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Title: Preliminary Report on the Bedrock Geology of the Devils Head, Robbinston, and Red Beach 7.5-minute Quadrangles, Maine

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This report is preliminary and has not been edited or reviewed for conformity with Maine Geological Survey standards.

Contents: 36 page report and map
INTRODUCTION

The area described in this report occupies a special position in the context of two major northeast trending lithotectonic belts in eastern Maine: Ludman's (1985) Cambrian-Ordovician St. Croix Belt and Gates' (1969) Silurian-Devonian Coastal Volcanic Belt. Most of the area is underlain by plutonic rocks which separate the two belts and belong to Chapman's (1962) Bays of Maine Igneous Complex. The relationship between the plutonic rocks and the volcanic rocks remains somewhat controversial. Yet, the nature of this relationship, whether or not they are consanguineous, is important for understanding the tectonic history of the area.

The principal concerns of this project were (1) to reassess the relative ages of the various plutonic rocks, (2) to characterize the extent of the gabbroic versus the granodioritic rocks, (3) to examine the roles of the various types of diabases, and (4) to reexamine the distinction between the various biotite granites.

Location

The area was mapped on three 7.5-minute quadrangles, Devils Head, Red Beach, and Robbinston, which together make up the Robbinston 15-minute quadrangle. The area is bounded to the west by longitude 67°15', to the south by latitude 45°00', and to the north and east by the St. Croix River.

There are three main watersheds. The southern part of the area drains to the south into Boyden Lake and Pennamaquan Lake, and on into Cobscook Bay at Pembroke via the Pennamaquan River. Howard Lake and Nashes Lake drain to the northwest and ultimately into the St. Croix River west of Calais. The present water level of Nashes Lake is maintained by three dams, all near the natural outlet of the East Branch. The purpose of the dams was to divert the flow eastward into Beaver Brook by way of a man-made canal. The remainder of the area drains to the east into the St. Croix River south of Calais.

The land underlain by plutonic rocks is highly irregular, consisting of numerous abrupt and closely spaced bedrock hills with a maximum elevation of 605 feet. In the southern and southeastern parts of the area, which are underlain by Silurian to Upper Devonian volcanic and sedimentary rocks, the land is relatively low and flat. In this part of the area, the lakes (Pennamaquan and Boyden) are large and very shallow in comparison with the ponds and lakes to the north. The deepest parts of either Pennamaquan or Boyden Lake are reputed by the local fishermen to be less than 3 m. In contrast, the very small Coleback Lake, at the southern
margin of the plutonic belt, and Moneymaker Lake, in the interior of the plutonic belt, are each approximately 30 m deep (N. Smith, pers. comm.).

The land is densely wooded with spruce, pine and yellow birch, on well-drained slopes. The valleys are generally boggy and characterized by thick sphagnum moss and cedar groves. Some of the lowlands are broad, open heaths. Active, small- to large-scale logging operations are carried out throughout the region.

Bedrock is well-exposed on virtually every hill, along the shores of most ponds and lakes, along the steeper parts of most streams, and along the shore of the St. Croix River. Artificial exposures are equally well-distributed along U.S. Route 1, secondary roads and trails, and in scores of granite and gabbro quarries.

Previous Work

Prior to 1914 there were three important geological studies in the Passamaquoddy Bay area of eastern Maine: Shaler (1886), Smith and White (1905), and Bastin and Williams (1914). Reconnaissance by Shaler (1886) and Smith and White (1905) focused on the paleontology of two Paleozoic rock sequences. The older stratified rocks were described as a series of volcanic flows and tuffs, interbedded with shale, arkose and limestone. Shaler (1886) assigned a Silurian (Niagaran or Cayugan) age to the fossils in the shales and limestones, but entertained the notion that the fossil assemblage in what is now known as the Eastport Formation could be as young as Lower Devonian. The younger stratified rocks, called Perry beds by Shaler (1886), were assigned an Upper Devonian age, based on plant remains. Shaler noted an unconformity between the Perry beds and older intrusive granite (Red Beach granite) but failed to recognize an unconformity with the older stratified rocks. The age of the granites was thought to be Laurentian (Precambrian). Smith and White (1905) provided a detailed account of the sedimentary and volcanic rocks of the Perry Formation. They assigned an Upper Devonian age and demonstrated an unconformable relationship with the Silurian-Devonian sedimentary and volcanic rocks. The Laurentian age for the granites was refuted in favor of a Late Silurian or Lower Devonian age. However, this proposal was not documented with any field evidence. Based on similarities in both appearance and inferred chemical composition, Smith and White (1905) suggested that the granites may have been the intrusive equivalents of the Silurian-Devonian felsic volcanic rocks.

Bastin and Williams (1914) conducted the first comprehensive geologic study in the Passamaquoddy Bay area. They subdivided the Silurian-Devonian volcanic and sedimentary rocks into five formations, which were, from oldest to youngest, the Quoddy Formation, the Dennys Formation, the Edmunds Formation, the Pembroke Formation, and the Eastport Formation. A minimum, composite thickness of 15,000 m was suggested. Clear evidence that granite (Red Beach granite) intruded the Eastport Formation indicated a Late Silurian or Lower Devonian age for the intrusive rocks. Like Smith and White (1905) before, Bastin and Williams (1914) suggested that what is now known as the Red Beach granite may have been the intrusive equivalent of the felsic volcanic rocks in the Eastport Formation.
Between 1914 and 1969, there were few publications bearing on the bedrock geology around Passamaquoddy Bay. In New Brunswick, Alcock (1946) mapped the Oak Bay Conglomerate, which is now believed to be the base of the Silurian-Devonian volcanic and sedimentary sequence (Gates, 1967, 1977, 1978). Other than Alcock's (1946) map, there were no publications that significantly added to the findings of Bastin and Williams (1914).

From 1960 to the present a number of studies have been devoted to the regional geology and both paleontological and radiometric dating of (1) the Silurian-Devonian sedimentary and volcanic rocks, (2) the Silurian and Devonian intrusive rocks, (3) the Cambrian-Ordovician rocks north of the intrusive rocks, and (4) the Upper Devonian Perry Formation. Berdan (1966) demonstrated a Lower Devonian (Gedinnian), or later, age for the Eastport Formation. Hence, the intrusive rocks, specifically the Red Beach granite, were emplaced between Lower and Upper Devonian. Gates (1967) showed that the Silurian-Devonian rocks in the Eastport area represent a portion of a much larger Coastal Volcanic Belt, extending from Topsfield, Massachusetts to Arasaig, Nova Scotia. The belt was shown to be the site of prolonged volcanic activity during the Silurian and Devonian. Paleontological reconstructions by Boucot (1968) and by McKerrow and Ziegler (1971) further emphasized the linear nature of the volcanic belt and its persistence through the Silurian and Lower Devonian.

Gates (1975, 1977, 1978) remapped the area covered by Bastin and Williams (1914). He defined two new formations, the Leighton Formation and the Hersey Formation, which were originally members of Bastin and Williams' (1914) Pembroke Formation. Gates suggested a composite thickness of at least 10,000 m for the Silurian and Lower Devonian volcanic and sedimentary rocks.

The first attempt at a comprehensive evaluation of the intrusive rocks in the Calais area was published in 1963 by Amos. The age relationships between nine types of intrusive bodies were investigated. The rocks were all part of Chapman's (1962) Bays of Maine Igneous Complex, and were all considered to be associated with the Devonian Acadian Orogeny. The range in compositions is from gabbro to granite.

Of the nine intrusive bodies described by Amos (1963), only the Red Beach granite intrudes and is unconformably overlain by volcanic and sedimentary rocks of Lower and Upper Devonian ages respectively. Abbott (1977, 1978a) conducted a detailed study of the internal structure of the Red Beach granite and showed that it consisted of six distinct intrusions.

Ludman (1974, 1975, 1977, 1978) working west of Calais, and Ruitenburg (1967; Ruitenburg and Ludman, 1978) working in New Brunswick, defined the Fredricton Trough strata and the Cambrian-Ordovician St. Croix Belt. Both belts are generally northwest of, and intruded by, the Bays of Maine Igneous Complex. It was shown that the Fredricton Trough strata and the St. Croix Belt were separated by a complex tectonic contact. Only the Cookson Formation, which is the youngest of the Cambrian-Ordovician sediments is exposed in the Robbinston 15-minute quadrangle.
Radiometric ages for granitic rocks in the Calais area have been determined by Spooner and Fairbairn (1970) using K-Ar ratios and both whole rock and mineral Rb-Sr ratios. Three granite bodies, the Meddybemps granite, the Charlotte granite, and the Red Beach granite, give ages close to 400 m.y. A radiometric age of $408 \pm 3$ m.y. for volcanic rocks in the Eastport Formation was determined by Fullagar and Bottino (1970). Westerman (1972, 1973) reported an age of $423 \pm 24$ m.y. for hornblende in the gabbroic rocks to the west of the Robbinston 15-minute quadrangle.

Acknowledgments

The mapping was begun in 1975 as part of my Ph.D. dissertation (Abbott, 1977). Financial support for the 1975 and 1976 field seasons was provided by the Daly Fund of Harvard University. I wish to acknowledge the late James B. Thompson, Sr. of Princeton, Maine for his hospitality while my wife and I stayed in his cottage on Big Lake.

