Bulletin 42

Bedrock Geology of the Bath 1:100,000 Map Sheet, Coastal Maine

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Bedrock Geology of the Bath 1:100,000 Quadrangle, Maine.

Cover photograph:

Upright folds in metamorphic rocks of the Bucksport Formation at Pemaquid Point Lighthouse. The spectacular exposures here reveal many such structural features to the careful observer. This photograph looks directly along the crest of a fold, with layering on the left tilting to the left and layering on the right tilting to the right. In the middle distance the form of the fold is clearly visible. On the skyline to the right is a large ridge underlain with white pegmatite, a very coarse-grained, igneous rock that intrudes the metamorphic rock.

Contents

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ABSTRACT

Bedrock that underlies the area of the Bath 1:100,000 map sheet includes metamorphosed sedimentary and volcanic rocks of Late Cambrian to Silurian age, gabbroic and granitoid intrusive rocks ranging from Late Silurian to Permian age, and basaltic or diabasic dikes of Mesozoic age. The metamorphic rocks have been assigned to seven tectono-stratigraphic sequences: Central Maine, Falmouth-Brunswick, Casco Bay, East Harpswell, Fredericton, Benner Hill, and Megunticook. These sequences are separated by inferred early tectonic thrust faults and late tectonic or post tectonic strike-slip faults of the Norumbega fault zone, so have uncertain relationships to each other. For a few structurally isolated units, the sequence assignment is not clear. Several stages of folding characterize each sequence and are believed to be mostly the result of Late Silurian to Early Devonian phases of the Acadian orogeny. Prograde metamorphism of the volcanic and sedimentary rocks ranges from staurolite grade to sillimanite + K-feldspar grade in a Buchan-type low-pressure metamorphic facies series. Multiple stages of Buchan series metamorphism are clearly indicated by large muscovite pseudomorphs at Small Point. At the highest grade (sillimanite + K-feldspar), pelitic rocks are extensively migmatized. ^{40}Ar/^{39}Ar cooling ages on hornblende from sequences east of the Flying Point fault suggest that major regional high-grade metamorphism occurred during the Silurian-Devonian Acadian orogeny. Younger hornblende cooling ages from the Falmouth-Brunswick sequence in the Brunswick area suggest a more limited region of high-grade metamorphism of Late Paleozoic age possibly related to the intrusion of Permian pegmatite and granite lenses. No unequivocal evidence of large-scale Alleghenian folding has been documented in the map area.

INTRODUCTION

This report, a companion to the *Bedrock Geology of the Bath 1:100,000 Quadrangle, Maine* (Hussey and Marvinney, 2002, which hereafter is referred to as the "Bath map sheet"), describes the bedrock geology of the highly indented south-central coast of Maine (Figure 1). Throughout much of the area bedrock outcrops are abundant, providing superior control in mapping the variety of metasedimentary, metavolcanic, and intrusive rocks that underlie the area. The purpose of this report is to describe the lithology of metamorphic and intrusive rock units, and to discuss the structure, metamorphism, age relations, and economic resources of this part of the southern Maine coast.

The metasedimentary and metavolcanic rocks represent seven lithotectonic sequences: the Central Maine, Falmouth-Brunswick, Casco Bay, East Harpswell, Fredericton, Benner Hill, and Megunticook sequences (Figures 2 and 3). Most sequences are separated by faults from the other sequences, so stratigraphic relationships among sequences are uncertain. The Central Maine sequence in central Maine preserves rocks of Late Ordovician to Early Devonian age, but only Late Ordovician to Early Silurian rocks are exposed here, in the very northwestern corner of the map area. The Falmouth-Brunswick sequence and Casco Bay Group are of probable Middle to Late Ordovician age. The East Harpswell Group is of Late Ordovician-Early Silurian age. The Fredericton sequence is probably Early Silurian. The Benner Hill sequence is Middle to perhaps Late Ordovician. Rocks of the Megunticook sequence are Late Cambrian to Early

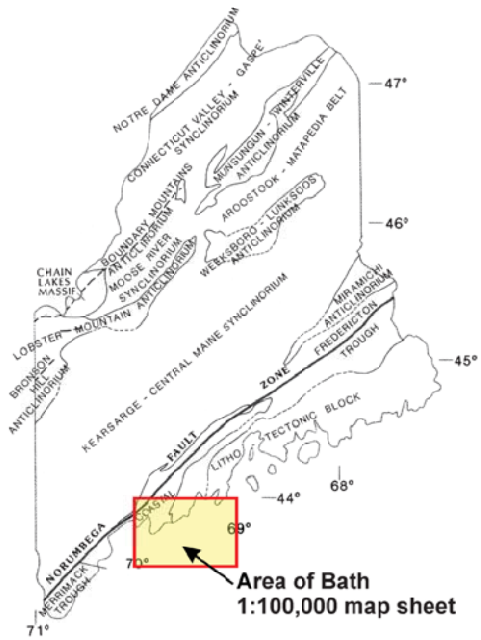

Figure 1. Location of the Bath map sheet in coastal Maine, showing major bedrock features of Maine (Osberg and others 1985).

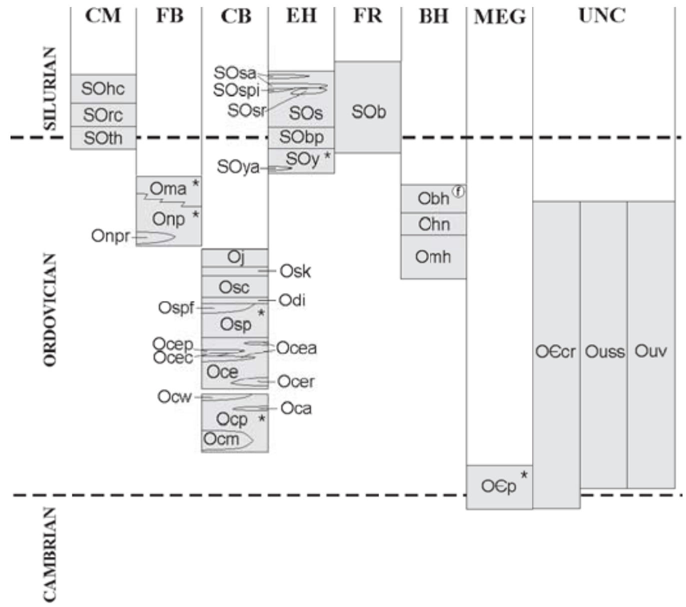

Figure 2. Stratigraphic diagram. Letter symbols indicate rock units on the Bath map sheet and in the text. Height of boxes reflects possible age range. For key to column headings see Figure 3. * = radiometric age control; f = fossil age control.

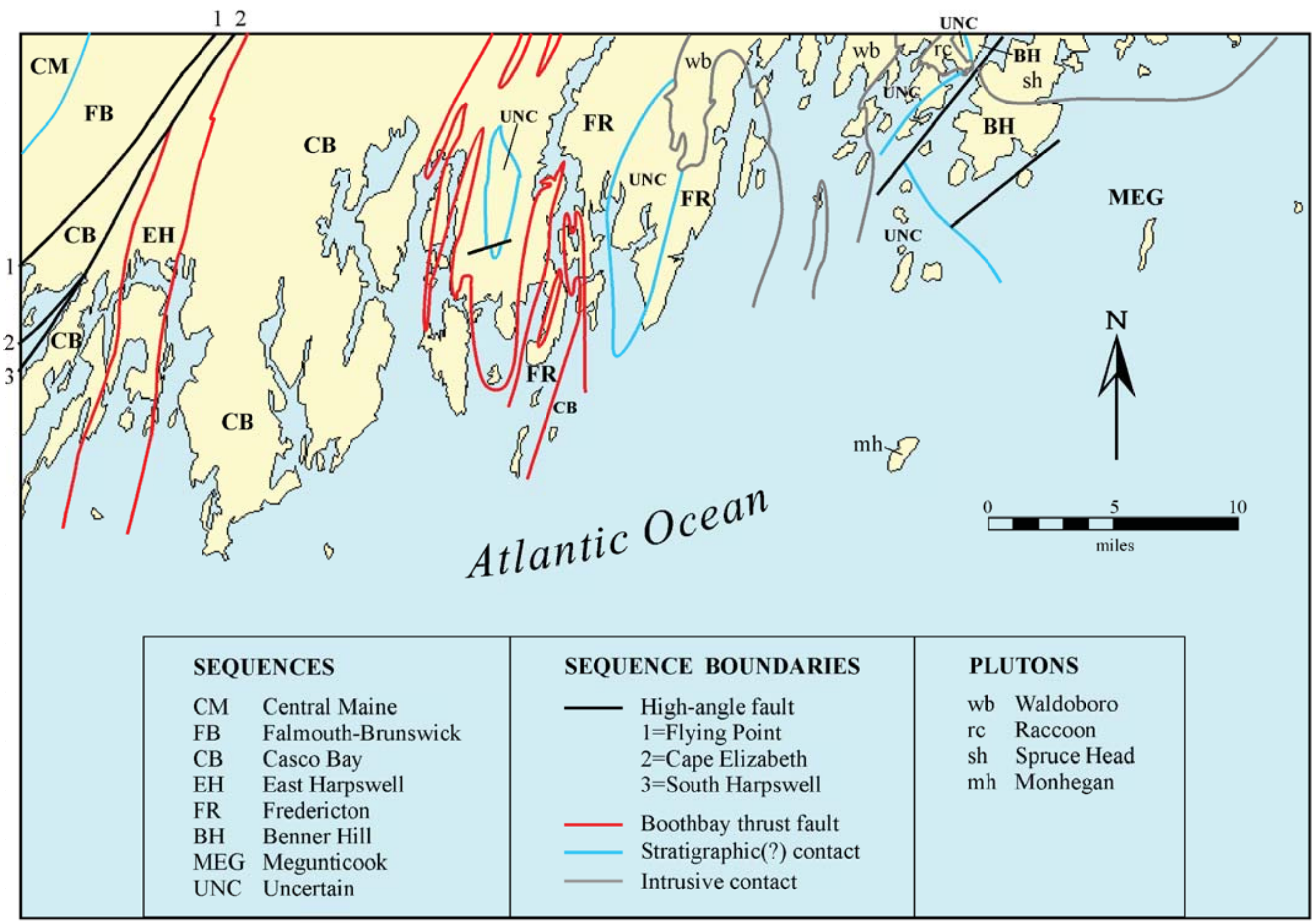

Figure 3. Location of tectono-stratigraphic sequences in the Bath 1:100,000 quadrangle.

Ordovician in age. These stratified rocks have been intruded by syn-tectonic to post-tectonic granite, quartz diorite, gabbro, granitic pegmatite, and a variety of small plutons, some Silurian but most of probable Devonian age, and by numerous undeformed and unmetamorphosed Mesozoic basalt and diabase dikes.

CENTRAL MAINE SEQUENCE

The Central Maine sequence consists of flyschoid metamorphosed feldspathic wackes and pelitic and calcareous rocks ranging in age from Late Ordovician to Early Devonian. It occupies the Central Maine trough, extending northeasterly through Maine in a 100 km-wide belt between the Coastal Lithotectonic block on the southeast and the Bronson Hill-Lobster Mountain-Weeksboro/Lunksoos anticlinoria on the northwest (Figure 1). Within the Bath map sheet, rocks of this sequence crop out only in a small part of the northwestern corner (Figure 3), and are represented by the Torrey Hill, Richmond Corner, and Hutchins Corner Formations (Figure 2).

*Torrey Hill Formation (SOth)**

The name "Torrey Hill Formation" comes from Torrey Hill near the center of the town of Freeport, west of the Bath map sheet, where typical outcrops of the formation are well exposed (Hussey, 1985). The formation consists of very rusty-weathering sulfidic quartz-muscovite-biotite-sillimanite-graphite ± garnet schist, with occasional thin micaceous quartzite interbeds.

This formation is included with the Central Maine sequence on the basis that the continuous, narrow map pattern in this map sheet and the Portland 1:100,00 map sheet (Berry and Hussey, 1998) to the west suggests conformity with the Richmond Corner Formation. To the east the Torrey Hill Formation lies in contact with different units of the Falmouth-Brunswick sequence. The eastern contact of the Torrey Hill Formation is shown as a normal contact on the Bath map sheet. The nature of the contact, however, is equivocal. Where the contact with the Nehumkeag Pond Formation is exposed in a roadcut, on the east side of the northbound lane of I-95, approximately 1.5 km west of the Bath map sheet, it appears conformable. Despite this local appearance, the contact of the Torrey Hill Formation with the Falmouth-Brunswick sequence is interpreted to be either an unconformity or a premetamorphic thrust fault because of the mapped low-angle truncation of units of the Falmouth-Brunswick sequence.

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Letters in* **boldface *type are used throughout the text to identify rock units shown on the Bath map sheet.*

Richmond Corner Formation (SOrc)

The Richmond Corner Formation (Hussey, 1985) lies east of, and adjacent to, the Hutchins Corner Formation. Typically, the Richmond Corner Formation consists of moderately migmatized dark to medium brownish gray slightly schistose quartz-plagioclase-biotite ± garnet ± sillimanite gneiss, and granofels, with sporadic isolated beds 2 to 5 cm thick of coticule (medium reddish brown garnet-quartz-plagioclase-biotite granofels). Calc-silicate interbeds are essentially absent. Garnet occurs as small (½ mm) euhedra and irregular patches up to 1 cm. The migmatization, and the presence of sillimanite and garnet, together with the rarity of calc-silicate form the principal bases for distinguishing rocks of the Richmond Corner Formation from those of the Hutchins Corner Formation. The two formations are otherwise very similar, characterized in general by a salt-and-pepper appearance due to the contrast between the dark biotite and the light feldspar and quartz in equant ½ to 1 mm grains.

Outcrops along I-295 in Yarmouth, Cumberland, and particularly Falmouth, expose the contact zone between the Hutchins Corner and Richmond Corner Formations which appears to be gradational over a 2 to 4 meter interval. There is no evidence for a fault contact. For these reasons, the Richmond Corner Formation is assigned to the Central Maine sequence, conformably below the Hutchins Corner Formation (Figure 2).

Hutchins Corner Formation (SOhc)

The name "Hutchins Corner Formation" (Osberg, 1988) is applied to some of the rocks previously mapped as "Vassalboro Formation" by Osberg and others (1985). As noted by Osberg (1988) "the Vassalboro Formation includes rocks that can be correlated lithologically with the Sangerville and Waterville Formations, as well as rocks older than the Waterville Formation. As a consequence, the name Vassalboro should be abandoned. . . . Rocks that lie beneath the Waterville Formation are called Hutchins Corner Formation (new name)."

Within the Bath map sheet, rocks of the Hutchins Corner Formation are medium to dark brownish gray 3 cm to >5 meter beds of quartz-plagioclase-biotite ± hornblende granofels and gneiss with sporadic 1 to 5 cm interbeds of greenish gray calc-silicate granofels. Rare pelitic interbeds contain sillimanite, indicating sillimanite or possibly sillimanite + K-feldspar grade metamorphism. Pegmatite and quartzo-feldspathic dikes and lit-par-lit stringers of simple mineralogy (quartz, albite, microcline, biotite, muscovite, and sporadically, schorl) are common.

FALMOUTH-BRUNSWICK SEQUENCE

The Falmouth-Brunswick sequence in the Bath map sheet (Figure 3) consists of the Mount Ararat and Nehumkeag Pond Formations (Figure 2). They were first mapped as members of the Cushing Formation (Hussey, 1985) because of their gener-

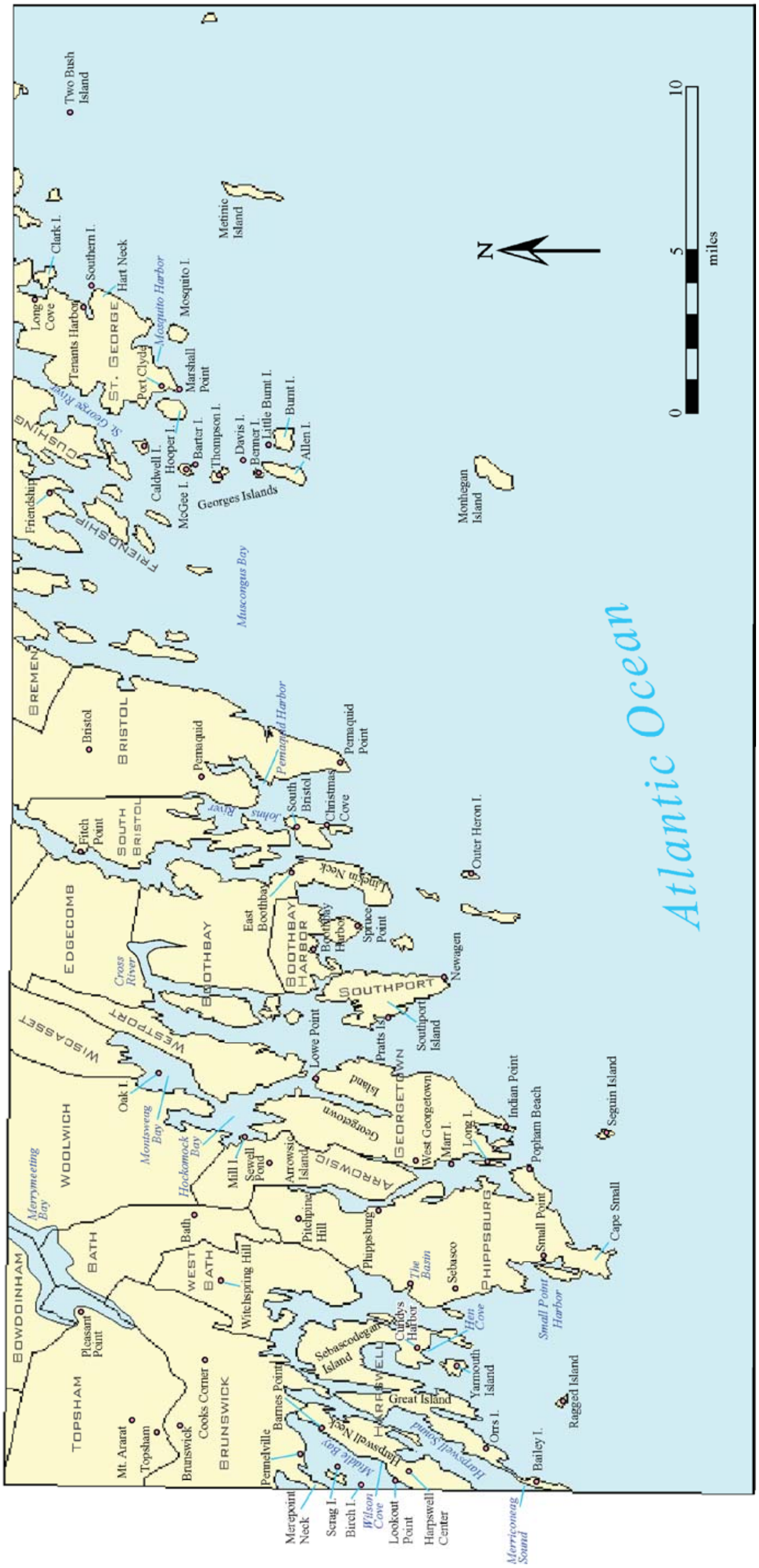


Figure 4. Geographic locations mentioned in the text. Block letters identify townships, or Minor Civil Divisions.

ally similar metavolcanic composition. However, subsequent studies have shown that (1) there are no reasonably close lithic correlations between the Cushing Formation on the one hand and the Mount Ararat and Nehumkeag Pond Formations on the other hand; (2) the Mount Ararat and Nehumkeag Pond Formations are separated from the Cushing Formation by the Flying Point fault, one of the principal segments of the Norumbega fault system (Swanson, 1995; Hussey, 1988, 1989); and (3) the sequences on either side of the Flying Point fault have been subjected to significantly different thermal histories (West and others, 1993). Because of these differences, the Nehumkeag Pond and Mount Ararat Formations are interpreted to constitute a separate sequence, perhaps of a different structural level. The type of boundary with the Central Maine sequence is not clearly known. It may be a thrust-fault boundary (Pankiwskyj, 1996) or it may be an unconformity as suggested by Osberg (1988; Tucker and others, 2001) from studies north of the Bath sheet.

The rocks of the Falmouth-Brunswick sequence are moderately migmatized, and have been metamorphosed to sillimanite or sillimanite + K-feldspar grade.

Nehumkeag Pond Formation (Onp, Onpr)

The Nehumkeag Pond Formation was named by Newberg (1984) for exposures near Nehumkeag Pond in the town of Pittston, north of the Bath map sheet. The dominant lithology is gray plagioclase-quartz-biotite ± garnet gneiss and granofels of probable metavolcanic origin (Figure 5). Along with this are thin- to medium-layered plagioclase-quartz-biotite granofels and gneiss with thin partings of biotite-rich gneissose schist of volcanogenic origin, and zones of quartz-plagioclase-biotite-muscovite-sillimanite ± garnet gneiss or schist interpreted to be metamorphosed interlayered aluminous wackes.

Minor units mappable at the 1:62,500 scale or larger include (1) impure marble, (2) rusty-weathering, sulfidic muscovite-biotite-quartz ± graphite schist, and (3) dark gray hornblende amphibolite with minor associated calc-silicate gneiss. These commonly occur together as discrete units, but for reasons of scale are lumped together on the Bath map sheet as **Onpr**. Other minor rock types form thin lenses in the formation.

Mount Ararat Formation (Oma)

The name for this formation is taken from the exposures on and around Mount Ararat, a low hill in Topsham, Maine. (See Figure 4 for localities in the Bath sheet mentioned in the text.) The name "Mount Ararat Member" was originally applied by Hussey (1985) when these rocks were first mapped and interpreted to be part of the Cushing Formation.

The Mount Ararat Formation typically consists of thin alternations (1 to 10 cm) of amphibolite and felsic granofels or gneiss (Figure 6). Proportions of the two rock types vary considerably; in some areas amphibolite dominates while in others felsic granofels dominates. The amphibolite consists of plagioclase, quartz, hornblende, biotite, minor sphene, and opaque minerals. The felsic granofels or gneiss consists of plagioclase, quartz, and biotite. The alternations of felsic and mafic layers are interpreted to have been beds of felsic and mafic volcanic ash prior to metamorphism. Thin layers of calc-silicate granofels occur sporadically with the amphibolite.

Distribution of outcrops of the Mount Ararat Formation relative to the Nehumkeag Pond Formation suggests a facies interfingering or structural interleaving of the two.

Figure 5. Nehumkeag Pond Formation along the Androscoggin River at the U. S. Route 202 bridge between Topsham and Brunswick, 100 meters east of where a sample of Nehumkeag Pond Formation was taken for radiometric dating.

Figure 6. Mt. Ararat Formation showing the alternation of dark amphibolite and light felsic gneiss layers. Location along the shore of the Androscoggin River at the west end of the footbridge between Topsham and Brunswick. (Green splotches are lichen.)

CASCO BAY GROUP

Rocks of the Casco Bay area were first mapped and named by Katz (1917) west of the Bath map sheet. He defined the Cape Elizabeth formation, Spring Point greenstone, Diamond Island slate, Scarboro phyllite, Spurwink limestone, Jewell phyllite, and Mackworth slate, which he referred to collectively as the Casco Bay Group. The units have since been renamed as formations, except for the modified Spurwink Metalimestone (Bodine, 1965; Hussey, 1985, 1988). The Mackworth Formation, which is not exposed in the Bath map sheet, is now correlated with the Eliot Formation of the Merrimack Group (Berry and Hussey, 1998) and is therefore no longer included with the Casco Bay Group. The Cushing Formation was mapped separately by Katz (1917) as the Cushing Granodiorite. Subsequent investigations by Bodine (1965) and Hussey (1971a, 1971b) revealed the fragmental volcanic nature of the formation, and Hussey (1971a, 1971b) included it as a stratigraphic unit at the base of the Casco Bay Group.

With the separation of the Mount Ararat and Nehumkeag Pond Formations from the original Casco Bay Group to form the separate Falmouth-Brunswick sequence, Hussey (1988) referred to the remaining parts of the Casco Bay Group as the "Saco-Harpswell sequence," thus introducing some confusion. In order to undo this confusion we now abandon the name "Saco-Harpswell sequence" and retain simply "Casco Bay Group" for the same rocks. The Casco Bay Group now includes Katz's original stratigraphic units (except for the Mackworth Formation which is correlated with the Eliot Formation of the Merrimack sequence), and the Cushing Formation, but not rocks of the Falmouth-Brunswick sequence.

Cushing Formation (Ocp, Oca, Ocm, Ocw)

The Cushing Formation consists predominantly of metamorphosed volcanic rocks of felsic to intermediate composition that lie below the Cape Elizabeth Formation. The Cushing Formation is subdivided into the Peaks Island, Merepoint, and Wilson Cove Members. Units of the East Harpswell Group that lie structurally below the Cape Elizabeth Formation in Harpswell (Figures 3 and 4) were formerly included as members of the Cushing Formation (Hussey, 1985). Recent radiometric age determinations, discussed below, show conclusively that these volcanic rocks are distinctly younger than, and therefore cannot correlate with, the Cushing Formation. The contact between the Casco Bay Group and the East Harpswell Group, nowhere exposed, is inferred to be either an unconformity or a pre-metamorphic thrust fault.

Peaks Island Member (Ocp). The Peaks Island Member of the Cushing Formation (Hussey, 1985, 1988) underlies a portion of the Bath map sheet in the general area of Middle Bay, Harpswell (Figure 4). To the southwest, this belt continues through Casco Bay to the town of Cape Elizabeth. This is the part of the Cushing Formation originally interpreted by Katz (1917) to be a deformed granodiorite pluton. The principal lithology is plagioclase-quartz-biotite-muscovite ± microcline granofels and gneiss. Textures and structures suggesting that these rocks are volcanic rather than intrusive in origin include (1) relict phenocryst fragments of plagioclase (oligoclase to andesine) and quartz suggestive of a crystal tuff; (2) relict fragments (highly stretched during tectonism) of older volcanic rock (Figures 7 and 8); (3) relict fiamme structure(?); and (4) relict bedding (Bodine, 1965; Hussey, 1971a). Composition of these metavolcanic rocks based on the metamorphic mineralogy, ranges from rhyolite to dacite with rhyodacite predominating.

Amphibolite (**Oca**), representing a basaltic to andesitic protolith, occurs at or near the top of the Peaks Island Member as a narrow (150 m-wide) lens extending from the north end of Middle Bay 10 km northeast to the Topsham shore of Merrymeeting Bay (Bath map sheet; Figure 4). Minor rock types include muscovite-biotite-quartz-plagioclase schist (Figure 9), and calc-silicate granofels or gneiss in lenses and concretions.

Part of the Peaks Island Member is overlain conformably by and locally interfingers with the Wilson Cove Member of the Cushing Formation. In other places, it is overlain unconformably(?) by the Cape Elizabeth Formation (discussed below).

Merepoint Member (Ocm). The Merepoint Member of the Cushing Formation is a rusty-weathering muscovite-biotite-quartz-plagioclase gneiss (Hussey, 1985, 1988). Its mineralogy is very similar to that of the Bethel Point Formation of the East Harpswell Group with which it was originally correlated (Hussey, 1971b). However, because of significant age differences (about 472 Ma for Merepoint *vs.* about 445 Ma for Bethel Point), the correlation is no longer tenable. Within the Bath map sheet, the Merepoint Member is exposed on Merepoint Neck,

Figure 7. Volcaniclastic texture of the Cushing Formation, Peaks Island Member, at Lookout Point, Harpswell Neck, Harpswell. Light- and dark-colored volcanic fragments suggest that these rocks are derived from fragmental volcanic rocks, and not a strongly deformed plutonic rock. (*30 meters west of Photo 4 on Bath map sheet.*)

Figure 8. Highly stretched clasts of volcanic and volcaniclastic fragments of the Peaks Island Member of the Cushing Formation. Same locality as Figure 7.

Brunswick (Figure 4), as a thin (about 100 meters) lens within gneisses of the Peaks Island Member.

Wilson Cove Member (Ocw). The Wilson Cove Member (Hussey, 1971b) is a distinctive thin unit of black, commonly sulfide-rich rock locally lying above the Peaks Island Member of the Cushing Formation, and below the Cape Elizabeth Formation (Figure 2). The most characteristic rock type is bedded, black garnet-biotite-quartz ± grunerite granofels (Figure 10). Other rock types include biotite-garnet schist; very rusty-weathering hard sulfidic quartzite (field description); and plagioclase-hornblende-biotite-grunerite granofels or gneiss.

In the vicinity of Lookout Point on Harpswell Neck (Figure 4) the Wilson Cove Member fingers out southward into white plagioclase-quartz-muscovite-biotite schistose granofels of the Peaks Island Member as mapped in detail by Hussey (1971b). Northeast of Lookout Point, the Wilson Cove Member is a coherent unit, the outcrop belt of which parallels the shore of Wilson Cove and then swings northward to where it is cut off by the South Harpswell and Cape Elizabeth faults in Middle Bay. On the west side of the faults, the Wilson Cove Member crops out in a narrow belt extending from the Pennelville area of Brunswick (Figure 4) a distance of 4 kilometers to the north-northeast where it pinches out against the Cape Elizabeth Formation. This pinch-out may be either (1) a regional low-angle angular unconformity or (2) a premetamorphic folded thrust fault at the base of the Cape Elizabeth Formation. The main outcrop belt of the Wilson Cove Member continues to the southwest mostly underwater, but emerges on Scrag Island and Birch Island at the very western edge of the map. It extends beyond the Bath sheet to be exposed on Little Iron Island, Black Rock, and Irony Island, names undoubtedly taken from the black, iron-sulfide-rich rocks of the unit.

