gabbroic body is inferred to lie at shallow depth beneath the surface. In many outcrops, melting appears to have been an in situ event, and the mobilizate has probably not migrated far from where it melted.

The effects of the igneous rocks on their hosts were widespread, as indicated by the distance of the biotite isograd from the major plutons. Small round porphyroblasts of cordierite define the next metamorphic zone and are abundant in pelitic rocks throughout the Cookson Group. These porphyroblasts enclose foliations attributed to F_2, and possibly F_3 as well. Andalusite porphyroblasts in the Cookson Group generally occur as small crystals about the size and shape of large grains of rice. They thus differ significantly from the large prismatic, generally chiastolitic, andalusite porphyroblasts characteristic of the Digdeguash Formation in the Big lake quadrangle. Andalusite-cordierite assemblages are widespread, particularly in the Woodland Formation. The distinctive habits of these minerals can be recognized even within the migmatite terrain where rafts of relict andalusite-cordierite are engulfed by mobilizate.

Sillimanite first occurs as fibrolite, but commonly forms prisms 1-3 mm long in the higher grade rocks and migmatites. Most of these coarse crystals are gray, but many, particularly on and south of Breakneck Mountain, are pale green in hand specimen. Quartzofeldspathic mobilizate forms medium to coarse-grained irregular masses in the migmatite, and also contains muscovite, apatite, and zircon. The aluminous restite generally consists of coarse-grained sillimanite, biotite, muscovite, and relict andalusite and/or cordierite. Green spinel was identified in one restite layer on the flanks of Farrar Hill.

Contact relationships between plutons described above suggest that at least some of the mafic rocks were still hot, and probably still liquid, at the time that later granites were injected. Detailed petrographic studies of the contact aureole surrounding the Pocomoonshine gabbro-diorite in the Big Lake quadrangle show that there was enough time between some of the emplacement events to permit retrograde metamorphism of pelitic rocks (DeMartinis, 1986; Bromble, 1983; Ludman et al., 1989). Textures in high-grade pelites in the southwestern part of the Calais quadrangle indicate a similarly complex intrusive history.

The first contact metamorphic event, here termed M_4, was caused by emplacement of gabbro and/or diorite. It is possible, as was the case of the Pocomoonshine gabbro-diorite, that even this event was composite and involved more than one stage of magma injection. In the intermediate to high-grade parts of the contact aureoles, but at conditions below those of the sillimanite isograd, relatively coarse grained andalusite formed in pelites of the Woodland and Calais Formations. In some exposures, these porphyroblasts have been partly retrograded to a fine-grained aggregate of sericite flakes. The sericite masses have, in turn, then been recrystallized to coarse muscovite sheets within which sillimanite needles have grown. The second prograde growth event, here termed M_{4a}, was associated with later plutonism, either of diorite or granite. It is not possible to estimate the time that elapsed between M_4 and M_{4a}.