Mapping was continued in 1986 under the sponsorship of the Maine Geological Survey. I am indebted to Marc Loiselle and Walter Anderson, both of the Maine Survey, for making the opportunity possible. I thank Marc Loiselle and Mal Hill -- Mal was mapping concurrently in the adjoining Calais 15-minute quadrangle -- for their helpful discussions regarding the regional and local geological problems.

For access to Howard Lake and various private roads, I thank Nelson Smith of Charlotte, the Clarkes of Howard Lake, and the Moosehorn National Wildlife Refuge.

STRATIFIED ROCKS

The oldest stratified rocks in the Robbinston 15-minute quadrangle are in the Cambrian-Orodovician Cookson Formation, which is in Ludman's (1974, 1975, 1977, 1978) St. Croix Belt. The Cookson Formation is unconformably overlain by the Silurian conglomerates of the Oak Bay Formation, which is interpreted as the base of the Silurian-Devonian Coastal Volcanic Belt (Gates, 1978). The Oak Bay conglomerate is not in physical contact with the main body of the Coastal Volcanic Belt, but separated from it by plutonic rocks of the Bays of Maine Igneous Complex. The Cookson Formation and Oak Bay Formation are exposed only along a short segment of the west bank of the St. Croix River near the northern tip of the map area.

South of the Bays of Maine Igneous Complex, but within the Robbinston 15-minute quadrangle, the oldest sediments are Silurian in age. These include undifferentiated shales, the Leighton Formation and Hersey Formation. The Leighton and Hersey Formations were formerly members of the Pembroke Formation of Bastin and Williams (1914). The Silurian strata are overlain by the Eastport Formation, which is the youngest formation in the Silurian-Devonian Coastal Volcanic Belt. In the eastern part of the area, red beds of the Upper Devonian Perry Formation unconformably overly the Eastport Formation, undifferentiated Devonian(?) shales, and the Red Beach granite.
Cookson Formation

Exposures of the Cookson Formation along the St. Croix River can be correlated along strike with the type section on Cookson Island in Oak Bay, 7 km to the northeast in New Brunswick. On Cookson Island the formation consists of rusty-weathering sulfidic, highly graphitic, dark gray to black slates and phyllites with some 10 cm thick interbeds of rusty-weathering buff psammites. The slates in the uppermost part of the Cookson Formation contain graptolites, which prove an earliest Ordovician age (Riva, pers. comm. to Ludman, 1985).

Ludman (1978) has mapped and described in detail the Cookson Formation and overlying Oak Bay Formation, where they crop out on the west bank of the St. Croix River in the Robbinston 15-minute quadrangle. Here the Cookson Formation consists of disrupted, alternating thin layers (1 to 2 cm) of rusty-weathering, dark brown to black graphitic phyllites and rusty, buff-colored psammites. The layering was presumably disrupted during the deformation responsible for the dominant N55E, vertical foliation. Ludman (1978) describes sandstones, siltstones, black phyllites, cherts, and pillow basalts. He is careful to note that some of the rock types, specifically the "dark gray-black quartzo-feldspathic metasandstones" and the "pinkish quartz-garnet pods, beds and stringers", have not been described elsewhere in the Cookson Formation.

Oak Bay Formation

The unconformity separating the Cookson Formation from the overlying Silurian Oak Bay Formation is exposed on Cookson Island in Oak Bay, New Brunswick. Immediately south of Calais, on the west bank of the St. Croix River, the unconformity is concealed by tidal flats and road fill. Here the Oak Bay Formation is a stretched pebble, polymict conglomerate. The well-rounded pebbles consist of quartzite, granite, quartz diorite, volcanic rock, and limestone (Ludman, 1981). The matrix consists of rusty-weathering dark brown pelite and psammithe. The plane of flattening of the pebbles is parallel to the foliation in the underlying Cookson Formation. There are rare tan-colored psammitic lenses, which define the attitude of the bedding as N60E, 60SE.

Ludman (1978) reported a small area of Silurian Waweig Formation stratigraphically above the Oak Bay Formation. The Waweig Formation has been tentatively correlated with the Leighton Formation (Gates, 1978). According to Ludman (1978) the Waweig Formation is admittedly "very poorly exposed". Its presence could not be confirmed in this preliminary study. Tentatively, I have shown on the accompanying map an inferred contact, concealed by recent sediment, between the Oak Bay conglomerate and mafic intrusive rocks of mixed gabbro and granodiorite. The contact is believed to be intrusive (Amos, 1963) on the basis that the metamorphism of the Oak Bay and Cookson Formations was due to heating by the gabbro and granodiorite. Near the contact, there are neither dikes of gabbro nor granodiorite in the Oak Bay conglomerate. Ludman (1978) reports numerous felsic dikes in the small wedge of Waweig Formation immediately above the Oak Bay Formation.
Leighton Formation

Gates (1975) described four members of the Leighton Formation, but only one of these, the gray shale member (Sls), is actually exposed in the southern part of the Robbinston 15-minute quadrangle. One other member, pyroclastic flows (Slt), is inferred from Gates' (1975) map, but would be concealed by Pennamaquan Lake. The age of the Leighton Formation is latest Silurian (Pridoli) (Berdan, 1971; Berry and Boucot, 1970).

The shale member (Sls) consists of gray to blue-gray siltstones, shales and mudstones. Locally, for instance immediately east of Coleback Lake, this member is characterized by alternating 1 to 2 cm thick layers of white-weathering limy shale and gray shale. The surfaces of weathered cliff exposures are commonly corrugated as the result of differential erosion of the limy and non-limy layers. The attitude of the bedding is approximately N20E, 30SE, but quite variable near contacts where the rocks have been intruded by hornblende granophyre (Drhg) or Charlotte granite (Dcg).

The base of the Leighton Formation is a fault inferred from Gates (1975) and concealed by Pennamaquan Lake.

Hersey Formation

The Hersey Formation (Shs) consists of maroon siltstones and mudstones, with lenses of gray shale (Gates, 1975). The Hersey Formation lies stratigraphically above a pyroclastic flow unit (Slt) of the Leighton Formation. The position of the contact beneath Pennamaquan Lake was inferred from Gates (1975). The Hersey Formation, along with the upper part of the Leighton Formation has been truncated by an early north-east dipping fault, above which is the Eastport Formation.

Undifferentiated Silurian Rocks

Undifferentiated Silurian black shales, argillite and feldspathic tuffs are inferred (Gates, 1975) in the southwest corner of the Robbinston 15-minute quadrangle. Most of these rocks are concealed by Pennamaquan Lake.

Eastport Formation

The Eastport Formation is the youngest in the Maine Coastal Volcanic Belt. The fossil assemblage in shales from the upper part of the formation, near the city of Eastport, indicate a lowermost Devonian (Gedinnian) age (Berdan, 1971; Berry and Boucot, 1970; Martinson, 1970). The whole rock Rb-Sr age for volcanic rocks in the Eastport Formation is $408 \pm 3$ m.y. (Fullagar and Bottino, 1970). The Eastport Formation underlies the southern part of the map area, in the vicinity of Boyden Lake. The strata, including sediments and both felsic and mafic volcanic
rocks, are exposed in the southeast plunging Boyden Lake syncline, which has been intruded by hornblende granophyre (Drhg) of the Red Beach granite. The contact to the southwest with the underlying Hersey and Leighton Formations is a fault, so that the base of the Eastport Formation is missing. Likewise, the top is missing because the upper part of the Eastport Formation is unconformably overlain by the Perry Formation.

In the Robbinston 15-minute quadrangle, the Eastport Formation consists of four members, from oldest to youngest, a lower basalt member (Debl), a shale member (Des), a felsic vitrophyre member (Dev) and an upper basalt member (Debu). This is in contrast to Amos (1963) who described eight members. By virtue of the Boyden Lake Syncline, which neither Amos (1963) nor Abbott (1977) recognized, and a postulated east-west trending down-to-north normal fault, the following correlations can be made between Amos' members and those defined here:

<table>
<thead>
<tr>
<th>Abbott</th>
<th>Amos (1963)</th>
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<tbody>
<tr>
<td>upper basalt (Debu)</td>
<td>{ middle basalt (Se/mb)</td>
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<td>{ part of upper basalt (Se/ub)</td>
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<td>{ lower rhyolite (Se/lr)</td>
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<td>felsic vitrophyre (Dev)</td>
<td>{ upper rhyolite (Se/ur)</td>
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<td>{ rhyolite (Se/rub)</td>
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<tr>
<td>shales (Des)</td>
<td>{ argillite (Se/aub)</td>
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<td>{ shale (Se/mb)</td>
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<tr>
<td>lower basalt (Debl)</td>
<td>{ part of upper basalt (Se/ub)</td>
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<tr>
<td></td>
<td>{ lower basalt (Se/1b)</td>
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</table>

Excellent exposures of the Eastport Formation are to be found near the contact with the hornblende granophyre (Drhg) and along the southern shore of Boyden Lake.