Cape Elizabeth Formation (Oce, Ocer, Ocep, Ocea, Ocec)

The Cape Elizabeth Formation is the most widely distributed formation of the Casco Bay Group within the map area. Its metamorphic grade ranges from staurolite to sillimanite + K-feldspar in a Buchan-type metamorphic facies series. At the highest grade it is extensively migmatized.

The characteristic lithology of the Cape Elizabeth Formation is light to medium gray quartz-plagioclase-biotite ± musco-

Figure 9. 10-m-thick lens of muscovite-biotite-quartz-plagioclase schist (darker layer indicated by the arrow) in the Peaks Island Member at Lookout Point, Harpswell Neck, Harpswell. (*About 25 meters east of Photo 4 on Bath map sheet.*)

Figure 10. Thin to medium beds of the Wilson Cove Member of the Cushing Formation exposed in a broad fold. The black garnet-biotite schist and granofels is well exposed at Lookout Point, Harpswell Neck. (*Photo 4 of Bath map sheet.*)

Figure 11. Well bedded light gray quartz-feldspar gneiss and quartz-mica schist, Hockomock Bay, Woolwich. This rock type is typical of the Cape Elizabeth Formation. (*Photo 3 of Bath map sheet.*)

Figure 12. Large muscovite pseudomorphs, probably after andalusite, in muscovite-biotite-quartz-staurolite-garnet-andalusite schist of the Cape Elizabeth Formation at Small Point, Phippsburg. Note the fresh staurolite growing into the large pseudomorph to the right of the quarter.

vite schist or gneiss with aluminum-rich pelitic interbeds of muscovite-biotite-quartz schist (Figure 11). The rock locally contains garnet depending on composition, and staurolite, andalusite, sillimanite, or K-feldspar, depending on grade of metamorphism. A considerable percentage of the formation lacks the pelitic interbeds, consisting of monotonous quartz-plagioclase-biotite schist or gneiss. Compositionally zoned calc-silicate lenses representing primary carbonate concretions are widely distributed throughout the formation. At staurolite or higher grade, grossularite and diopside are present in the centers of these concretions. At several localities, and in particular on Orrs and Bailey Islands (Figure 4), boudined amphibolite and chlorite-biotite schist layers are present and may represent thin mafic sills intruded prior to metamorphism.

Exposed along the eastern shore of Bailey and Orrs Islands and on Jaquish Island (just west of the Bath map sheet) is a 1- to 3-meter wide conformable lens of hornblende-tremolite-talc-biotite schist within the Cape Elizabeth Formation (**Oce**). This probably represents a metamorphosed ultramafic sill. It has been mined on a small scale. In his report on the first geological survey of the State of Maine, Jackson (1837) briefly mentions a small talc (talcum of his day) mining operation on Jaquish Island, and this is probably an extension of the Bailey Island lens.

Locally in the Harpswell Neck and Cundys Harbor areas of Harpswell (Figure 4), a belt of very rusty-weathering muscovite-quartz-biotite-staurolite or sillimanite schist (**Ocer**) crops out at the base of the Cape Elizabeth Formation.

In the Small Point area of Phippsburg (Figure 4), the Cape Elizabeth Formation is more pelitic (**Ocep**), consisting of brownish gray biotite-muscovite-staurolite-andalusite and/or sillimanite-garnet-quartz $\pm$ cordierite schist. At the southernmost tip of the peninsula, staurolite porphyroblasts occur as twinned euhedra up to 2 cm long. Andalusite is locally abundant, forming large poikiloblasts up to 5 cm in maximum dimension. Muscovite pseudomorphs up to 4 cm long after andalusite(?) of an earlier metamorphic event are very common in the more pelitic beds (Figure 12).

Several thin belts of amphibolite (**Ocea**) and associated units are mapped within the Cape Elizabeth Formation. The amphibolites represent two or more separate stratigraphic horizons, though their relationships to each other are not well known. They are shown on Figure 13 and are described here from west to east. Just west of Bath, a two-km long and 200-m wide belt of amphibolite and associated slightly rusty-weathering marble and calc-silicate granofels is present within migmatized Cape Elizabeth rocks. This lens may be more extensive, but has not been traced further north or south along strike. In and around The Basin in Phippsburg, and extending around the northern part of the Phippsburg synform (Figure 13), is another similar association, dark gray amphibolite, white marble, and coarse-grained skarn-like calc-silicate granofels with diopside, grossularite, vesuvianite, and scapolite. A small prospect in this unit on the north shore of The Basin is a world-class specimen locality for the mineral grossularite (Thompson and others, 1991), popularly known as “cinnamon” garnet. This belt and the Bath belt may represent the same stratigraphic horizon within the Cape Elizabeth Formation.

On Georgetown Island, amphibolite without marble or calc-silicate rock crops out in a belt from the southern part of Robinhood Cove to Indian Point (Figure 13). The amphibolite exposed on Seguin Island, about 4 km south of the tip of Georgetown Island, is probably a continuation of this belt. It is associated with a sequence of thin units of rusty schist, marble, and calc-silicate granofels which are not shown separately on the Bath map sheet. Also associated with the amphibolite, and separately represented on the Bath sheet as **Ocec**, is a distinctive reddish-brown garnet-magnetite-grunerite(?) granofels, known as coticule (Figure 14). Some specimens of the garnet have a

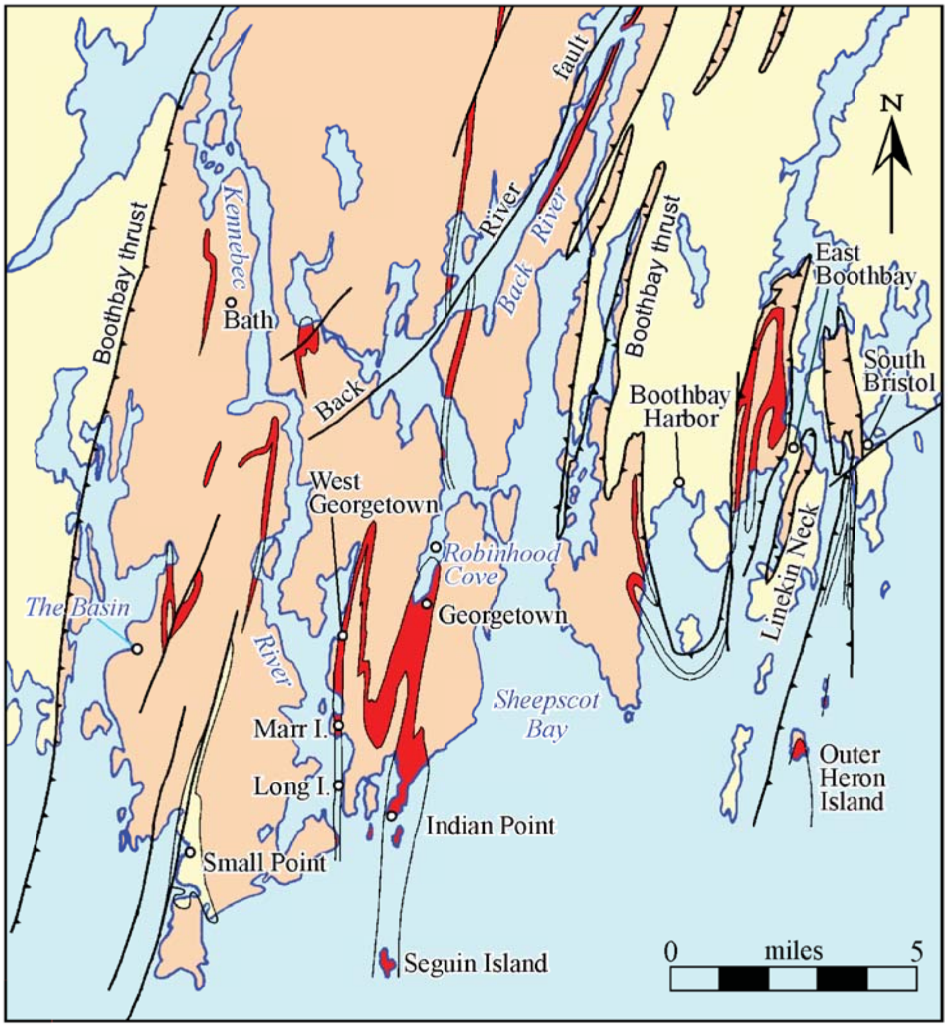


Figure 13. Amphibolite (**Ocea**) and related units (**Ocec**, **Ocep**) in the Cape Elizabeth Formation. Red=amphibolite and related units; Peach=Cape Elizabeth Formation, undifferentiated; Yellow=other rocks, beneath the Boothbay thrust or in upper Casco Bay Group. Plutons omitted for clarity.

smooth, dense texture, resembling jasper. The coticule is characteristically interbedded with quartz-plagioclase-biotite granofels in beds one to 4 cm thick. The coticule apparently pinches out at Robinhood Cove, but appears again on the western side of the island, being particularly well exposed in the West Georgetown area and on Marr and Long Islands in the lower Kennebec River (Figure 13). A second belt of coticule (**Ocec**) occurs at the north end of Arrowsic Island, and probably represents the same stratigraphic horizon as the Georgetown belt.

A thin but conspicuous belt (**Ocea**) of amphibolite and closely associated calc-silicate granofels (in part, very coarse-grained) occupies a fault-broken and folded belt near the Back River in Woolwich, Wiscasset, and Westport (Figure 13). The amphibolite is 10 to 15 m wide, consisting of hornblende, plagioclase, quartz, and biotite. Separated from this by about 20 meters of normal quartzo-feldspathic Cape Elizabeth lithology is a thin calc-silicate granofels or skarn, characteristically with bright

Figure 14. Coticule layer (**Ocec**) in the Cape Elizabeth Formation on Marr Island in the lower Kennebec River. Dark grains in pink garnet rock are magnetite.

green diopside and reddish orange grossularite, the combination of which gives the rock a brightly colored aspect that was responsible for the useful, if not highly technical, field term "Christmas-tree rock."

Lastly, a belt of amphibolite (**Ocea**) within the Cape Elizabeth Formation crops out in a convoluted complex of F_1 and F_2 folds in the East Boothbay area and some of the islands south of Boothbay Harbor (Figure 13). It occupies a position near the Boothbay thrust at the structural base of the Cape Elizabeth Formation. This amphibolite is of simple mineralogy (plagioclase-hornblende-biotite).

The Cape Elizabeth - Cushing Contact

Careful examination of the Bath map sheet from Middle Bay (just west of Harpswell Neck) northeast to Merrymeeting Bay reveals the pinch-out of different minor units of the Cushing Formation against the base of the overlying Cape Elizabeth Formation. Alternative explanations for the relations shown include: (1) the Cape Elizabeth - Cushing contact is an angular unconformity in which the various members of the Cushing Formation were tilted slightly and partly eroded before deposition of the Cape Elizabeth Formation, (2) the truncation of units at the base of the Cape Elizabeth represents a low angle pre-F_2 folded thrust fault, or (3) the apparent truncation reflects facies variations in the Cushing Formation. Alternative 1 is favored because of simplicity, the lack of other indications of major faulting, and the presence of grit zones locally at the base of the Cape Elizabeth Formation in the Portland area (Hussey, 1988).

Spring Point Formation (Ospb, Ospf)

The Spring Point Formation, named for Spring Point, South Portland, near the entrance to Portland Harbor (west of the Bath map sheet) conformably overlies the Cape Elizabeth Formation (Figure 2). The mafic member (**Ospb**) consists of thin-bedded hornblende-garnet-plagioclase amphibolite (Figure 15), hornblende-cummingtonite amphibolite, and a distinctive garnet-hornblende-quartz-plagioclase band 3 m thick. In Harpswell Sound a felsic member (**Ospf**) of thin bedded light gray quartz-plagioclase-biotite-muscovite schistose granofels is mapped at the upper part of the formation. The amphibolites represent metamorphosed basaltic to intermediate volcanic rocks, probably pyroclastic in origin in view of the conspicuous bedding present. The quartzo-feldspathic upper member represents either felsic pyroclastic waterlaid volcanics or slightly reworked volcanogenic sediments.

Rocks assigned to the Spring Point Formation are also exposed in a convoluted, narrow belt in the middle of the Cape Small synform and on the east flank of the Phippsburg synform (Figure 16). On the Bath map sheet, those belts are included in "Upper Casco Bay Group, undifferentiated" (**Ocbu**) because they are so thin.

Diamond Island Formation (Odi)

The Diamond Island Formation, named for Great Diamond and Little Diamond Islands in Casco Bay, is a thin unit conformably overlying the Spring Point Formation (Figure 2). Within the Bath map sheet, the Diamond Island Formation crops out in the Cape Small and Phippsburg synforms (Figure 16), included on the Bath map sheet in **Ocbu**. There, a distinctive black, rusty-weathering quartz-graphite-muscovite phyllite occurs in association with, and presumably above, the amphibolite and calc-silicate gneiss tentatively correlated with the Spring Point Formation.

In the Harpswell Sound area (Figure 4) the Diamond Island Formation has not been observed within the Bath map sheet. It may be present but not exposed between outcrops of the Spring Point and Scarboro Formations; or it may be absent because of stratigraphic pinch-out, tectonic thinning, or faulting. It is present on Barnes Island approximately 2 km west of the map area (Hussey, 1971b).

Scarboro Formation (Osc)

The Scarboro Formation, named for the town of Scarboro (now Scarborough), is exposed on the shores of Harpswell Sound at the very western edge of the Bath map sheet. The following description is based on exposures at the northwestern end of Bailey Island (Figure 4). There, the Scarboro Formation is rusty-weathering fine-grained muscovite-biotite-garnet-quartz ± staurolite ± andalusite schist. Andalusite typically occurs as large poikiloblasts enclosing all other phases. In nearby exposures just west of the Bath map sheet along Merriconeag Sound, the Scarboro Formation includes non-rusty schist of the same mineralogy, and some graphitic dark-matrix schist with biotite, chlorite, and minor graphite, chloritoid, and staurolite.

Figure 15. Thin-layered amphibolite characteristic of the lower part of the Spring Point Formation (**Ospb**). Garnets have been deformed and granulated by post-metamorphic deformation possibly associated with right-lateral strike-slip movement on segments of the Norumbega fault system. North end of the Bailey Island-Orrs Island bridge, Harpswell.

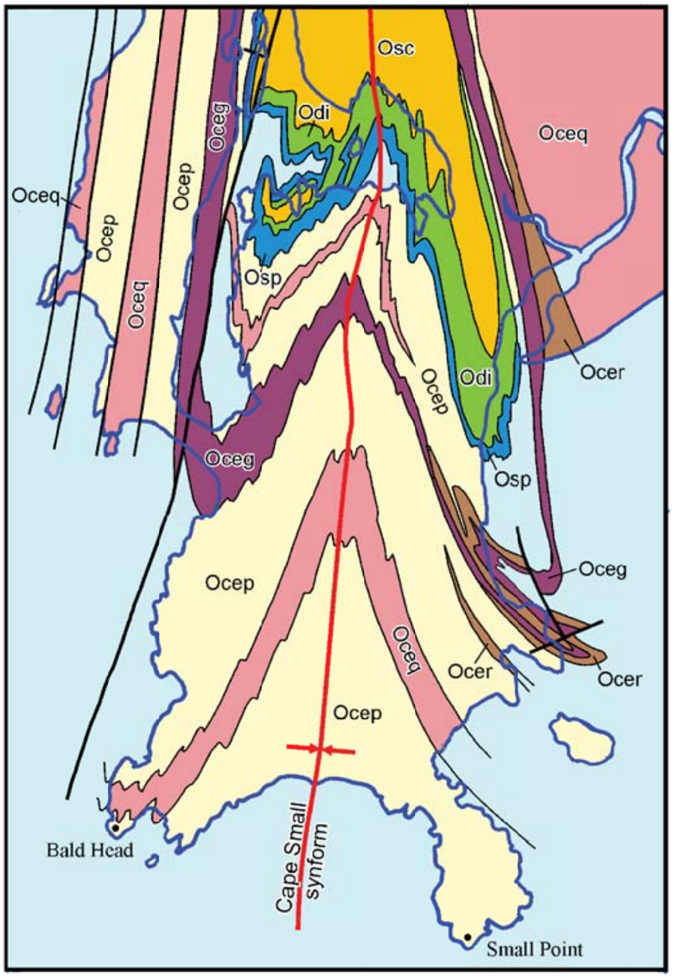


Figure 16. Detailed map of the Small Point area showing intermediate scale recumbent F_1 folds. One set in the southeast part of the map is outlined by the calc-silicate and biotite granofels unit (**Oceg**). The other set, in the northern part, is outlined by the Spring Point (**Osp**) and Diamond Island (**Odi**) Formations. The larger north-trending folds that control the major geometry are F_2 folds. (Unpublished detailed mapping of the Small Point 7½' quadrangle by A. M. Hussey II, 1970-1972.) **Osc** = Scarboro Fm; **Odi** = Diamond Island Fm; **Osp** = Spring Point Fm; **Oce** = Cape Elizabeth Fm; **Ocep** = pelitic phase of **Oce**; **Oceq** = quartzose phase of **Oce**; **Oceg** = calc-silicate and biotite granofels lens in **Oce**; **Ocer** = rusty weathering schist in **Oce**.

Farther east, in the Small Point area, pelitic schist stratigraphically above the Diamond Island Formation is correlated with the Scarboro Formation (Figure 16). As with the Spring Point and Diamond Island Formations, this occurrence is included in the "Upper Casco Bay Group undifferentiated" unit (**Ocbu**) on the Bath map sheet.

Spurwink Metalimestone (Osk) and Jewell Formation (Oj)

At the very western edge of the map sheet, the two units above the Scarboro Formation are exposed. The Spurwink Metalimestone (Hussey, 1985, 1988) is a fine-grained metalimestone thinly interbedded with phyllite. The Jewell Formation is lithologically identical to the Scarboro Formation, and is distinguished only by stratigraphic position above the thin Spurwink unit. These two formations, named for the Spurwink River in Scarborough and Cape Elizabeth and for Jewell Island in Casco Bay, are more widely exposed west of the Bath map sheet.

EAST HARPSWELL GROUP

Rocks of this group were originally included as members of the Cushing Formation (Hussey, 1971b, 1985, 1988). However, radiometric ages (presented below) suggest that the lowest unit, the Yarmouth Island Formation, is Late Ordovician-Early Silurian, younger than any dated rocks of the Casco Bay Group. Lacking evidence of large scale overturning of the sequence, the newly recognized age relationships warrant separation of these rock units into a distinct lithostratigraphic sequence, the East Harpswell Group, as proposed here (Figure 2). The Yarmouth Island, Bethel Point, and Sebascodegan are now regarded as formations of this group.

The East Harpswell Group is exposed in a single north-northeast-trending anticline, the Hen Cove anticline (Figures 3 and 17). The Yarmouth Island Formation is exposed in the core of the fold in the southern part of the belt, where the plunge is gently northward. It is overlain by the Bethel Point Formation, which wraps around the Yarmouth Island Formation in the south and forms the core of the fold to the north where the plunge is nearly horizontal. The Sebascodegan Formation is exposed mainly on the west and east flanks of the fold.

Yarmouth Island Formation (SOy, SOya)

The Yarmouth Island Formation consists dominantly of light gray metamorphosed felsic to intermediate volcanic rocks with lesser calc-silicate granofels or gneiss, amphibolite (some of which may be of sedimentary rather than igneous origin), and feldspathic volcanogenic metasedimentary rocks. The dominant lithology is light gray feebly thin-bedded to massive plagioclase-quartz-gedrite-garnet-cummingtonite gneiss and granofels, probably representing relatively magnesian volcanics of dacitic composition (Figure 18). Other rock types, occurring as thin beds or zones, include plagioclase-quartz-biotite-sillimanite-garnet granofels, locally with cordierite, poikiloblastic staurolite, and pseudomorphs of muscovite, margarite, hercynitic spinel, and chlorite after staurolite (Faiia, 1996). These aluminous granofelses probably represent post-eruptive submarine alteration and reworking of the dacitic fragmental volcanic rocks. Andalusite has been observed in a quartz vein cutting the sillimanite-bearing rocks at one locality. Units within the formation, mappable at 1:24,000 scale (Hussey, 1971b), include calc-silicate gneiss with marble interbeds, and amphibolite. Only one of the amphibolite members (**SOya**) is shown on the Bath sheet. Most amphibolite is intimately associated with or

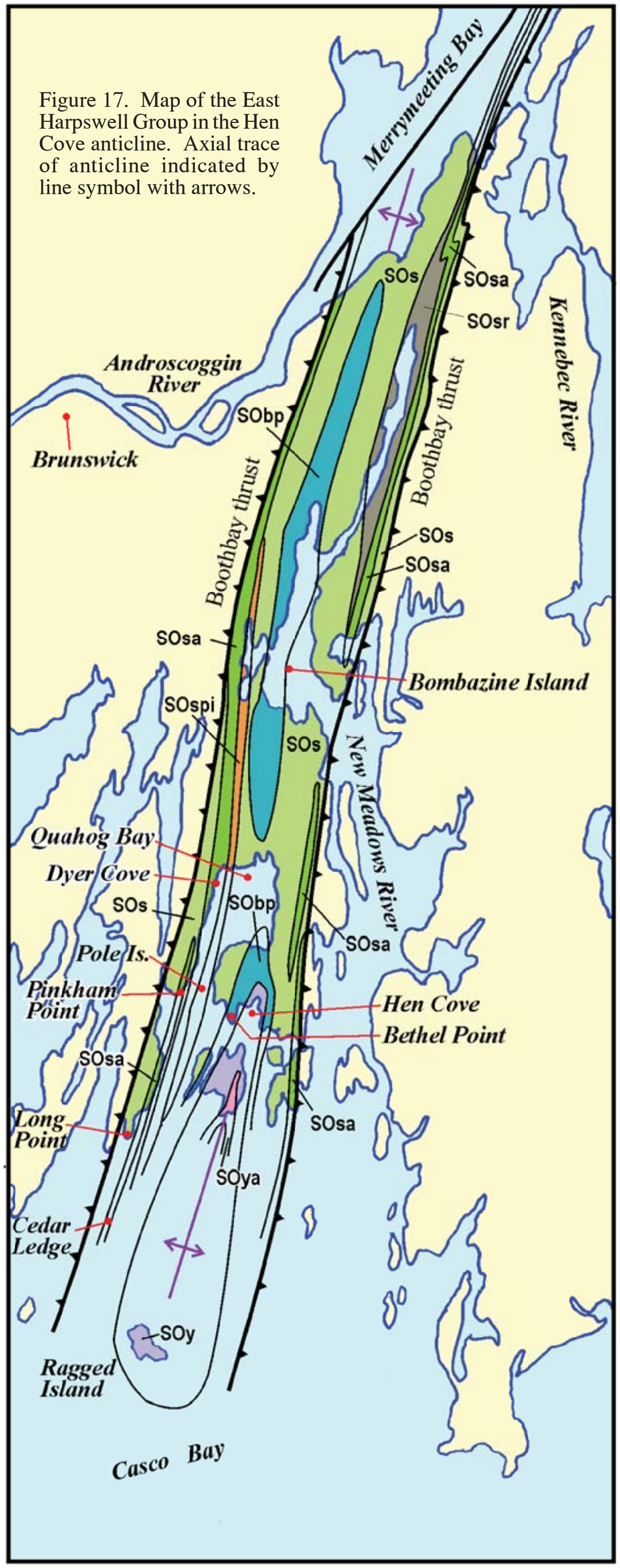


Figure 17. Map of the East Harpswell Group in the Hen Cove anticline. Axial trace of anticline indicated by line symbol with arrows.

Figure 18. Yarmouth Island Formation at Hen Cove, Harpswell showing faint compositional layering (bedding ?) typical of the intermediate to felsic metavolcanics that constitute the principal lithology of the formation. A sample for radiometric dating was taken 20 meters to the east of this photo.

has interbeds of calc-silicate rock, and may represent metamorphosed calcareous sediments rather than mafic metavolcanics.

The Yarmouth Island Formation is restricted in outcrop to the core of the Hen Cove anticline at its southern end (Figure 17), and is structurally, and probably stratigraphically, the lowest unit of the East Harpswell Group.

Bethel Point Formation (SObp)

The Bethel Point Formation (Hussey, 1971b, 1985) has a simple and consistent lithology. It consists of very rusty-weathering sulfidic quartz-muscovite-biotite schist with rare quartz-plagioclase-biotite-muscovite granofels interbeds. East of Brunswick (Figure 17), the formation includes a 5-10 meter wide lens of marble that is not known elsewhere. Within the Bath map sheet the Bethel Point Formation crops out only in the core and limbs of the variably-plunging Hen Cove anticline, and separates the Yarmouth Island Formation from the Sebascodegan Formation. The contacts with these formations appear conformable.

Sebascodegan Formation (SOs, SOsa, SOsr, SOspi)

On the western limb of the Hen Cove anticline (Figure 17), the Sebascodegan Formation consists of thinly interbedded rocks of the following lithology. From most to least abundant they are: (l) light gray plagioclase-quartz-biotite-granofels or gneiss, locally preserving volcanic breccia structure; biotite commonly forms lineated clots giving the rock a coarsely spotted appearance; (2) medium greenish gray calc-silicate granofels with grossularite; meionite (Ca-scapolite) was noted in thin section from calc-silicate granofels exposed on Bombazine Island in New Meadows estuary just north of Sebascodegan Island (Figure 17); (3) quartz-plagioclase-biotite-muscovite-

Figure 19. Two-meter wide lens of pure calcite marble in the Dyer Cove type amphibolite of the Sebascodegan Formation. Roadcut, east side of Maine Route 24, 3 km south of U. S. Highway 1, Cooks Corner, Brunswick.

Figure 20. Coarse-grained amphibolite (plagioclase, hornblende, biotite, sphene) of the Pinkham Point type amphibolite of the Sebascodegan Formation at Long Point, Great Island, Harpswell.

sillimanite granofels; and (4) plagioclase-quartz-biotite-cummingtonite granofels. Interbedded throughout the exposures are 1- to 2-meter-thick sections of rusty weathering biotite-muscovite-quartz schist.

Minor mappable units shown on the Orrs Island 1:24,000-scale map sheet (Hussey, 1971b), not all of which are shown separately on the Bath map sheet, include rusty-weathering sulfidic quartz-plagioclase-biotite granofels, schist, and gneiss (**SOsr**), locally with chromian muscovite (formerly referred to as fuchsite); three types of amphibolite (**SOsa**), described below; calc-silicate granofels (**SOspi**); and feldspathic biotite-tourmaline quartzite. The most mineralogically variable amphibolite, informally referred to as the Dyer Cove type after Dyer Cove (Figure 17; Hussey, 1985) consists of hornblende, gedrite, cummingtonite, light-brown biotite (probably magnesium-rich), and plagioclase in the compositional range labradorite-bytownite. Some outcrops show thin interbeds of calc-silicate rock, occasionally with calcite. The Dyer Cove type amphibolite includes a 2-meter-thick bed of massive pure calcite marble (Figure 19). Its outcrop belt is well marked by a linear series of narrow, shallow quarries where the marble was quarried during the early and middle 19th century for industrial and agricultural purposes. Because of its calcium-rich composition, this amphibolite type is interpreted to be a metamorphosed impure carbonate. In the same belt, especially along strike to the north and on the east limb of the Hen Cove anticline at essentially the same stratigraphic horizon (Figure 17) is a second type of amphibolite, of much simpler mineralogy (plagioclase-hornblende-biotite-sphene), more typical of a metamorphosed volcanic or intrusive rock of mafic to intermediate composition. Another belt of amphibolite, extending from Pinkham Point, Harpswell, to Cedar Ledge, and a 20-meter-wide unit at Long Point, Harpswell (Figure 17), constitute a third distinctive type of amphibolite. Generally of simple mineralogy, with hornblende, andesine, biotite, and sphene, this amphibolite type is significantly coarser-grained (Figure 20). The third type of amphibolite may represent metamorphosed pre-tectonic diorite sills.

The calc-silicate granofels unit, informally referred to here as the Pole Island member of the Sebascodegan Formation (**SOspi**), occurs as a 10-km-long lens on the west limb of the Hen Cove anticline, but does not crop out along the eastern limb (Figure 17; see also Hussey, 1971b). The typical rock type of this lens is light greenish gray quartz-plagioclase-hornblende-biotite-microcline-clinozoisite-diopside ± grossularite granofels. The feldspathic quartzite unit, likewise, is exposed only on the west limb of the Hen Cove anticline, forming a 50-meter-wide belt east of the Dyer Cove type amphibolite and west of the Pole Island member. On the Bath sheet, the quartzite unit is not shown separately, but is included in **SOspi**.

