Maine Geological Survey
Studies in Maine Geology: Volume 1
1988

Lithotectonic Stratigraphy, Deformation, Plutonism, and Metamorphism, Greater Casco Bay Region, Southwestern Maine

Arthur M. Hussey II
Department of Geology
Bowdoin College
Brunswick, Maine 04008

ABSTRACT

The stratified rocks of the greater Casco Bay area include the Casco Bay Group, Cross River formation, and rocks previously mapped as the Bucksport Formation, all of probable Precambrian to Ordovician age. The Bucksport-type rocks are now correlated with the Sebascodegan formation, originally the Sebascodegan member of the Cushing Formation of the Casco Bay Group. Bounding sequences are the Late Ordovician-Devonian Kearsarge-central Maine sequence, Ordovician Penobscot and Benner Hill sequences, and Precambrian to Ordovician Merrimack Group.

The Casco Bay Group is interpreted to represent two distinct lithotectonic packages. One lies on the west side of the Flying Point fault and consists of the Nehumkeag Pond, Mount Ararat, Torrey Hill, and Richmond Corner members of the Cushing Formation. The other, east of the Flying Point fault, includes the remaining members of the Cushing Formation (Peaks Island, Wilson Cove, Merepoint, Bethel Point, and Yarmouth Island members), and the Sebascodegan, Cape Elizabeth, Spring Point, Diamond Island, Scarboro, Spurwink, Jewell, and Macworth Formations of the Casco Bay Group. The western package is referred to for discussion purposes as the Falmouth-Brunswick sequence, and the eastern package as the Saco-Harpswell sequence.

Major west-dipping thrust faults separate 1) the Kearsarge-central Maine sequence from the Falmouth-Brunswick sequence (the Hackmatack Pond fault), 2) the Falmouth-Brunswick sequence from the Saco-Harpswell sequence (the Beech Pond fault), and 3) the Sebascodegan formation of the Boothbay area from the Cross River formation (Boothbay thrust). The Cross River formation is a correlative of sedimentary rocks of either the Penobscot sequence or the Benner Hill sequence. The Cape Elizabeth Formation overlies different units of the Cushing Formation of the Saco-Harpswell sequence either because of regional tilting and erosion of the Cushing Formation pile prior to Cape Elizabeth deposition or because of lateral facies variations within the Cushing Formation.

The uppermost unit of the Casco Bay Group, the Macworth Formation, is conformable to the underlying Jewell Formation, and based on lithic similarity may correlate with either the Vassalboro Formation or the Berwick Formation, thus establishing a sedimentary continuum either between the Saco-Harpswell and Kearsarge-central Maine sequences or between the Saco-Harpswell sequence and the Merrimack Group.

Intrusion of granite, granodiorite, and diorite occurred from Early Devonian to Mississippian time. Post-tectonic diabase and basalt dikes of Triassic to Cretaceous age are the youngest rocks exposed in the region.

All metasedimentary rock sequences were metamorphosed and multiply deformed during either the Acadian orogeny or an earlier, pre-Taconic orogeny. Minor late recumbent folds of the Falmouth-Brunswick sequence may be related to forceful intrusion effects of the Acadian orogeny. Major thrust faults are probable effects of the Acadian orogeny. Strike-slip movement on faults of the Norumbega fault zone predate emplacement of Mississippian plutons but are later than Acadian regional metamorphism. Normal faults are post-metamorphic and are probably related to initiation of continental rifting in Late Triassic time.

INTRODUCTION

The purpose of this paper is to review the stratigraphy, structure, correlations, age, metamorphism, and plutonic igneous activity of the rocks of the Casco Bay region, southwestern Maine (Fig. 1). This paper discusses the problems of stratigraphic correlation, age interpretation, and structural analysis of the metamorphosed stratified rocks of the greater Casco Bay region. Relations to other bounding sequences (Merrimack Group, Kearsarge-central Maine sequence, and units to the east of the Casco Bay sequence) are reviewed.

The stratigraphic sequence of the study area includes the Casco Bay Group, the Cross River formation, and the Sebascodegan formation, part of which was previously mapped as the southern Maine continuation of the Bucksport Formation typically exposed in eastern central Maine. The interpretation of the Casco Bay Group presented in this paper is that it is divisible into two distinct lithotectonic packages, the Falmouth-Brunswick sequence consisting of members of the Cushing Formation exposed west of the Flying Point fault and the Saco-Harpswell sequence consisting of members of the Cushing Formation east of the Flying Point fault plus formations of the Casco Bay Group above the Cushing Formation (Table 1 and Fig. 2).

TABLE 1. CORRESPONDENCE OF LITHOTECTONIC PACKAGES TO ROCK STRATIGRAPHIC UNITS OF THE CASCO BAY GROUP.

Rock stratigraphic units	Lithotectonic packages
Casco Bay Group	
Macworth Formation	
Jewell Formation	
Spurwink Metalimestone	
Scarboro Formation	
Diamond Island Formation	
Spring Point Formation	Saco-Harpswell sequence
Cape Elizabeth Formation	
Sebascodegan formation	
Cushing Formation	
Wilson Cove member	
Bethel Point member	
Merepoint member	
Yarmouth Island member	
Peaks Island member	
Nehumkeag Pond member	
Mount Ararat member	Falmouth-Brunswick sequence
Torrey Hill member	
Richmond Corner member	

As a result of recent mapping, the rocks previously represented as the Bucksport Formation in the Boothbay area are here interpreted to be stratigraphic equivalents of the lithically similar Sebascodegan member of the Cushing Formation (Hussey, 1985). Because of the regional extent and great thickening of this unit in the Boothbay area, it is here separated from the Cushing Formation and raised to formational rank. It interfingers with the Cushing Formation in the Brunswick area.