The lower and upper basalts (Debl and Debu) are distinguished on the basis of stratigraphic position. Otherwise there are insufficient reliable characteristics to tell one from the other. Each member contains dark green, occasionally maroon, homogeneous basalt, brecciated basalt, tuffaceous basalt and amygdaloidal basalt. The homogeneous basalts, which tend to predominate, are made up of ophitic intergrowths of clinopyroxene and 0.5 mm laths of plagioclase (An$_{55-75}$, Abbott, 1977). Amos (1973) reported augite (c$_{a}z$ = 38-40) and somewhat more albitic plagioclase (An$_{52-65}$). Samples invariably have chlorite, epidote and calcite in varying amounts, as the products of late greenschist metamorphism. Magnetite is the dominant opaque mineral.
The shale member (Des) is similar in most respects to the shale member of the Leighton Formation. The Eastport shale member includes gray to blue-gray shales, mudstones, siltstones with some calcareous interlayers, and the hornfelsed equivalents of these. Rhythmically layered sequences of thin (<1 cm) graded (siltstone to shale) beds are relatively common. Cross-bedding was observed locally. The shale member is restricted to a single, faulted lens between the lower basalt (Debl) and the vitrophyre member (Dev). There is not necessarily an equivalent member to the south in the Eastport quadrangle, although a tentative correlation with Gates' (1975) shale member is strongly implied.

The felsic vitrophyre member (Dev) of the Eastport Formation consists of pink-weathering maroon tuffs, tuff breccias and black to maroon flow-banded vitrophyre. Small (<2 mm) subhedral to euhedral pink alkali feldspar phenocrysts are common in all variants.

The banded vitrophyre consists of maroon to black lamellae of highly variable thicknesses up to 1 cm, set in a fine-grained, saccaroidal lighter colored matrix. The dark lamellae are discontinuous and relatively flat except where they have been bent around alkali feldspar phenocrysts. The tuffs and tuff breccias contain angular felsic volcanic rock fragments up to 2 cm in length. Dark lamellae are present in the matrix, but here they are intensely contorted, in contrast to the planar arrangement of lamellae in the non-fragmental banded vitrophyre.

The dark vitrophyre lamellae consist of spherulitic and micrographic intergrowths of quartz and alkali feldspar. Locally, two, three, or more phenocrysts of quartz, alkali feldspar and mafic minerals form small irregular aggregates, which are probably xenoliths. Individual quartz phenocrysts rarely exceed 2 mm in diameter and are invariably embayed by the aphanitic groundmass. Sericite, chlorite, epidote, and hematite are the products of late low-grade metamorphism.

Undifferentiated Silurian-Devonian Rocks

Undifferentiated Silurian-Devonian sediments (SDu) are poorly exposed between Trimble Mountain and the St. Croix River. The sediments are well-beded, hornfelsed shales. Near the contact with the coarse-grained biotite granite (Drcbg), the shales are interbedded with 6 to 10 cm thick layers of limestone. The shales are recrystallized to an aphanitic, equigranular groundmass of 0.25 mm plagioclase laths. Ovoid clots (6 mm in diameter) of chlorite and sericite are locally abundant. Magnetite and metamorphic minerals including chlorite and sericite fill the interstices between the plagioclase microlaths. Quartz was not observed.

Perry Formation

The post-orogenic Perry Formation represents a fluvio-lacustrine basin, the limits of which were peripheral to Passamaquoddy Bay (Smith and White, 1905; Bastin and Williams, 1914; Schluger, 1973). Plant fossils in the lacustrine facies indicate a Late Devonian age (Smith and White, 1905;
Most of the formation consists of coarse sediments and basalt flows. Gates (1975, 1977) mapped three members: (1) red to maroon boulder and pebble conglomerate (Dpc); (2) sandstone, siltstone and mudstone (Dpm); and (3) basalt flows (Dpb). Of these, only the conglomerate and the basalt flows are mappable in the Robbinston 15-minute quadrangle. The basal conglomerate rests unconformably on the Eastport Formation, undifferentiated Silurian-Devonian rocks and the hornblende granophyre (Drhg) of the Red Beach granite. The clasts are well-rounded, range in size up to 2 m (Amos, 1963), and consist mostly of coarse- and medium-grained biotite granite (Drcbg, Drmbg, Dbg). Other granite types are also represented, as well as gabbro, granodiorite and various sedimentary and volcanic lithologies. The matrix is arkosic. Bedding is not well-defined in the coarser conglomerates except where there are channel-fill lenses of quartz sandstone or arkosic sandstone.

The trace of the unconformity is exposed in two parts, a western segment and an eastern segment. Along the former, which runs from Lamb Cove southward to the southeast end of Boyden Lake, the conglomerate dips gently (5°) to the east. Along the latter segment, which runs from Brooks Cove southward to Mill Point and marks the western limit of an inlier of hornblende granophyre, the basal conglomerate dips to the west. The inferred shape of the surface of the unconformity suggests that the inlier of hornblende granophyre was a topographic high within the basin of deposition during the Late Devonian.

At Lamb Cove the basal conglomerate rests on undifferentiated Silurian-Devonian shales. The surface of the unconformity is generally smooth and gently undulating with only local irregularities. Here the well-rounded clasts rarely exceed 35 cm.

At Brooks Cove, the base of the Perry Formation lies on an irregular zone of spheroidally weathered granite, which has been interpreted as the result of Devonian weathering (Abbott, 1977, 1978a). The extent of the zone is somewhat ill-defined due to the Pleistocene overburden, but consists of well-rounded spheroids of granite up to 2 m in diameter. The matrix consists of poorly sorted arkose, with angular grains. The texture of the matrix resembles that of the granite spheroids, suggesting the in situ breakdown of the granite. The spheroidally weathered zone grades upward into conglomerate with clasts of varied lithologies, like the conglomerate found elsewhere near the unconformity.

The underlying granite is brick red to purple near the unconformity. This coloration is preserved on glacial surfaces, road cuts and in freshly broken hand specimens. Going away from the unconformity, the hornblende granophyre grades in color over a distance of about 1.5 km from the characteristic brick red at the unconformity to light pinkish gray or gray. In samples of the hornblende granophyre collected near the unconformity the original assemblage of mafic minerals (hornblende, minor biotite, magnetite and ilmenite) has been completely metamorphosed to chlorite, epidote, sericite, hematite and calcite. Plagioclase is extensively replaced by epidote and sericite. The effects of the metamorphism decrease gradationally away from the unconformity. East of the Perry Formation, the inlier of hornblende granophyre is uniformly brick red to purple and shows extensive alteration throughout. Clasts of granite in the Perry Formation show the same alteration and brick red coloration.
The distribution of the red coloration and the presence of the spheroidally weathered zone at Brooks Cove suggest the effects of Devonian weathering. Presumably the epidote, chlorite and sericite were due to a later, low grade metamorphism of the original weathering products. The effects of the metamorphism are not nearly so pronounced in those rocks, well away from the unconformity, which presumably had not previously been so intensely weathered.

Basalt flows belonging to the Perry Formation occur in the southeast corner of the map area. The position of the base of the main sequence of flows was drawn from Amos (1963), Gates (1975), and my own reconnaissance. I have not yet examined the area in detail. The flows consist of brown-weathering, dark green to black, homogeneous basalt, locally brecciated, with scoriaceous and amygdaloidal variants. Amos (1963) identified some pillow basalts.

Part of an isolated flow is exposed in one outcrop on the northeast shore of Boyden Lake, close to the base of the formation. The extent and thickness of the flow are not known.

**INTRUSIVE ROCKS: AN OVERVIEW**

The intrusive rocks in the Calais area are the easternmost in Chapman's (1962) Bays of Maine Igneous Complex. The complex ranges in composition from gabbro to granite. All of the rocks were considered by Amos (1963) to be Devonian in age, emplaced during or after the Acadian Orogeny. There is now some controversy regarding the ages. At least some of the mafic and felsic rocks in the Bays of Maine Igneous Complex may be Silurian. It should be noted that gabbro, diabase, and basalt occur throughout the Silurian-Devonian Coastal Volcanic Belt, indicating a long-standing source of mafic magma from Early Silurian to Early Devonian (Gates, 1977). Felsic volcanic rocks also occur throughout the sequence (Bastin and Williams, 1914; Gates, 1975), hence there must also have been a long-standing source of felsic magma, very likely in close proximity to the basaltic magma. Some manifestation of coexisting mafic and felsic magmas might therefore be expected in the Silurian and Lower Devonian plutonic rocks of the Bays of Maine Igneous Complex. Based on his work on Vinalhaven Island, Mitchell (1986) has presented compelling evidence for comingling mafic and felsic magmas in the Bays of Maine Igneous Complex. Similar evidence exists in the Calais area and will be presented here.

The age relationships between the various intrusions are based on the evidence presented in Figure 1. The Red Beach granite (Drhg, Drqrg, Drqpg, Drfbg, Drscbg, Drmbg, r), Charlotte granite (Degr), and miscellaneous biotite granite (Dbg), are demonstrably younger than the Eastport Formation. These granites are not cut by mafic intrusions, except for one diabase dike (di) believed to be related to the basalts in the Perry Formation. The older intrusive rocks in the Bays of Maine Igneous Complex, gabbro (SDga), granodiorite (Sdgd), and diabase (Sdgd), may be wholly, or in part, older than the Eastport Formation. In his original geologic map, presented as part of his Ph.D. thesis, Amos indicated that the gabbros may be Lower Silurian in age, altogether predating the Silurian-Devonian volcanic rocks.
**Criteria for Age Relationships of the Intrusive Rocks**

<table>
<thead>
<tr>
<th>Red Beach Granite and Charlotte Granite Formation</th>
<th>Inclusions</th>
<th>Dikes</th>
<th>Quenched Margin</th>
<th>Clasts</th>
<th>Truncated Dike*</th>
<th>Plagioclase Cores</th>
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<td>Fine-grained granophyre (r)</td>
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<td>Diabase (SDDp)</td>
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<td>Granodiorite (SDgd)</td>
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<td>Gabbro (SDga)</td>
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<td>Eastport Formation or Leighton Formation</td>
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*The age relationship between the Charlotte Granite and the Red Beach Granite is one of the most difficult to demonstrate. Although the Charlotte Granite is close to the Drhg unit of the Red Beach Granite immediately northwest of Coleback Lake, even here the two rock types are separated by a septum of Sbd as narrow as 2 m. At the one exceptional location a 1 m wide dike of Drhg in Sbd is truncated by the Charlotte Granite.*

#The principal mode of trimodal distribution of core compositions.