FREDERICTON SEQUENCE

The Fredericton sequence, exposed in a belt extending from the Bath map sheet (Figure 3) through eastern Maine (Figure 1) to Fredericton, New Brunswick, typically consists of metamorphosed calcareous turbidites and pelites. It is represented by the Flume Ridge and Digdeguash Formations in eastern Maine (Ludman, 1987) and by the Bucksport and Appleton Ridge Formations in mid-coast Maine (Bickel, 1976; Berry and Osberg, 1989). Of these, only the Bucksport is exposed in the Bath map sheet (Figure 2).

Bucksport Formation (SOb)

The Bucksport Formation consists dominantly of fine-grained 5-cm-bedded to massive, medium brownish gray quartz-plagioclase-biotite-hornblende granofels, with 2 to 10 cm beds of medium greenish gray calc-silicate granofels. Some exposures lack calc-silicate rock but these intervals, with the

Figure 21. Upright folds in the Bucksport Formation at Pemaquid Point Lighthouse. This photograph looks directly along the crest of an F_2 antiform. In the middle distance the form of the fold is clearly visible. Thin pegmatite sills are common along bedding contacts. On the skyline to the right is a large ridge underlain by a pegmatite dike. (*Photo 6 of Bath map sheet.*)

available outcrop, cannot be resolved into distinct mappable subunits. Rusty weathering biotite-muscovite-quartz schist in intervals 1 to 3 meters thick occurs sporadically throughout the formation. Aluminous pelitic interbeds are virtually lacking. Coarse grained irregularly-textured (1 to 4 cm) motley green and orangish skarn-like calc-silicate rock with grossularite, diopside, and hornblende occurs at scattered locations in the formation, close to the thrust contact with the Cape Elizabeth Formation in the East Boothbay-Boothbay Harbor area.

All exposures of the Bucksport Formation in the Boothbay Harbor-Pemaquid area are very extensively injected by pegmatite ranging from thin lit-par-lit stringers a few centimeters thick to sills, dikes, or irregular masses up to 20 meters wide (Figure 21). Between these, the granofelsic texture and bedding are usually well preserved. Some exposures that appear to be more feldspathic are migmatized and gneissic. In the contact zone with the Cross River Formation in the Johns River-Bristol area (Figure 4), the rocks of the Bucksport Formation are strongly gneissic.

MEGUNTICOOK SEQUENCE

The Megunticook sequence (Osberg and Guidotti, 1974) represents the southwestward extension of the St. Croix Belt of eastern Maine (Ludman, 1987). In the Bath map sheet, this sequence is represented by the Penobscot Formation (Figure 2) exposed on islands at the east edge of the map (Figure 3). Rocks of uncertain sequence which might belong to the Megunticook sequence include the sulfidic and nonsulfidic migmatites of the Cross River Formation, sulfidic schist of the Friendship area, and rusty migmatites exposed on the outer islands of the Georges Islands archipelago (Eusden and others, 1996). Until stratigraphic relationships are better understood, those rocks are listed below under "sequence uncertain."

Penobscot Formation (O€p)

Rocks exposed on Metinic Island, toward the eastern edge of the map sheet (Figure 4), are assigned by Guidotti (1979) to the Penobscot Formation (formerly his Owls Head unit) of the Megunticook sequence. According to Guidotti (1979), "The rocks there are virtually identical with the strata at Owls Head," just north of the Bath map sheet. Guidotti (Maine Geological Survey, unpublished report, 1973) describes the rocks at Owls Head as "Mainly thick-bedded, dark biotite quartzites, schists, and granulites plus massive meta-graywacke or andesite tuffs. Most outcrops have rusty weathering surfaces. Also considerable bedded, buff-weathering quartzite and some metamorphosed mafic volcanics. . . . Some rusty weathering pelites and minor limestones." The informal Owls Head unit has since been correlated with the Penobscot Formation (Osberg and others, 1985; Berry and Osberg, 1989; Berry and others, 2000).

Two Bush Island at the northeast corner of the Bath map sheet (Figure 4), is underlain by rusty-weathering metamorphic rocks that Guidotti (1979) suggests may belong to the Penobscot Formation (his Owls Head unit), based on reconnaissance from a boat. Rusty-weathering metamorphic rocks on Mosquito Island (Figure 4) were originally assigned by Guidotti (1979) to the Benner Hill sequence, but he now assigns them (Berry and others, 2000) to the Penobscot Formation of the Megunticook sequence. The structural relationship of Mosquito Island to smaller islands to the southwest, tentatively assigned to the Benner Hill sequence on the Bath map sheet, is not firmly established.

BENNER HILL SEQUENCE

The Benner Hill sequence (Osberg and Guidotti, 1974; Guidotti, 1979; Berry and others, 2000) occupies an area between the Waldoboro pluton and the Spruce Head pluton (Figure 3). It includes the Mosquito Harbor Formation, the Hart Neck Formation, and the Benner Hill Formation (Figure 2).

Two unnamed units in the Friendship area (Figure 4), one containing amphibolite, calc-silicate rocks, and marble, and the other containing rusty-weathering schist, have been previously assigned to the Benner Hill sequence (Hussey, 1971c; Newberg, 1979). Work in the Thomaston 7½´ quadrangle to the north of the Bath map sheet by Berry and others (2000) suggests, however, that those two units might not belong to the Benner Hill sequence. Considering this interpretation, those units are presented below under the heading of "sequence uncertain."

Mosquito Harbor Formation (Omh)

The Mosquito Harbor Formation (Berry and others, 2000) is named for exposures on the northern shore of Mosquito Harbor, northeast of Port Clyde (Figure 4). The unit is characterized by light-colored feldspathic quartzite and coarse-grained gray mica schist interbedded on a ¼ to 1 cm scale (Guidotti, 1979).

Figure 22. Wildly contorted quartzite and schist layers in the Mosquito Harbor Formation of the Benner Hill sequence at Marshall Point, Port Clyde. The complicated layering and folding in the thin, light-colored quartzite layers is the result of several events. Some folds may be soft-sediment slumps. The foliation is an early metamorphic feature. Most of the folds, shear zones, and migmatite probably accompanied the intrusion of nearby igneous rocks. (*Photo 7 of Bath map sheet.*)

When weathered, the rock develops a pronounced "ribbed" surface due to the thin quartzite layers that stand out in relief. Figure 22 shows the character of this unit at Marshall Point in Port Clyde (Figure 4) where it is migmatitic and deformed. The unit commonly includes layers up to 30 cm thick of flaggy-bedded dark green amphibolite. A few thicker amphibolite layers are also present. On the Bath map sheet, gneisses immediately east of the Waldoboro pluton are assigned to this unit with uncertainty, although if the interpretation of Berry and others (2000) proves correct, that assignment may not be tenable.

The Mosquito Harbor Formation is overlain conformably by the Hart Neck Formation, with the contact gradational over a thickness of 50 meters (Guidotti, 1979).

Hart Neck Formation (Ohn)

The Hart Neck Formation (Berry and others, 2000) is named for shoreline exposures on Hart Neck, south of Tenants Harbor (Figure 4). It is characterized by Guidotti (1979) as a heterogeneous unit consisting of numerous gray-weathering, biotitic rock types including quartzite, granofels, quartzose metapelite, grits, and quartz-pebble metaconglomerate, with granofels, grits, and metapelite being most common. Garnet is rare. Bedding thickness is commonly 3 to 10 cm, but ranges from a few millimeters up to 3 meters thick. Some of the quartz metapelites are fissile with mm-scale light-colored quartz laminae, and are difficult to distinguish from those in the Mosquito Harbor Formation. Metapelites in the Hart Neck Formation are almost always closely associated with biotite granofels and grits, both of which are nearly absent in the Mosquito Harbor Formation. The quartz-pebble metaconglomerate, though present only in thin units, is one of the most distinctive rocks of the Hart Neck Formation. Pebbles are mostly quartzite and vein quartz ranging up to 10 cm and set in a biotitic quartzite matrix.

The contact of the Hart Neck Formation with the overlying Benner Hill Formation is fairly sharp and interpreted to be conformable (Guidotti, 1979; Berry and others, 2000).

Benner Hill Formation (Obh)

The Benner Hill Formation (Osberg and others, 1985) consists mostly of thinly interbedded rusty-weathering quartz-mica schist and quartzite. In most areas thin bedlets rich in pale garnet characterize the formation (Osberg and Guidotti, 1974). In a few places rocks of this lithology are interbedded with mafic metavolcanic rocks, some of which have relict structures resembling pillows. Rusty mica schist is interbedded with garnet-bearing rocks typical of the Benner Hill Formation on Southern Island at the mouth of Tenants Harbor (Figure 4; Guidotti, 1979). Black, graphite-rich schist occurs at the base of the formation in the Thomaston quadrangle (Berry and others, 2000).

In places, such as along the west shore of the St. George River estuary just south of the Spruce Head pluton, rocks with abundant garnet bedlets are on strike with rusty-weathering quartz-mica schists described informally as the Prison Farm lithology (Hussey, 1985). This map relationship suggests that the Prison Farm unit is a facies variant of the Benner Hill Formation (Osberg and Guidotti, 1974; Guidotti, 1979; Osberg and others, 1985). Berry and others (2000) offer as an alternative explanation that a major regional thrust fault separates the Benner Hill Formation to the east from the Prison Farm unit and other units to its west.

Rocks Exposed on the Georges Islands, St. George

Eusden and others (1996) and Eden and Pavlik (1996) have mapped non-rusty to slightly rusty interbedded micaceous metawacke and metapelite on the islands comprising the inner part of the Georges Islands group off Port Clyde (Figure 4). Eusden (2001, unpublished compilation map) now correlates rocks on the northern island (Caldwell Island) with the Hart Neck Formation, and rocks on adjacent islands to its south and east (Little Caldwell, Teal, and Hooper Islands) with the Mosquito Harbor Formation. At the top of the Mosquito Harbor Formation is a thin, yet persistent unit of amphibolite and garnet coticule. The formations project directly to the mainland units at Port Clyde, so they are correlated with reasonable confidence. Isolated exposures along the shores of a few southerly islands in the Georges Island group (Davis and Benner Islands) are tentatively assigned to the Mosquito Harbor Formation because of their somewhat similar lithology. But due to lack of offshore exposure, stratigraphic continuity with other units of the Benner Hill sequence cannot be established, making their stratigraphic position somewhat tentative.

SEQUENCE UNCERTAIN

For several rock units, especially in the eastern part of the Bath map sheet, it is not clear to which stratigraphic sequence they belong due to structural isolation, insufficient exposure, the presence of intervening plutons, or unknown age. As more is learned about these rocks, it may be possible to assign them to one of the sequences already described, or they may need to be assigned to new sequences. The following units are described generally from west to east.

Cross River Formation (O€cr, O€crg)

The Cross River Formation is named from exposures in and around the tidal basin of the Cross River in Boothbay (Figure 4; Hussey, 1985). In this area, the core of the Boothbay anticline, the main part of the formation (**O€cr**) is an extremely migmatized rusty-weathering gneiss. Locally where least migmatized, it consists of very sulfidic muscovite-graphite-sillimanite-quartz schist. Where most migmatized, the original metamorphic character is obliterated and the rock is a rusty-weathering quartz-plagioclase-biotite-muscovite gneiss with megacrysts of feldspar scattered throughout (Figure 23). The migmatite includes rafts of restitic quartzite, amphibolite, and metamorphosed calc-silicate concretions, all randomly oriented. In the Cross River area (Figure 4) a thin granofels unit (**O€crg**) is mapped at the top of the formation. This unit consists of fine-grained dark gray quartz-plagioclase-biotite-garnet granofels with salt-and-pepper texture. Interbedded with this, particularly near the top, adjacent to outcrops of the Bucksport Formation, are zones of medium-grained amphibolite with large irregular porphyroblasts of garnet. The contact between the Bucksport and Cross River Formations is exposed in a small outcrop along the northwest shore of Cross River in the town of Boothbay (Figure 4). There, regrettably, the contact relation of the two formations is obscured by a pegmatite sill one meter thick. Conformability that is suggested by parallelism of bedding on either side of the contact thus cannot be confirmed. There is no evidence of shearing or faulting at this locality.

The Cross River Formation (**O€cr**) is exposed in a second belt to the east, in the core of the Pemaquid Harbor anticline. In this belt, the formation includes the same rusty-weathering migmatite as in the Cross River area, but also contains non-rusty, less migmatized quartz-plagioclase-biotite ± sillimanite gneiss. The granofels unit (**O€crg**) has not been identified there. In both areas, the Cross River Formation crops out in the cores of antiforms and is structurally overlain by the Bucksport Formation (cross-sections A-A´ and B-B´ on the Bath map sheet).

Unnamed amphibolite unit (Ouv)

Amphibolite with associated calc-silicate rocks and impure marble is mapped in a belt east of the Waldoboro pluton in Friendship (Figure 4). Locally, the amphibolite beds show well-preserved relict pillow structures with vesicular texture (Figure 24) indicating they are metavolcanic rocks. In most places, however, the pillows are strongly stretched by deformation. This unit is between gneisses possibly equivalent to the Mosquito Harbor Formation to its west, and unnamed sulfidic schists to its east (Hussey, 1971c; Newberg, 1979). The amphibolite unit is not repeated to the east as would be expected if the sulfidic schist unit were in the core of a map-scale fold.

Unnamed sulfidic schist (Ouss)

Several areas of unnamed sulfidic schist (**Ouss**) are mapped east of the Waldoboro pluton. One of these areas is

Figure 23. Extremely migmatized "popcorn" gneiss that characterizes most of the rusty-weathering lower portion of the Cross River Formation, Edgecomb.

Figure 24. Metamorphosed pillow basalt of the unnamed metavolcanic unit (**Ouv**), Friendship. The sequence to which this unit belongs is uncertain. (*Photo 8 of Bath map sheet.*)

along the shore in Friendship, east of the unnamed amphibolite unit (**Ouv**) (Hussey, 1971c). This unit projects northeastward into the Thomaston 7½' quadrangle (north of the Bath map sheet) where it was mapped informally as the Prison Farm unit by Guidotti (Maine Geological Survey, unpublished report, 1973; Osberg and Guidotti, 1974). The most prominent rock type is rusty-weathering muscovite-biotite-quartz schist with abundant completely to partially pseudomorphed andalusite and staurolite porphyroblasts. Minor quartzite and quartz-biotite schist are present. Bedding, where discernable, is on a 3 to 10 cm scale. In Friendship, the rusty schist contains abundant sheets of amphibolite ranging from ½ to 3 meters thick, which may represent metamorphosed mafic sills.

Another area of sulfidic schist, in the outer part of the Georges Islands (Burnt, Little Burnt, Allen, Benner, and Davis islands; Figure 4) has been referred to informally as the Allen Island Formation (King, 1994). It consists of rusty-weathering micaceous and feldspathic quartzite and medium-grained to coarse-grained muscovite-biotite-sillimanite schist. Bedding thickness varies from 1 cm to 1 m. Oval lenses of calc-silicate rock are fairly common (Eusden, written communication, 2001).

CORRELATIONS AND AGES OF THE STRATIFIED ROCKS

Ages of most stratified rocks in the Bath map sheet are only loosely constrained. No bedrock fossils are known from anywhere in the Bath map sheet. Even beyond the map sheet, fossils are altogether unknown from the Casco Bay and East Harpswell Groups or Falmouth-Brunswick sequence. Fossils are known from elsewhere in the central Maine and Fredericton sequences, though not in the particular formations exposed in the Bath map sheet. The Hart Neck Formation of the Benner Hill sequence has yielded Ordovician fossils in the Rockland area, about 13 km north of the Bath map sheet; rocks correlative with the Penobscot Formation of the Megunticook sequence contain Early Ordovician fossils in southern New Brunswick, about 200 km distant.

Radiometric ages have been determined for volcanic rocks of the Casco Bay Group (Cushing and Spring Point Formations), the Falmouth-Brunswick sequence (Nehumkeag Pond and Mount Ararat Formations), and Megunticook sequence (Penobscot Formation). Radiometric ages of many of the plutonic rocks provide a minimum possible age of the rocks they cut. Most sequences are cut by dated Devonian plutons, and some by Silurian plutons. Numerous $^{40}Ar/^{39}Ar$ hornblende ages (West and others, 1988, 1993) date post-metamorphic cooling which does not further constrain ages of the stratified rocks themselves.

The following sections discuss correlations of units within and beyond the map sheet based on similarity of rock type and similarity of unit sequences in order to constrain regional stratigraphic and structural models. Age equivalence is not necessarily implied.

Central Maine sequence

The Hutchins Corner Formation has been traced from the type area near Palermo, Maine, to the northwest corner of the Bath map sheet through regional mapping (Hussey, unpublished reconnaissance mapping; Newberg, 1984; Pankiwskyj, 1996; Osberg, 1988). The Torrey Hill Formation is correlated with the Beaver Ridge Formation in the Brooks-Palermo area (Pankiwskyj, 1996). Pankiwskyj, however, assigns the Beaver Ridge Formation to the Falmouth-Brunswick sequence, and infers a major thrust fault (Hackmatack Pond fault) between it and the Hutchins Corner Formation of the central Maine sequence. Further comparisons of stratigraphic relations, lithology, deformation styles, and radiometric ages are necessary to resolve the question of sequence assignment.

The Richmond Corner and Torrey Hill Formations were originally designated as members of the Cushing Formation (Hussey, 1985; Newberg, 1984). They were elevated to formation rank when rocks west of the Flying Point fault were separated from the Cushing to form the Falmouth - Brunswick sequence (Hussey, 1988, 1989). Reexamination of many of the easternmost exposures of biotite granofels originally included with the Hutchins Corner Formation revealed the presence of sparing garnet and sillimanite; consequently they were reassigned to the Richmond Corner Formation. Despite these differences of mineralogy, the two formations are otherwise similar in general appearance. This, along with the fact that the rocks of the Torrey Hill, Richmond Corner, and Hutchins Corner Formations appear to be a conformable sequence, warrants reassignment of these two formations to the Central Maine sequence rather than the Falmouth-Brunswick sequence. Since the Torrey Hill Formation lies adjacent to different units of the Nehumkeag Pond and Mount Ararat Formations, the lower (eastern) contact of the Torrey Hill Formation is either a pre-metamorphic folded thrust fault or an unconformity.

Falmouth-Brunswick sequence

The Falmouth-Brunswick sequence consists in the Bath sheet of the Nehumkeag Pond Formation and its various members, and the Mount Ararat Formation. The Mount Ararat Formation may correlate with the Marden Hill and Parmenter Cemetery Formations in the Palermo area on strike 60 km to the northeast (Pankiwskyj, 1996). Preliminary U-Pb ages on zircons from the Mount Ararat and Nehumkeag Pond Formations suggest a Middle Ordovician age for these formations. John Aleinikoff (written communication, 2002) obtained a 458 ± 3 Ma TIMS age for a 1-meter wide granitic gneiss sill cutting the Mount Ararat Formation at Little River on the east side of Wolf Neck, Freeport. He also analyzed zircons by SHRIMP from felsic interbeds of the Mount Ararat Formation at the same locality that were discordant, but suggest an age of about 450 Ma. SHRIMP analysis of zircons from the Nehumkeag Pond Formation in the Androscoggin River between Brunswick and Topsham (Figure 4) were also discordant, but suggest an age of about 460 Ma. A U-Pb monazite age of 316 ± 1 Ma from the same sample (Aleinikoff, personal communication, 1994) is probably a metamorphic age of some sort, and may even represent a mixed population of monazites of different ages. These preliminary ages are consistent with the 460 ± 2 Ma age reported for the Carrs Corner Formation (correlated with the Nehumkeag Pond) in Palermo, north of the Bath map sheet (Tucker and others, 2001).

The few radiometric ages available suggest that rocks of the Falmouth-Brunswick sequence may be somewhat younger (ca. 460 Ma) than rocks of the Casco Bay Group (ca. 470 Ma). This supports the interpretation that the Falmouth-Brunswick sequence is not part of the Cushing Formation. The Falmouth-Brunswick sequence may represent a basement to the Late Ordovician - Devonian rocks of the Central Maine sequence.

Casco Bay Group

Units of the Casco Bay Group correlate with rocks along strike to the north-northeast in the Liberty-Palermo area mapped by Pankiwskyj (1976, 1996) and West (2000). This correlation is based primarily on similarity of lithologic sequence.

U-Pb zircon dating of the Peaks Island Member of the Cushing from Danford Cove in South Portland (Hussey and Bothner, 1995, stop 2) gives eruption ages for the upper part of the member of 471 ± 3 Ma (J. N. Aleinikoff, in Hussey and others, 1993) and 473 ± 2 Ma (Robert D. Tucker, personal communication, 1998). Another age constraint on the Casco Bay Group is the 469 ± 3 Ma U-Pb zircon age for the Spring Point Formation in the Liberty area, north of the Bath map sheet (Tucker and others, 2001). The dates show that these volcanic rocks were erupted in Middle Ordovician time. Overlying parts of the Casco Bay Group may be Middle to Late Ordovician. Felsic and intermediate volcanic rocks of similar age are reported by Moench and Aleinikoff (2002) for the Ammonoosuc Volcanics in the Bronson Hill belt of New Hampshire.

The relationship of the Cape Elizabeth Formation to the Merrimack Group of southern Maine and southeastern New Hampshire has been a matter of uncertainty and confusion. Originally, Katz (1917) correlated the Eliot Formation of the Merrimack Group with the Cape Elizabeth Formation. Ongoing work by Hussey demonstrates that Katz (1917) included two lithically dissimilar rock units as part of the Cape Elizabeth Formation. That part of Katz's (1917) Cape Elizabeth outcrop belt extending from Saco northeastward toward Portland is now correlated with the Eliot Formation. These rocks have the same calcite and ankerite-rich modal composition as the Eliot Formation in the Eliot area at the southwestern tip of Maine, and are otherwise lithically identical. Also, rocks in Casco Bay that Katz (1917) mapped as the Mackworth Formation are lithically similar, and are thus correlated with the Eliot Formation (Hussey and others, 1993; Berry and Hussey, 1998). In addition, Katz (1917) mapped as part of the Cape Elizabeth Formation those heavier bedded but similar carbonate-rich rocks in the Two Lights State Park area in the town of Cape Elizabeth. He suggested that the rocks at the locality of High Head in Two Lights State Park are typical of the Cape Elizabeth Formation. Hussey and others (1993) recognize the similarity of those rocks to the Kittery Formation of the Merrimack Group, with which they are now correlated. In contrast, the other rocks that Katz (1917) mapped as part of the Cape Elizabeth Formation are the pelitic and psammitic rocks that lie in sequence above the metavolcanic rocks of the Cushing Formation and beneath the mafic metavolcanic rocks of the Spring Point Formation. These rocks are characterized by an aluminous composition in which pelitic mineral assemblages (with sillimanite, andalusite, staurolite, or garnet) are developed at the higher grades of metamorphism as in the Bath 1:100,000 map sheet. At similarly high grades of metamorphism in the Portland area, rocks equivalent to the Eliot Formation develop a calc-silicate paragenesis (with epidote, hornblende, or diopside).

In light of our present understanding, thus it appears that Katz (1917) mapped as "Cape Elizabeth" two contrasting and unrelated groups of rocks, the one carbonate-rich, and the other pelitic. This mapping of two units under one name and the designation of High Head at Two Lights State Park as a reference locality for the Cape Elizabeth Formation (now Kittery Formation), might seem to warrant abandoning the name. However, since the name "Cape Elizabeth" is so widely used and generally understood to represent the package of pelitic/psammitic rocks of the Casco Bay Group below the Spring Point Formation (Osberg and others, 1985, for example), it would be inappropriate to rename the formation. Because there are other localities within the town of Cape Elizabeth where these pelitic rocks are in stratigraphic order within the Casco Bay Group, the name Cape Elizabeth can appropriately be retained; only the type locality need be changed, but that is beyond the limits of the Bath map sheet.

Within the Bath map area, all rocks represented as Cape Elizabeth lie conformably beneath the Spring Point Formation and are pelitic to subpelitic.

East Harpswell Group

The Yarmouth Island Formation is exposed in the core of the Hen Cove anticline. It is structurally overlain, in turn, by the Bethel Point, Sebascodegan, and Cape Elizabeth Formations. Originally, Hussey (1971b) interpreted this to be a conformable stratigraphic sequence, with the Yarmouth Island oldest and the Cape Elizabeth youngest. Recently, Robert D. Tucker (personal communication, 1995) obtained a U-Pb age of 445 ± 2 Ma on intermediate to felsic metatuffs from the upper part of the Yarmouth Island Formation, indicating it is latest Ordovician to earliest Silurian in age. The Bethel Point and Sebascodegan Formations, still interpreted to lie conformably above the Yarmouth Island Formation, are also taken to be latest Ordovician to early Silurian. This means that the entire East Harpswell Group is younger than any of the rocks of the Casco Bay Group, including the Cape Elizabeth Formation *that structurally overlies it*. Consequently, the contact of the East Harpswell Group with the structurally overlying Casco Bay Group is now interpreted to be a major thrust fault (the Boothbay fault; discussed below).

The age of the Sebascodegan Formation now appears to be about the same as that of the Bucksport Formation. This age and the lithologic similarity of parts of the two formations suggests that they may be equivalent. The Hutchins Corner Formation of central Maine and the Berwick Formation of southern Maine and New Hampshire may also correlate. No correlatives for the Yarmouth Island or the Bethel Point Formations are known in the area.

Fredericton sequence

About 20 km north of the Bath map sheet, the Bucksport Formation is intruded by the Late Silurian North Union Granite Gneiss dated at 422 ± 2 Ma (Tucker and others, 2001), indicating a Silurian or older age for the Bucksport Formation. In that same area, the Bucksport Formation is interpreted to be conformable and interstratified with the Appleton Ridge Formation (Stewart, 1998; West, 2000; Tucker and others, 2001), which has been correlated with the fossiliferous Digdeguash Formation of southern New Brunswick that contains Early Silurian graptolites (Fyffe and Riva, 2001). These relationships indicate a Silurian to perhaps Late Ordovician age for the Bucksport Formation. The Bucksport Formation correlates with the Flume Ridge Formation of eastern Maine.

Benner Hill sequence

Rocks of this sequence have been mapped in the Bath map sheet around Port Clyde (Figure 4; Guidotti, 1979) and north of the Bath map sheet into the Thomaston area (Osberg and Guidotti, 1974). This belt contains the type localities for all three formations (Berry and others, 2000). In the Thomaston 7½ ' quadrangle, a siliceous coquinite near the top of the Hart Neck Formation has yielded highly deformed, yet identifiable, brachiopods. Boucot (Boucot and others, 1972; Boucot, 1973) confidently interprets the fauna to be of Caradocian (Late Ordovician) age, although Neuman (1973) presents a case for possibly an older Ordovician age.

Megunticook sequence

Fossils have not been found in the Megunticook sequence in the Bath map sheet. Tremadocian (Early Ordovician) graptolites, however, are present in the Calais Formation on Cookson Island in the St. Stephen area, southern New Brunswick (Ruitenberg and Ludman, 1978). The Calais Formation is correlated with the Penobscot Formation by Ludman (1987) and Berry and Osberg (1989). Tucker and others (2001) report a Late Cambrian-Early Ordovician U-Pb zircon age of 503 ± 5 Ma for a metamorphosed fragmental volcanic rock at the base of the Penobscot Formation, north of the Bath map sheet in Lincolnville. On the basis of the fossil age, the U-Pb age, and correlation, the Penobscot Formation in the Bath map sheet is assigned a Late Cambrian-Early Ordovician age.

Sequence uncertain

Much of the Cross River Formation (**O€cr**) may correlate with parts of the Penobscot Formation on the basis of its rusty and pelitic character. Some lower parts of the Cross River in the Pemaquid anticline are only slighly rusty and similar to parts of the Megunticook Formation in Lincolnville. This would indicate a Cambrian to Early Ordovician age for the Cross River Formation. Its contact with the overlying Bucksport Formation would therefore be either an unconformity or a low-angle fault.

The unnamed amphibolite unit (**Ouv**) had been assigned previously to the Benner Hill sequence because of its position between sulfidic schist of the Prison Farm unit to its east and gneisses possibly equivalent to the Mosquito Harbor Formation to its west (Hussey, 1985). Also, the Benner Hill Formation contains amphibolites, some of which reportedly may preserve relict pillow structure (Guidotti, 1979). Arguments against assigning the **Ouv** unit to the Benner Hill sequence include the association of marble and calc-silicate rocks with the pillow lavas, which are not known in the Benner Hill Formation, the absence of the Hart Neck Formation between the amphibolite unit (**Ouv**) and the possible Mosquito Harbor rocks (**Omh?**), and the lack of repetition of the amphibolite unit to the east of the unnamed sulfidic schist. Furthermore, the thrust fault proposed by Berry and others (2000) if extrapolated southward, would separate the unnamed amphibolite unit from the Benner Hill sequence. Therefore, the assignment of this unit to the Benner Hill sequence is now considered uncertain. An alternative might be the Megunticook sequence, since thin units of pillow basalt and marble are known below sulfidic schists at the base of the Penobscot Formation (Berry and Osberg, 1989). Correlation is hampered by migmatization against the Waldoboro pluton, intense deformation, and lack of continuity to the northeast.