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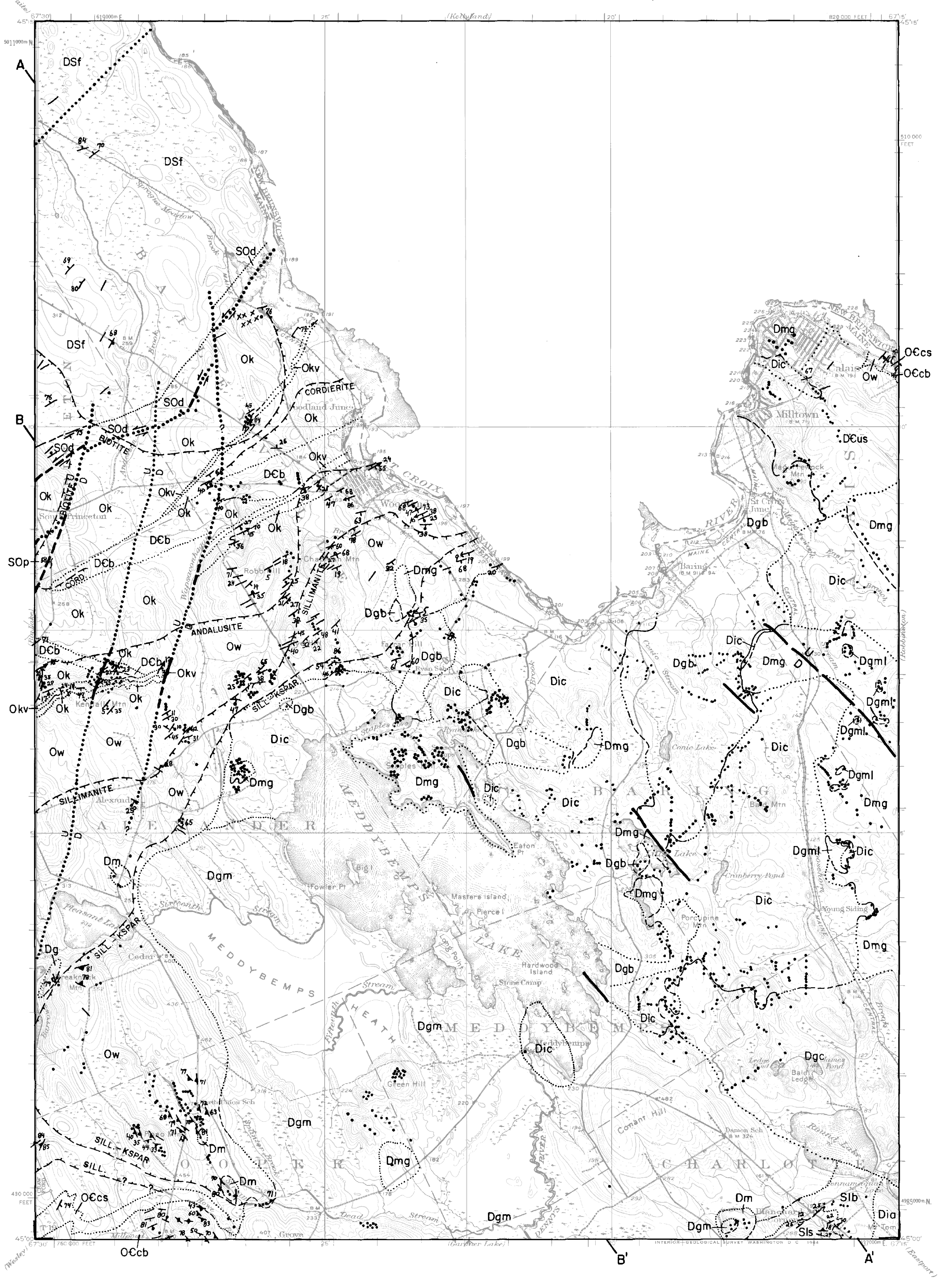


EXPLANATION

INTRUSIVE ROCKS

Dg Granite (affinity unknown)

- **Dgml** Granite of Magurrewock Lakes
- **Dgm** Meddybemps granite
- **Dgc** Charlotte granite
- **Dgb** Baring granite

D€us Undifferentiated plutonic rocks with areally extensive roof pendants and xenoliths of Cookson Group strata.

Dm Intermediate and/or mafic rock

Dmg Gabbro

Dic Gabbro-diorite intrusive complex

Dia Mt. Tom andesite

D€b Baileyville Dike

STRATIFIED ROCKS

FREDERICTON TROUGH

DSf **Flume Ridge Formation**: Variably calcareous sandstones, siltstones, and slates. Green and ankeritic in chlorite zone, with large detrital muscovite flakes. Purplish in biotite zone, with blue-white calc-silicate layers, stringers, and pods.

SOd **Digdeguash Formation**: Well graded, gray, turbiditic grits, sandstones, and slates. Characterized by large andalusite crystals in contact aureoles. At highest metamorphic grade, anatexis produces migmatitic sillimanite gneiss.

SOp **Pocomoonshine Lake Formation**: Thinly laminated carbonaceous pelite and siltstone.

COASTAL VOLCANIC BELT

Sl **Leighton Formation**

- **Slb** Basalt member
- **Sls** Siltstone/mudstone member

DSvu Undifferentiated volcanic rocks (on cross section only)

----------------------------------Inferred Unconformity----------------------------------

COOKSON GROUP

Ok **Kendall Mountain Formation**: Quartzofeldspathic arenite interlayered with minor carbonaceous pelite; massive quartzite, quartzofeldspathic and lithic arenite; thin felsic tuffs and basalts.