**Figure 1. Criteria for age relationships of the intrusive rocks.**
Westerman (1972, 1973) reported a radiometric K/Ar age of $423 \pm 24$ m.y. for hornblendes from a gabbro belonging to the Bays of Maine Igneous Complex. This supports a Silurian age for the gabbros. It follows that the gabbro, diabase (SDd), and basalts in the Silurian-Devonian volcanic rocks may be contemporaneous with rocks of similar composition in the Bays of Maine Igneous Complex. The felsic volcanic rocks may be correlative with granodiorite (SDgd), the Baring granite (not exposed in the Robbinston 15-minute quadrangle) and felsic rocks in map units SDdp and SDm. There is a great need for a comparative study of the stable isotopes and REE's in the mafic rocks of the Coastal Volcanic Belt and the Bays of Maine Igneous Complex.

Several inconsistencies were encountered in applying Amos' (1963) classification scheme to the mafic and intermediate rocks, specifically with regard to his gabbro-norite and diorite units. The problem involves the admitted heterogeneity of Amos' (1963) diorites. The actual range of compositions is from gabbro to monzogranite and the relationship between different varieties is in some places gradational; while in other places, discontinuous. For this reason and for reasons which will become apparent, Amos' (1963) classification scheme for the mafic and intermediate rocks has been abandoned. Instead, I have mapped four units, gabbro (SDga), granodiorite (SDgd), dikes containing diabase pillows (SDdp), and mixed rocks (SDm). The areas shown as gabbro-norite by Amos (1963) coincide closely with a distinct variety of gabbro characterized by large ($\leq 3$ cm) euhedral to subhedral buff-colored plagioclase phenocrysts. Much of what Amos (1963) had mapped as diorite is included in the gabbro unit of this study. All of the different varieties of gabbro are intergradational. What remains of Amos' (1963) diorite unit is mostly granodiorite, interpreted here as the least (?) contaminated and most voluminous manifestation of an otherwise homogeneous unit ranging in composition from diorite to monzogranite. Rocks in the granodiorite unit are readily distinguished from those in the gabbro unit, both texturally and mineralogically. The color index is, however, not a reliable guide to distinction. The mixed unit (SDm) of this study is gradational with the granodiorite and consists of various products of the hybridization of the granodiorite and either xenoliths of gabbro or inclusions of diabase. The diabase pillow unit (SDdp) forms dikes that cut gabbro, and may simply be apophyses of the mixed rocks (SDm). The granodiorite, dikes of diabase pillows, and mixed rocks all intrude the gabbro. Such a relationship is not clear in Amos' (1963) treatment of these rocks.

**MAFIC AND INTERMEDIATE INTRUSIONS**

**Gabbro (SDga)**

The gabbro unit includes olivine gabbro, norite, anorthositic norite, hypersthene gabbro, hornblende gabbro, and leucogabbro. The most voluminous variety is hornblende gabbro. Generally the rock is homogeneous, except for local occurrences of rhythmic layering (Amos, 1963). Individual beds in rhythmically layered sequences are usually 5 to 10 cm thick, and show a gradation from gabbro to anorthositic gabbro. Amos (1963) has observed that the rhythmically layered rocks are beneath the non-layered rocks and that the contact between the two varieties is
gradational with "numerous alternations". Locally, the rhythmic layering has been disrupted and plastically deformed, probably in response to various flow and slumping mechanisms in the magma chamber during the accumulation of the layers. Of particular interest is Amos' (1963) observation that the attitude of the undisrupted layering is parallel to that of metasediments to the northwest. This suggests that the gabbros have undergone the same deformation as the rocks in the St. Croix Belt. There is no evidence for a similar relationship involving the younger granitic rocks.

The gabbroic rocks are generally equigranular, medium- to coarse-grained, and range in color from black to greenish gray. The texture is distinctly ophitic in hand specimen. Typically, the grain size is in the range 5 to 7 mm, although locally the average grain size reaches 11 mm and even more in some pegmatitic segregations. The typical gabbro contains, in decreasing abundance, plagioclase, common hornblende, augite, orthopyroxene, and magnetite. Small amounts of primary olivine or quartz+orthoclase may also be present. Sphene and apatite occur as accessory minerals. The rocks contain minor amounts of metamorphic biotite, chlorite, sericite, and epidote. Amos (1963) presents a comprehensive survey of modal analyses for the gabbroic rocks.

Plagioclase occurs in two forms, large (≤ 4 cm) euhedral to subhedral buff-colored phenocrysts, and small (≤ 4 mm) euhedral to subhedral gray laths. The large buff-colored phenocrysts are not always present, but seem to be fairly well restricted to the areas mapped as norite-gabbro by Amos (1963). Plagioclase phenocrysts may or may not be chemically zoned with respect to An content, even in the same sample. Amos (1963) reports zonations from cores of An_{70} to rims of An_{40}, but he does not specify whether this is for the large buff phenocrysts or for the small phenocrysts in the matrix. Clinopyroxene and orthopyroxene fill the interstices in an ophitic manner. Hornblende commonly forms reaction rims on the clinopyroxenes. The amount of hornblende replacing augite varies from sample to sample. Magnetite and, when present, quartz+orthoclase or olivine are interstitial. Amos (1963) reported the following range of composition for augite, Wo_{56}En_{32}Fs_{12} to Wo_{32}En_{65}Fs_{10} for orthopyroxene, En_{65} to En_{71}; and for olivine, Fo_{63} to Fo_{76}. Variations in the assemblage of minerals and the compositions of the minerals parallel variations in other layered gabbro intrusions, such as the Skaergaard Intrusion of the Bushveldt Complex (Amos, 1963).

Granodiorite (SDgd)

Granodiorite occurs primarily in NE-SW trending, elongated bodies that intrude gabbro. The northeast end of the largest body splays into a system of tapering dikes. Elsewhere, narrower intrusions of granodiorite are separated, one from the other, by screens, possibly roof pendants, of gabbro. The granodiorite is intruded by the Red Beach granite, Charlotte granite and other biotite granites (SDbg).

The rock is relatively homogeneous in grain size, mineralogy and general appearance. Most of the variation is in the modal proportions of the minerals. The typical rock is a light to dark, blue-gray biotite.
hornblende granodiorite. The texture is equigranular and medium-grained (1 to 2 mm).

Plagioclase phenocrysts are subhedral to euhedral, and rarely exceed 2 mm in length. Amos (1963) reports zonations in the range from An_{29} to An_{50}. The hornblende and biotite occur as small (<1 mm) grains, which are evenly distributed in the rock, giving a distinctive pepper-in-salt texture, readily distinguishable from the ophitic texture of the gabbros. Quartz and perthite are interstitial. Magnetite and apatite are common accessory minerals; chlorite, sericite and epidote are the products of late, low-grade metamorphism.

Although the general appearance of the granodiorites is relatively constant, there is considerable variation in the modal composition (Amos, 1963), overlapping the quartz diorite and diorite fields in the CIPW classification system. Near the margins of the granodiorite bodies, in the mixed rocks unit (SDm), and in dikes, there is even greater variation toward gabbroic and granitic compositions. The various compositional varieties are intergradational. The extreme variants are found near the contacts with country rock and xenoliths such that the local variation is in direct proportion to the degree of disaggregation of the foreign material.

Mitchell (1986) suggested that the major bodies of granodiorite at the southwest end of the Bays of Maine Igneous Complex may be simply well-homogenized hybrids of felsic and mafic magmas. Other relationships between the mafic and intermediate rocks described by Mitchell (1986) are similar to relationships in the Calais area. Based on field relationships and a preliminary whole rock Rb/Sr age of 410 m.y. (Ludman, 1985), the granite of Baring is the only major felsic intrusion in the area that might be contemporaneous with some of the mafic intrusive rocks. If the granodioritic compositions (which I believe to be the "purest" manifestation of the unit) is indeed a hybrid, the felsic component may be related to the granite of Baring.

Mixed Rocks (SDm)

The mixed rocks unit consists of rounded to angular inclusions of gabbro, and lesser amounts of diabase pillows (see next rock description). The inclusions and diabase pillows are set in a dioritic to granitic matrix. The composition of the matrix varies with respect to the volume percent of inclusions and the degree of disaggregation of the inclusions. The gabbro fragments range in size from centimeters up to hundreds of meters. The diabase inclusions are usually less than 30 cm in size, but can reach 2 m or more. The rocks form a continuum from essentially inclusion-free granodiorite to essentially homogeneous gabbro. At one extreme, the unit might best be described as brecciated gabbro; at the other, as granodiorite with sporadic inclusions of gabbro. Consequently, the contact between the mixed rocks and the gabbro, and the contact between the mixed rocks and the granodiorite unit are somewhat arbitrary. The contacts were placed so as to define those areas with approximately 10 to 90 percent gabbro inclusions in a granodioritic matrix.
There are two modes of occurrence: (1) as a contact facies of the granodiorite intrusions, and (2) as isolated patches in the gabbro. The first mode of occurrence suggests that the second may represent parts of the fractured roofs of subjacent bodies of homogeneous granodiorite. The different areas of granodiorite exposed at the surface may all be parts of a single body, with the mixed rocks being a marginal facies.