The unit of unnamed sulfidic schist (**Ouss**) at Friendship (Figure 4) traces northward into the Prison Farm unit of Osberg and Guidotti (1974). If it is a facies of the Benner Hill Formation (Osberg and Guidotti, 1974; Guidotti, 1979), then the unnamed schist is Ordovician. If it is not part of the Benner Hill sequence (Berry and others, 2000) then its age is unknown, but presumably Cambrian or Ordovician, since it appears to share the same Silurian metamorphism with the Benner Hill sequence (West and others, 1995).

Rusty metawackes and metapelites (**Ouss**) mapped on the outer Georges Islands have been correlated by Eusden and others (1996) with the Penobscot Formation of the St. Croix belt. Alternatively these rusty rocks may correlate with the unnamed sulfidic schist in Friendship, which maps northward into the Prison Farm unit in the Thomaston 7½´ quadrangle.

The few small exposures on the outer Georges Islands tentatively assigned to the Mosquito Harbor Formation (**Omh?**) are in contact with unnamed sulfidic schist. If this sulfidic schist is part of the Penobscot Formation, the contact might represent the Benner Hill sequence resting in stratigraphic contact above the Megunticook sequence. Local relationships on the outer islands, however, suggest that the sulfidic schist is younger than the rocks labeled "**Omh?**" (King and Eusden, 1994). It is partly due to this apparent inconsistency that the assignment to the Mosquito Harbor Formation is questioned, and the unnamed sulfidic schist is not assigned to the Penobscot Formation.

INTRUSIVE ROCKS

There is a variety of metamorphosed and unmetamorphosed plutonic rocks in the Bath map sheet. The metamorphosed intrusive bodies are mostly dike-like or sill-like. These include the Lincoln Sill, Edgecomb Gneiss, Oak Island Gneiss, and small unnamed metadiorite and metagabbro plutons. Minor metamorphosed dikes and sills of mafic and ultramafic composition are sporadically distributed in the Cape Elizabeth and Cushing Formations.

Unmetamorphosed igneous rocks range from Silurian to Mesozoic age. Major granitic intrusions are the Silurian Spruce Head pluton and the Devonian Waldoboro pluton. Gabbro and diorite are present in the Raccoon pluton in the northeastern part of the map in the town of Cushing, and a gabbro pluton of unknown size underlies Monhegan Island (Figure 4; Lord, 1900). A belt five km wide in the Woolwich-Bath-Phippsburg area (Figure 4) is characterized by numerous highly elongate two-mica-garnet granite plutons. Some have weakly developed foliation, but most are massive. Some of these minor intrusions are of granodiorite to quartz diorite composition. Granitic pegmatite dikes, lenses, and irregular masses are common throughout areas where the metamorphic rocks are strongly migmatized. Mesozoic dikes of basalt and diabase are sparse but relatively well distributed in the area. Only one, the Christmas Cove dike, is shown on the map.

Raccoon pluton (Srgb, Srgbh)

Gabbro and diorite form an irregular igneous complex on the west side of the St. George River estuary near the northeastern corner of the Bath map sheet (Figure 3). Within the pluton, Sidle (1991) recognizes noritic gabbro, hornblende gabbro, and diorite. Noritic gabbro (**Srgb**) is dark olive to brownish green, containing plagioclase, augite (varying to ferroaugite), non-pleochroic green to colorless orthopyroxene, magnetite, and minor amounts of hornblende and biotite. Cumulate layers with assemblages plagioclase-orthopyroxene and plagioclase-orthopyroxene-augite occur in the noritic gabbro. Igneous lamination is weakly to moderately developed. Sidle (1991) reports that diorite and amphibole gabbro (**Srgbh**) are the predominant rock types of the pluton. No systematic descriptions or modes are given for these rocks.

South of the Raccoon pluton, in the towns of Cushing and Friendship on either side of Meduncook River estuary, Sidle (1991) maps foliated masses of diorite which he states "are gradational with northeastward-striking amphibolites and amphibolite schists." These amphibolites are included in the unnamed amphibolite unit (**Obv**) of the Benner Hill sequence on the Bath map sheet. Some of the coarser-grained metadiorites may represent feeder reservoirs for the pillow-structured amphibolites described above.

Spruce Head pluton (Ssg, Ssgb, Ssgd)

The southern third of the Spruce Head pluton is exposed in the northeastern corner of the Bath map sheet (Figure 3). An extensive investigation of its geochemistry and petrology was done by Ayuso and Arth (1997). According to them, it is a composite pluton consisting predominantly of granodiorite and granite with subordinate yet substantial volumes of gabbro, diorite, and tonalite. Ayuso and Arth (1997) identified four petrographic groups, each with its own trace element and rare earth element composition. They deduce at least three distinct pulses of magma, all in close temporal and spatial relationship. Most of the pluton in the Bath map sheet is shown generally as coarse-grained, massive to foliated biotite-muscovite granodiorite and granite and hornblende-biotite granodiorite (**Ssg**). The gabbro (**Ssgb**) and diorite to granodiorite (**Ssgd**) units of Ayuso and Arth are shown separately.

In the early 1900's the granite (**Ssg**) was quarried extensively in the Tenants Harbor area along the coast (Figure 25).

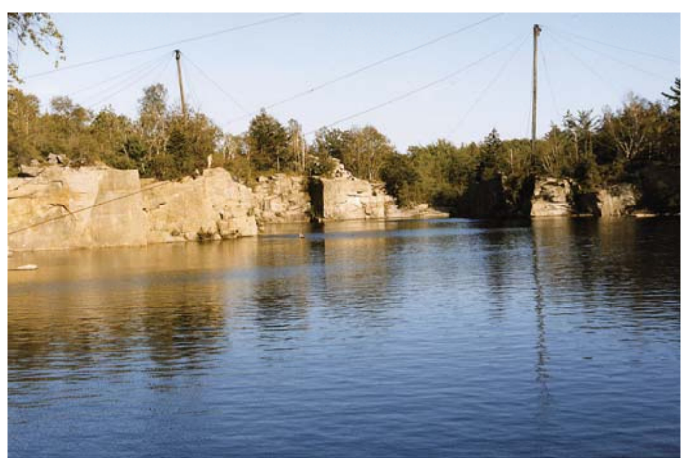


Figure 25. Granite quarry at Long Cove, Tenants Harbor. Quarries like this were an important part of Maine's economy in the early 1900's. Durable Maine granite was used in the construction of many government buildings in the eastern U.S. Still standing are two derricks that were used to hoist blocks out of the quarry. (*Photo 10 of Bath map sheet.*)

Several quarries that were active at the time are described by Dale (1907). Chayes (1952) included specimens of Spruce Head granite in his modal analysis of New England calc-alkaline granites. The most recent age given for the Spruce Head pluton is a 421 ± 1.0 Ma concordant zircon age from hornblende granite (Tucker and others, 2001).

Monhegan pluton and other gabbro and diorite bodies (Sgb)

According to the mapping of Lord (1900), gabbroic rocks occupy Monhegan Island, adjacent Manana Island, and Duck Rocks. He mapped three phases, (1) olivine norite, (2) gabbro-diorite, and (3) hornblende gabbro. Olivine norite occupies the southern two-thirds of Monhegan Island, and gabbro diorite the northern third, with hornblende gabbro confined to a small oval zone within the gabbro-diorite near the north tip of the island.

Lord (1900) describes the olivine norite as coarse-grained, feldspathic ("resembling, in part, at least, the olivine bearing anorthosyte of the Saguenay District, Canada"), purplish gray to steel gray in color, and consisting of plagioclase, olivine, hypersthene, magnetite, diallage, and hornblende. Minor variants are characterized as troctolite, olivine gabbro, and gabbro "so intimately associated that no distinctive lines could be drawn between them in the field." The olivine norite and associated phases pass gradationally into gabbro-diorite and hornblende gabbro of the northern end of the island. These phases are finer grained and variegated in color due, as Lord (1900) notes, to irregular inclusions of quartz-bearing, light gray diorite.

Randomly-oriented mafic dikes of basalt or diabase from a few millimeters to one meter in thickness cut both major phases of the Monhegan pluton. Mineralogically they range in composition from hypersthene gabbro to gabbro diorite, quite similar to the major phases of the pluton. Younger than the mafic dikes are a variety of felsic dikes of relatively uniform strike (N 50 to 60 degrees W) in the northern half of the island. Some of these felsic dikes can be mapped across the entire width of the island. They are rare in the olivine norite . They range from a few centimeters to a few meters in thickness and display a wide variety of textures from aplitic to pegmatitic. Principal minerals present are albite, quartz, muscovite, orthoclase, garnet, apatite, and magnetite.

Other bodies of gabbro and diorite, some with textures of commingled magmas, are mapped in the Port Clyde area (Guidotti, 1979) and on the St. Georges Islands (Eden and Pavlik, 1996).

Lord noted the similarity of the gabbroic rocks of Monhegan with occurences on Vinalhaven, the St. George Peninsula (gabbro associated with the Spruce Head pluton), and at Addison, Maine. These occurrences are now considered to be of Late Silurian age (Bradley and others, 1998), and it is likely that the Monhegan Gabbro and other mafic putons of the Georges Islands and Port Clyde are of similar age.

Miscellaneous metamorphosed mafic to intermediate plutons (DSmdg)

Near the southern tip of Southport Island at Newagen (Figure 4) a small (0.9 x 0.5 km) pluton of metadiorite or metagabbro (**DSmdg**) intrudes highly migmatized Cape Elizabeth Formation. Marginal portions of the pluton are amphibolite with gneissic foliation or weak schistosity, and are heavily injected by irregularly textured garnetiferous granite. Spatial relations of the metagabbro and granite suggest contemporaneous injection and mixing of granitic and gabbroic magmas. Later pegmatites intrude these rocks irregularly. Foliation in the amphibolite is parallel to the gneissic foliation in the Cape Elizabeth host rock. Toward the interior of the pluton, relict ophitic texture is present. A similar but much smaller body of metadiorite or metagabbro is present near Pratts Island along the west shore of Southport Island, about 3 km north-northwest of Newagen (Figure 4).

At Fitch Point along the east shore of the Damariscotta River estuary (Figure 4) a roughly oval pluton approximately 0.8 km in diameter intrudes heavily injected biotite granofels of the Bucksport Formation. The rock is a metamorphosed gabbro with relict equigranular texture and weak tectonic foliation (**DSmdg**). Locally, the metagabbro has abundant almost monomineralic garnet xenoliths up to 4 cm long and irregular poikiloblastic masses. The xenoliths resemble coticule beds which are common in the Cape Elizabeth Formation elsewhere but not in the surrounding Bucksport Formation at this locality. Garnets of similar habit and distribution have been described from the Kinsman Quartz Monzonite by Clark and Lyons (1986). They interpret that these garnets formed by magmatic crystallization. The garnets in the metagabbros of the Bath map sheet may have had a similar magmatic origin.

Oak Island Gneiss (DSoi)

The Oak Island Gneiss crops out in a belt varying from 250 to 650 meters wide for a distance of 11 km in the towns of Wiscasset, Westport, Woolwich, and Georgetown (Figure 4). As described by Hussey (1992), "The dominant lithology of this unit is a light pink to light gray moderately foliated granite gneiss cut by relatively abundant irregular stringers of pink pegmatite. Associated with this, particularly on Oak Island and the western half of Chewonki Neck (Bath map sheet), are concordant layers 6 cm to several meters thick of medium dark gray dioritic gneiss. Concordant stringers of strongly migmatized metapelite of the host Cape Elizabeth Formation are common within the granitic gneiss, and foliation of the granite gneiss is commonly defined by discontinuous thin clots of muscovite and sillimanite."

Edgecomb Gneiss (DSeg)

The Edgecomb Gneiss was named and defined by Hatheway (1969) from exposures in the Wiscasset quadrangle just

Figure 26. Light and dark bands of the Edgecomb gneiss (**DSeg**). The dark bands are composed mostly of the minerals hornblende and biotite. The light bands are mostly quartz and plagioclase. *(Photo 2 of Bath map sheet.)*

north of the Bath map sheet. It is a concordant body along the contact between the Cape Elizabeth Formation and the Sebascodegan Formation. It occupies a belt 0.25 km wide extending southward into the Bath map sheet a distance of 4 km before pinching out. The Edgecomb Gneiss is a medium dark gray plagioclase-quartz-biotite-hornblende orthogneiss with conspicuous plagioclase augen up to 1 cm in length (Figure 26). The augen in places resemble deformed phenocrysts. Lacking direct age determinations, it is presumed to be of Silurian-Devonian age.

Two-mica granite (DSg) plutons, Woolwich-Phippsburg belt

Small granite plutons, ranging from 0.2 to 1.5 km in width and 1 to 6 km in length, are concentrated in a belt extending from Popham Beach in Phippsburg northward to East Brunswick, Woolwich, Bath and Wiscasset (Figure 27; Bath map sheet). These plutons are generally elongate parallel to the regional structure, intrude primarily the Cape Elizabeth Formation, and are restricted to zones of migmatization where the Cape Elizabeth metapelites have been metamorphosed to sillimanite + K-feldspar grade. All of the plutons are composed of light gray, fine- to medium-grained biotite-muscovite ± garnet granite. Most of the granites are nonfoliated to weakly foliated, but a few are moderately well foliated. Contacts with the country rock are relatively sharp and not chilled. Schlieren and recognizable xenoliths of country rock are rare. Two plutons, Towesic Neck and Bath (Figure 27) stand out from the others in being irregularly textured (fine-grained to locally pegmatitic), moderately foliated, and slightly rusty weathering, and generally transitional to the surrounding migmatite. No radiometric ages are available for these plutons, but based on variabilities of foliation, they may show the same Silurian to Devonian age range as reported by Tucker and others (2001) for granitic plutons on strike to the northeast in the Liberty area.

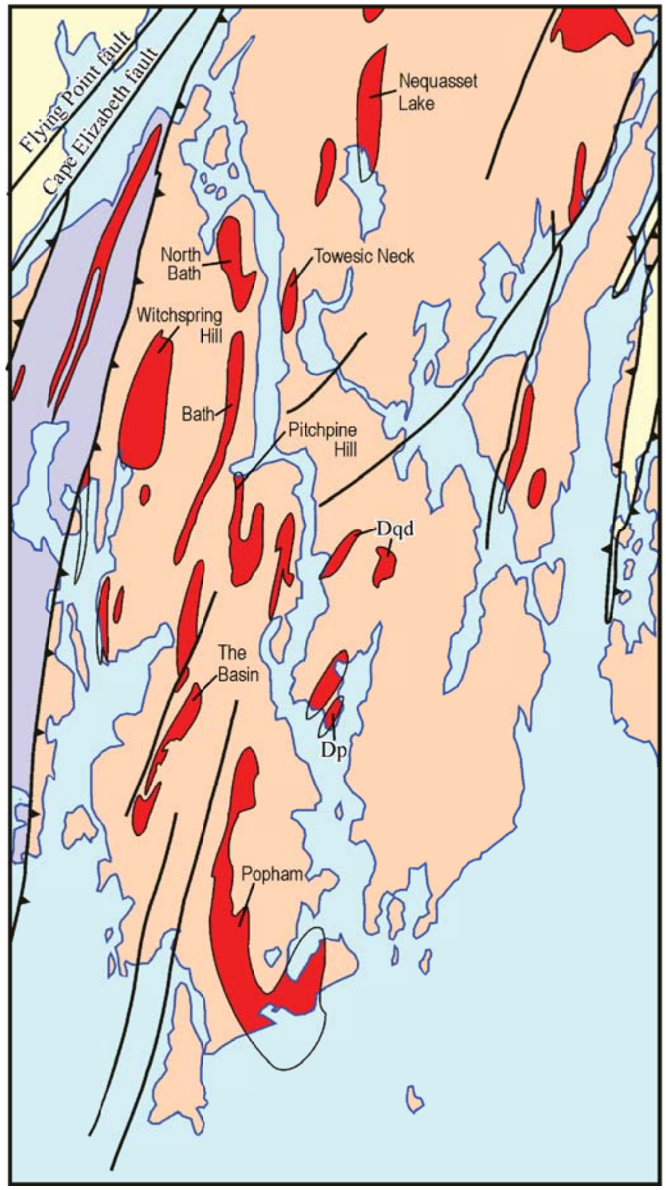


Figure 27. Belt of elongate granite plutons (red) in west-central part of the Bath map sheet. Names of several plutons are given. Most intrude the Cape Elizabeth Formation (peach) and some intrude the East Harpswell Group (purple). Bodies of quartz diorite (**Dqd**) and pegmatite (**Dp**) are indicated.

Lincoln Sill (Dls)

The Lincoln Sill, named by Trefethen (1937) for its excellent exposures in Lincoln County, is present in the Bath map sheet in two separate areas. In the Boothbay Harbor area (Figure 4) it crops out in a thin concordant antiformally-folded belt varying from 50 to 150 meters in width. For the most part it lies within the limits of the Bucksport Formation. Where it terminates to the north, on the western limb of the Boothbay anticline northwest of Boothbay Harbor, the sill widens. From distribution of outcrops of the sill, the Cape Elizabeth Formation, and the

Bucksport Formation, it would appear that the sill cuts across minor folds of the contact and is locally in contact with the two formations implying it postdates the inferred Boothbay thrust. The second belt of the sill is a narrow concordant lens near the Cape Elizabeth-Bucksport contact at the northern edge of the map. This is the southern end of the main body that extends northward to the Liberty area.

Two distinctive lithologic varieties comprise the Lincoln Sill in the study area. Where the sill is wide, interior parts preserve the original igneous mineralogy and texture. In these places the rock is a coarse-grained porphyritic mafic syenite with orthoclase phenocrysts in a groundmass of orthoclase, augite, hornblende, biotite, and minor hypersthene. The orthoclase phenocrysts retain euhedral compositional zoning and delicate microperthitic structure. Where the body is thin, the dominant rock type is a megacrystic biotite-hornblende-orthoclase schist. The megacrysts of purplish gray orthoclase are oriented with the two greater dimensions parallel to schistosity, yet retain delicate euhedral compositional zoning (Elders, 1969). Pankiwskyj (1976) and Tucker and others (2001) have applied the igneous rock name shonkinite (or metashonkinite where metamorphosed) to the distinctive rock that comprises the sill.

The age of the Lincoln Sill is latest Silurian to earliest Devonian, based on a 418 $\pm$ 1 Ma U-Pb zircon age from the nonfoliated phase of the sill in the Liberty area, north of the Bath map sheet (Tucker and others, 2001). Knight and Gaudette (1991) reported somewhat younger results from Rb-Sr whole rock and mineral analyses and U-Pb zircon analyses scattered in the 360 to 390 Ma range.

Quartz diorite at Georgetown (Dqd)

Two small bodies of quartz diorite have been mapped on the north end of Georgetown Island (Figures 4 and 27). The western body is approximately 1 km long and 0.1 km wide, elongate in a N 40^o E direction which is at an angle of about 35 degrees to the regional trend of foliation of the metamorphic rocks, but nearly parallel to, and south of, the trace of the Back River fault. The eastern body is irregular but more nearly equant. Both are strongly foliated (Figure 28), generally parallel to their contacts. This is thought to be an igneous foliation because it is parallel to the pluton contact which locally is discordant to the structural trend of the metamorphic rocks. The rock is medium gray with essential plagioclase and quartz; varietal biotite and hornblende, and accessory apatite, sphene, zircon, and opaques. Zircon from the eastern body gives a Middle Devonian U-Pb age of 376 $\pm$ 3 Ma (J. Aleinikoff, written communication, 2002).

Waldoboro pluton (Dwga, Dwgp, Dwgn, Dwgl)

The Waldoboro pluton (Waldoboro Pluton Complex of Sidle, 1991, 1992; Sidle and Barton, 1992; Barton and Sidle, 1994) is a large irregular pluton centered around Muscongus Bay in the towns of Friendship, Bristol, and Bremen (Figure 4), and extending north of the Bath map sheet to Waldoboro. It is intimately mixed with migmatized metapelitic rocks tentatively assigned to the Cape Elizabeth Formation and lit-par-lit injected biotite and calc-silicate rocks assigned to the Bucksport Formation. Sidle (1991) maps several granitic phases in the pluton. The principal phase is garnet-bearing two-mica foliated granite variable to granodiorite (included on the Bath map sheet under the symbol **Dwgn**). Other varieties include: (1) fine to medium-grained, weakly foliated garnet-bearing leucogranite (**Dwgl**); and (2) very light gray, white, or pale pink moderately foliated garnet-bearing aplitic granite (**Dwga**). A U-Pb zircon age of 368 $\pm$ 2 Ma is reported by Tucker and others (2001) for muscovite-biotite granite of the Waldoboro pluton from a quarry by Route 1 east of the center of Waldoboro. This phase of the pluton is not exposed in the Bath map sheet (Sidle, 1991).

One of the most conspicuous phases (**Dwgp**) of the Waldoboro pluton, named the South Pond Porphyry by Newberg (1979), is a coarsely porphyritic foliated biotite-muscovite granite with megacrysts of K-feldspar (Figure 29) up to 11 cm long (Sidle, 1991). Along its eastern margin, the South Pond Porphyry is strongly sheared. Megacrysts are elongate and have serrated margins. The matrix is characterized by protomylonitic to mylonitic fabric. On the east, the porphyry is in contact with gray sillimanite-bearing gneiss which may in part be equivalent to the Mosquito Harbor Formation of Guidotti (1979; Berry and others 2000), and in part may represent extremely sheared porphyry. This suggests that the eastern edge of the porphyry represents a major shear zone, perhaps a continuation of the Sennebec Pond fault. On the west the South Pond Porphyry abuts different granitic phases of the Waldoboro pluton. Sidle (1991) interprets the map pattern in the Friendship 7½' quadrangle as suggesting that the South Pond Porphyry cuts the main phase (**Dwgn**) of the Waldoboro pluton, although he notes that field relations elsewhere argue for a predominantly gradational contact between

Figure 28. Strongly foliated quartz diorite (**Dqd**), north end of Georgetown Island. Foliation is defined by thin partings rich in biotite. A sample was taken from this locality for U-Pb dating of the pluton. (*Radiometric age locality 2 of Bath map sheet.*)

Figure 29. Megacrystic South Pond Porphyry (**Dwgp**), Dump Road, Friendship. Many of the megacrysts of K-feldspar are euhedral and appear to have been rotated at a late stage of consolidation of the matrix. Some of the foliation is probably a solid-state deformational fabric.

the two. The aplite-granite phase (**Dwga**) appears to cut the South Pond Porphyry in the Friendship - Long Island area.

Granitic pegmatites

Granitic pegmatites (**Dp**) are very abundant in the Bath map sheet, particularly where the host rock has been metamorphosed to sillimanite or sillimanite + K-feldspar grade. In the Falmouth-Brunswick sequence, two temporally distinct suites of pegmatites are present. The older suite consists of relatively small but abundant pegmatites that occur as neosomes in migmatites. Brookins (Brookins and Hussey, 1978) obtained an Rb-Sr whole rock age of 367-377 Ma (recalculated here using ^{87}Rb decay constant of 1.42×10^{-11}/yr), suggesting a Middle to Late Devonian age for this older suite. North of the Bath map sheet, Tucker and others (2001) report U-Pb zircon and monazite ages of small pegmatite bodies intruding the Falmouth-Brunswick sequence near Gardiner of 367 ± 1 Ma, and at Greely Corner, Palermo, of 371 ± 1 Ma, within the same age range.

Tomascak and Francis (1995) identify a younger suite of pegmatites in the Topsham - Brunswick area (Figure 4) that are almost universally associated with small concordant lenses of two-mica granite. Figure 30 shows one of the larger pegmatites exposed in the quarry of the Consolidated Feldspar Company in Georgetown. The younger pegmatites in the Topsham area give U-Pb ages on monazites ranging from 268 to 275 Ma (Tomascak and others, 1996), thus suggesting a Permian age for intrusion of both pegmatite and granite. These pegmatite and granite bodies are larger than the migmatite neosomes and form a nearly continuous narrow zone within the Mount Ararat and Nehumkeag Pond Formations from Brunswick northward through Topsham into Bowdoinham (Figure 4). ^{40}Ar/^{39}Ar hornblende cooling ages of 266 and 270 Ma from this vicinity (West and others, 1993) indicate cooling soon after intrusion. Quarries and mineral production from the larger pegmatites within the map area have been described in detail by Cameron and others (1954) and Shainin (1948).

Large pegmatites (greater than 25 meters thick, and up to a few hundred meters long) occupy a belt extending from Brunswick northeastward through Bowdoinham and are restricted to the Falmouth-Brunswick sequence. These large pegmatities commonly show zonal mineral development (Cameron and others, 1954; Shainin, 1948). The zones inward from the contact with the country rock are the border zone, wall zone, intermediate zone, and core. Border zones in contact with wall rock are thin, discontinuous, and finer grained than interior parts. According to Shainin (1948), border zones of pegmatites in the Topsham area generally vary from one inch to one foot in thickness, have sharp contacts with the wall rock, and consist of fine-grained aggregate of quartz, plagioclase, perthite, biotite, muscovite, and garnet. Wall zones make up the bulk of most pegmatites and consist of graphic granite, coarse crystals of quartz, plagioclase, perthite, and biotite. The biotite in wall zones commonly forms large bladed crystals up to 25 cm long and 8 cm wide. The longest observed were 20 feet long, eight feet wide, and three inches thick and apparently formed along fractures (Shainin, 1948, p. 17). Intermediate zones, where present, consist of quartz, muscovite, and perthite with subordinate biotite and garnet. Perthite crystals commonly attain dimensions of two to ten feet. Core zones are generally centrally located, small, disconnected segments separated by wall or intermediate zone material, and consist of coarse perthite and/or quartz. Cavities are rare in the pegmatites of the area, but Palache (1934) described one from the Fisher Quarry in Topsham from which crystals of cleavelandite, topaz, herderite (more correctly hydroxyl-herderite), beryl, tourmaline, cassiterite, columbite, microlite, and apatite were recovered. Figure 31 shows the discoverer, Benjamin Burbank, standing in the cavity in 1934.

Figure 30. West wall of intermittently active gem pegmatite quarry, Georgetown. Wall to the left is rock of the Cape Elizabeth Formation. The larger part of the quarry, out of sight to the rear, was operated for K-feldspar until 1942 by the Consolidated Feldspar Company.

The pegmatites within the Casco Bay Group commonly show a variation in mineralogy that is closely dependent on the composition of the host rock. In aluminous phases of the Cape Elizabeth Formation, pegmatites have abundant fibrolitic sillimanite. These pegmatites generally have pink K-feldspar, and if black tourmaline is present, small bluish acicular grains of dumortierite (an aluminum borosilicate) are sparingly present also. Albite is commonly milky-white with a slight greenish cast indicating a minor degree of deuteric alteration to saussurite. Where pegmatites are present in dominantly quartz-plagioclase-biotite-muscovite phases of the Cape Elizabeth Formation, and in the Bucksport Formation, sillimanite is absent and the K-feldspar is generally white or pale buff. Dumortierite is generally not present. The local dependence of mineralogy of these pegmatites on the composition of the host rock suggests very local derivation by the process of partial melting of the host rock that has led to migmatization. This relation suggests the possibility that the neosomes and larger pegmatite lenses may be temporally closely related. These pegmatites show abundant evidence of having been intruded during deformation. Some preserve a crude foliation, and thin lenses are commonly folded semiconcordantly with the country rock.

Light gray, non-foliated pegmatites of simple mineralogy (quartz, perthitic microcline, albite, biotite, and minor muscovite and black tourmaline) occur throughout the Bucksport Formation. They are generally discordant irregular stringers ranging from 10 cm to 30 m in width. They are especially well exposed in coastal outcrops at the end of Linekin Neck in the town of Boothbay, and at Pemaquid Point in Bristol (Figure 4). At Pemaquid Point some of the thinner pegmatites are folded nearly concordantly with bedding of the Bucksport Formation.

Figure 31. Topaz and hydroxyl-herderite gem pocket at the Fisher Quarry, Topsham. Finder of the pocket, Benjamin Burbank is standing in the pocket after the gemstones and mineral specimens had been removed. (Photo formerly in Portland Society of Natural History collection, photographer unknown.)

Figure 32. Christmas Cove dike exposed on Mountain Road, Great Island, Harpswell. The youngest of the rock units exposed in the area, the Christmas Cove dike was intruded during the Mesozoic Era and spans the length of the map sheet. Outcrops of this unit are often blocky, as shown in this photograph, because of several orientations of spaced fractures. Here the dike dips moderately to the north (left). (*Photo 12 of Bath map sheet.*)

Christmas Cove dike

The Christmas Cove dike (Figure 32) is the largest and most extensive of the mafic dikes mapped in the Bath map sheet. It is known to extend from Falmouth in the Portland area, to the south end of Barter Island just off Port Clyde (Figure 4), a distance of 70 km. On the Bath map sheet it is represented by a red line as several discontinuous but essentially on-strike segments from Harpswell Neck in a N 80^{o}E direction to Barter Island. It varies in dip from vertical to 45 degrees and in thickness from 15 to 35 meters. Columnar jointing is well developed and was the means of recognizing the dike on Barter Island during an overflight of the Muscongus Bay area. The rock is a fine-grained non-porphyritic diabase with diabasic texture. Minerals present, based on thin section examination, include plagioclase (labradorite), titaniferous augite, pigeonite, and magnetite.