The Macworth Formation is interpreted to be either the equivalent of the Vassalboro Formation of the Kearsarge-central Maine sequence or the Berwick Formation of the Merrimack Group.

STRATIGRAPHY

Complete descriptions of the groups, formations, and members in the discussion area are presented in an open-file report (Hussey, 1985). The names of new formations and members proposed there are used informally in this discussion (all place names, however, have been cleared and reserved for future formal use). The informality of a name is indicated by not capitalizing the rock-stratigraphic rank of the unit (for example, Cross River formation, Merepoint member). In the following discussion, only the more generalized character of these units will be given.

Falmouth-Brunswick Lithotectonic Sequence

The members of the Cushing Formation as earlier defined (Hussey, 1985) lying west of the Flying Point fault (Fig. 2) constitute a lithotectonic sequence distinct from the Cushing Formation east of the Flying Point fault. Referred to here as the Falmouth-Brunswick sequence, this package consists of the Nehumkeag Pond, Mount Ararat, Torrey Hill, and Richmond Corner members of the Cushing Formation. There are four reasons for separating this sequence from the rest of the Cushing Formation. 1) The Cushing Formation east of the Flying Point fault lacks the thin alternations of amphibolite and quartz-feldspar-biotite granofels typical of the Mount Ararat member, areally the most extensive unit of the Falmouth-Brunswick sequence. Amphibolites within the Cushing Formation east of the Flying Point fault are much thicker and more localized. 2) There is no correlation of lithologic sequences from one side of the Flying Point fault to the other. 3) The sequence west of the Flying Point fault, and not that to the east, is similar to metavolcanic sequences of pre-Silurian age in New Hampshire, and eastern and central Massachusetts. 4) Seismic reflection evidence suggests that the Falmouth-Brunswick sequence has been thrust in from the west.

The Nehumkeag Pond member consists of thin- to medium-bedded and massive, non-rusty-weathering, medium to light gray, quartz-plagioclase-K-feldspar-biotite-muscovite gneiss and granofels. It has been moderately migmatized and injected by non-foliated and weakly foliated pegmatite. Prior to metamorphism these rocks were felsic to intermediate pyroclastic volcanic rocks. Minor units within the member include thin but mappable lenses of marble and calc-silicate gneiss, rusty gneiss and schist, and massive amphibolite.

The Mount Ararat member, the most extensive member of the Falmouth-Brunswick sequence, consists of alternations of light gray, quartz-plagioclase-biotite gneiss and granofels, and dark gray amphibolite commonly interbedded on a scale of 2 to 10 cm. The Mount Ararat member includes a rusty pelitic