Pillow Diabase (SDdp)

Diabase is found sporadically throughout the northern part of the area, where it is integrally related to gabbro, granite and granodiorite. The diabase is somewhat anomalous in that it occurs only as inclusions in an intermediate or more felsic host. Dikes or other forms of intrusions of diabase alone, in any other rock type, have not been observed. The diabase inclusions have a number of different forms, in a wide range of sizes up to several meters. The shapes include (1) simple well-rounded pillows (Figure 2a), (2) crenated pillows, outward pointing lobes alternating with inward pointing cusps (Figure 2b), (3) amoeboid pillows, outward pointing lobes alternating with inward pointing lobes (Figure 2c), and (4) angular inclusions. For each type of inclusion the margins may be sharp or diffuse. The composition of the surrounding material becomes more mafic in direct relationship to the diffuseness of the margins.

The simple, well-rounded pillows commonly occur in aggregates in which the pillows have been deformed against one another (Figure 2a). The proportion of the matrix varies substantially, regardless of the pillow type, from isolated pillows in an otherwise homogeneous felsic matrix to more than 90 percent pillows. In the latter case, the pillows tend to have coalesced, perhaps by gravity settling, such that most of the interstitial felsic magma has been expelled. Commonly, all that remains of the matrix is a thin film between pillows and anti-crenated volumes of felsic rock (inward directed lobes alternating with outward directed cusps). The deformation of the pillows suggests that the diabase was plastic when it was introduced into the felsic host. The simple and crested pillows have thin (2 to 5 mm) aphanitic rinds which have been interpreted as the result of quenching. Whereas inclusions, like clasts in a sediment, are considered to be older than the enclosing material, the quenched margins on the diabase pillows suggest the opposite. The apparent contradiction can only be reconciled if the diabase was injected, while still molten, into a cooler felsic magma. The initial shapes would then be controlled by the surface tension of the diabase magma against the felsic magma. This would produce the simple, rounded pillows. The crested shapes may represent deformed pillows, or pillows that were frozen in the process of subdividing. The amoeboid pillows would represent a more fluid interdigation of the two magmas. The absence of quenched margins on the amoeboid pillows suggests that the host, into which the diabase magma was injected, was preheated. This is consistent with the felsic magma being unusually fluid, at least when compared with the felsic magma in which the simple and crested pillows were formed.

Many diabase pillows have been intruded along narrow fractures by the felsic matrix, presumably at a time when the pillows were essentially
Figure 2. a. Simple, well-rounded diabase pillows.
b. Crenate pillow.
c. Margin of an amoeboid pillow.

Scale bar is 25 centimeters.
crystallized, but the matrix was still fluid. The angular diabase inclusions probably represent the fragments of more thoroughly fractured pillows.

The diabase pillow complexes, that is diabase plus felsic matrix, occupy dikes in the gabbro. Angular fragments of gabbro are also present in the granodiorite matrix. The walls of the dikes are rarely exposed. Figure 3 is a sketch map of one side of a dike filled with a diabase pillow complex. The dike trends N-S and is zoned with respect to the proportion of diabase pillows. There is a swarm of N-S trending diabase pillow dikes cutting the gabbro immediately south of Vose Pond. The dikes rarely exceed 4 m in width.

Diabase pillows, parts thereof, as well as angular fragments of gabbro also characterize the mixed rocks associated with the granodiorite unit. It may be that the diabase pillow dikes are simply apophyses of the mixed rocks. If so, then, in accordance with Mitchell's (1986) model, the whole of the granodiorite may be a well-homogenized hybrid of the diabasic magma and a granitic magma, with the diabase pillows being preserved only where quenched along the margins of the granodiorite (mixed rocks) and in dikes. For reasons already stated, the felsic component may be related to the granite of Baring.

Diabase (SDd)

Diabase and gabbro intruded all of the formations in the Silurian-Devonian Coastal Volcanic Belt (Gates, 1975, 1978). The intrusions are sills, or lenticular to tabular, subconformable plutons. Three diabase sills were recognized in the Robbinston 15-minute quadrangle, and a fourth was inferred from Gates (1975). The three mapped intrusions are immediately east of Coleback Lake. The two largest of these may be parts of a once continuous body, now cut by a NW trending dextral strike-slip fault and truncated by hornblende granophyre (Drhg).

The diabase is dark gray-green, medium-grained (~2 mm) and subtrachytic. The primary minerals are, in decreasing modal abundances, plagioclase, augite, magnetite and sphene. The effects of metamorphism were responsible for extensive albitization and saussuritization of the plagioclase, chloritization of the augite, and partial replacement of the magnetite by hematite. Calcite and epidote occur in veins, along joints and as replacements of the primary diabase minerals near veins and joints.

As was suggested earlier, the diabase (SDd) and gabbro found in the Silurian-Devonian Coastal Volcanic Belt may be contemporaneous with some of the gabbro (SDga) and diabase (SDdp) in the Bays of Maine Igneous Complex. Whether or not the magmas came from the same source remains to be tested geochemically.

Diabase (d1)

One dike of diabase intrudes hornblende granophyre (Drhg) and possibly the basal conglomerate of the Perry Formation at Brooks Cove. The dike is very likely a feeder for the basalts (Dpb) higher in the Perry Formation.
Figure 3. Map of east wall of a dike containing diabase pillows. The pillow complex is exposed on the east bank of East Branch, approximately 1 kilometer northeast of Vose Pond.
Mt. Tom Andesite (SDa)

The only remaining intermediate or mafic intrusive rocks in the area belong to the Mt. Tom basaltic andesites, named by Bastin and Williams (1914). These rocks, which underly the extreme southwestern corner of the Robbinston 15-minute quadrangle, have not yet been examined as part of this preliminary investigation. The name implies that the rocks are volcanic, but according to Gates (1975, 1978) the upper contact, which dips to the east, and is exposed along the west shore of Pennamaquan Lake, is intrusive, indicating that the unit is plutonic. The role of the Mt. Tom andesites in the overall geology of the area is unknown.

THE FELSIC INTRUSIVE ROCKS

In the broadest classification there are three groups of granitic rocks: (1) the Charlotte granite (Dbg), (2) the Red Beach granite, and (3) satellite dikes and smaller plutons of biotite granite (Dbg). The Charlotte granite underlies the southwestern part of the Robbinston 15-minute quadrangle. Most of the body lies to the west, outside of the mapped area (Amos, 1963). The Red Beach granite underlies roughly 40 percent of the mapped area, within a quadrangle, the corners of which are Coleback Lake, Nashs Lake, Devils Head and Mill Cove on the St. Croix River. The body is actually a composite of six distinct intrusions (Abbott, 1977, 1978a). Two of the biotite granite members (Drcbg and Drmbg) of the Red Beach granite are here correlated with the Charlotte granite. This contradicts Amos (1963) who considered the Charlotte granite to be distinctly older than the Red Beach granite. It will be shown that the Charlotte granite is younger than the hornblende granophyre member of the Red Beach granite (Drhg), and consequently could be contemporaneous with the coarse- and/or medium-grained biotite granites of the Red Beach granite (Drcbg and/or Drmbg). The third major occurrences of granite are in dikes and small plutons, collectively referred to as biotite granite (Dbg). These granite bodies are scattered throughout the gabbro (SDga) and granodiorite (SDgd). The principal bodies consist of (1) a swarm of east-west trending dikes immediately west of Devils Head, (2) an east-west trending, south dipping lenticular pluton, just south of Elliot Mountain, and (3) a northeast trending gabbro-block laden region between Howard Lake and the Charlotte granite. Modal and textural similarities between the biotite granites (Dbg), the Charlotte granite, and the coarse- and medium-grained biotite granites of the Red Beach granite, strongly suggest that they are all manifestations of the same episode of magmatism. Although the interior of the Charlotte granite is texturally distinct from the other biotite granites, near the eastern margin it grades into rock that is virtually indistinguishable from the coarse-grained biotite granite of the Red Beach granite. The biotite granites (Dbg) southwest of Howard Lake appear to be apophyses of the Charlotte granite. On the basis of the distribution of the various rock types between Howard Lake and the Charlotte granite, it is difficult to avoid drawing a contact (dotted) between biotite granite (Dbg) and the Charlotte granite. However, the contact was rather arbitrarily placed and is probably altogether meaningless insofar as the two rock types are probably parts of the same intrusion.
Amos (1963) subdivided the Red Beach granite into two intrusions, hornblende granophyre followed biotite granite. An older quartz monzonite was recognized, but he did not include it in the Red Beach granite. I have distinguished two varieties of quartz monzonite (Abbott, 1977, 1978a) which are here referred to as quartz-poor and quartz-rich granophyres (Drqpg and Drqrg). Because these granophyres have a close textural and mineralogical affinity for the hornblende granophyre (Drhg), they are grouped here with the Red Beach granite. The quartz-rich granophyre is considered to be a variant of the main body of the hornblende granophyre. Amos' (1963) biotite granite was reinterpreted (Abbott, 1977, 1978a) as four distinct intrusions. Altogether, at least six distinct intrusions make up the Red Beach granite. Partial modal analyses (quartz, plagioclase and perthite) are presented graphically on the accompanying geologic map.