McHone (McHone and others, 1995; McHone, 1996) correlates this with the Higganum dike of Connecticut and Massachusetts and interprets it to be part of a large feeder system for Jurassic-age flood basalts associated with rifting that accompanied the opening of the central Atlantic Ocean. ^{40}Ar/^{39}Ar analyses of whole rocks from the Christmas Cove dike produced discordant age spectra ranging in age from 196 to 205 Ma, indicating a Late Triassic to Early Jurassic time of emplacement (West and McHone, 1997).

STRUCTURAL GEOLOGY

The stratified rocks of the Bath map sheet have been folded and thrust faulted during multiple phases of deformation mostly associated with the Acadian orogeny. They have been subse-

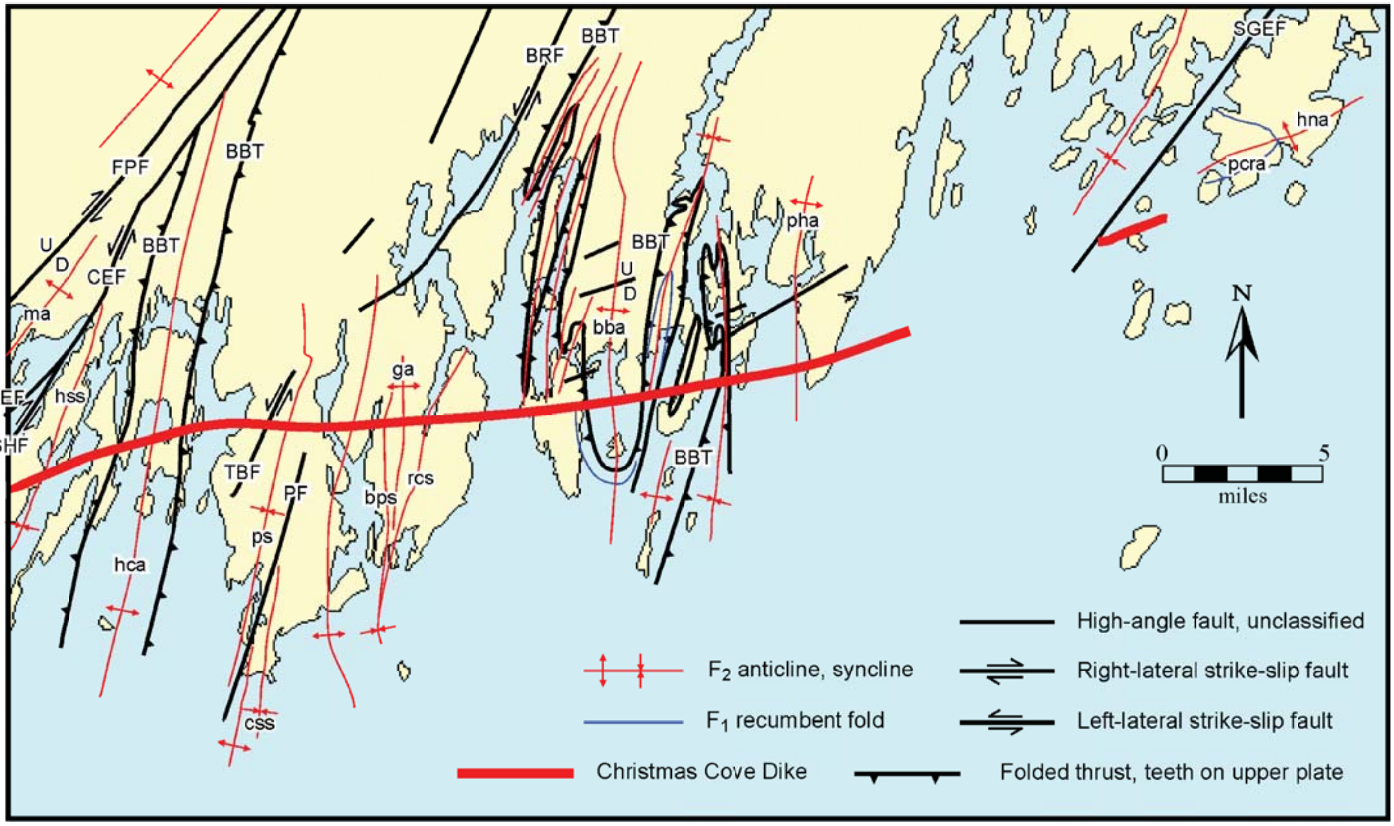


Figure 33. Map showing major folds, faults, and the Christmas Cove dike. Abbreviations: bba, Boothbay anticline; BBT, Boothbay thrust; bps, Bay Point synform; BRF, Back River fault; CEF, Cape Elizabeth fault; css, Cape Small synform; D, down; FPF, Flying Point fault; ga, Georgetown antiform; hca, Hen Cove anticline; hna, Hart Neck antiform; hss, Harpswell Sound syncline; ma, Merepoint anticline; pcra, Port Clyde refolded anticline; PF, Phippsburg fault; pha, Pemaquid Harbor anticline; ps, Phippsburg synform; rcs, Robinhood Cove synform; SGEF, St. George estuary fault; SHF, South Harpswell fault; TBF, The Basin fault; U, up.

quently disrupted by strike-slip, and high-angle normal and reverse faulting. Locations of major folds and faults are shown on the map in Figure 33. Folds are described first, then faults.

Folds

Rocks of the Casco Bay Group preserve the clearest record of multiple folding. The earliest folds, designated F_1 folds, are recumbent folds formed during the first deformation, D_1. Structural features produced during D_1 include minor recumbent parasitic folds, cleavages (schistosity, spaced cleavage), downward-facing beds (as determined by graded bedding), and, rarely, lineations, all of which have been folded by subsequent deformations. In most areas where they are seen, F_1 folds are minor features and only rarely affect the map pattern of formations. Exceptions to this are seen in the Small Point and Boothbay Harbor areas. Figure 16 shows relatively small-scale but mappable recumbent folds of minor units in the Cape Elizabeth Formation at Small Point. Hinges of these folds are not seen in outcrop, but are indicated by the intricate distribution of the exposures of these units.

A second regional deformation, D_2, produced widespread upright folds, designated F_2 folds. Hinges of minor F_1 recumbent folds, refolded by F_2 upright folds, are seen at isolated localities in the Cape Elizabeth Formation at Small Point (Figure 6a of Hussey, 1988). Evidence of the presence of pre-F_2 folds is the folded spaced cleavage that characterizes the more quartzose beds of the formation (Figure 34). Minor parasitic folds seen in outcrop are mostly F_2 folds that deform a pre-D_2 muscovite-dominated schistosity, but commonly have a syn-D_2 biotite schistosity that is parallel to F_2 axial planes. Post-D_2 small-scale folds include crenulations of cleavage or schistosity and sinistral vertical kink bands. The major map-scale folds are described from west to east.

Folds in the Falmouth-Brunswick sequence and the Central Maine sequence. At the western edge of Merrymeeting Bay (Figure 4), in the Nehumkeag Pond Formation, the easternmost belt of the **Onpr** unit outlines the nose of a fold that closes to the southwest (Bath map sheet). It is interpreted as an antiform(?) plunging gently to the southwest. The two western belts of rusty schist (**Onpr**) may represent either long extended antiformal(?) fold hinges, or simply lenses of similar lithology. Roadcuts

Figure 34. Fracture cleavage in the Cape Elizabeth Formation at Bald Head on Small Point, Phippsburg. Lighter "layers" are fold hinges, and limbs are areas where biotite has been concentrated as quartz was removed by pressure solution. Three episodes of folding are represented here. The earliest phase, related to recumbent folding, produced the spaced cleavage. The second phase is represented by the fold hinges preserved as the more quartzose bands. The third phase is represented by the open upright folding of the bands. The first phase is correlated with F_1 recumbent folding, and the third phase is correlated with later upright to slightly overturned F_2 folding. The intermediate phase was only observed in this vicinity.

Figure 35. Strongly overturned folds in the Nehumkeag Pond Formation (**Onp**). Two antiformal hinges are separated by a minor synformal hinge (highlighted in white). Roadcut on the northbound lane of I-95, 0.6 mi (1 km) south of milemarker 79, just southeast of Bench Mark 133 on the Brunswick 7½´topographic quadrangle map.

Figure 36. Recumbent synform in the Nehumkeag Pond Formation (**Onp**). White lines highlight the form of the fold. At the far left end of the photograph, a minor rusty gneiss unit occupies the core of the fold. Note the folding of migmatite stringers which indicates folding postdates migmatization. Road cut on northbound lane of I-95, about 1 mile north of Figure 35 location.

along the northbound lane of I-95 in Topsham expose beautiful examples of strongly overturned antiforms (Figure 35) and synforms (Figure 36). These folds plunge gently to the north-northeast with axial planes dipping 35-40 degrees southeast.

The outcrop belt of the Falmouth-Brunswick sequence in the northwestern corner of the map is inferred to be a regional scale antiform (Figures 33 and 37). The fold nose toward the eastern edge of the outcrop belt of the sequence would represent the core of this fold.

Merepoint anticline. The Merepoint anticline (**ma**, Figure 33) is defined by the map pattern of the Merepoint Member and the stratigraphic sequence of the Cushing Formation. Based on the mapped distribution of rusty schist of the Merepoint Member, the anticline is inferred to plunge to the northeast.

Harpswell Sound syncline and Hen Cove anticline. The Harpswell Sound syncline (**hss**, Figure 33) and the Hen Cove anticline (**hca**, Figure 33) comprise a gently and variably plunging upright to slightly overturned macroscopic F_2 fold set. The center of the Harpswell Sound syncline preserves rocks of the upper part of the Casco Bay Group, the youngest unit of which, the Jewell Formation, barely catches the west edge of the map in the core of the syncline. Continuing along the axial trace to the southwest, the Scarboro, Spurwink, and Jewell Formations are more extensively exposed (Hussey, 1971b; Berry and Hussey, 1998). The axial trace of the Harpswell Sound syncline is deflected toward the southwest in the area of Harpswell Sound due to the influence of later sinistral, west-northwest-trending, steeply dipping kink bands (Figure 38). At one locality near the northern end of the sound where an individual bed of metasandstone in the Cape Elizabeth Formation can be followed for over 120 meters, local strike of bedding varies by 20^o from the regional strike over that distance. This disparity is accounted for by the abundance of left-lateral kink bands.

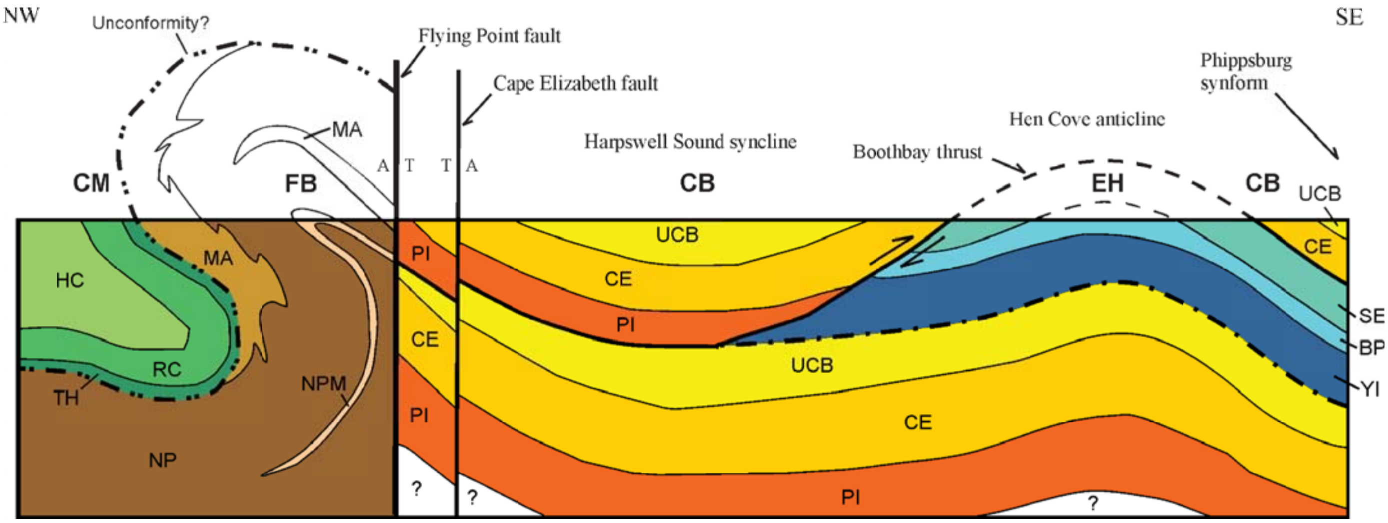


Figure 37. Schematic cross section from northwest corner of the Bath map sheet southeast to the edge of the Phippsburg synform at Phippsburg village. Inferred relations are shown of the Casco Bay Group (CB) to the East Harpswell Group (EH), and the Central Maine sequence (CM) to the Falmouth-Brunswick sequence (FB). The East Harpswell Group is inferred to be autochthonous below the Boothbay thrust, and may sit unconformably on the Casco Bay Group (dash-dot line). Surface exposures of CB are allochthonous. Other abbreviations: A: relative fault movement away from viewer; BP: Bethel Point Fm.; CE: Cape Elizabeth Fm.; HC: Hutchins Corner Fm.; MA: Mount Ararat Fm.; NP: Nehumkeag Pond Fm.; NPM: marble, amphibolite, and sulfidic schist in NP; PI: Peaks Island Member of the Cushing Fm.; RC: Richmond Corner Fm.; SE: Sebascodegan Fm.; T: relative fault movement toward viewer; TH: Torrey Hill Fm.; UCB: upper units of the Casco Bay Group, undivided; YI: Yarmouth Island Fm. Section not to scale. Units not colored where projected above ground.

The Hen Cove anticline exposes the formations of the East Harpswell Group, with the oldest in the core and younger units symmetrically disposed about the axial trace (Figure 17). Dips are away from the core of the anticline. On the limbs of the Hen Cove anticline, rocks of the Casco Bay Group lie in thrust-fault contact with the East Harpswell Group* (Figures 33 and 37).

Figure 39 shows orientations of minor folds around the Harpswell Sound syncline and adjacent parts of the Hen Cove anticline interpreted to be mostly parasitic F_2 folds of bedding in the Cape Elizabeth, Cushing, and Sebascodegan Formation.† The similar orientations of axial planes of both east- and west-verging folds suggests congruence of these folds and reinforces their interpretation as F_2 parasitic folds. Dominant schistosity, dominated by the parallelism of biotite, is parallel to the axial planes of these folds.

The map pattern of the units around the Harpswell Sound syncline closing to the northeast indicates that this structure plunges generally southwest. Axes of the minor folds on both limbs of the syncline are congruent and plunge predominantly to the south-southwest (Figures 39d and 39e). Offshore submarine topography just south of Ragged Island suggests that the Hen Cove anticline closes to the south at its southernmost known extent, its plunge there being to the south-southwest. The plunge then reverses to where it definitely plunges gently northeast between Yarmouth Island and the south end of Quahog Bay (Figure 17). It then reverses again to become southwest in the northern end of Quahog Bay. Plunges of minor folds in the axial zone of the Hen Cove anticline are consistent with this interpretation.

A careful analysis of the predominance of east-verging vs. west-verging parasitic folds on the different limbs of the Harp-

Figure 38. Steeply-dipping kink bands typical of the latest stage of deformation of the Cape Elizabeth Formation. They are consistently left-lateral, as can be seen when viewed from above. Road cut, west side of Maine Route 123 on Harpswell Neck near Harpswell Center.

*A pedantic argument might be raised about whether the Hen Cove fold is properly called an anticline; since the Cape Elizabeth Formation is older than the Yarmouth Island Formation, the oldest rocks are not in the core of the fold. But the alternative term, antiform, is defined as a fold of this shape in which the age of units is not known. This also does not apply. In fact, no term has been coined (nor is one needed) to address the case of a folded thrust complex. We use the term anticline here and in the Boothbay area folds where we interpret the *tectonostratigraphy* as essentially upward facing.

† In the following discussion of parasitic folds, the sense of asymmetry is expressed in terms of fold vergence as defined by Marshak and Mitra (1988, Fig. 11-13, p. 219, and Fig. 16-7, p. 367). Use of fold vergence eliminates confusion when dealing with a population of minor parasitic folds that show reversals of plunge of axes, or that have horizontal axes within a small area. A dextral north-plunging parasitic fold set has the same fold vergence as a sinistral south-plunging parasitic fold set.

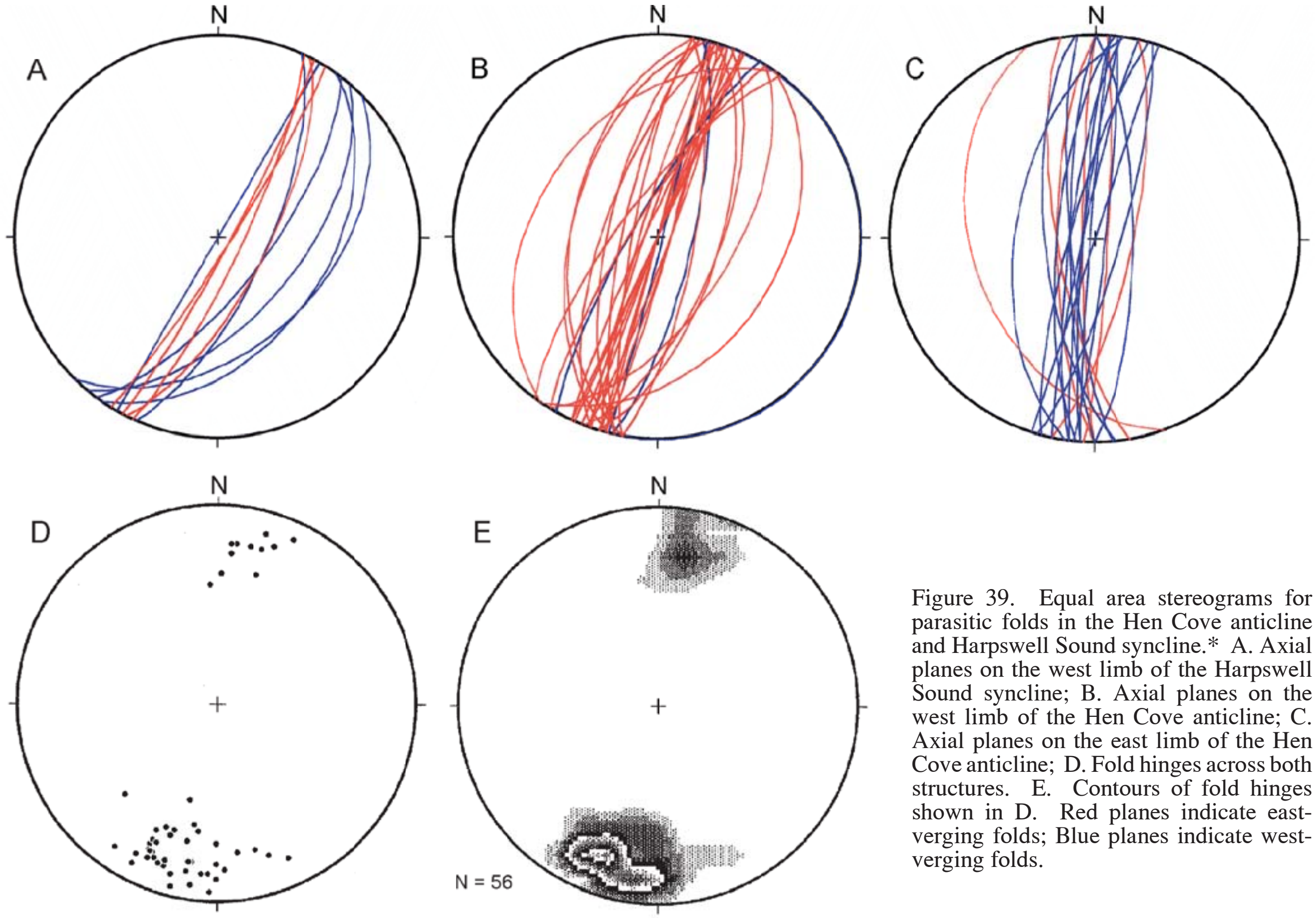


Figure 39. Equal area stereograms for parasitic folds in the Hen Cove anticline and Harpswell Sound syncline.* A. Axial planes on the west limb of the Harpswell Sound syncline; B. Axial planes on the west limb of the Hen Cove anticline; C. Axial planes on the east limb of the Hen Cove anticline; D. Fold hinges across both structures. E. Contours of fold hinges shown in D. Red planes indicate east-verging folds; Blue planes indicate west-verging folds.

swell Sound and Hen Cove folds (Figure 39) reveals a correlation with position on the major F_2 folds. The presence of some minor folds with opposite vergence suggests either (1) intermediate scale F_2 folds or (2) minor folds of more than one fold generation.

The minor folds within the Harpswell Sound syncline have a well-developed schistosity, dominated by biotite, parallel to their axial planes. Muscovite is roughly parallel to fold axial planes, but not as perfectly as the biotite. In the area of the Harpswell Sound syncline, metamorphic conditions were apparently conducive to recrystallization of both biotite and muscovite from an earlier schistosity that was parallel to the axial planes of F_1 recumbent folds.

In contrast, the west limb of the Hen Cove anticline shows extensive parasitic folding of muscovite-dominated schistosity. The rotation sense of these folds is generally compatible with their position on the west limb of the anticline (Figure 39b). These minor folds of the S_1 muscovite schistosity are interpreted to be F_2 folds and are probably the same age as the upright folds of the Cape Elizabeth Formation around the Harpswell Sound syncline in which schistosity, dominated by biotite, is parallel to their axial planes. This agrees with observations of schistosity and minor folds of the Cape Elizabeth Formation in the Small Point area of Phippsburg (described below).

Within the more competent Yarmouth Island Formation of the East Harpswell Group, the arch bend of the Hen Cove anticline is seen at three exposures. The most spectacular of these is a shoreline exposure on the eastern side of Yarmouth Island (Figure 40). Minor folds on the eastern limb at this locality are compatible with the position of the arch bend and are interpreted to be parasitic F_2 folds (Figure 41). On the east limb of the Hen Cove anticline, the Bethel Point Formation is very thin, with essentially no parasitic folding.

Phippsburg and Cape Small synforms. The Phippsburg synform (**ps**, Figure 33) is mapped from the west side of Cape Small at the southern tip of Phippsburg (Figure 16) north to Doubling Point on the Kennebec River. The structure is complex due to minor faults and deflection that may be related to the intrusion of the Pitchpine Hill pluton. This fold is regarded as an F_2 fold. Relics of earlier recumbent folds are outlined by detailed mapping of thin units in the Cape Small synform just east of Hermit Island, Small Point (Figure 16), but parasitic folds to these are infrequently seen in outcrop. In the southern end of the structure at Cape Small (Figure 16), parasitic folds are extremely common

* All stereograms are lower hemisphere, equal area projections, produced by the computer program Stereonet v. 4.6 Academic Version © 1988-1993 by Richard Almendinger. On contoured diagrams, N is the number of data points and contour interval is 2% per 1% area.

Figure 40. A broad fold in the Yarmouth Island Formation (**SOy**) on Yarmouth Island, Harpswell, looking north. Geologist Arthur Hussey is standing at the crest of the Hen Cove anticline which is responsible for surface exposures of units of the East Harpswell Group. (*Photo 5 on Bath map sheet.*)

Figure 41. North-plunging sinistral (west-verging) parasitic folds of a calc-silicate lens in the Yarmouth Island Formation, east shore of Yarmouth Island, Harpswell. These parasitic folds are on the east flank of the Hen Cove anticline at a point about 5 meters east of the main arch bend of the fold pictured in Figure 40. Thin layers that stand out in relief are quartzose calc-silicate granofels. Intervening deeply weathered layers are calcite-bearing.

and are seen mostly as folds of muscovite schistosity and S_1 fracture cleavage. Muscovite schistosity must therefore have been formed during D_1 deformation. In the minor F_2 folds at Cape Small, biotite locally forms a weakly developed S_2 schistosity. This schistosity is essentially parallel to axial planes of the numerous parasitic folds of the Harpswell Sound syncline and Hen Cove anticline where muscovite as well as biotite is parallel to F_2 axial planes. Hussey has interpreted these relations to indicate that the D_2 deformation and the accompanying recrystallization of muscovite and biotite into axial plane parallelism has been much more intense in the Harpswell Sound syncline area than in the Cape Small area.

Robinhood Cove synform, Georgetown antiform, and Bay Point synform. Three closely related structures that merge southward to form a single synform on Georgetown Island are recognized on the basis of the map pattern of the coticule (**Ocec**), amphibolite (**Ocea**), and other associated minor units of the Cape Elizabeth Formation (Figure 13). The folds from west to east are the Bay Point synform (**bps**, Figure 33), the Georgetown antiform (**ga**, Figure 33), and the Robinhood Cove synform (**rcs**, Figure 33). The Bay Point synform is defined by the belt which includes scattered outcrops of coticule, amphibolite, and rusty schist (**Ocep**) which probably are equivalent collectively to the same units better exposed and separately mapped around the Robinhood Cove synform. The Georgetown antiform decreases in amplitude to the south, and the two bordering synforms merge into one at the south shore of Georgetown Island. These are all interpreted to be F_2 folds. To the north of Georgetown Island the continuity of the Georgetown antiform is obscured by lack of suitable marker horizons. In the vicinity of Westport Island, to the north of Georgetown Island, the distribution of outcrops of the thin amphibolite and calc-silicate member (**Ocea**) within the Cape Elizabeth Formation suggests a general convergence to the south. This may indicate an antiform plunging south(?), but disruption by the Back River fault and lesser unnamed faults make this interpretation uncertain. The axial trace of the Robinhood Cove synform on Georgetown Island is deflected northeastward (Figure 33) and can be recognized along the northeastern shore of the Island at Lowe Point (Figure 4). Here the foliation in migmatized Cape Elizabeth rocks abruptly changes from strikes averaging N 30^{o}E and dips to the southeast, to northwest strikes and dips to the southwest. The structure here postdates not only the gneissic foliation and schistosity, but also migmatite stringers in the Cape Elizabeth Formation. Figures 42 and 43 are stereographic plots of axes and axial planes of minor F_2 and possibly later folds associated with the Georgetown antiform and Robinhood Cove synform, respectively. These plots illustrate the predominance of plunges to the south. Also, there is a greater range of fold orientations in the Robinhood Cove synform as indicated by more scatter in Figure 43.

Boothbay anticline. The Boothbay anticline (**bba**, Figure 33) is delineated by the outcrop belt of the southern body of the Lincoln Sill and by the western outcrop belt of the Cross River Formation centered around the towns of Boothbay and Boothbay Harbor (Figure 4). This structure is doubly plunging. To the north it plunges north and on its southern end it plunges south. Parasitic folds around the southern end of the Boothbay anticline plunge consistently south (Figure 44). The number of east-verging *vs.* west-verging parasitic folds measured on the two

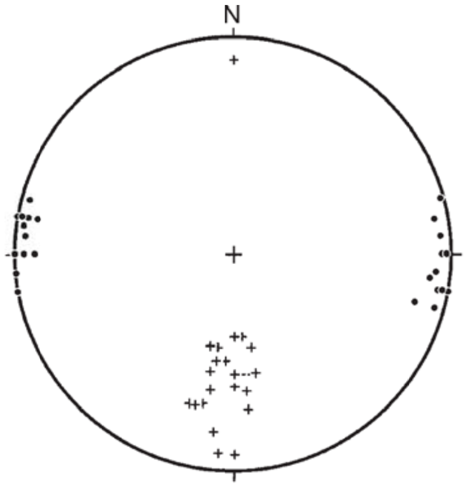


Figure 42. Orientation of parasitic folds, Georgetown antiform. Symbols: dot = pole to axial plane; + = fold hinge.

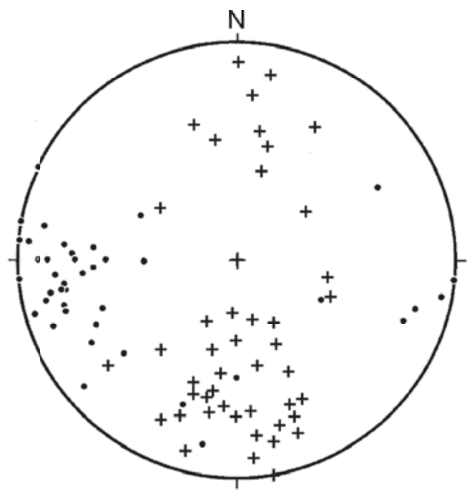


Figure 43. Orientation of parasitic folds, Robinhood Cove synform. Symbols: dot = pole to axial plane; + = fold hinge.