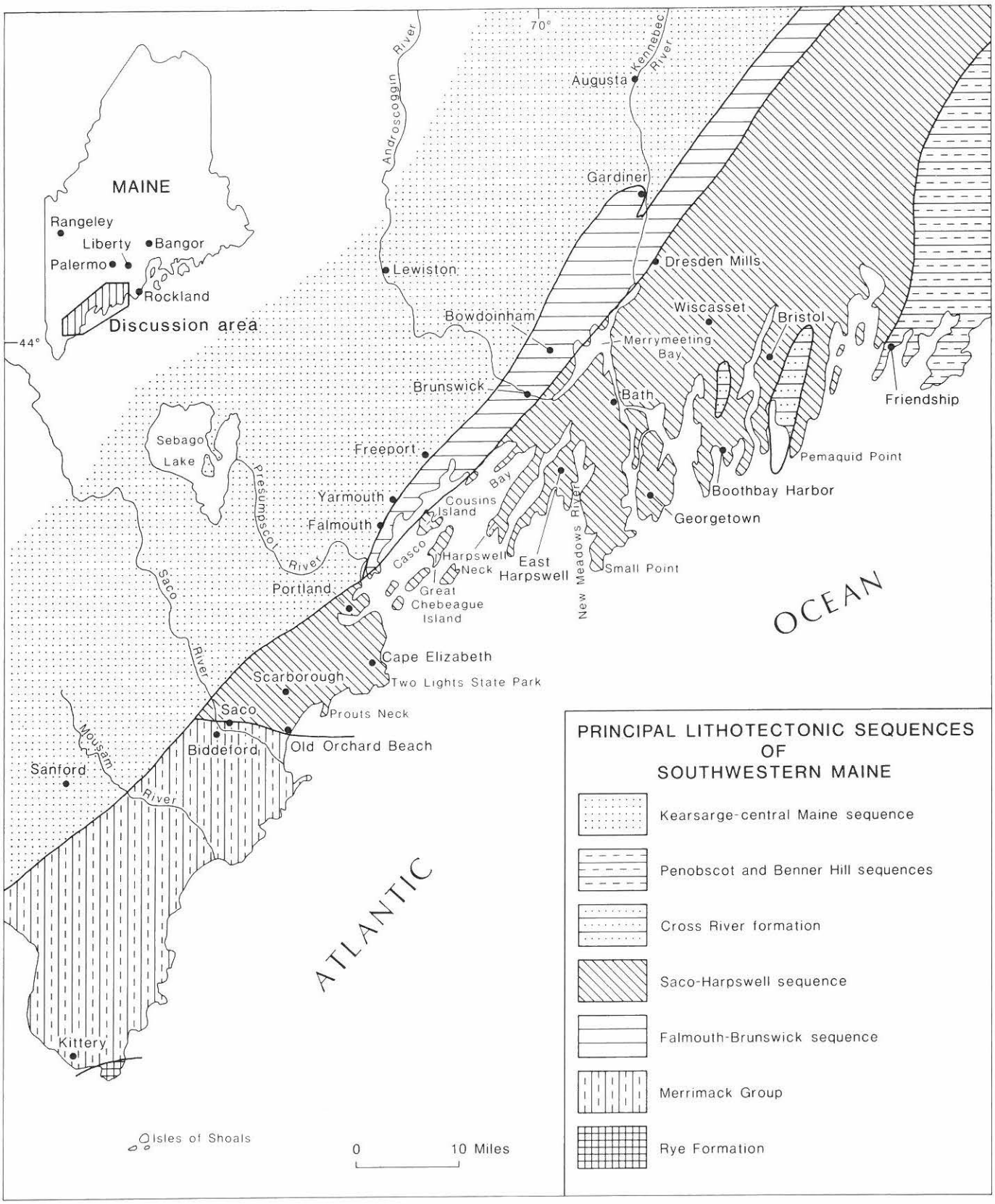

Figure 1. Map showing location of study area, principal lithotectonic sequences of southwestern Maine, and names of places referred to in the text.

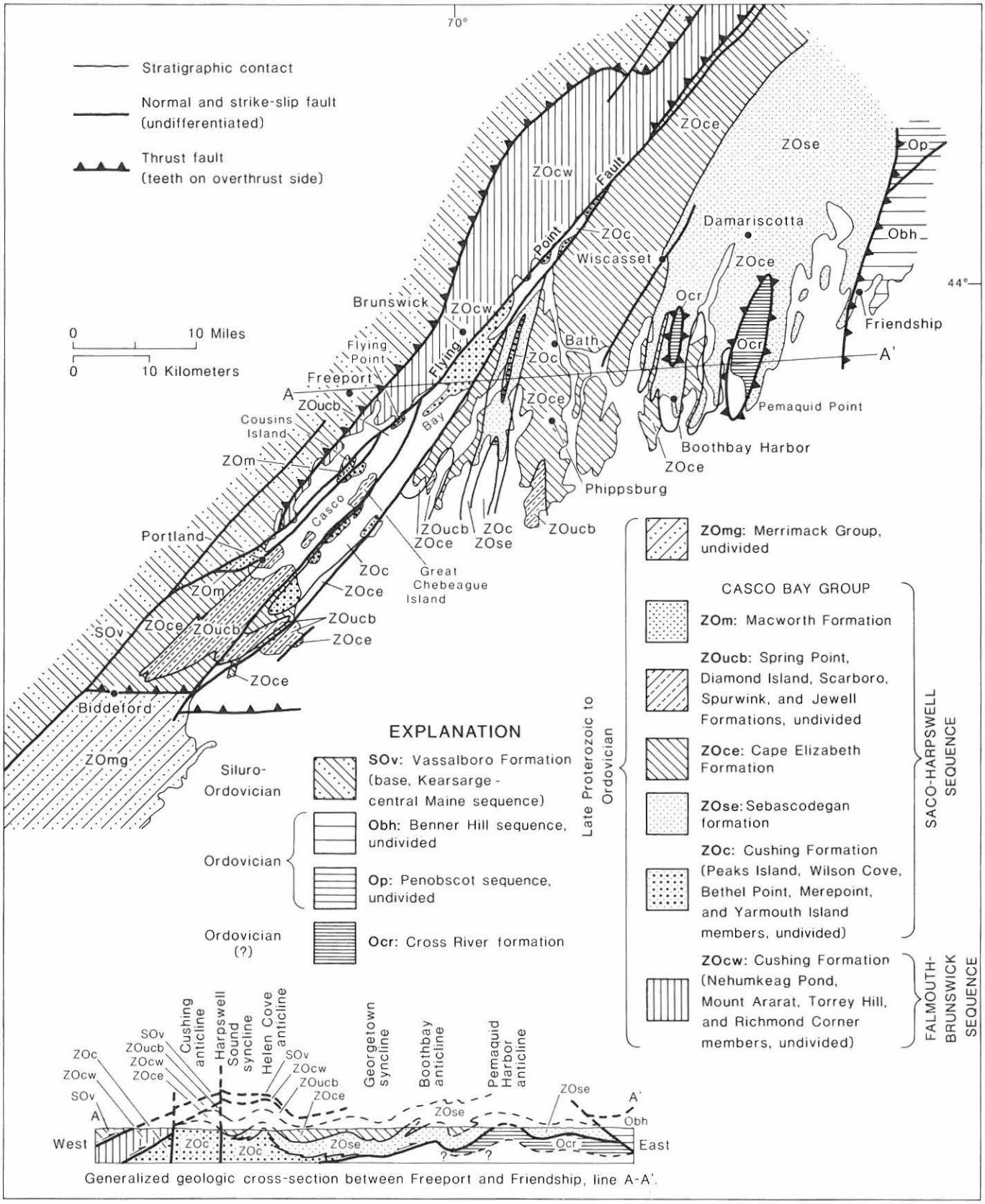

Figure 2. Generalized geologic map and cross section of the greater Casco Bay area, Maine. Plutonic rocks are omitted to emphasize lithotectonic relations.

schist lens and occasional mappable massive amphibolite lenses. The abundance of thin amphibolite beds distinguishes this unit from the Nehumkeag Pond member and from members of the Cushing Formation east of the Flying Point fault. Prior to metamorphism, the biotite gneiss/granofels and thin amphibolite layers were probably felsic and basic volcanic tuffs.