Most of the following petrography is excerpted from Abbott (1978a) with modifications and additions reflecting the new correlations just outlined. The reader should refer to the explanation on the accompanying geologic map. Thereon is represented a comprehensive compilation of the tentative correlations involving all of the igneous (and sedimentary) rocks. The description of the felsic rocks proceeds from the oldest to the youngest units in the Red Beach granite.

Quartz-poor and Quartz-rich Granophyres (Drqpg, Drqrg)

Both the quartz-poor and quartz-rich granophyres are medium-grained, with euhedral to subhedral phenocrysts of plagioclase, averaging 3 mm in length. Microscopic examination shows that the matrix is a fine-grained, locally micrographic, intergrowth of quartz and microperthite. The perthite forms thin (~ 0.25 mm) continuous rims on the plagioclases, such that quartz is not found in contact with plagioclase. In outcrop the rocks range in color from waxy black to gray. The dominant mafic mineral is edenite-hornblende, which occurs as subhedral to anhedral phenocrysts or aggregates of phenocrysts. Magnetite and ilmenite are interstitial between plagioclase and hornblende, or they are found as inclusions in the hornblende. Accessory minerals include zircon and apatite. The rocks have been extensively altered to chlorite, epidote and sericite as the result of late, low-grade metamorphism.

Both the quartz-poor and the quartz-rich granophyres occur as isolated patches in the hornblende granophyre. The largest outcrop is of the quartz-poor variety, located between Rand Lake and Goulding Lake. The remaining exposures are all of the quartz-rich variety. Contacts with the hornblende granophyre are gradational over a few meters for both varieties. The quartz-rich granophyre also occurs along the southern margin of the hornblende granophyre near the contact with the Eastport Formation.

The quartz-poor granophyre is interpreted as a separate intrusion that is older than the hornblende granophyre (Amos, 1963). The unit is confined to high elevations and probably represents a roof pendant in the hornblende granophyre (Abbott, 1977, 1978a).
The quartz-rich granophyre is interpreted as a variant of the hornblende granophyre, resulting from the assimilation of country rock, specifically the Eastport Formation. The high elevation exposures in the interior of the hornblende granophyre may be close to the original roof of the hornblende granophyre.

Hornblende Granophyre (Drhg)

The hornblende granophyre resembles the quartz-poor and quartz-rich granophyres to such an extent that it is very difficult to distinguish between the three rock types in the field. The principal differences are in the modal analyses. Generally the hornblende granophyre is lighter in color, being pinkish gray or gray.

Aside from variations in color, the hornblende granophyre is remarkably homogeneous in average grain size and texture. The rock is characterized by euhedral, blocky plagioclases (cores An$_{30-41}$; rims An$_{10-12}$) that rarely exceed 3 mm in length. The plagioclases are set in a micrographic matrix of quartz and microperthite. Perthite also occurs as euhedral to subhedral phenocrysts that are generally smaller than the plagioclases.

The plagioclase phenocrysts are rimmed by perthite, such that quartz is not found in contact with plagioclase (Abbott, 1978b). The rimming alkali feldspar is optically continuous with the matrix perthite in micrographic intergrowth with quartz. Edenite occurs as anhedral blocky phenocrysts and also as interstitial grains in the matrix. Biotite is present in some samples, particularly in the western part of the intrusion. When present, biotite is commonly intergrown with, or mantles, the hornblende. Anhedral magnetite and ilmenite occur as inclusions or embayments in the hornblende or biotite. Apatite and zircon are present as accessory minerals; metamorphic minerals include chlorite, epidote and hematite.

From east to west in the hornblende granophyre, the plagioclases become increasingly more rounded as the perthite rims become thicker. At the same time, the quartz-perthite matrix becomes coarser and the micrographic texture becomes less distinct. These textural changes are gradational and most likely due to variations in the rate of cooling across the body. The textures suggest a faster cooling rate in the east than in the west.

Irregular, ovoid to spherical miarolitic cavities are common in the eastern half of the intrusion. The cavities range in diameter from 2 to 3 mm up to 1 cm, and are lined with euhedral quartz and alkali feldspar crystals.

The contact of the hornblende granophyre with the Silurian-Devonian volcanic rocks to the south, and with gabbro to the west, is sharp and smoothly curved with only local irregularities. There are inclusions of various lithologies, including the Silurian-Devonian volcanic and sedimentary sequence (mostly basalt), gabbro, and diorite. The inclusions are angular with sharp contacts, and they range in size from centimeters to
tens of meters. Inclusions of gabbro or diorite occur only near the contact with the gabbro, along the western margin of the hornblende granophyre. Inclusions of basalt and other rock types associated with the Maine Coastal Volcanic Sequence are distributed throughout the interior of the hornblende granophyre and along the southern margin. The distribution of the plutonic versus the volcanic inclusions suggests that the hornblende granophyre was roofed by Silurian-Devonian volcanic and sedimentary rocks.

Fine-grained Biotite Granite (Drfbg)

The fine-grained biotite granite is an equigranular, white to light gray rock with an average grain size of approximately 1 mm. The rock contains single phenocrysts and aggregates of euhedral plagioclase laths ranging in length from 0.5 to 1 mm. Individual plagioclases occur as inclusions in quartz and perthite, giving rise to a poikilitic texture in these minerals. The poikilitic grains have anhedral outlines. The mafic minerals include biotite, magnetite and ilmenite.

There is a trimodal distribution of plagioclase core compositions (Abbott, 1977, 1978a), a dominant mode which is normally zoned (cores An\_23-26; rims An\_6-12), and two minor modes; one, reversely zoned (cores An\_13-18; rims An\_21-24) and the other normally zoned but more calcic than the dominant mode (cores An\_40-44; rims An\_7-17). The two minor modes are believed to have been incorporated from the country rock. The core compositions of the last mode just mentioned are consistent with plagioclase cores in the granodiorite (SDgd). The dominant mode is interpreted as primary.

The fine-grained biotite granite is relatively homogeneous in grain size and texture, showing neither a quenched margin against older rocks nor evidence of recrystallization at contacts with younger members of the Red Beach granite. The contact with the older intrusions (SDga, SBgd) is sharp, irregular and characterized by numerous dikes ranging in width from less than a centimeter up to 500 m. East of Nashs Lake the fine-grained biotite granite contains massive blocks of granodiorite up to 0.18 km long and 0.3 km wide. The shapes of the blocks fit the outline of the intrusion; thus indicating that they were not displaced very far from their original sites. Indeed, the blocks may be roof pendants.

A note is perhaps appropriate here regarding the age of the fine-grained biotite granite relative to other units in the Red Beach granite. In Figure 1, the age of the fine-grained biotite granite was fixed on the basis of the plagioclase core composition. Most of the plagioclases (the dominant mode) have core compositions (An\_23-26) between those for the hornblende granophyre (An\_30-41) and those for the coarse-grained biotite granite (An\_19-23). This suggests that the fine-grained biotite granite is younger than the hornblende granophyre (even though the two rock types are never found in contact) and older than the coarse-grained biotite granite.

Coarse-grained Biotite Granite (Drcbg)
The coarse-grained biotite granite is nearly equigranular with a maximum grain size of about 1 cm. The rock is salmon-pink in the freshest quarry exposures and brick red in weathered exposures along the shore of the St. Croix River and in lowlands adjacent to heaths, streams and ponds. There is little variation in the maximum grain size throughout the body up to the contacts, and even in dikes as narrow as 2.5 cm. Evidently, the granite intruded preheated country rock.

Plagioclase (cores An_{19-23}; rims An_{11}) occurs as subhedral blocky phenocrysts that commonly form aggregates. Small (<1 mm) plagioclases occur as inclusions in perthite.

Perthite is the most abundant mineral. It occurs as large (0.5 x 1.0 cm) anhedral to subhedral phenocrysts. Perthite also occurs as small (<5 mm) subhedral to ovoid phenocrysts rimmed by oligoclase. The mantled perthites make up only a small fraction of the total perthite, except near the contact with the hornblende granophyre. Near this contact the "rapakivi" perthites locally account for as much as half of the total perthite.

Interstitial perthite and quartz are intergrown micrographically, particularly near the southern margin of the intrusion. Here the micrographic intergrowths go hand-in-hand with the mantled perthites.

The mafic minerals include biotite, magnetite and ilmenite. Metamorphic minerals include chlorite, epidote and sericite.

Miarolitic cavities are common, being particularly evident in exposures along U.S. Route 1 and along the shore of the St. Croix River. The cavities are irregular, elongated and range in length from 1 to several centimeters.

In the coarse-grained biotite granite, small inclusions of country rock are rarely preserved more than a couple meters from the contact. Two large inclusions, possibly roof pendants, of gabbro over 700 m long each were mapped between Rand Lake and Howard Lake. South of Rand Lake, dikes of the granite as narrow as 2.5 cm cut the quartz-poor granophyre. Between Howard Lake and Rogue Lake at least three coarse-grained dikes as wide as 60 m cut gabbro. The dikes are straight, have sharp contacts and seldom contain inclusions.

Medium-grained Biotite Granite (Drmgb)

The medium-grained biotite granite shows all the essential features of the coarse-grained biotite granite, but on a slightly finer scale. The maximum grain size is approximately 7 mm. The major textural differences are fewer plagioclase-mantled perthites, but more of the micrographically intergrown quartz and perthite. Miarolitic cavities, similar to those in the coarse-grained biotite granite, are locally abundant. The mafic mineralogy is the same.