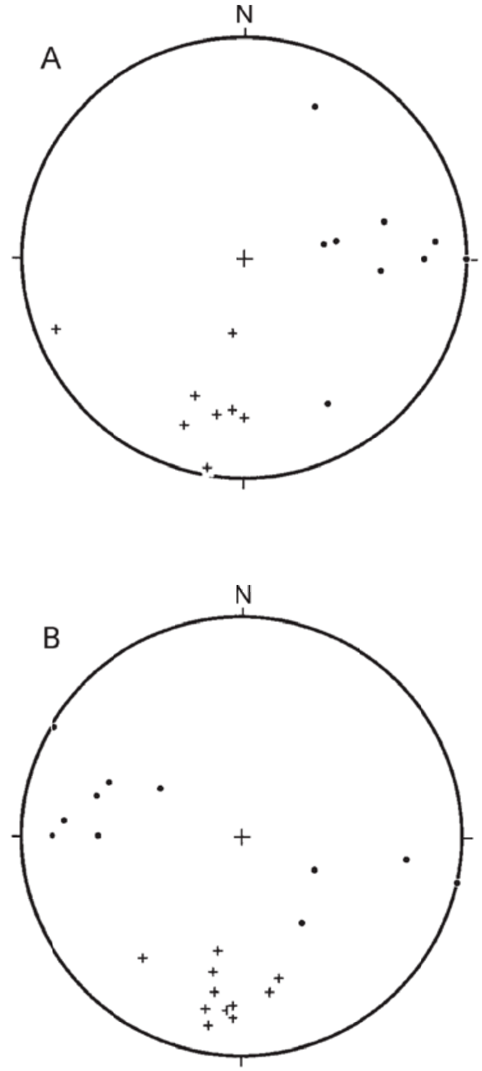


Figure 44. Orientation of F_2 parasitic folds in the Boothbay anticline. Symbols: dot = pole to axial plane; + = fold hinge. A. Folds on the west limb of the Boothbay anticline. B. Folds on the east limb of the Boothbay anticline.

limbs of the Boothbay anticline are statistically insufficient to use in predicting the nature of the major fold. The fact that the minor folds in the south part of the Boothbay anticline plunge predominantly south, in the same direction as the convergence of formation contacts, establishes that the structure is antiformal.

The Boothbay anticline is interpreted to be a major F_2 structure, deforming the Bucksport and Cape Elizabeth Formations, Boothbay thrust, and the Lincoln Sill. It should be noted that the Lincoln Sill on both limbs of the Boothbay anticline lacks the parasitic folding that is so abundantly developed in the Bucksport Formation. The significance of this may be related to the time of intrusion versus the time of F_2 folding, or to rheological differences of the two rock types during deformation.

Along the east central shore of Southport Island southwest of Boothbay Harbor (Figure 45a), an intermediate scale isoclinal reclined synform plunging 20 to 30 degrees south is defined by the outcrop belt of the amphibolite in the Cape Elizabeth Formation (**Ocea**), the Bucksport Formation (**SOb**) and by folded schistosity and foliation within the amphibolite and pelitic Cape Elizabeth rocks. A minor antiformal hinge is inferred to lie just east of the synform in the vicinity of Capitol Island. These two structures likely represent F_1 folds that have been refolded by the F_2 Boothbay anticline (Figure 33).

East Boothbay recumbent folds. The amphibolite unit within the Cape Elizabeth Formation (**Ocea**) is exposed extensively in the area north and west of East Boothbay (Figure 13). The convoluted shape of the outcrop belt of this unit indicates that an early (F_1) recumbent fold set has been refolded by later (F_2) folds. Inferred axial traces for folds of both ages are shown on Figure 45b. The mapped portion of the amphibolite mostly represents the core of a recumbent fold that has been refolded by a south-plunging, map-scale F_2 synform (Figures 45b and 45c).

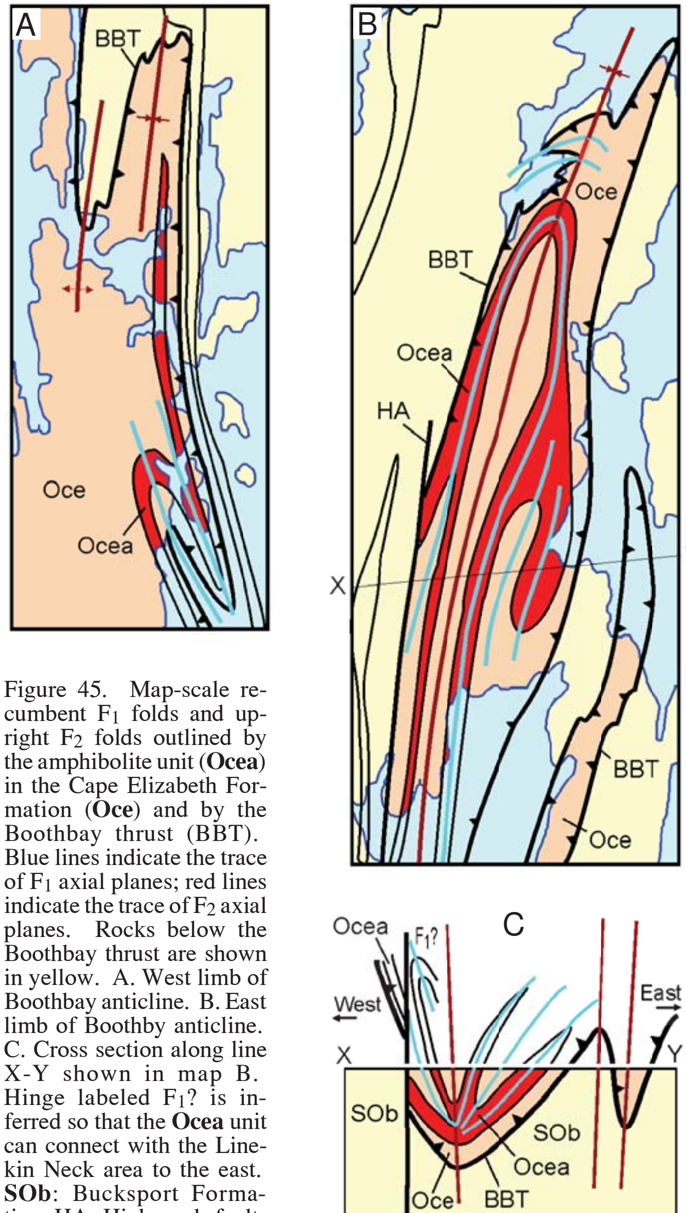


Figure 45. Map-scale recumbent F_1 folds and upright F_2 folds outlined by the amphibolite unit (**Ocea**) in the Cape Elizabeth Formation (**Oce**) and by the Boothbay thrust (BBT). Blue lines indicate the trace of F_1 axial planes; red lines indicate the trace of F_2 axial planes. Rocks below the Boothbay thrust are shown in yellow. A. West limb of Boothbay anticline. B. East limb of Boothby anticline. C. Cross section along line X-Y shown in map B. Hinge labeled F_1? is inferred so that the **Ocea** unit can connect with the Linekin Neck area to the east. **SOb**: Bucksport Formation. HA: High-angle fault.

The early fold is inferred to close generally to the east, with a minor west-closing infold on the east limb of the F_2 synform (Figure 45c). On the west limb of the F_2 synform, positions of the F_1 fold limbs are mapped tenuously due to their thinness, incomplete outcrop, and the extensive development of pegmatites. The inferred upper limb of the recumbent fold is mapped southward to where it is cut by a high-angle fault just east of Spruce Point, Boothbay Harbor (Figure 4). The western (lower) limb is cut by the fault farther north, near the middle of Figure 45b. This F_1 fold probably reappears on Southport Island in the reclined synform just west of the Boothbay anticline (Figure 45a). The same amphibolite (**Ocea**) is also in the Linekin Neck area to the east, implying that a major west-closing F_1 hinge, now eroded, was present at higher structural levels (labeled "F_1?" in Figure 45c).

The orientations of parasitic folds in this area (Figure 46) are similar to those in the area of the Boothbay anticline, suggesting they are F_2 folds. Intermediate-scale F_2 hinges of the amphibolite are inferred from the orientation of lamination within the amphibolite, change of rotational sense of minor folds of amphibolite lamination, and bedding in both the Cape Elizabeth and Bucksport Formations.

Folds in the Linekin Neck - South Bristol area. Several doubly-plunging macroscopic anticlines with intervening synclines have been mapped between East Boothbay and South Bristol (Figure 4). They are delimited on the basis of alternating outcrop belts of the Cape Elizabeth and Bucksport Formations (Hussey, unpublished mapping in the Boothbay 15´ quadrangle). The Cape Elizabeth Formation crops out in synclines and the Bucksport in anticlines. On Figure 33, scale limitation permits only a generalized representation of these folds. The detailed character of the folds is not clear. In many areas, plunges of minor folds do not agree with mapped closing directions, and plunges of minor folds reverse frequently with no indication from map pattern of similar changes in direction of fold closures. This inconsistency of plunge direction may be due to the presence of both F_1 and F_2 parasitic folds. The easternmost of the macroscopic folds is a syncline first recognized by Kirk (1971). It extends southward to Outer Heron and nearby islands south of Linekin Neck, East Boothbay (Figure 13), as suggested by Kirk (1971) and as shown on the Bath map sheet, or it may close near South Bristol, in which case the outer island exposures of amphibolite may represent the upper limb of a major recumbent fold.

Figure 47 shows stereograms of minor folds on the west, central, and eastern parts, respectively, of this general belt. Minor folds on the west are predominantly west-verging (Figure

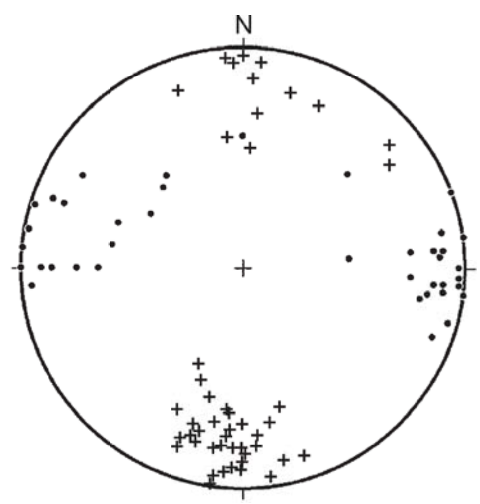


Figure 46. Orientation of parasitic folds, East Boothbay recumbent fold belt. Symbols: dot = pole to axial plane; + = fold hinge.

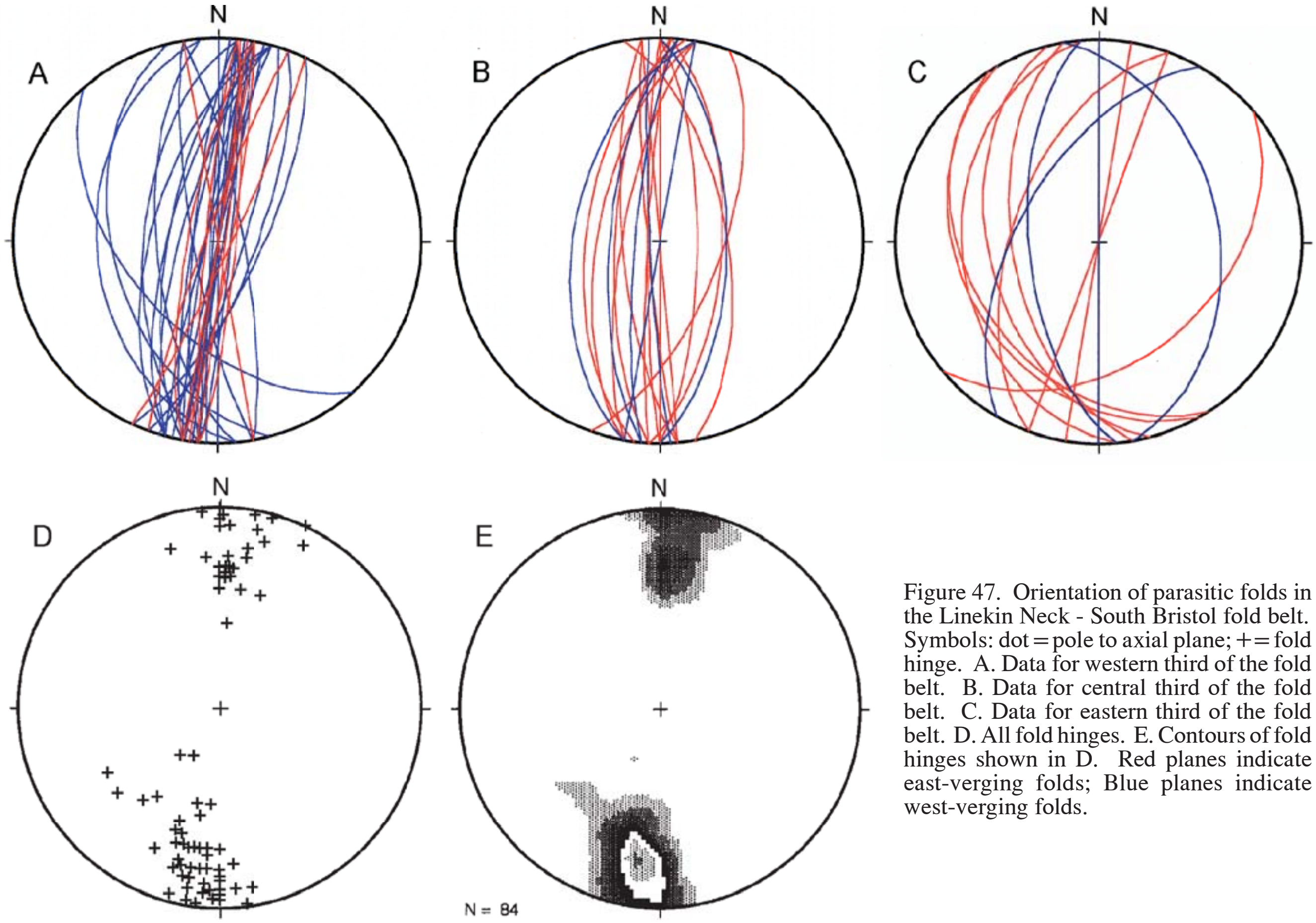


Figure 47. Orientation of parasitic folds in the Linekin Neck - South Bristol fold belt. Symbols: dot = pole to axial plane; + = fold hinge. A. Data for western third of the fold belt. B. Data for central third of the fold belt. C. Data for eastern third of the fold belt. D. All fold hinges. E. Contours of fold hinges shown in D. Red planes indicate east-verging folds; Blue planes indicate west-verging folds.

47a) and on the east they are mostly east-verging (Figure 47c). This suggests that the fold belt in the Linekin Neck-South Bristol area is, overall, a complex F_2 syncline between the Pemaquid Harbor and Boothbay anticlines.

Pemaquid Harbor anticline. The Pemaquid Harbor anticline (**pha**, Figure 33) is defined by the eastern outcrop belt of the Cross River Formation on the east shore of Johns Bay in the town of Bristol (Figure 4). A crude antiformal structure is indicated by the general orientation of foliation, dipping steeply to the east on the east side, and dipping moderately to steeply to the west on the west side.

Port Clyde refolded anticline. Guidotti (1979) has mapped a large-scale, complex anticline in the Port Clyde-Tenants Harbor area (**pcra**, Figure 33). From his map pattern and structural data we infer that rocks of the Benner Hill sequence were folded into an anticline and then refolded antiformally. The earlier anticline is defined by the symmetry of units getting younger away from the Mosquito Harbor Formation both to the east and to the west. In the Hart Neck area Guidotti (1979) describes the later fold, the Hart Neck antiform (**hna**, Figure 33), as plunging about 35^{o} to the northeast. Attitudes of bedding indicate that to the west the fold has been irregularly warped, perhaps due to the intrusion of granite and diorite plutons in the area. This younger fold (**hna**) is probably a different age from F_2 folds west of the Waldoboro pluton.

Faults and shear zones

Faults within the Bath map sheet, shown in Figure 33, include a major folded thrust (Boothbay thrust), major segments of the right-lateral Norumbega ductile shear system (Flying Point and South Harpswell faults), and several longitudinal high-angle brittle faults locally showing silicification and brecciation (Cape Elizabeth, Back River, The Basin, Phippsburg, St. George Estuary, and other unnamed faults). Several short transverse faults with east-northeast to northwest trends and offsets of generally less than 100 meters, are shown in Figure 33. In addition, minor brittle faults, too small to be shown at the scale of the Bath map sheet, are common throughout the map area.

Faults and deformational fabrics of the western third of the Bath map sheet were included in the Casco Bay shear-zone system defined by Swanson (1999a, 1999b). This zone widens from about 4 km in the Bath map area to about 15 km in the south end of Casco Bay in the Portland 1:100,000 map sheet (Berry and Hussey, 1998). Between the well-defined fault strands which show intense deformation, metamorphic rocks contain a pervasive but less severe dextral shear fabric in a belt ~35 km wide, extending eastward to the general area of Muscongus Bay (Figure 4) in the Bath map sheet (West, 1999, p. 171).

Our view differs somewhat from Swanson's in that we do not think that all these features are related to Late Paleozoic dextral deformation. Some named faults that he included in the Casco Bay shear-zone system are better described as younger brittle normal faults related to the Early to Middle Mesozoic rifting and breakup of Pangea. In addition, some have left-lateral horizontal offset. A more detailed evaluation of the movement sense and deformational style of many faults is better supported by geologic features in the Portland 1:100,000 map sheet to the west and is not pursued here.

Thrust faults. Boothbay thrust. The most significant structural feature within the map area is a major folded thrust, here named the Boothbay thrust (**BBT**, Figure 33). The contact of the Cape Elizabeth Formation with the Bucksport and Sebascodegan Formations is inferred to be the Boothbay thrust surface (Figure 37; sections A-A´ and B-B´ on the Bath map sheet). This thrust is interpreted from the widespread presence of older rocks (Casco Bay Group) above younger rocks (East Harpswell Group, Fredericton sequence). The proposed thrust is deformed by map-scale F_2 folds. It is inferred to have been formed prior to high-grade metamorphism because metamorphic isograds are not displaced; rocks on the upper and lower plates show no difference in grade of metamorphism. This could explain why fault-related fabrics and structures have not been observed at contacts of the juxtaposed sequences.

Exposures of the Bucksport Formation in the central third of the map represent autochthonous rocks of the lower plate of the thrust. This essentially follows the representation on the *Bedrock Geologic Map of Maine* (Osberg and others, 1985). In the area of the Hen Cove anticline, the contact between the Sebascodegan and Cape Elizabeth Formations is interpreted to be a continuation of this thrust (Figure 17). By this interpretation the East Harpswell Group is exposed in a window through the upper plate. Within the Bath map sheet, all exposures of the Casco Bay Group are in the upper plate of the Boothbay thrust and are therefore allochthonous. Figure 37 schematically represents the inferred structural relations between the lower and upper plates of the fault in the northwestern part of the Bath map sheet.

Direction of vergence of this thrust is not clearly indicated by evidence within the map sheet; however, an eastward vergence is favored because it appears to require far less transport than does a westward vergence, considering the distribution of the major rock units of the Casco Bay Group just to the west. This may be consistent with the interpretation of Tucker and others (2001) who include an early east-directed thrust, although they prefer a west vergence for the major thrusting in the region northeast of the Bath map sheet.

Possible blind thrust. The original relationship between the East Harpswell and Casco Bay Groups is not exposed on the map. It is shown in cross section (Figure 37) by a heavy line beneath the Yarmouth Island Formation. Present knowledge of age relationships allows that this contact may be an unconformity. Alternatively, a folded thrust may separate these rocks.

Norumbega fault system. *Flying Point fault.* The Flying Point fault (**FPF**, Figure 33) trends northeastward through the Town of Brunswick, and separates the Falmouth-Brunswick sequence from the Casco Bay Group. This fault preserves evidence of both deep-seated ductile dextral shear deformation (Swanson, 1992, 1999a, 1999b) and later west-side-up normal-fault movement (West and others, 1993; West, 1999). Within the Bath map sheet, the only exposures that may represent the trace of the fault occur at the northern tip of Pleasant Point in Topsham (Figure 4). Here, protomylonitized feldspathic gneiss of the Peaks Island Member of the Cushing Formation is juxtaposed against sheared migmatized gneiss assigned to the Nehumkeag Pond Formation of the Falmouth-Brunswick sequence. Quartz veins in the migmatites and quartz in the pegmatite stringers in the fault zone are finely granulated to a translucent sugary texture. North of the map area, the ductile faulting aspects of the Flying Point fault appear to trace into the Sandhill Corner fault of Pankiwskyj (1996), one of the dextral mylonitic segments of the Norumbega fault system.

The idea that the Flying Point fault has undergone later normal movement, probably in Mesozoic time, comes from $^{40}Ar/^{39}Ar$ studies of the cooling history of biotite, muscovite, and K-feldspar reported by West (1999) and West and others (1993). West (1999, p. 174) states, "A significant discordance in $^{40}Ar/^{39}Ar$ ages suggests that in early Mesozoic time a large thermal contrast existed in the rocks now juxtaposed across the Flying Point fault. Final juxtaposition and contemporaneous cooling between rocks currently juxtaposed across the Flying Point fault did not occur until after Triassic time." West and others (1993) interpreted this time-temperature discontinuity to reflect significant (~4 km), post-Paleozoic, east-side-down displacement along the Flying Point fault.

South Harpswell fault. The South Harpswell fault (**SHF**, Figure 33) is another segment of dextral ductile high strain shear deformation of the Norumbega fault system (the Casco Bay shear-zone system of Swanson, 1999a). Features of ductile dextral shear movement in the area of Lookout Point on Harpswell Neck (Figure 4) have been elegantly described and interpreted by Swanson (1995, 1999a). This high strain zone is parallel to the western shore of Harpswell Neck, and near the head of Middle Bay (Figure 4) it appears to be cut out by the Cape Elizabeth fault.

Displacement across the Norumbega fault system is uncertain because the faults are parallel to strike and do not offset identifiable strain markers. Based mainly on the geometry of shear structures, Swanson (1999b) suggests that right-lateral movement integrated across the Casco Bay shear-zone system may be in the 100 to 150 km range. In eastern Maine, Chunzeng (2001) demonstrated pluton offsets of 25 km across one strand, the Kellyland shear zone. When added to other faults and shear zones of the Norumbega system, Ludman and others (1999) estimate total dextral displacement of 120 to 150 km in eastern Maine.

Brittle Faults. Cape Elizabeth fault. A northeast- trending fault (**CEF**, Figure 33) is inferred to pass between Birch Island and Harpswell Neck in the westernmost part of the Bath map sheet. This fault is responsible for a significant (~6 km) left-lateral horizontal offset of the contact between the Wilson Cove Member of the Cushing Formation and the Cape Elizabeth Formation. In addition, the sillimanite/staurolite-out isograd, which is closely mapped on the west shore of Harpswell Neck (Hussey, 1971b), is offset left-laterally through Middle Bay an unknown distance (outcrops of pelitic rocks in the Middle Bay area are too sparse to closely locate the isograd west of the fault). This fault is on strike with the Cape Elizabeth fault that is well exposed on the southwest shore of Casco Bay in Cape Elizabeth (Hussey, 1989). There, the fault is marked by extensive silicification and local brecciation. Swanson (1999a) included the Cape Elizabeth fault as a part of his Casco Bay shear-zone system. We interpret it to be a younger brittle fault that may correlate with the late, brittle deformation associated with the Flying Point fault. The left-lateral offset of the Wilson Cove-Cape Elizabeth contact may be due in part to dip-slip fault movement (down to the east) along the shared limb of an intermediate-scale sinistral fold set, in which case the actual displacement could be relatively minor.

Back River fault. The Back River fault (**BRF**, Figures 33 and 13) is a late left-lateral fault, traced from just east of Wiscasset southwestward along the linear course of Back River between Wiscasset and Westport, through Hockomock Bay and onto Arrowsic Island in the vicinity of Mill Island (Figure 4; Hussey, 1992). It is delineated on the basis of (1) the offset of the amphibolite member of the Cape Elizabeth Formation on Westport Island and the southern end of Wiscasset Township; (2) by the offset of the Oak Island Gneiss; (3) the apparent truncation of a small granite pluton (**DSg**) on the north side of Montsweag Bay in Wiscasset; (4) by strong retrograde alteration of biotite to chlorite in rocks adjacent to the fault zone; and (5) silicified zones with drusy quartz vugs. The only exposure of the fault zone is at Mill Island, Arrowsic (Figure 4), where a small exposure of hard, extensively silicified granite gneiss can be seen. Exposures of granite and pegmatite on Mill Island in the vicinity of the silicified zone, and near Sewell Pond, Arrowsic, show repeated thin fracture zones filled with drusy quartz (Figure 48) subparallel to the trace of the fault. Total horizontal offset is approximately 1.5 km in a left-lateral sense as indicated by offset of the amphibolite member of the Cape Elizabeth Formation (**Ocea**) and the Oak Island Gneiss (**DSoi**). Fault movement postdates the principal episode of metamorphism, as well as intrusion and consolidation of granite plutons and pegmatite pods.

The Basin fault. The Basin fault (**TBF**, Figure 33) extends from the Sebasco area of Phippsburg north-northeastward through The Basin to just south of Pitchpine Hill (Figure 4). This fault is delineated on the basis of truncation of many minor units within the Cape Elizabeth Formation, offset of **Ocea**, truncation of several minor granite bodies in the area (**DSg**), and several minor silicified zones with drusy quartz vugs and occasional agate. Deflection of schistosity close to the fault trace suggests left-lateral movement. The fact that the fault is so nearly on strike with the trace of the Back River fault suggests that The Basin fault might be an extension of the Back River fault. However, the outcrop belt of **Ocea** in the north end of Phippsburg, and the two bodies of granite that lie between the ends of the two faults, show no evidence of offset. Movement along The Basin fault post-dates consolidation and cooling of the three minor granite plutons which are offset in the vicinity of The Basin in Phippsburg. It is a late brittle fault as indicated by the brecciated silicified zones along its trace.

Phippsburg fault. The Phippsburg fault (**PF**, Figure 33) is inferred along, and to be the cause of, the very marked lineament that parallels Maine Route 209 between Phippsburg village and the north end of Small Point Harbor (Figure 4). The actual fault zone is not exposed, and the offset of several minor units within the **Ocbu** unit suggests only minor movement along the fault.

St. George Estuary fault. The estuary of the St. George River between Cushing and St. George (Figure 4) follows the trend of an inferred fault, here referred to as the St. George Estuary fault (**SGEF**, Figure 33). The existence of this fault is suggested by the linear trend of the estuary, by offset of formational contacts, by the marked difference in migmatization, and by the significant difference in structural trends on either side of the fault. On the northwest side bedding and schistosity strike uniformly north-northeast, parallel to the fault trace, and the rocks are not significantly migmatized. On the southeast side, in contrast, structural trends are very irregular

Figure 48. Drusy quartz vein in granite, Mill Island, Arrowsic. Numerous similar veins are present in a small granite intrusion adjacent to the silicified zone marking the trace of the Back River fault.

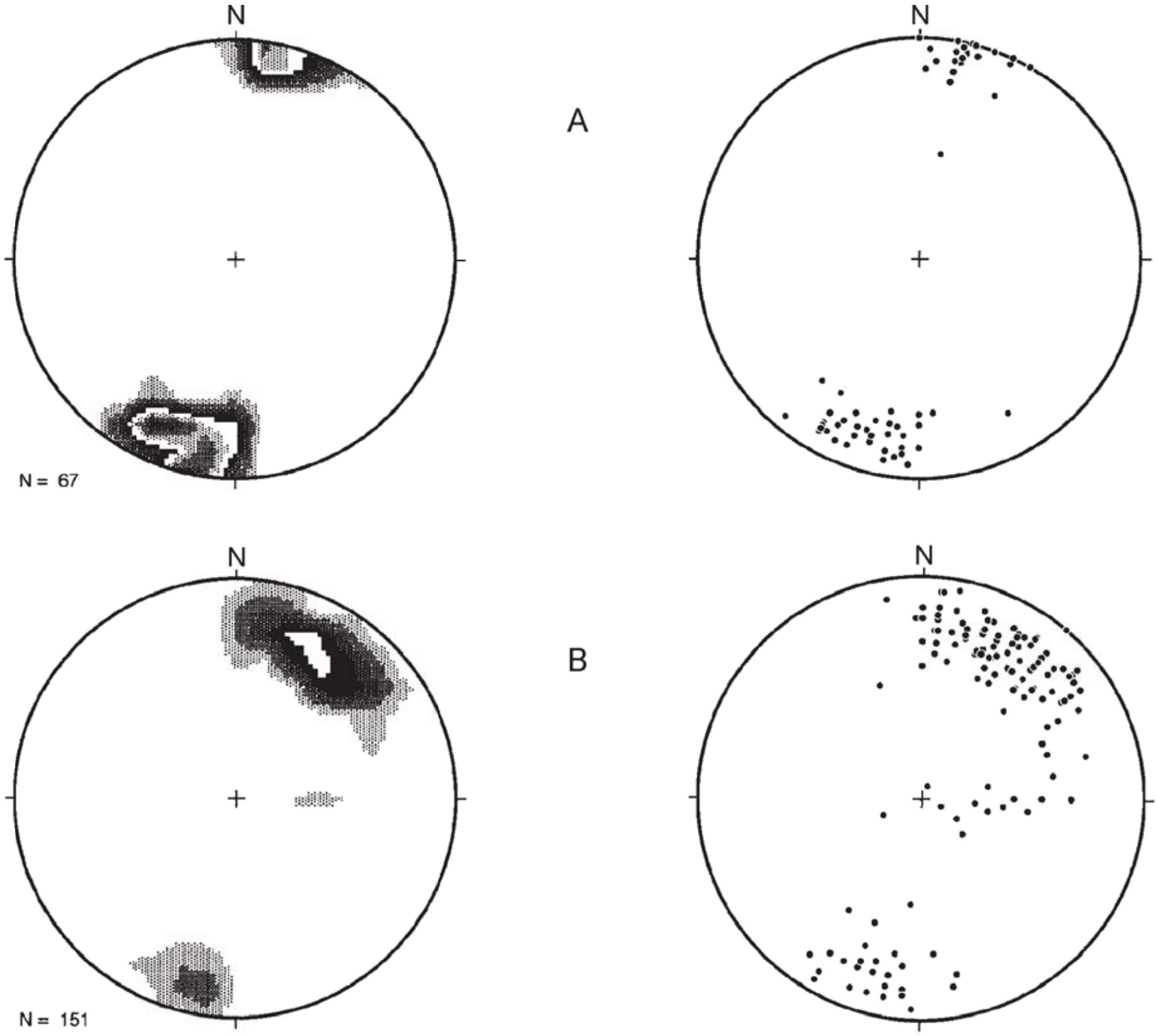


Figure 49. Orientation of lineations in the Harpswell Sound syncline and Hen Cove anticline area. Each contour diagram on the left corresponds to the data shown in the stereogram to the right. A. Mineral lineations. B. Crenulation lineations. C. Intersection lineations. D. Bedding mullion lineations. E. Rodding of quartz veins.

and the rocks are strongly migmatized and extensively injected by granite. Mapped contacts between formations on the Port Clyde Peninsula generally trend westerly toward the fault. Because there are no exposures of the fault zone itself, the nature of faulting, whether ductile or brittle, dip- or strike-slip, east- or west-dipping, cannot be ascertained, nor can an estimate of amount of offset be made.