The Torrey Hill member is a thin unit consisting almost entirely of very sulfidic, graphite-bearing, sillimanite-rich schist. The Richmond Corner member is predominantly medium gray, biotite-garnet-quartz-feldspar, salt and pepper-textured schist. Interbedded pink coticule and zones of rusty-weathering, biotite-quartz-feldspar schist are common. Sillimanite is locally present in both rusty and non-rusty schist. The Torrey Hill and Richmond Corner members were pelitic sediments prior to metamorphism.

Contacts between formations of the Falmouth-Brunswick sequence have not been observed but are inferred to be conformable. Exposures close to the mapped position of these contacts lack all indications of structural discordance. No evidence for the stratigraphic sequence of these formations has been observed to date. The Hackmatack Pond fault (Pankiwskyj, 1978) separates the Falmouth-Brunswick sequence from the Vassalboro Formation of the Kearsarge-central Maine sequence. This fault coincides with a west-dipping reflector in the Quebec-western Maine seismic reflection profile (Stewart et al., 1986) in the Palermo area (north of the study area). The Beech Pond fault (Newberg, 1985) and the Flying Point fault (Hussey, 1985) separate the Falmouth-Brunswick sequence on the west from the Saco-Harpswell sequence on the east. The Flying Point fault is the contact southwest from Dresden Mills, and the Beech Pond fault is the contact northeast from Dresden Mills. The Beech Pond fault approximately coincides with the emergence of a west-dipping reflector on the Quebec-western Maine seismic reflection profile and is interpreted as a major west-dipping thrust. This fault is the principal boundary between the Falmouth-Brunswick and Saco-Harpswell lithotectonic sequences; south of Dresden Mills it is offset by the Flying Point fault.

Saco-Harpswell Lithotectonic Sequence

The Casco Bay Group (Hussey, 1985) east of the Flying Point fault constitutes a second lithotectonic package, referred to here as the Saco-Harpswell sequence. This package consists of the Peaks Island, Yarmouth Island, Bethel Point, Mere Point, and Wilson Cove members of the Cushing Formation east of the Flying Point fault, and the Sebascodegan, Cape Elizabeth, Spring Point, Diamond Island, Scarboro, Spurwink, Jewell, and Macworth Formations.

The lower part of this sequence, the Cushing Formation, consists predominantly of quartzo-feldspathic metavolcanic rocks and volcanogenic metasedimentary rocks with minor amphibolite, and pelitic and calcareous metasedimentary rocks. In general, the Cushing Formation east of the Flying Point fault shows a variation from a volcanic-dominant sequence to a sedimentary-dominant sequence from west to east in its outcrop belt. The Peaks Island member consists of dominantly massive but occasionally thin- to medium-bedded felsic to intermediate pyroclastic metavolcanic rocks with minor volcanogenic metasedimentary rocks. The metavolcanic rocks range from rhyolite to dacite. Volcaniclastic structures such as relict phenocryst fragments and breccia blocks of varying felsic to intermediate volcanic composition are preserved in outcrop areas from South Portland to Harpswell Neck. Amphibolites are rare in this member.

The Wilson Cove member is the uppermost member of the Cushing Formation. It consists of black, locally very sulfidic garnet-rich biotite schist, with minor sulfidic amphibolite and two-mica schist. The Wilson Cove member interfingers with felsic metavolcanics of the Peaks Island member on Harpswell Neck. It is locally absent in the central parts of Casco Bay but is again present on Prouts Neck in Scarborough*.

The Merepoint member of the Cushing Formation is a sulfidic and feldspathic two-mica schist with minor sillimanite. It is exposed in the core of the Merepoint anticline in the northern part of Casco Bay.

Tne Yarmouth Island and Bethel Point members are exposed in the core of the Hen Cove anticline (Fig. 3). The lower of these, the Yarmouth Island member, consists of weakly thin-bedded to massive, felsic to intermediate metavolcanic rocks with interbedded sillimanite and/or staurolite-bearing feldspathic gneisses, and zones of calc-silicate gneiss and amphibolite up to 20 m thick. Gedrite and cordierite are common in the felsic to intermediate metavolcanic rocks.

The Bethel Point member is a uniform sequence of very sulfidic two-mica schist with minor thin beds of two-mica feldspathic quartzite. This member is correlated with the Merepoint member of the Cushing Formation on the basis that both are semipelitic to pelitic sulfidic schists.

The Sebascodegan formation was formerly the Sebascodegan member of the Cushing Formation, being the uppermost member of the formation in the East Harpswell area. It is raised to formational status here by its extension into the Boothbay Harbor area and its correlation with rocks formerly mapped as the Bucksport Formation (Osberg et al., 1985). These rocks apparently thicken to the east and are exposed over a broad enough area to warrant formational rank. Through facies change, the Sebascodegan formation grades into that part of the Peaks Island member of the Cushing Formation above the Merepoint member in the general vicinity of the coast just south of Brunswick.

In East Harpswell (Fig. 1), the Sebascodegan formation consists of interbedded thin- to medium-bedded, quartz-plagioclase-biotite gneiss and granofels, greenish gray calc-silicate gneiss, and sillimanite-bearing quartzo-feldspathic biotite gneiss and

*At present, the official spelling of the town is Scarborough. The original spelling of the formation named after that town by Katz (1917) was Scarboro, and the latter spelling is used throughout this discussion for referring to the formation.