It would be extremely difficult to make a distinction between the coarse- and medium-grained biotite granites if it were not for a
gradational fine-grained quenched margin surrounding the latter. The quenched margin was forced against the fine-grained biotite granite, granodiorite, the mixed rocks unit, and the coarse-grained biotite granite.

In the vicinity of Devils Head, gabbro was locally intensely brecciated during the emplacement of the medium-grained biotite granite, so as to form a shatter zone. The shatter zone ranges in width from 0.2 to 0.7 km and consists of angular blocks of gabbro separated by medium-grained biotite granite or the quenched margin material. Locally the granite in the shatter zone contains inclusions of the fine-grained biotite granite. In the field the quenched margin resembles the older fine-grained biotite granite. However, a sufficient number of inclusions of the fine-grained biotite granite in the quenched margin were found to (1) substantiate the distinction between the two, and (2) indicate the presence of the shatter zone in the fine-grained biotite granite.

Charlotte Granite (Dog)

Much of the Charlotte granite, especially near the contact with gabbro, is virtually indistinguishable from the coarse- or medium-grained biotite granites of the Red Beach granite. The rock is an equigranular, white to salmon, medium- to coarse-grained (5-10 mm) biotite granite. Plagioclase occurs as small (2-3 mm) subhedral to euhedral phenocrysts and locally as rims on perthite phenocrysts. The plagioclase phenocrysts are zoned (cores An$_{30-32}$; rims An$_{21-29}$; Amos, 1963). The plagioclase that rims the perthite phenocrysts is oligoclase. Where present, the mantled perthites are euhedral to well-rounded. Mantled and unmantled perthites are usually found together. Perthite also forms interstitial, micrographic intergrowths with quartz. The mantled perthites and micrographic quartz-perthite intergrowths are best developed near the eastern margin of the Charlotte granite. Indeed, in the interior of the body, more than 500 m from the eastern contact, these special features were not observed.

Biotite and magnetite are interstitial. Zircon was the only observed accessory. Chlorite has replaced some of the biotite. Locally, near the contact with the Leighton Formation, the biotite has been partially or completely replaced by magnetite.

A fine-grained, aplitic quenched margin is preserved locally along the contact with the Leighton Formation. Originally (Abbott, 1977, 1978a), the quenched margin has been interpreted as a separate, later intrusion. The present mapping effort revealed that the contact between the quenched margin and the coarse interior of the Charlotte granite is gradational.

The contact between the Charlotte granite and the Leighton Formation/hornblende granophyre deserves closer attention, because of its importance in establishing the correct age relationship between the Charlotte granite and the hornblende granophyre. Figure 4 is a detailed map of the contact near Coleback Lake. With one exception, there are no simple dike or inclusion relationships involving the two intrusive rocks. The granite and the granophyre are virtually everywhere separated by a narrow septum of hornfelsed shale. A narrow (1 m) dike of hornblende granophyre cutting the hornfelsed shale at a narrow part of the septum was
EXPLANATION

Dcg Charlotte Granite, q = quenched margin
Drhg hornblende granophyre
Debl basalt, Eastport Fm.
Sls Shale, Leighton Fm.

Figure 4. Sketch map of intrusive relationships near Coleback Lake.
found, after excavation toward the Charlotte granite, to be truncated by
the quenched margin of the Charlotte granite. Hence, the Charlotte granite
is younger than the hornblende granophyre. This contradicts the earlier
interpretations of Amos (1963) and Abbott (1977, 1978a).

Biotite Granite (Dbg)

For the most part, the satellite intrusions of biotite granite consist
of homogeneous equigranular, medium-grained (5-7 mm) white to salmon-pink
biotite granite. The plagioclase occurs as subhedral to euhedral
phenocrysts. Amos (1963) reports that the plagioclases are reversely
zoned, with cores of An$_{23-27}$ and rims of An$_{30-32}$. Perthite forms subhedral
phenocrysts, some of which are rimmed by plagioclase. Quartz and biotite
are interstitial. Locally there is a fine-grained aplitic variant,
especially in the narrow intrusions, and dikes. Usually the aplitic
material is in close juxtaposition with coarse biotite granite.

The similarities between the biotite granite (Dbg), the medium-grained
biotite granite (Drmbg), coarse-grained biotite granite (Drcbg) and the
Charlotte granite (Deg) suggest that they are very closely related and may
be manifestations of essentially the same episode of magmatism.

Fine-grained Granophyre (r)

The youngest of the felsic intrusive rocks is the fine-grained
granophyre. The rock resembles porphyritic rhyolite, but occupies dikes
cutting all of the other intrusions of the Red Beach granite. The average
grain size is less than 0.5 mm, and in most cases, much finer. The most
characteristic features are flow banding and spherulitic intergrowths of
radiating fibers of quartz and alkali feldspar. The spherulites are
developed to varying degrees in different samples, forming aggregates
separated by an aphanitic equigranular matrix of quartz and alkali
feldspar. Commonly the quartz and alkali feldspar in the matrix are
micrographically intergrown.

Quartz, plagioclase and perthite also form large (≤7 mm) individual
phenocrysts and clusters of phenocrysts. Plagioclase commonly forms rims
on individual perthite phenocrysts. The proportion of phenocrysts and
glomerocrysts versus matrix ranges from zero to 50 percent. Individual
unmantled alkali feldspar phenocrysts are generally well-rounded and
locally embayed by the aphanitic matrix. Quartz phenocrysts are more or
less equidimensional, well-rounded with small, irregular embayments of the
matrix. Glomerocrysts of two or more phenocrysts have internal grain
boundaries reminiscent of those in the coarse- or medium-grained biotite
granites. By all indications, the phenocrysts and glomerocrysts are
xenocrysts and xenoliths derived for the most part from coarse- and medium-
gained biotite granites.

Amos (1963) referred to the fine-grained granophyre dikes as apophyses
of his biotite-bearing member of the Red Beach granite. Necessarily, areas
of coarse-grained granite cut by the dikes were classified into a separate
unit which Amos (1963) referred to as miscellaneous granites, even though
the miscellaneous granites were identical in every other respect to his biotite granite member of the Red Beach granite. At least three fine-grained granophyre dikes were found by Abbott (1977) well within what Amos had designated as the biotite-bearing member of the Red Beach granite (Drcbg, Drmbg, Drfbg of this study).

CONDITIONS OF EMPLACEMENT OF THE RED BEACH GRANITE

Miarolitic cavities, granophyric texture, anti-rapakivi texture (plagioclase mantled by alkali feldspar), and general fine grain size are common features in volcanic rocks, and their presence in the Red Beach granite suggests a shallow to near surface depth of emplacement. This is supported by the low grade of regional metamorphism in the surrounding sediments at the time of magmatic intrusion (sub-greenschist). Using mineral equilibria involving biotite, alkali feldspar, magnetite and ilmenite, Abbott (1977, 1978a) estimated the depth of emplacement for the different intrusions of the Red Beach granite. The range of lithostatic pressures was calculated to be from 270 bars to 490 bars, consistent with depths from 0.8 km to 1.5 km. Within this range, the mole fraction of Fe" in biotite \( \frac{X_{Bio}}{Fe"} = \frac{Fe"}{Fe" + Ti + Fe" + Mg + Mn} \) was found to be the most sensitive indicator of variation. The values of \( X_{Bio}^{Fe"} \) (0.45 to 0.49) in the hornblende granophyre and fine-grained biotite granite suggest shallow depths of emplacement within the calculated range. The higher values of \( X_{Bio}^{Fe"} \) (0.51 to 0.53) for the coarse- and medium-grained biotite granites are consistent with somewhat deeper levels of emplacement. Within the range of calculated total pressures, specific textural features are further suggestive of varying conditions.

In the quartz-poor granophyre and hornblende granophyre, graphic intergrowths of fine grain size indicate rapid cooling commensurate with shallow levels of emplacement. The fine grain size of the fine-grained biotite granite indicates similar shallow conditions. All three intrusions represent emplacement under conditions of low pressure within the calculated range.

The coarse grain size, relatively small amount of graphic intergrowth and homogeneity of the coarse- and medium-grained biotite granites suggest a slower rate of cooling under a thicker, more insulating cover. The intrusions, along with the Charlotte granite and other biotite granite (Dbg), most likely consolidated under a high lithostatic pressure within the calculated range. The coarse grain size cannot be due solely to emplacement in preheated country rock because of the quenched margin of the medium-grained biotite granite. The quenched margin indicates rapid cooling followed by slower cooling. This is consistent with intrusion into cool country rock under somewhat thicker cover than suggested by the pervasive fine grain size and granophyric texture in the quartz-poor granophyre and hornblende granophyre.

In the fine-grained granophyre, spherulites, aphanitic grain size and preserved flow structures typify extreme quenching conditions consistent with a near surface level of emplacement.
The depth relationships are portrayed schematically in Figure 5, which has been modified from Abbott (1977, 1978a). The intrusions of the Red Beach granite contain inclusions of basalt, presumably derived from the Eastport Formation. The distribution of the inclusions further suggests that the magma chamber for at least the hornblende granophyre was roofed in the Eastport Formation. Because the Red Beach granite is comparatively small, it is reasonable to assume that all of the intrusions were emplaced at about the stratigraphic level of the Eastport Formation. The apparent variation in lithostatic pressure must therefore be attributed to one or both of two mechanisms: (1) subsidence and uplift, respectively coupled with sedimentation and erosion, or (2) construction and subsequent erosion of volcanic structures.