Miscellaneous minor faults. Several faults of relatively short mappable extent and minor offset are shown on the Bath map sheet. Many of these are late faults (probably Mesozoic) with an east-northeasterly trend, parallel to the principal east-northeast regional joint set, and have gouge, fault breccia, or slickensides along the fault planes where they can be observed along the shore or in roadcuts. Numerous minor indentations of shorelines are probably the result of wave erosion of similar incoherent material (gouge?) along minor late faults where they are exposed along the shore.

Lineation

Lineations in the metamorphic rocks of the Bath map sheet include (1) parallelism of acicular minerals, mostly hornblende and sillimanite; (2) parallel elongation of platy minerals such as biotite, and to a lesser extent muscovite; (3) mineral streaks; (4) intersection of various S-surfaces; (5) bedding mullions (3 mm to 2 cm cylindrical sculpturing of bedding surfaces); (6) rodding and smearing of quartz veins; and (7) minute axes of crenulation of schistosity. Figures 49 and 50 portray stereographically lineations by type for several structurally defined areas.

In the Harpswell Sound syncline and Hen Cove anticline, mineral lineations, S-surface lineations, bedding mullions, and quartz-vein rodding have similar orientations (Figure 49). They plunge gently to moderately toward S 15-35^{o} W or N 15-35^{o} E, essentially parallel to axes of parasitic folds in this area. Crenulation axes (Figure 49b) plunge gently to moderately to the

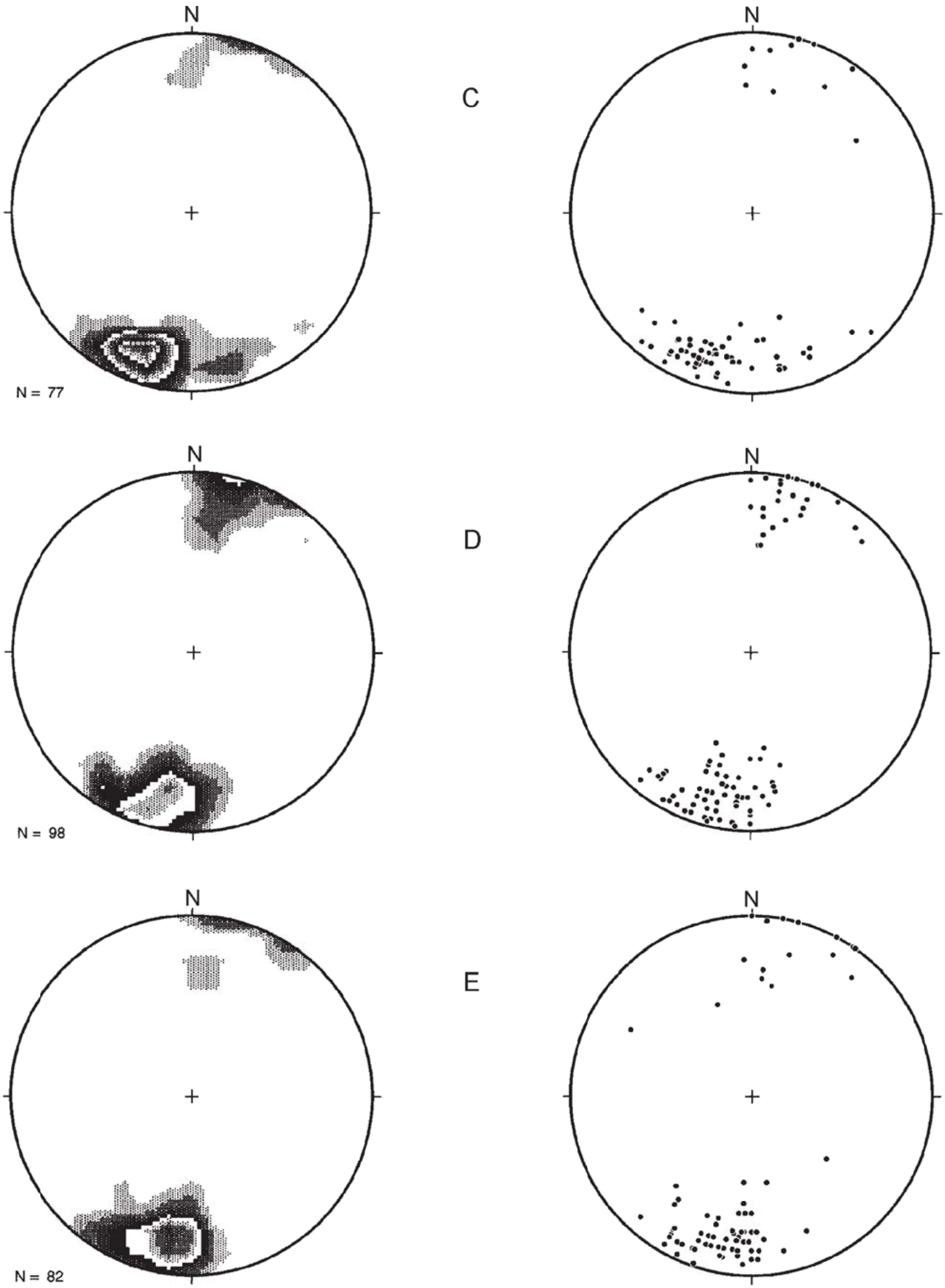


Figure 49. Continued.

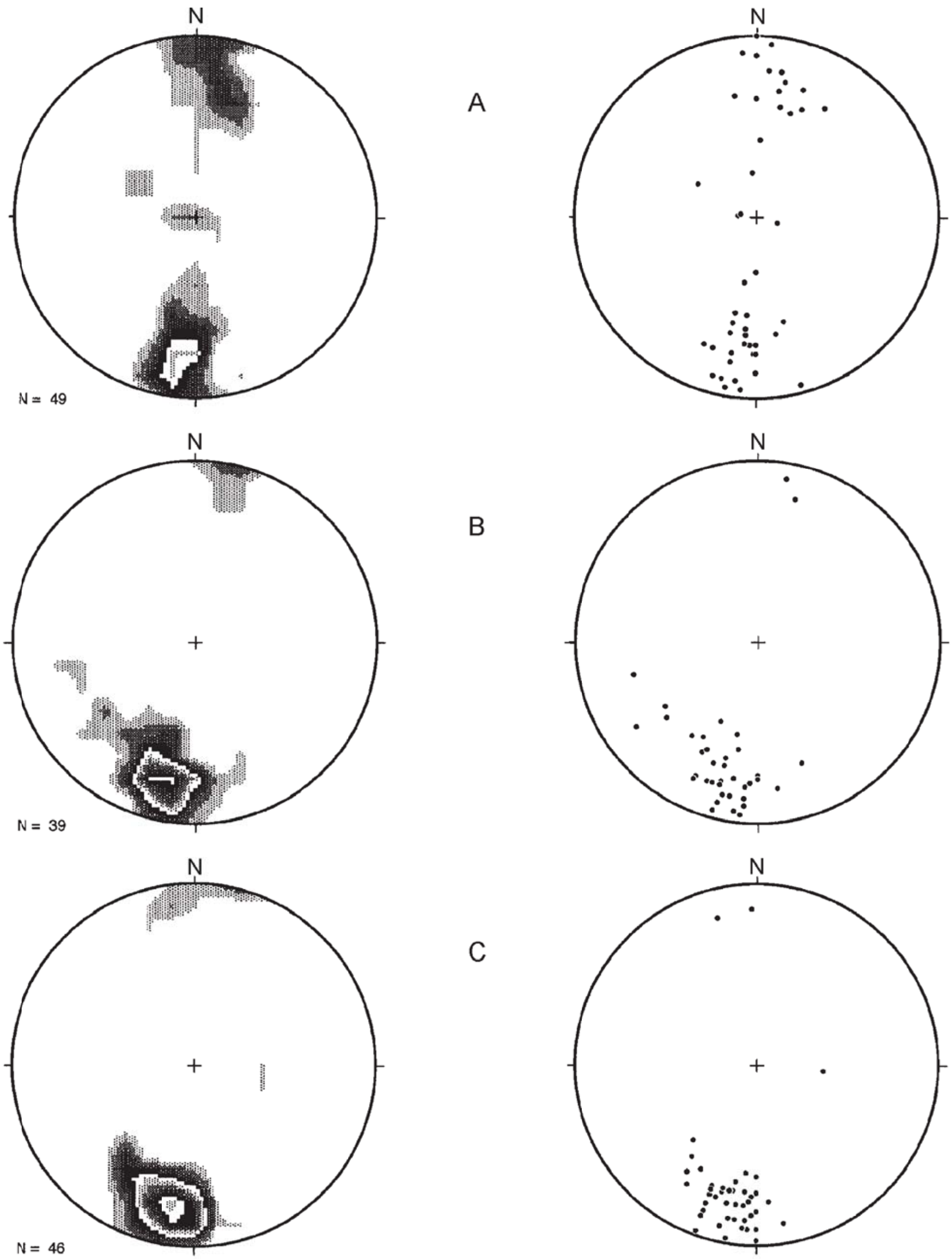


Figure 50. Orientation of lineations. Each contour diagram on the left corresponds to the data shown in the stereogram to the right. All types of lineations are represented together on each diagram. A. Lineations in the Georgetown antiform and Robinhood Cove synform. B. Lineations in the Boothbay anticline. C. Lineations in the South Bristol - Linekin Neck fold belt.

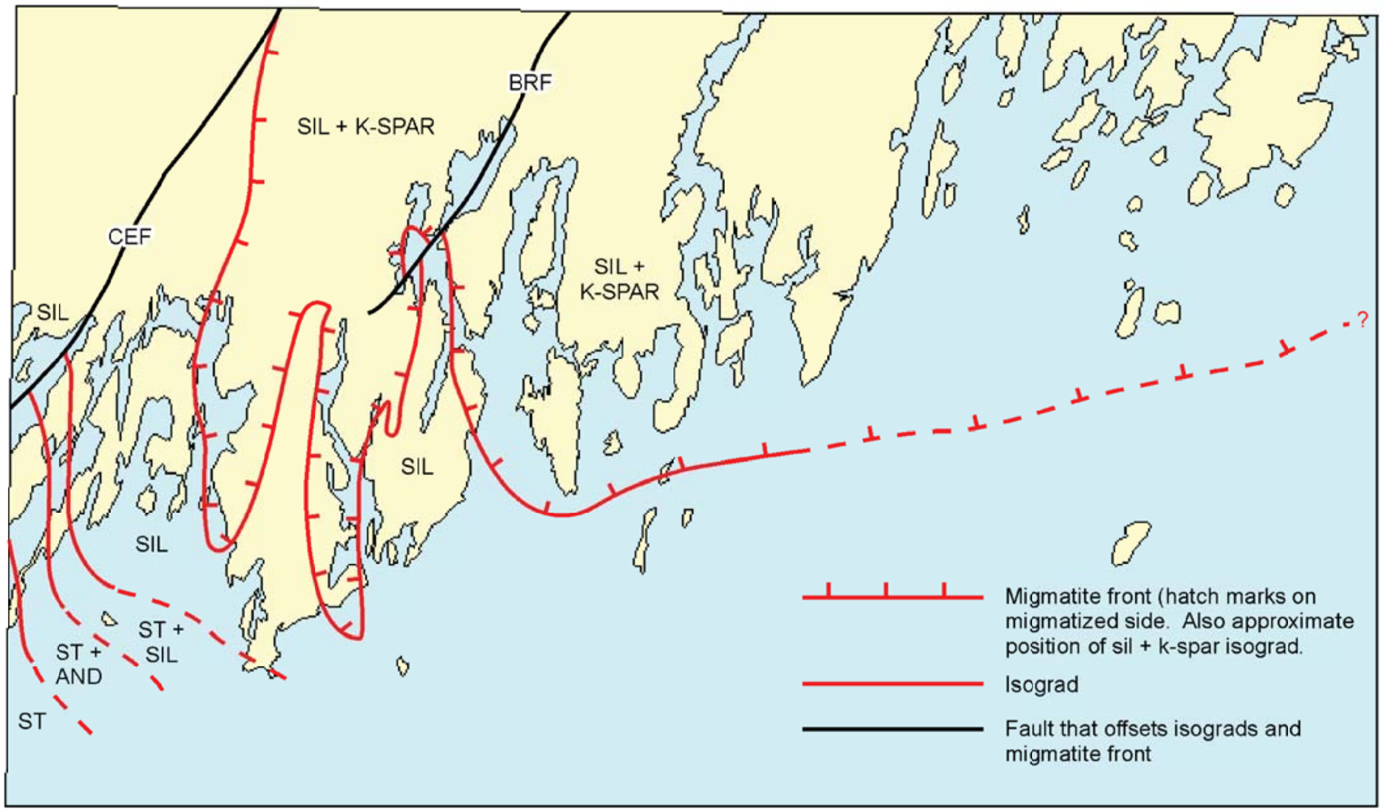


Figure 51. Map showing the approximate positions of metamorphic isograds and the limits of extensive migmatization in the Bath map sheet (modified from Grover and Lang, 1995). ST = staurolite, AND = andalusite, SIL = sillimanite, K-SPAR = alkali feldspar. CEF = Cape Elizabeth fault, BRF = Back River fault.

northeast, representing oblique but mostly vertical shortening in the plane of schistosity.

Similarly, mineral, mullion, and quartz-vein rodding lineations in the Boothbay anticline (Figure 50b) and in the South Bristol-Linekin Neck fold belt (Figure 50c) show relatively little scatter and are essentially parallel to the axes of parasitic folds in each area. Steep lineations are rare.

In contrast, lineations of all types in the area of the Georgetown antiform and Robinhood Cove synform (Figure 50a), show a moderate scatter of plunge angles with steep to vertical plunges common. Directions of plunges of these lineations show less scatter about a nearly north or south direction than the axes of parasitic folds (Figures 42 and 43).

METAMORPHISM AND MIGMATIZATION

Metasedimentary and metavolcanic rocks of the Casco Bay Group in southwestern Maine have been metamorphosed in a low pressure Buchan-type metamorphic facies series ranging from middle greenschist to upper amphibolite facies. Within the map sheet the metamorphic grade ranges from staurolite grade to sillimanite + K-feldspar grade (Figure 51). Most of the area is at sillimanite or sillimanite + K-feldspar grade. Lower grades are seen in the Portland area to the west.

Within the staurolite + andalusite zone of metamorphism at the western edge of the map sheet (Figure 51) the typical mineral assemblage in pelitic rocks is muscovite-biotite-quartz-oligoclase-staurolite-andalusite. Chloritoid is occasionally present. Almanditic garnet is present but sparse. Andalusite occurs in two habits, as large poikiloblasts, and as idioblastic to hypidioblastic graphite-choked porphyroblasts commonly with retrograde muscovite rims. In this zone, short milky quartz lenses 1 to 4 meters in length commonly have pink andalusite masses with abundant muscovite. Occasionally within the andalusite there are idiobasts of blue corundum (usually less than 2 mm in length) and staurolite. Sillimanite is very sparse and is usually isolated from contact with andalusite. Where sillimanite occurs in the quartz veins, it can usually be found in minute amounts within biotite grains in the host schist, indicating that the grade of metamorphism is actually slightly higher than is suggested by megascopic occurrences of the critical indicator minerals in hand specimen.

Within metapelites in the staurolite + sillimanite zone, andalusite is absent except for occasional remnants in the quartz veins. Sillimanite is recognizable in hand specimen. In the mafic rocks of the Spring Point Formation, hornblende, andesine, and garnet are typical minerals present. In rocks at Small Point at the southern tip of Phippsburg (Figure 16), andalusite coexists, probably metastably, with sillimanite. Large twinned staurolite porphyroblasts are locally abundant. Other minerals characteristic of staurolite + sillimanite grade metamorphism in metapelites are biotite, plagioclase, cordierite, garnet, and muscovite. Muscovite occurs both as matrix mica, forming the schistosity, and as large (1 to 3 cm long) pseudomorphs after andalusite or possibly untwinned staurolite (Figure 12; Lang and Dunn, 1990; Grover and Lang, 1995). In places, fresh staurolite forms large (1 to 2 cm long) twinned porphyroblasts, and andalusite occurs as large poikiloblasts up to 4 cm in diameter, engulfing all other phases.

In the sillimanite zone, staurolite is not present. The narrow zone marking the transition from staurolite + sillimanite zone to sillimanite zone can be seen along the northwest part of the Harpswell Neck shoreline at Barnes Point (Figure 4). Within the sillimanite zone the typical assemblage in the metapelites is muscovite + quartz + sillimanite + biotite + plagioclase ± garnet ± cordierite. In mafic rocks pale hornblende (pale green in thin section), plagioclase, cummingtonite, and gedrite are common phases. Calc-silicate assemblages include pale bluish green hornblende, diopside, sphene, grossularite, clinozoisite, microcline, quartz, and rarely, scapolite.

The sillimanite + K-feldspar zone coincides closely with the development of migmatites. Migmatization is most extensive in the metapelites, where original schistosity is obliterated and the rock takes on the typical gneissic structure of migmatites. K-feldspar commonly occurs as small grains in the shape of bow ties with rounded ends. In the migmatite areas, amphibolites, quartzo-feldspathic and calc-silicate assemblages of the Sebascodegan and Bucksport Formations are relatively free of migmatite, except for the extensive introduction of even-walled pegmatite sills, stringers, and dikes. This contrast in migmatization is particularly well shown in the two members of the Cross River Formation exposed in the Boothbay anticline (Figure 33). The upper member (**O€crg**) consisting of fine-grained quartz-plagioclase-biotite-garnet granofels is essentially unmigmatized, whereas the underlying rusty sillimanite-graphite gneiss is so thoroughly migmatized as to mask such structural features as relict bedding, schistosity, and lineations. It should be pointed out that the migmatite front within the Casco Bay Group, shown in Figure 51, is crudely concordant with the geometry of major F_2 upright folds.

Rocks of the Falmouth-Brunswick sequence have been metamorphosed to sillimanite and possibly sillimanite + K-feldspar grade within the Bath map sheet. All rocks are significantly migmatized and injected by pegmatites. Evidence for the geobarometric environment during metamorphism of this sequence is lacking within the Bath map sheet, but along strike in the Freedom area, Pankiwskyj (1976, 1996) reports the presence of kyanite in the paragenesis of aluminous schist lenses in the Falmouth-Brunswick sequence, suggesting higher pressure Barrovian metamorphism for that area. The extent of the higher pressure metamorphism is not known. Pankiwskyj (personal communication, 1997) suggests that it may be related to pre-metamorphic thrust faulting with attendant thickening of the sedimentary pile, and probably is synchronous with minor and map scale F_1 recumbent folding.

TIMING OF VOLCANISM, SEDIMENTATION, DEFORMATION, METAMORPHISM, AND PLUTONISM

Figure 52 summarizes the best available radiometric ages from the Bath map sheet and adjacent areas that bear on the age of volcanism, sedimentation, deformation, metamorphism, and plutonism. In the Megunticook sequence, a relatively small volcanic event occurred at the end of the Cambrian. Otherwise, practically all rocks in the Megunticook and Benner Hill sequences represent various Ordovician marine sediments. By contrast, the Falmouth-Brunswick sequence, East Harpswell and Casco Bay Groups together record volcanic activity for much of the Ordovician and perhaps into the Early Silurian, with rocks dated from about 472 Ma to about 445 Ma.

In the Early Silurian, marine clastic sedimentation continued in the Central Maine, East Harpswell, and Fredericton trough(s). By Late Silurian (circa 420-425 Ma) rocks of the eastern part of the Bath map sheet, in the Megunticook and Benner Hill sequences, had been deformed and metamorphosed to amphibolite facies (West and others, 1995). Moreover, many of the post-tectonic plutons in that area have been dated in the same Late Silurian age range (Tucker and others, 2001). The largest of these exposed in the Bath map area is the Spruce Head pluton. Tucker and others (2001) consider this plutonic, metamorphic, and presumably deformational event to be an early phase of the Acadian orogeny.

To the north of the Bath map sheet (Tucker and others, 2001), the Fredericton sequence and Casco Bay Group are intruded by some Late Silurian plutons of the same age as some plutons east of the Sennebec Pond fault. Tucker and others (2001) suggest, however, that the peak metamorphism in the Liberty area is Devonian, whereas peak metamorphism east of the Sennebec Pond fault is Silurian (West and others, 1995). The extent to which the Fredericton and more western sequences may have been deformed and metamorphosed in the Late Silurian has not been established, due primarily to the intensity of the younger, Devonian events.

The Sennebec Pond fault projects into the Bath map sheet along the east side of the Waldoboro pluton. To its west, the Cape Elizabeth Formation in the Small Point area shows clear evidence of two stages of metamorphism (Hussey, 1988). The earlier stage is indicated by the large pseudomorphs of muscovite described above. The later stage is indicated by porphyroblasts of fresh staurolite and large poikiloblasts of fresh andalusite in the same rocks. As discussed above, the Cape Elizabeth Forma-

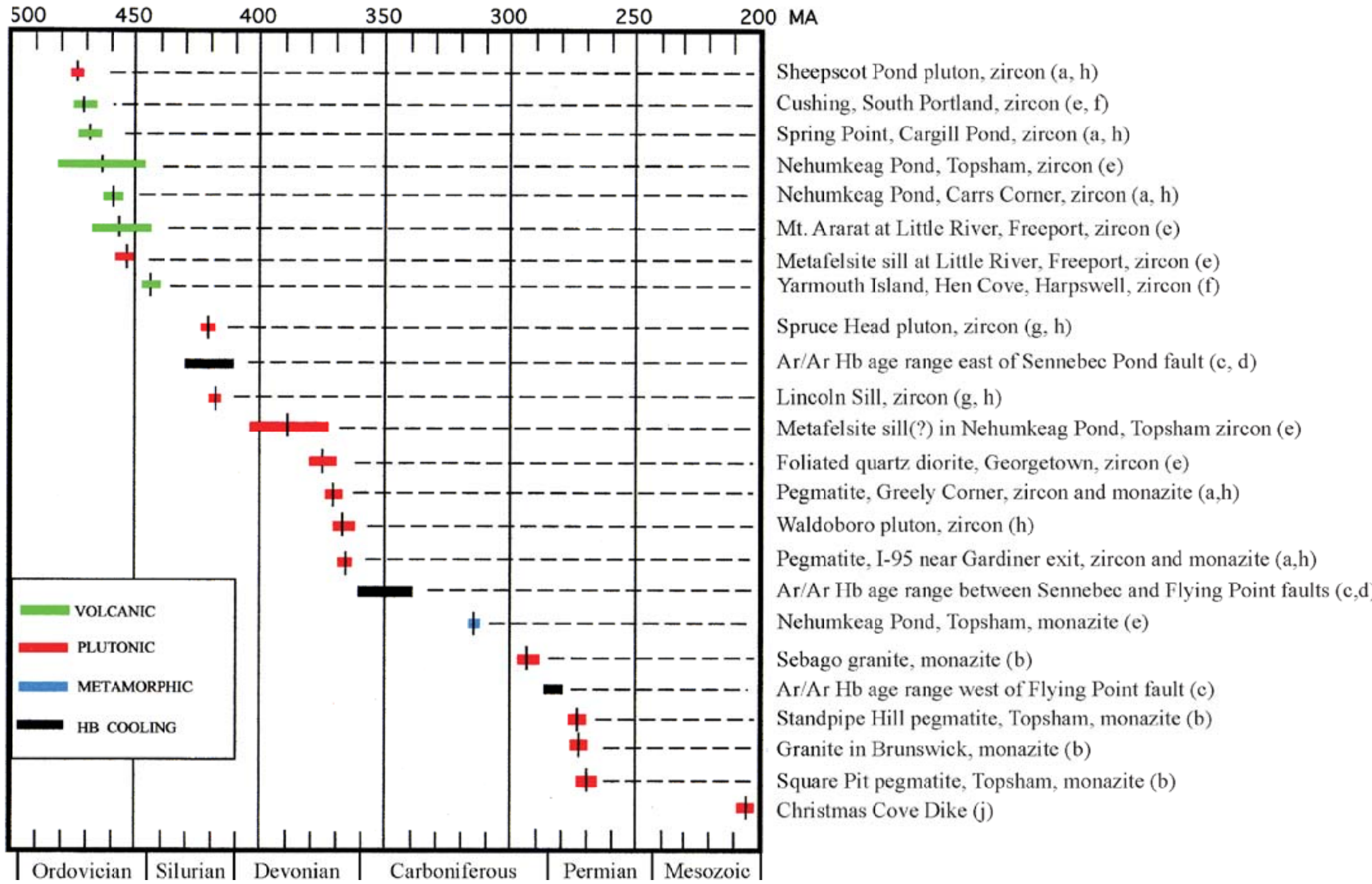


Figure 52. Chart of radiometric age determinations in the Bath map sheet and surrounding area. Compiled from various sources including (a) Osberg and others (1995), (b) Tomascak and others (1996), (c) West and others (1993), (d) West and others (1995), (e) J. F. Aleinikoff (personal communication, 1994, 2002), (f) Robert D. Tucker (personal communication, 1995), (g) Bradley and others (1998), (h) Tucker and others (2001), (i) Brookins and Hussey (1978), and (j) West and McHone (1997). Length of bar indicates uncertainty.

tion at Small Point displays two deformational events. The younger, D_2, was accompanied by a metamorphic event, presumably the event that crystallized hornblendes which give Early to Middle Devonian cooling ages. The age of the earlier metamorphism at Small Point is unknown, but it may be of Late Silurian age and correlative with that of the area east of the Sennebec Pond fault. If this is the case, it may be that rocks on both sides of the Sennebec Pond fault experienced the same thermal events, even though they differ in intensity. Thus, the Sennebec Pond fault may not strictly separate two regions of distinct thermal histories. More information is needed on the time of metamorphism to test this hypothesis.

Movement of the Boothbay thrust predates F_2 folding and metamorphism, and may be contemporaneous with F_1 recumbent folding and cleavage development. The relationship of the Lincoln Sill to the thrust fault is perplexing. It is folded by, and therefore predates, F_2 deformation. It predates peak Acadian metamorphism. The 418 Ma zircon age reported by Tucker and others (2001) indicates a time of intrusion of latest Silurian to earliest Devonian. It is tempting to think that the intrusion is in some way related to the large-scale thrusting that formed the Boothbay thrust sheet. However, the uncertainty of the mechanism of its intrusion and the fact that the sill does not occupy the sole of thrust but is slightly below it, in the autochthonous part of the Bucksport Formation, remain unexplained.

West of the Sennebec Pond fault, $^{40}Ar/^{39}Ar$ hornblende cooling ages (Figure 52) indicate that metamorphism occurred during an Early to Middle Devonian phase of the Acadian orogeny (West and others, 1988, 1993). As reported by West and others (1993) the latest hornblende cooling ages of the Casco Bay Group range between 340 and 360 Ma, compatible with regional cooling after Acadian metamorphism.