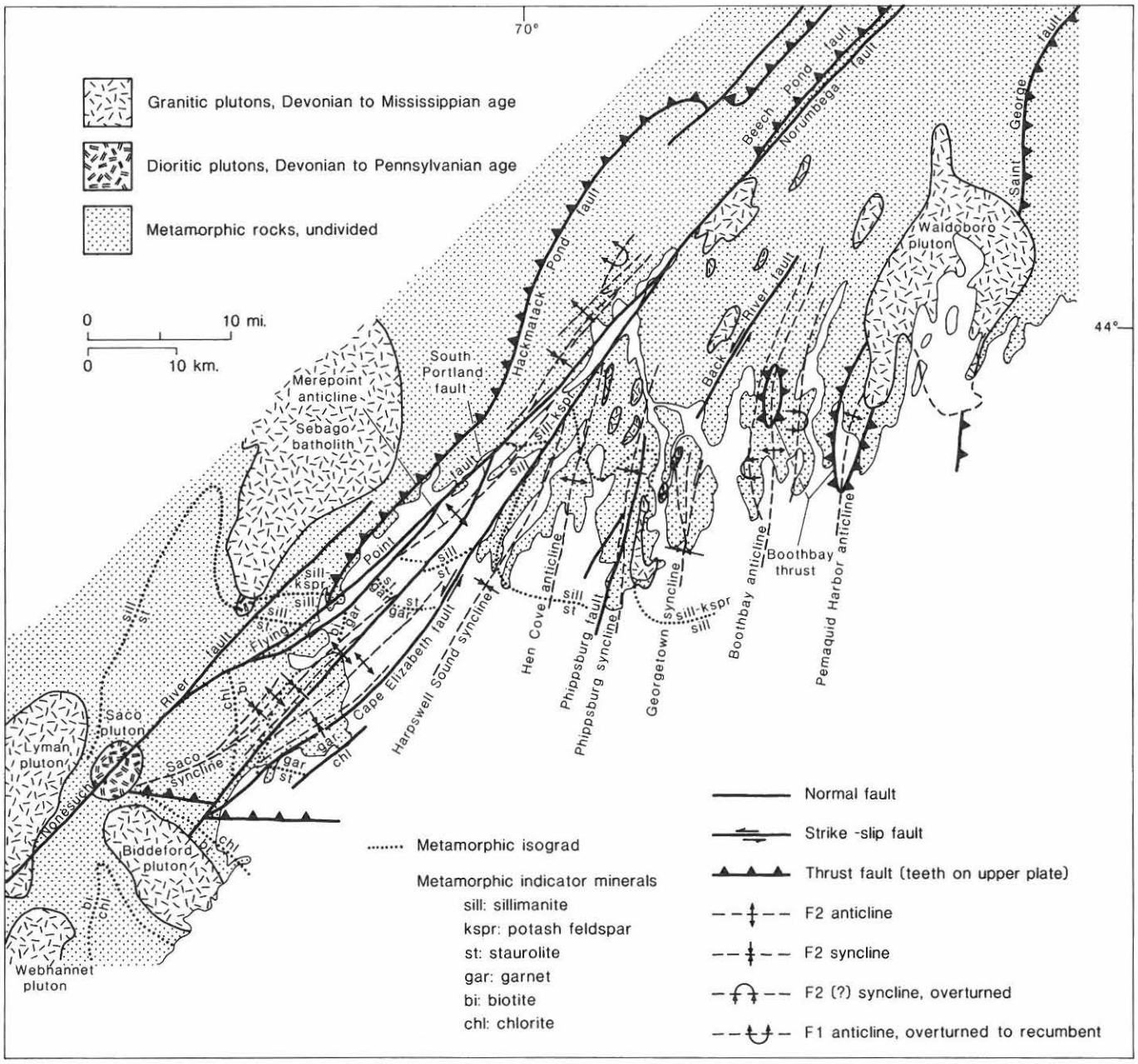

Figure 3. Structural, metamorphic, and plutonic map of the greater Casco Bay area, southwestern Maine.

granofels. Prior to metamorphism these were felsic to intermediate pyroclastic volcanic rocks, and calcareous and argillaceous feldspathic wackes reworked from them. The quartzofeldspathic biotite gneiss and granofels locally preserve relict volcanic breccia structures similar to those of the Peaks Island member of the Cushing Formation. In the Harpswell area, the Sebascodegan formation includes lenses up to 50 meters thick of calc-silicate granofels or gneiss with very minor biotite granofels. It also includes sulfidic biotite granofels lenses up to 50 meters thick, and amphibolite lenses locally with thin marble.

The amphibolite occurs as three distinct lithologic types: 1) fine-grained, evenly foliated, salt and pepper-textured, plagioclase-hornblende amphibolite, probably of volcanic origin; 2) coarse-textured, hornblende-andesine-biotite amphibolite, the texture of which is suggestive of intrusive diorite parentage; and 3) association of mineralogically complex amphibolite, calc-silicate gneiss, and phlogopitic biotite schist. A characteristic lithic sequence of this latter type amphibolite is a central thin layer of calc-silicate bounded in order on each side first by cummingtonite-anthophyllite-hornblende amphibolite and then by bronze-colored, phlogopitic biotite schist. The

presence of calc-silicate in the assemblage and the calcic composition of the plagioclase (bytownite) in all the associated lithologies suggests a non-igneous parentage for type 3 amphibolites. They may represent calcareous or dolomitic sediments interbedded with shale. The amphibolite layers may be the product of metamorphic differentiation between these two lithologies.