METAMORPHISM

Ludman (1978) reported cordierite-andalusite phyllite and quartz-garnet pods in the Cookson Formation at the northern tip of the mapped area. Various other hornfelsed lithologies at the contact with the intrusive rocks suggest that the metamorphism was caused by the thermal aureole associated with the intrusive rocks.

The amount and distribution of magnetite in the sedimentary and volcanic rocks adjacent to the hornblende granophyre and Charlotte granite suggest that the magnetite was formed by contact metamorphism (Abbott, 1977, 1978a). The unusually high proportion of magnetite can be detected easily with a magnet and affects compass readings. The high magnetite content gives rise to a distinct aeromagnetic signature in the regional survey by Zietz (USGS open file). The survey, a portion of which is portrayed in Figure 6, shows two prominent linear magnetic highs, outlining the southern margin of the hornblende granophyre. The first of these trends roughly ENE, with the axis parallel to the southern contact of the hornblende granophyre, but centered over the Eastport Formation. The anomaly dies out beneath the cover of the Perry Formation, in such a way as to indicate that the contact between the hornblende granophyre and the Eastport Formation (beneath the Perry Formation) intercepts the St. Croix River at Mill Cove. The axis of the second magnetic anomaly trends roughly NWW, parallel to the contact between the Charlotte granite and the Leighton Formation. The axis is centered over the Leighton Formation just outside the granite intrusion.

The distribution of magnetite-bearing rocks and their tough, fine-grained nature suggest the effects of contact metamorphism. The hand specimen characteristics are consistent with their having been hornfelsed. Later, low-grade regional metamorphism was responsible for the growth of hematite, albite, calcite, and the hydrated minerals, chlorite, epidote, and sericite. This mineral assemblage affected not only the Silurian-Devonian volcanic and sedimentary rocks (Gates, 1977), but also the Bays of Maine Igneous Complex (Abbott, 1977, 1978a) and the Perry Formation (Gates, 1977).
Present level of erosion

Decreasing Age

Silurian

L. Devonian

Red Beach Granite

Missing Strata

U. Devonian

2 = granodiorite
1 = gabbro
8 = fine-grained granophyre
7 = medium-grained biotite granite
6 = coarse-grained biotite granite
5 = fine-grained biotite granite
4 = hornblende granophyre
3 = quartz-poor granophyre

Figure 5. Oscillogram, summarizing local diastrophism (modified from Abbott, 1977, 1978).
Figure 6. Aeromagnetic map of the Red Beach granite, contoured in gammas, from Zietz (USGS open file). The magnetic intensity represents the residual after removing the IGRF (International Geomagnetic Reference Field) from the total magnetic intensity. RBG-h = hornblende granophyre, RBG-b = biotite granites, Dcg = Charlotte granite, SDga = gabbro, SDgd = granodiorite, Dpc = Perry Formation, DE = Leighton and Eastport Formations.
STRUCTURAL GEOLOGY

The oldest deformation in the area, corresponding to Ludman's (1978) \( F_1 \), was responsible for northeast trending upright, isoclinal folds. In the Robbinston 15-minute quadrangle, the deformation affected only the sedimentary and volcanic rocks of the Cookson Formation, Oak Bay conglomerate and Waweig Formation, on the north side of the Bays of Maine Igneous Complex. The deformation took place in Early Devonian and is assigned to the Acadian Orogeny. There are no correlative folds in the Silurian-Devonian volcanic and sedimentary rocks to the south of the Bays of Maine Igneous Complex.

The earliest folding in the Leighton and Eastport Formations is represented on the accompanying geologic map by the broad, southeast plunging Boyden Lake syncline. This fold is by all indications contemporaneous with the Cobscook Bay anticline, which has been assigned to the Acadian Orogeny by Gates (1975, 1978). On the basis of the attitude of the rhythmic layering in the gabbroic rocks, Westerman (1972) has suggested that the early intrusive rocks were tilted at the same time. If so, then the fact that the Boyden Lake syncline is truncated by the hornblende granophyre indicates that the gabbros were deformed before the emplacement of the felsic plutonic rocks.

At least four generations of faulting can be identified in the Robbinston 15-minute quadrangle. The oldest fault marks the base of the Eastport Formation. It is probably a normal fault (Gates, 1975) and has been folded in the Boyden Lake syncline. The second generation of faulting trends northwest and is dominantly dextral strike-slip (Gates, 1975). One such fault bisects the Boyden Lake syncline. The third generation of faulting is represented by an east-west trending normal fault, which was proposed in order to account for the repetition of stratigraphy on the north limb of the Boyden Lake Syncline. All three generations of faults affecting the Eastport Formation are truncated by the hornblende granophyre.

A fourth episode of faulting was restricted to the intrusive rocks. These faults, one parallel to the northeast shoreline of Nashs Lake, another parallel to the southwest shoreline of Howard Lake, are probably normal faults (Abbott, 1977, 1978a). The faults were recognized by Amos (1963), but extended during the current mapping effort much further to the northwest, on the basis of silicified fault gauge and various displaced intrusive units. The Nashs Lake fault and the Howard Lake fault divide the plutonic rocks into three blocks. Abbott (1977) has suggested that the sense of movement was down-to-west, such that the present level of erosion exposes successively shallower sections through the plutonic complex, from east to west. This is consistent with the following interpretation of the distribution of the different rock types relative to the Red Beach granite: east of Nashs Lake, blocks of gabbro and granodiorite occur only near the northern margin of the Red Beach granite, and the coarse- and medium-grained biotite granites are at their widest. In the central crustal block, between Howard Lake and Nashs Lake, a large area of gabbro, nearly surrounded by granite, appears to be a flap of the roof of the biotite granites. Southwest of Howard Lake, northeast trending, block-laden dikes of biotite granite suggest the fractured roof of a larger, subjacent body.
Amos (1963) showed a third fault of the same type, immediately east of Birch Mountain, but this could not be substantiated.

A northeast trending normal fault cuts the Perry Formation in the southeast corner of the Robbinston 15-minute quadrangle (Amos, 1963; Gates, 1975). The age of the fault relative to the Nashs Lake and Howard Lake faults remains uncertain.

**SUMMARY OF GEOLOGICAL HISTORY**

Figure 7 is a tentative compilation of the geologic history of the Robbinston 15-minute quadrangle. The Cookson, Oak Bay and Waweig Formations are treated only to an extent commensurate with their combined exposed area in the quadrangle, which is not much. Readers interested in the correlation of tectonic events between the St. Croix Belt and the Coastal Maine Volcanic Belt should consult Ludman (1981). Gates (1969, 1977, 1978) gives detailed accounts of the geological history of the Coastal Maine Volcanic Belt.

What I should like to emphasize is the prolongation of the time interval during which the Bays of Maine Igneous Complex was emplaced. The principal pieces of evidence for this area are (1) the early radiometric date of 423 \(+24\) m.y. reported by Westerman (1972, 1973) for the gabbroic rocks, (2) the likelihood that the gabbroic and granodioritic rocks were deformed prior to the emplacement of the granitic rocks, and (3) the prolonged mafic magmatism throughout the deposition of the Maine Coastal Volcanic Belt (Gates, 1977, 1978). With regard to the last item, as I mentioned earlier, certainly there must be some manifestation of this magmatism in the Bays of Maine Igneous Complex.

The history of the Acadian Orogeny in eastern coastal Maine is the history of the Maine Coastal Volcanic Belt. By all indications, the same can be said for the Bays of Maine Igneous Complex, which may have been initiated at the same time, and very definitely endured to a more recent time than the youngest of the exposed volcanic rocks. Whereas the mafic intrusive rocks and the volcanic rocks are presumably syn-orogenic, the granitic rocks (except for the granite of Baring) are clearly post-orogenic. The early gabbro and granodiorite intrusions and the younger granitic intrusions were emplaced under different tectonic circumstances. My current preference is that the gabbro-granodiorite intrusions were emplaced under tensional conditions in an ensialic back-arc basin; hence, are pre- to syn-orogenic; whereas, the granitic rocks were emplaced under tensional conditions during crustal relaxation after the peak of the Acadian Orogeny. It follows that the late granitic magmatism could not be genetically related, by differentiation, to the gabbro-granodiorite magmatism, as I had suggested earlier, specifically with regard to the Red Beach granite (Abbott, 1977, 1978).
<table>
<thead>
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<th>Time (my)</th>
<th>Event</th>
<th>Location</th>
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<tr>
<td>400</td>
<td>Unconformity</td>
<td>Regional greenschist (G 77)</td>
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<tr>
<td>408</td>
<td>Strike-slip (G 75)</td>
<td>Boyden L. Syn.</td>
</tr>
<tr>
<td>423</td>
<td>Isoclinal, affecting only Cookson, Oak Bay, Wawelg (L 78)</td>
<td>Contact M.</td>
</tr>
<tr>
<td>393</td>
<td>Unconformity</td>
<td>Perry Fm.</td>
</tr>
</tbody>
</table>

Figure 7. Summary of geologic history of the Robbinston 15' quadrangle.

(A 77, 78) = Abbott (1977, 1978); (F & B 70) = Fullagar and Bottino (1970); (G 75), (G 77) = Gates (1975, 1977); (L 78) = Ludman (1978); (S & F 70) = Spooner and Fairbairn (1970); (W 72, 73) = Westerman (1972, 1973).
REFERENCES