Middle to Late Devonian ages are more common for intrusive rocks in the Bath map sheet west of the Sennebec Pond fault. The Waldoboro pluton, which intrudes the Bucksport and Cross

River Formations, the foliated quartz diorite in Georgetown that intrudes the Casco Bay Group, and pegmatites that intrude the Falmouth-Brunswick sequence have all been dated at Middle to Late Devonian. The $^{40}Ar/^{39}Ar$ hornblende cooling ages of West and others (1988) imply that the peak, amphibolite facies metamorphism was also Middle to Late Devonian. Thus, migmatization of the Falmouth-Brunswick sequence, and probably also of the Casco Bay Group between the Sennebec Pond and Flying Point faults, is associated with the Middle to Late Devonian phase of the Acadian orogeny.

Rocks of the Falmouth-Brunswick and Central Maine sequences in the northwestern corner of the Bath map sheet have been deformed by folds that are strongly overturned to the west (Figures 35 and 36). Vergences are predominantly to the east on the northwest limb of the major antiform that dominates the outcrop belt of the Falmouth-Brunswick sequence (Figure 37). These folds affect both gneissic foliation of the paleosome and thin foliated pegmatitic stringers of the neosome (Figure 36), thus postdating migmatization. Some pegmatitic stringers and dikes cut these folds (Figure 35) suggesting a second generation of pegmatite injection, possibly related to intrusion of the Permian-age pegmatites of the Topsham area studied by Tomascak and others (1996). Folding of the Falmouth-Brunswick and Central Maine rocks may thus be related to Early Carboniferous transpression that was responsible for dextral shearing of the Norumbega fault system. Ages of undeformed pegmatites in the Gardiner area (Figure 52) on strike to the north of the map area suggest major pegmatite intrusion during the Late Devonian, as a thermal effect of the Acadian orogeny. The rocks of the Gardiner area are also migmatized. Sorting out the ages of migmatization and deformation in the Topsham-Brunswick area requires additional detailed radiometric age studies.

In the Tenants Harbor area (Figure 4), most of the rocks have been affected by retrograde metamorphism (Guidotti, 1979, 1989). Andalusite and staurolite have been replaced by muscovitic pseudomorphs, and irregular biotite clots presumably have replaced an Fe-Mg mineral. The age of the retrograde metamorphism is not known, but the preservation of delicate pseudomorph shapes suggests it was post-tectonic, implying only that it was post-Silurian.

A major thermal event, of Late Pennsylvanian to Permian age (Alleghenian?), affected the rocks of the Falmouth-Brunswick sequence and probably a large area of the Central Maine sequence west of the Flying Point fault (Figure 33). Tomascak and others (1996) report a U-Pb monazite age of 293 ± 2 Ma for the Sebago granite northwest of the Bath map sheet. According to West and others (1988, 1993), $^{40}Ar/^{39}Ar$ hornblende cooling ages within 60 km east of the Sebago pluton, including the northwest corner of the Bath map sheet, are remarkably consistent, between 283 and 287 Ma (Figure 52). Farther northeast, in the Gardiner-Augusta area, the hornblende cooling ages become abruptly older (approximately 323 Ma), increasing northeast to 372 Ma. The older ages reflect cooling from Acadian metamorphism, but the younger ages are likely related to Late Pennsylvanian-Permian heating associated with the intrusion of the Sebago granite.

A small area in the Brunswick-Topsham vicinity gives somewhat younger ages. Tomascak and Francis (1995) report U-Pb monazite ages for two-mica granite lenses and pegmatites ranging from 268 to 275 Ma. West and others (1993) report two similar hornblende cooling ages in this area, of 266 and 270 Ma, anomalously young compared with the 283-287 Ma ages of the surrounding region. This suggests that the Topsham pegmatite district may represent a localized thermal pulse 15 to 20 m.y. younger than the Sebago granite. Not enough precise age dates are currently available to define this late event.

There is no indication in this area of an Alleghenian compressional event. However, Swanson (1995, 1999b) suggests the possibility of a late Paleozoic transpressional shear event associated with movement on the Norumbega fault system and with the injection of the late pegmatite and granite lenses noted above.

The timing of ductile dextral shearing and subsequent brittle faulting in south-central Maine is discussed by West and others (1993) and most cogently by West (1999). The region of pervasive dextral shear fabric, covering two-thirds of the map area, postdates metamorphism east of the Flying Point fault, inasmuch as porphyroblasts that formed during Acadian metamorphism are commonly sheared and flattened. West (1999) points out that ductility of these rocks probably required temperatures above 320^{o}C, or about the closure temperature for argon diffusion in muscovite. He reports $^{40}Ar/^{39}Ar$ muscovite cooling ages for the region of the Bath map sheet to range from 350 to 298 Ma, Late Devonian to Early Carboniferous.

Localized dextral high strain zones cut through the region of pervasive dextral strain. West and Lux (1993) report a $^{40}Ar/^{39}Ar$ age of about 290 Ma (Early Permian) on muscovite that they believe grew or recrystallized during mylonitic deformation on the Sandhill Corner fault, north of the Bath map area. Dextral mylonitic deformation on other strands of the Norumbega fault system, including the Flying Point and South Harpswell faults, may have been active at this time. Tomascak and others (1996) note that intense ductile deformation of the Flying Point fault in the Topsham area predates undeformed pegmatites and granites with ages as old as 275 Ma.

Relative age of brittle normal and possibly left-lateral strike-slip faulting is not well constrained by offset of geological features. The only rocks that are not offset by faults are the basaltic dikes. Of these, the only dated dike is the large, throughgoing Christmas Cove dike for which West and McHone (1997) report preliminary ages ranging from Late Triassic to Early Jurassic. The mineral cooling ages described above imply that normal faulting along the Flying Point fault occurred after Early Triassic time (West, 1999), and the age of the Christmas Cove dike suggests that movement happened prior to Early Jurassic. Normal fault movement is believed to be a result of crustal

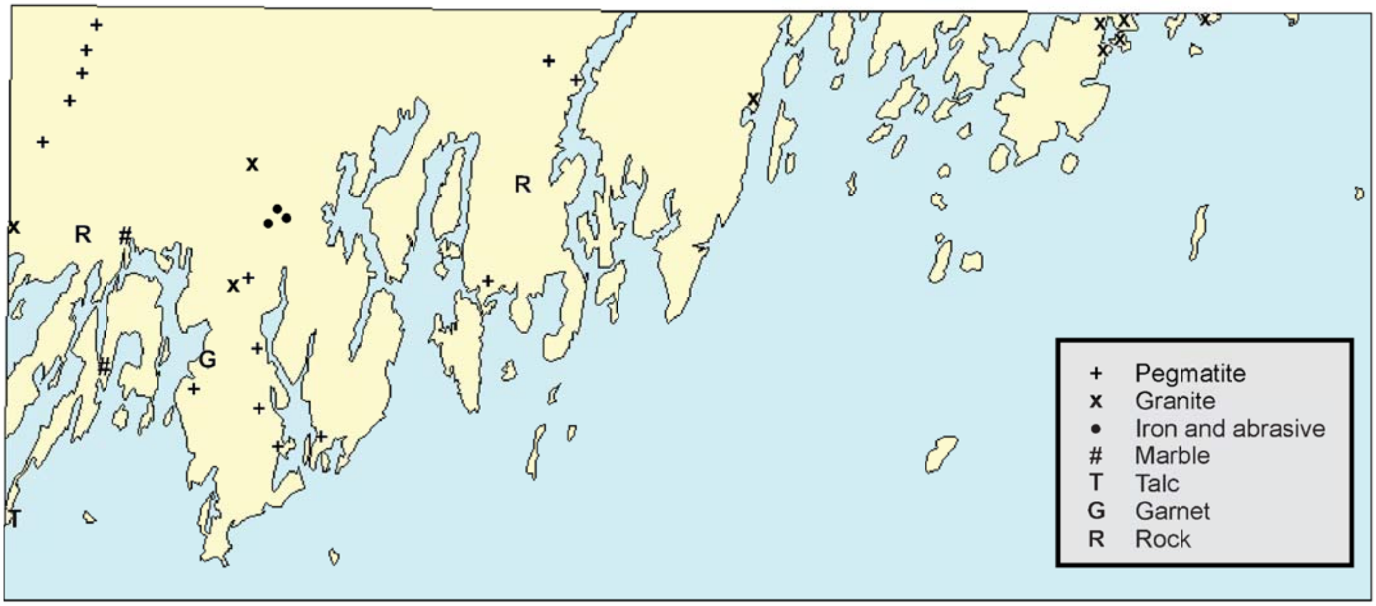


Figure 53. Localities of quarries, mines, and prospects in the Bath map sheet. Most are inactive.

extension associated with the initial breakup of Pangea. The regional setting for a left-lateral component of motion on the Cape Elizabeth, The Basin, and Back River faults is not clear.

MINERAL RESOURCES AND PAST MINING ACTIVITY

The principal economic extractive activity in the Bath map sheet is the production of sand and gravel from unconsolidated glacial deposits. Current bedrock mining activity is restricted to the quarrying of durable rock which is crushed and sized for fill and road metal. In addition, old spoils piles from pegmatite mines are being removed for fill. At present, there is no other bedrock mining of any consequence. Locations of quarries, mines, and prospects are shown on Figure 53.

Mining of feldspar has taken place from many pegmatites in the Topsham, Georgetown, and Phippsburg areas (Caldwell and Austin, 1957). The largest mines in the area were the Consolidated Feldspar Company mines in Topsham and Georgetown (Figure 53). In addition to feldspar, minor amounts of strategic mica were produced during World War II. Feldspar mining began in the mid-1800's and ceased in the middle to late 1950's. The last company to operate was the Consolidated Feldspar Company. After the closing of feldspar operations and the sale of the properties, Emery Booker of Brunswick attempted a commercial operation in Tophsam, producing chicken grits by grinding and size sorting materials from the spoils piles. Today some of these pegmatites are being prospected and mined on a limited scale for mineral specimens and gemstones. Minerals other than feldspar and quartz that have been found in pegmatites in the map area include beryl, columbite, samarskite, allenite, uraninite (massive and small octahedral crystals), tourmaline, cleavelandite, apatite, dumortierite, chrysoberyl, rose quartz, garnet, cassiterite, cookeite, eosphorite, lepidolite, spodumene, zircon, torbernite, autinite, and uranophane (Thompson and others, 1991).

In the past, granite was produced from quarries at several localities in the Spruce Head pluton, and from a small number of quarries in the Waldoboro pluton and the Raccoon pluton within the map area. Smaller quarries were opened and operated in Bath, Phippsburg, Brunswick, and Bristol (Figure 53). The Clark Island Quarry near Tenants Harbor in St. George was opened in 1870 in biotite-muscovite granite of fine to medium even-grained texture in the Spruce Head pluton (Dale, 1907). As of 1905, the quarry opening measured 500 feet x 300 feet with an average depth of 25 feet. Long Cove Quarry (Figure 25) in the town of Tenants Harbor was opened in 1873, producing the same type of granite as from the Clark Island Quarry. As of 1907 the quarry was 1000' long, 500' wide, and an average of 40 feet deep (Dale, 1907). The Hocking Granite Quarry, located in St. George, at the very northern edge of the map sheet, produced granite essentially like that from the Clark Island Quarry and was one of the last operations in the area to close. As of 1960 most quarrying had ceased, but the company was producing crushed rock. The granite dust from this crushing operation was marketed under the trade name *Vitamite* as a soil additive for potash. Some small quarries were opened in gabbro-diorite of the Raccoon pluton. In the Waldoboro pluton, the only sizable opening in the Bath map sheet is the Round Pond Quarry in the town of Bristol. According to Dale (1907), the quarry was opened in 1885 and consisted of two openings, one 100 feet square, and the

Figure 54. Flooded adit to small underground working in magnetiferous garnet granofels (coticule) of the Cape Elizabeth Formation (**Ocec**), Arrowsic, Maine. This and a nearby surface pit may be the "iron mine" referred to by Morrill (1955) and was probably operated by the Bath Iron Mining and Manufacturing Company around 1866.

Figure 56. Walter Anderson, emeritus State Geologist of Maine, standing on the spoils pile adjacent to the Arrowsic Iron Mine. The open-pit mine is just beyond the top of the pile.

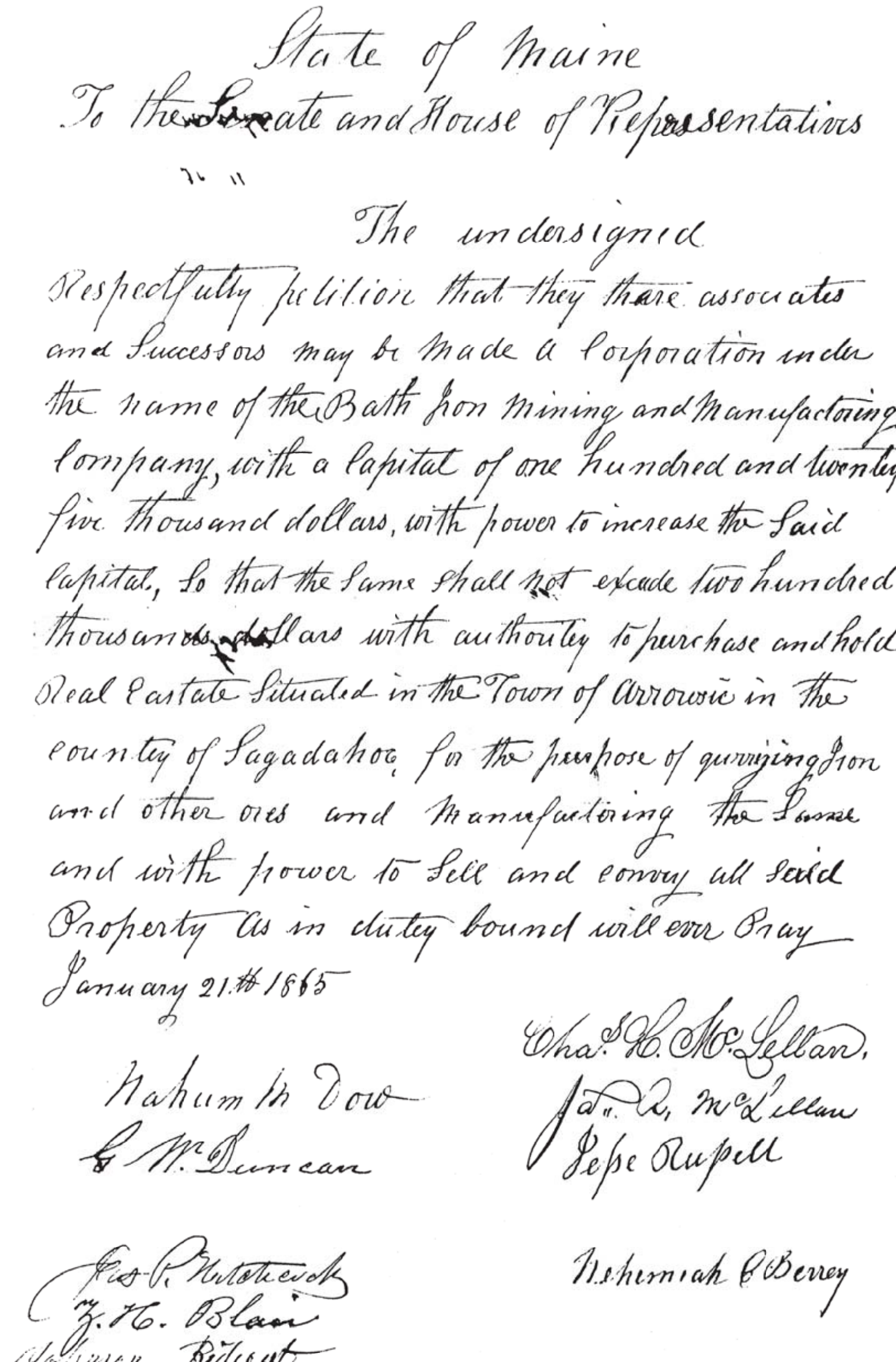
Figure 55. Iron and "emery" prospect pit of the Arrowsic Iron Mine. Depth of pit to water level is about 5 meters.

other 400 feet by 100 feet, each ranging in depth from 10 to 65 feet.

Seven small prospect pits in the coticule unit of the Cape Elizabeth Formation were encountered by Hussey during detailed mapping on Arrowsic Island and Georgetown Island (Figure 53). Most pits are small - generally less than 20 feet x 20 feet by 10 feet deep. One pit on Arrowsic Island just off Doubling Point Road has a nearby adit about 4 feet high that is presently flooded about three feet inside the opening (Figure 54). Morrill (1955) makes reference to iron mining and "emery" mining in Arrowsic, and apparently these openings (Figures 55 and 56) were the prospects for iron ore (magnetite) and abrasive (garnet) which are abundant in the coticule. Since corundum has not been reported from here, it is not a true emery deposit. The prospects are believed to have been worked by the Bath Iron Mining and Manufacturing Company, a company chartered by act of the Maine Legislature in 1865. Figure 57 is a reproduction of the petition of a number of businessmen in the Bath area to the Maine legislature, and Figure 58 is a copy of the legislative document that established the Bath Iron Mining and Manufacturing Company. Prospecting operations apparently were carried out shortly after incorporation, and then quickly abandoned because of lack of sufficient ore for economic production of either iron or abrasive material. No mention of the Bath Iron Mining and Manufacturing Company or its operations of which the writer is aware appears in the Maine Mining Journal, published in Bangor between 1881 and 1883. Nor is there any mention of iron ore or emery mining in discussions of the results of the geological survey of the State of Maine during the late 1850's and earliest 1860's by Hitchcock (1861, 1862), or earlier by C. T. Jackson (1837, 1838, 1839).

Marble from two localities in Brunswick, one north of the bridge to Great Island (Harpswell) and the other in East Brunswick, was quarried and burned for agricultural lime probably in the mid 1800's. The East Brunswick locality is a narrow strip mine following a local zone of marble in the Bethel Point Formation (**SObp**); and the other locality is a series of strip mines 10 to 15 feet wide and 8 to 10 feet deep following the white marble lens (the same unit as shown in Figure 19) in the amphibolite (**SOsa**) of the Sebascodegan Formation. A third locality, where lime was burned, but where there is no clear evidence of its having been mined, is on The Basin in Phippsburg near the grossularite mineral-collecting locality in the Cape Elizabeth Formation (**Ocea**). On the east side of the small point at the garnet locality can be seen the remains of the kiln that was used for producing quicklime.

Talc was mined in the early 1800's on a very limited basis from the 1-meter-wide pre-metamorphic sill within the Cape Elizabeth Formation on the east shore of Bailey Island (Jackson,

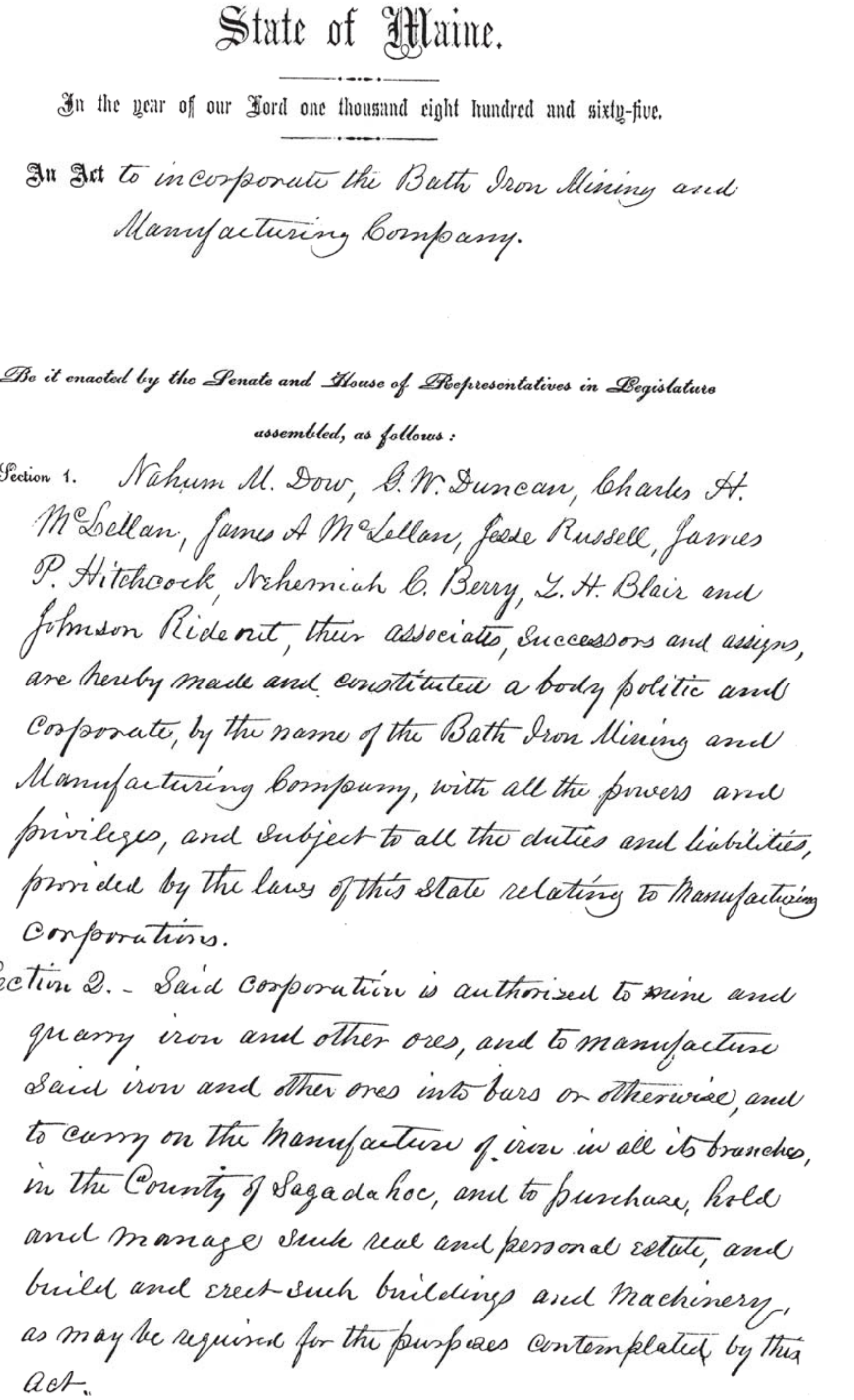


State of Maine
To the Senate and House of Representatives

The undersigned
Respectfully petition that they their associates and Successors may be made a Corporation under the name of the Bath Iron Mining and Manufacturing Company, with a Capital of one hundred and twenty five thousand dollars, with power to increase the Said Capital, So that the Same Shall not excede two hundred thousand dollars with authoritey to purchase and hold Real Eastate Situated in the Town of Arrowsic in the countey of Sagadahoc for the purpose of quarrying Iron and other ores and Manufacturing the Same and with power to Sell and convey all said Property As in dutey bound will ever Pray
January 21st 1865

Chas. H. McLellan,
Jas. R. McLellan
Jesse Rupell
Nahum M. Dow
G. M. Duncan
Nehemiah C. Berry
Jas P. Hitchcock
Z. H. Blair
Johnson Rideout

Figure 57. Photocopy of petition to the Maine legislature to form the Bath Iron Mining and Manufacturing Company. Document from Maine State Archives, Augusta.



State of Maine.

In the year of our Lord one thousand eight hundred and sixty-five.

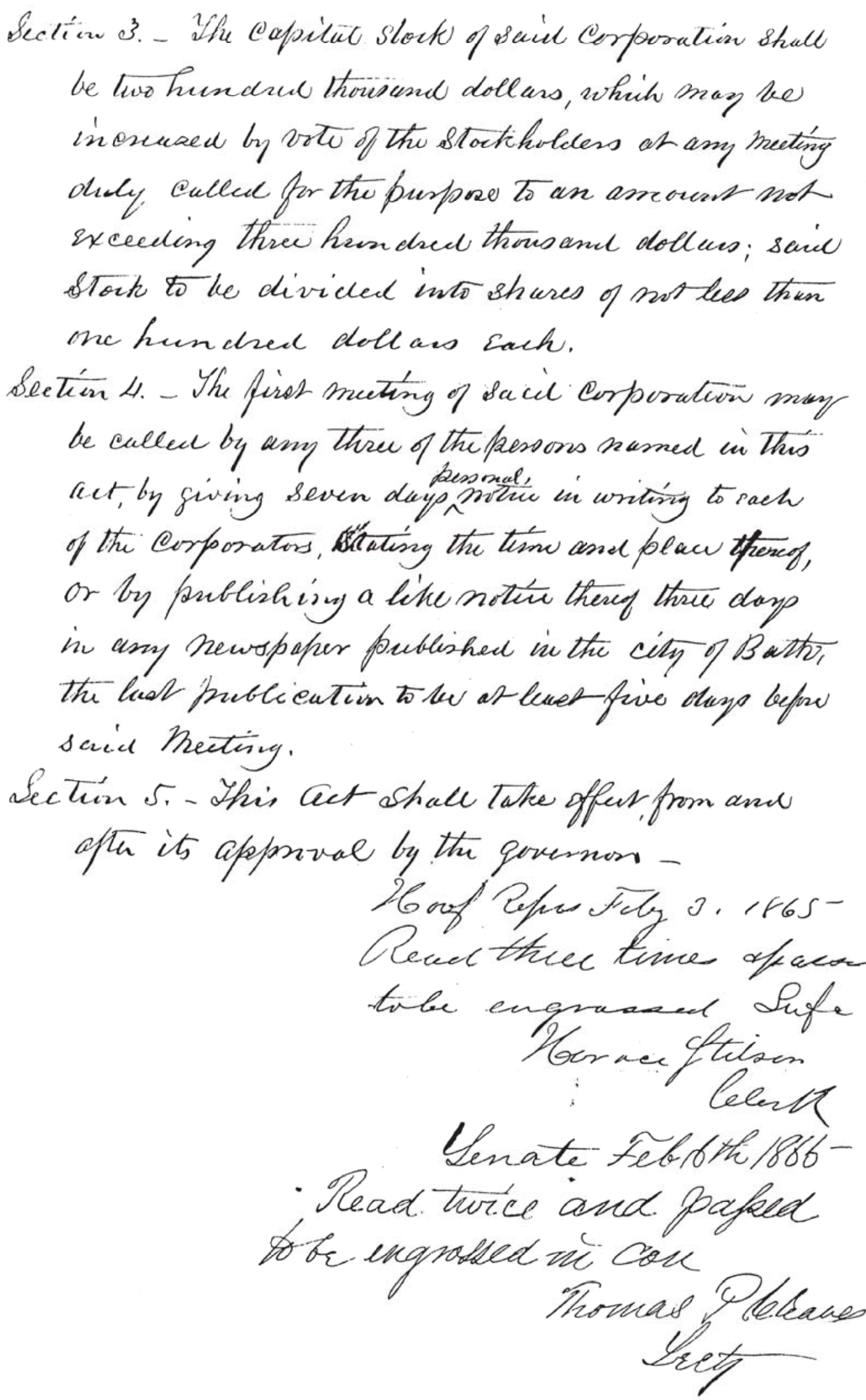
An Act to incorporate the Bath Iron Mining and Manufacturing Company.

Be it enacted by the Senate and House of Representatives in Legislature assembled, as follows:

Section 1. Nahum M. Dow, G. W. Duncan, Charles H. McLellan, James A McLellan, Jesse Russell, James P. Hitchcock, Nehemiah C. Berry, L. H. Blair and Johnson Ridenit, their associates, successors and assigns, are hereby made and constituted a body politic and corporate, by the name of the Bath Iron Mining and Manufacturing Company, with all the powers and privileges, and subject to all the duties and liabilities, provided by the laws of this State relating to Manufacturing Corporations.

Section 2. - Said corporation is authorised to mine and quarry iron and other ores, and to manufacture said iron and other ores into bars or otherwise, and to carry on the manufacture of iron in all its branches, in the County of Sagadahoc, and to purchase, hold and manage such real and personal estate, and build and erect such buildings and machinery, as may be required for the purposes contemplated by this act.

Figure 58. Photocopy of legislative document authorizing the establishment of the Bath Iron Mining and Manufacturing Company, 1865. Document from Maine State Archives, Augusta.


Section 3. – The Capital Stock of said Corporation shall be two hundred thousand dollars, which may be increased by vote of the Stockholders at any meeting duly called for the purpose to an amount not exceeding three hundred thousand dollars; said Stock to be divided into shares of not less than one hundred dollars each.

Section 4. – The first meeting of said Corporation may be called by any three of the persons named in this act, by giving seven days personal notice in writing to each of the Corporators, stating the time and place thereof, or by publishing a like notice thereof three days in any newspaper published in the city of Bath, the last publication to be at least five days before said Meeting.

Section 5. – This Act shall take effect from and after its approval by the governor –

House of Reps Feby 3. 1865 –
Read three times & passed
to be engrossed Sufs
Horace Stilson
Clerk

Senate Feb 6th 1866 –
Read twice and passed
to be engrossed in conc
Thomas P Cleaves
Secty

Figure 58. Continued.

1837). Small blocks of quarried rock, possibly dating from this time, can be seen at that locality.

Flagstone was produced from a quarry in amphibolite of the Sebascodegan Formation on property that is now part of the Brunswick Naval Air Station. Production from this quarry ceased when the property was acquired by the Navy Department in the 1940s. Slabs of amphibolite probably produced from this quarry can be seen in many homes and businesses in the greater Brunswick area as patio pavers, retaining wall blocks, and dividing wall blocks.

ACKNOWLEDGMENTS

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