Units of the Casco Bay Group above the Cushing Formation (Table 1) constitute a conformable sequence of pelitic and semipelitic metasedimentary rocks with minor metavolcanic rocks, ribbon metalimestone, and metapsammite. Areally, the most extensive and probably thickest unit of this part of the Casco Bay Group is the Cape Elizabeth Formation which directly overlies the Cushing Formation and Sebascodegan formation. The Cape Elizabeth Formation is a thin- to medium-bedded association of quartz- plagioclase-biotite-muscovite schist or phyllite, and muscovite-biotite schist or phyllite. A variety of aluminosilicate minerals are present. These include sillimanite, staurolite, garnet, and more rarely andalusite, depending on grade of metamorphism. Minor lithologies within the Cape Elizabeth Formation include amphibolite, which may be associated with calc-silicate and marble, sulfidic sillimanite or staurolite-rich schist, and coticule beds (pink garnet-biotite-quartz granofels). Amphibolite commonly forms non-mappable beds that are strongly boudined and extensively chloritized.

The Spring Point Formation consists primarily of metamorphosed basic and intermediate volcanic tuffs and flows. These are represented now by chlorite-spessartite phyllite, actinolite gneiss, and hornblende-garnet amphibolite locally with cummingtonite and rarely anthophyllite. The upper part of the formation, particularly in the Harpswell area, consists of thin-bedded, quartzo-feldspathic, biotite-muscovite granofels with local thin interbeds of chlorite-hornblende schist.

The Diamond Island Formation is a distinctive thin (35-50 m) unit of finely foliated sulfidic, black, quartz-muscovite-graphite phyllite. It rarely shows bedding.

The Scarboro and Jewell Formations are essentially identical in lithology, consisting of sulfidic and non-sulfidic phyllite or schist. Garnet, staurolite, chiastolite, and chloritoid are present at appropriate grades of metamorphism. Prior to metamorphism, these schists and phyllites were sulfidic and non-sulfidic shales. Both formations have local lenses up to several tens of meters thick of very greenish, chloritic phyllite interpreted to represent basic pyroclastics.

The Spurwink Metalimestone separates the Jewell and Scarboro Formations. It is a thin-bedded alternation of ribbony-appearing, gray, fine-grained marble and quartz-biotite phyllite. The quartzose phyllite beds are extensively boudined.

The Macworth Formation is the highest formation of the Casco Bay Group. It is a monotonous sequence of drab brownish gray, thin-bedded to thinly laminated, calcareous quartz-biotite phyllite. On the eastern edge of Cousins Island in Casco Bay, presumably at a higher grade of metamorphism, the formation consists of thin-bedded alternations of quartz-plagioclase-biotite granofels and greenish, calc-silicate granofels. These lithologies are closely similar to the Vassalboro and Berwick Formations at intermediate grade of metamorphism. On the north end of Great Chebeague Island in Casco Bay a sequence of drab, thinly laminated, grayish brown phyllite above the Jewell Formation is mapped and correlated as part of the Macworth Formation. This is a critical correlation inasmuch as it establishes the stratigraphic position of the Macworth Formation as the highest unit of the Casco Bay Group.

Recognition of the formations of the Casco Bay Group above the Cushing Formation in the area east of the New Meadows River (Fig. 1) is uncertain because of thickness changes, apparent facies changes, and repetition of amphibolites (all of which are possible correlatives of the Spring Point Formation) in the stratigraphic column. Near the western shore of the town of Phippsburg, on the east side of the New Meadows River, the writer (unpublished work) has mapped an amphibolite with associated calc-silicate skarn and marble. The same unit defines the northern part of the Phippsburg syncline (Fig. 3) south of Bath. A similar amphibolite without the calc-silicate skarn, but with coticule and rusty schist defines the Georgetown syncline (Fig. 3). A conspicuous, multiply deformed amphibolite of similar lithology also crops out in the Boothbay Harbor area (Hussey, 1986). Finally, an amphibolite with associated marble occupies a narrow belt approximately 3 km long in the west edge of the city of Bath. In all these belts, the amphibolite and associated rocks occur within typical Cape Elizabeth rocks, pelitic and psammitic. One or the other of these may correlate with the Spring Point Formation or they may simply be one or more lenses in the Cape Elizabeth Formation.

In the core of the Phippsburg syncline in the Small Point area south of Bath, there is a narrow belt of amphibolite (in part sulfidic) and associated calc-silicate gneiss and marble. Adjacent to this is a belt of rusty-weathering black phyllite. The black phyllite is identical to the Diamond Island Formation. The adjacent amphibolite is less like the typical Spring Point Formation as mapped at high metamorphic grade in the Orrs Island area (Hussey, 1971b) than are the amphibolites noted above. The rocks above and below the amphibolite/black phyllite sequence are indistinguishable from each other. These consist of sillimanite or andalusite-rich metapelites with thin intervals of Cape Elizabeth-like, quartz-feldspar-biotite-garnet schist. As a whole, these schists are not like the typical Cape Elizabeth lithology or the typical Scarboro-Jewell lithology. Associated with these aluminous pelites are lenses of metasedimentary rock types (thin-bedded calc-silicate and biotite granofels, garnet-biotite schist, very rusty-weathering, light gray muscovite schist, and calc-silicate marble) that are not present in either the Cape Elizabeth Formation or Scarboro-Jewell sequence elsewhere. If these differences are attributed to facies variations, then the correlation of the black phyllite with the Diamond Island Formation is reasonable. Correlation of the associated amphibolite with the Spring Point Formation would follow, and the amphibolite belts mentioned above would constitute a member within the Cape Elizabeth Formation. This correlation is currently favored.