- **Okv** Volcanic member

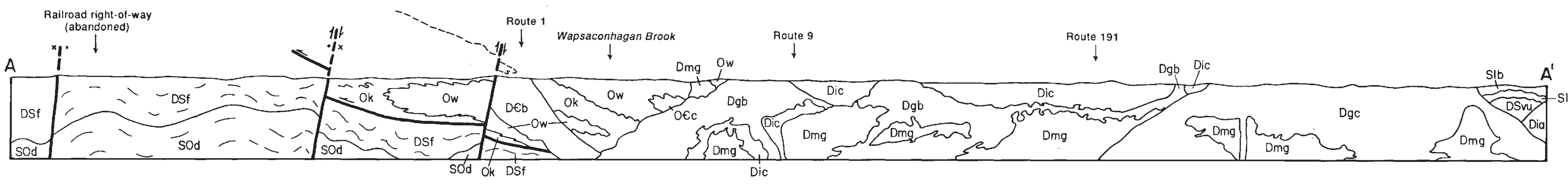
Ow **Woodland Formation**: Interbedded, well graded, quartzofeldspathic wacke and both carbonaceous and non-carbonaceous pelites; minor thick-bedded quartzofeldspathic wacke and calc-silicate granofels.

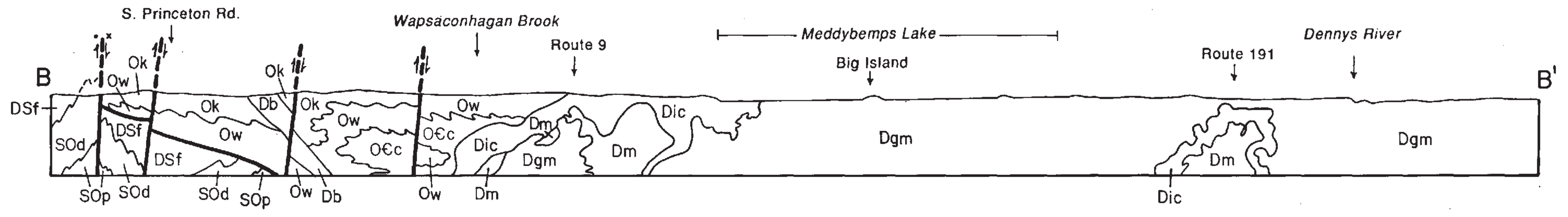
O€c **Calais Formation**: Interbedded black, highly graphitic, pyritiferous shale; pillowed and massive basalt; garnet-quartz coticule.

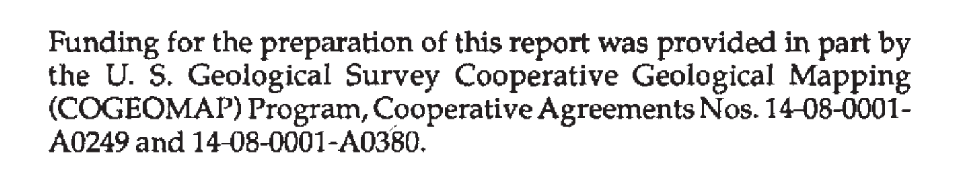
- **O€cs** Black, highly graphitic, pyritiferous shale
- **O€cb** Pillowed and massive basalt

SYMBOLS

———— — —	Lithologic contact: observed, covered, inferred
▬ ▬ •••••	Fault: covered, inferred
┬ ┬ ┬ ┬	Metamorphic isograd
50 60	Bedding, inclined, vertical, overturned (dot indicates facing direction)
—	Trend of bedding in pavement outcrop
60	Cleavage, inclined, vertical
65	Bearing and plunge of minor fold
84	Metamorphic layering, inclined, vertical
70	Joint, inclined, vertical
×	Outcrop







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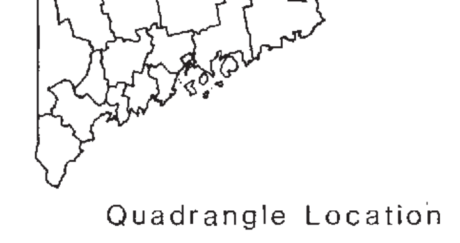
Quadrangle Location

BEDROCK GEOLOGY
OF THE
CALAIS QUADRANGLE, MAINE
BY
ALLAN LUDMAN
MALCOLM HILL
1990

Maine Geological Survey
DEPARTMENT OF CONSERVATION
Augusta, Maine 04333
Walter A. Anderson, State Geologist

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