Contact Relations. Contacts have been observed between the

Cape Elizabeth Formation and members of the Cushing Formation and between all other formations of the Casco Bay Group, except the Macworth and Jewell Formations. With the exception of the contact between the Cape Elizabeth and Cushing Formations (see discussion below), all are sharp and apparently conformable. The Macworth Formation is mostly fault-bounded with the Flying Point fault on the northwest side and an unnamed normal fault on the southeast (Fig. 2). The Torrey Hill member of the Falmouth-Brunswick sequence and the Vassalboro Formation occur on the northwest side of the Macworth Formation, and various units of the Saco-Harpswell sequence adjoin the formation on its southeast side (Fig. 2). On the north end of Great Chebeague Island in Casco Bay the actual contact between the Macworth and Jewell Formations is concealed by a short interval of mud-flat cover, but structural evidence suggests that the Macworth Formation is conformable with the Jewell Formation.

The Cape Elizabeth Formation overlies the Sebascodegan formation on both limbs of the Hen Cove anticline in the Harpswell area. On the east limb of the Cushing anticline it overlies either the Wilson Cove member of the Cushing Formation or, where that is absent, the Peaks Island member. On the west side of the Cushing anticline, the Wilson Cove member is everywhere absent and the Cape Elizabeth Formation overlies the Peaks Island member. Close to the contact on that side, and within the Peaks Island member, are two zones of very rusty-weathering white muscovite schist that are not seen on the eastern side of the Cushing anticline. On the east side of the Cushing anticline at Chimney Rock in Cape Elizabeth, the contact between the Cape Elizabeth Formation and the Peaks Island member of the Cushing Formation is occupied by a 1 m thick zone of quartz-feldspar, fine granule metaconglomerate suggesting the possibility of an unconformable contact. At other localities, the contact appears conformable. These relations, i.e., the Cape Elizabeth Formation overlying different members of the Cushing Formation and the apparent across-strike variations within the Cushing Formation, raise the following speculations about the nature of the contact between the Cape Elizabeth and Cushing Formations, and the relationship between the different members of the Cushing Formation (Fig. 4). The across-strike variations within the Cushing Formation may be explained by members of the Cushing Formation that have been tilted and are younging toward the east below the Cape Elizabeth Formation (Fig. 4a). This would suggest either a major unconformity or possibly a major thrust contact. Alternatively, the relations may reflect facies changes within the Cushing Formation from a volcanic pile on the west to an apron of reworked volcanic detritus on the east. In this case the Cape Elizabeth-Cushing contact is either conformable or locally disconformable (Fig. 4b). Critical field data to distinguish between these hypotheses are lacking; however, model b is favored because of the correlation of the Merepoint member of the Cushing Formation with the Bethel Point member.

Regional correlations and age of the units of the Casco Bay Group will be discussed in a following section.

Cross River formation

The Cross River formation is exposed in the cores of two antiforms in the Boothbay area. The principal lithology is extremely migmatized, very rusty-weathering, sulfidic, sillimanite-rich and locally graphite-rich gneiss and schist, with local beds of feldspathic biotite quartzite often represented only as disoriented rafts in the migmatite. At the top of the formation in the western of the two exposure belts, is a thin, but mappable, unnamed member consisting of non-migmatized, salt and pepper-textured amphibolite, and biotite granofels with large garnet porphyroblasts.

The Cross River formation is similar to sulfidic schists of both the Benner Hill sequence of Osberg and Guidotti (1974) and the Penobscot Formation of Bickel (1976) (Fig. 2). Both of these lie east of the Sebascodegan/Bucksport outcrop belt and are separated from the Cross River formation by the St. George fault, an east-dipping thrust (Fig. 3).

AGE RELATIONS AND CORRELATIONS

Paleontological Control

Age relations of the rocks of the greater Casco Bay area are poorly known. No fossils occur within rocks of the Casco Bay Group, Cross River formation, and Sebascodegan formation. The only paleontological control is for sequences bounding these packages. Strongly deformed brachiopods of Ordovician age (Boucot et al., 1972; Neuman, 1973) occur in a quartzite lens

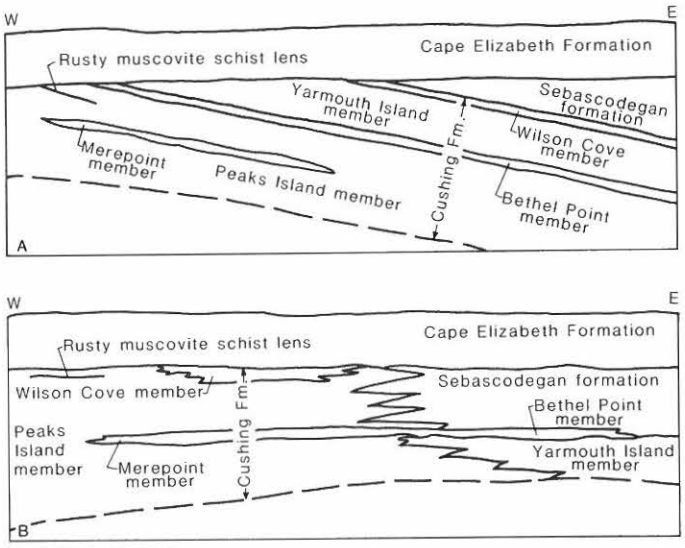

Figure 4. Alternative models for the relationship of the Cape Elizabeth Formation to the underlying units of the Cushing Formation. (a) Members of the Cushing Formation form a tilted sedimentary pile beneath the Cape Elizabeth Formation; (b) Members of the Cushing Formation are a series of sedimentary facies below the Cape Elizabeth Formation. Alternative B is preferred because it allows the suggested correlation of rusty schist on Merepoint, Brunswick, with the Bethel Point member of the Cushing Formation.

in the Benner Hill sequence of Osberg and Guidotti (1974) near Rockland, Maine. Graptolites of uncertain, but inferred Early Silurian age have been reported from the Vassalboro Formation of the Kearsarge-central Maine sequence (Osberg, 1980). Arenig (Early Ordovician) age graptolites have been recovered from the Cookson Formation, interpreted to be a correlative of the Penobscot Formation (Ruitenberg and Ludman, 1978). The usefulness of this limited paleontological control depends on the validities of inferences made regarding stratigraphic and structural relations of the different stratigraphic packages involved.

Radiometric Ages of Metamorphic Rocks

Relatively few radiometric age determinations are available for inferring the ages of the stratified rocks of the greater Casco Bay area (Table 2). Gaudette et al. (1983) report an Early Ordovician Rb/Sr whole rock age for the Mount Ararat member of the Cushing Formation in the Gardiner area (Fig. 1). Brookins and Hussey (1978) give an Early Ordovician Rb/Sr whole rock age for the Cape Elizabeth and Cushing Formations of the Casco Bay Group. They report an Rb/Sr whole rock age of 481 ± 40 Ma for the Cushing Formation, but this represents a mix of ages of the Mount Ararat member of the Cushing Formation of the Falmouth-Brunswick sequence and the Peaks Island member of the Cushing Formation of the Saco-Harpswell sequence. These members were not separately mapped at the time.

The interpretation of the whole-rock Rb/Sr ages of the metavolcanic and metasedimentary sequences has been the subject of much confusion. Brookins (pers. commun., 1986) believes these ages represent time of formation of the rocks, that is, time of sedimentation/diagenesis and volcanism. Others, (e.g., Lyons et al., 1982), argue that such radiometric ages are reset at least partially, if not entirely, by major episodes of metamorphism and therefore represent a time of orogeny and metamorphism, the time of formation of the rocks being somewhat earlier than this. This question must be resolved by radiometric age specialists before such age determinations can be applied to the geochronological problems of the lithotectonic sequences of the greater Casco Bay area.

Radiometric Ages of Intrusive Rocks

Radiometric ages of intrusive rocks (Table 2) establish a minimum age of Middle to Late Devonian for the stratified rocks of the greater Casco Bay area. Knight and Gaudette (1987) report a Late Devonian Rb/Sr age for the Waldoboro pluton (Fig. 3) which intrudes the Cross River and Sebascodegan formations. Brookins (pers. commun., 1976) obtained a whole rock Rb/Sr age of 385 Ma for weakly foliated and folded, generally concordant pegmatites of the Falmouth area, and 375 Ma for discordant, evenly-walled unfoliated pegmatite dikes in the same area. These ages suggest injection of the pegmatites during late stages of the Acadian orogeny.

A minimum age of Middle Ordovician is indicated for the Merrimack Group that bounds the Casco Bay Group on the south (Fig. 1). Gaudette et al. (1984) report a Middle Ordovician Rb/Sr age for the Exeter pluton that intrudes the Kittery and Eliot Formations of the Merrimack Group in southeastern New Hampshire. Zartman and Naylor (1984) give a Late Ordovician zircon age for the Newburyport pluton that intrudes the Kittery Formation in southeastern New Hampshire and adjacent Massachusetts. Gaudette et al. (1984) also indicate a minimum age of Middle Ordovician for the Rye Formation of southwestern Maine and southeastern New Hampshire. They report a 477 Ma age for a small diorite pluton that intrudes the Rye Formation on Appledore Island in the Isles of Shoals off Kittery.

Correlations and Ages of the Stratified Rocks of the Greater Casco Bay Area

Cape Elizabeth Formation. The Cape Elizabeth Formation traces into the Hogback Schist described by Perkins and Smith (1925) in the Palermo area and is probably equivalent to the high-grade sillimanite-bearing migmatites of the Passagassawakeag Gneiss of Bickel (1976). The following are some additional possible correlations of the Cape Elizabeth formation based on lithic similarity:

1) With the non-rusty schists of the Benner Hill sequence. In the Friendship area (Fig. 1) just east of the study area, numerous septa of Sebascodegan-like rocks in the southern end of the

TABLE 2. RADIOMETRIC AGES OF METAMORPHIC AND PLUTONIC ROCKS BEARING ON THE GEOCHRONOLOGY OF THE GREATER CASCO BAY AREA, SOUTHWESTERN MAINE

Rock unit	Method	Age (Ma)	Reference
		METAMORPHIC	
Mt Ararat m, Cushing Fm	Rb-Sr	494 ± 25	Gaudette et al. (1983)
Cushing Fm	Rb-Sr	481 ± 40	Brookins and Hussey (1978)
Cape Elizabeth Fm	Rb-Sr	485 ± 30	Brookins and Hussey (1978)
		PLUTONIC	
Diorite, Isles of Shoals	Rb-Sr	477	Gaudette et al. (1984)
Exeter pluton	Rb-Sr	473 ± 37	Gaudette et al. (1984)
Webhannet pluton	Rb-Sr	390 ± 10	Gaudette et al. (1982)
Webhannet pluton	Zr	403 ± 13	Gaudette et al. (1982)
Three Mile Pond pluton	Rb-Sr	381 ± 14	Dallmeyer and Van Breeman (1981)
Newburyport quartz diorite	Zr	450 ± 15	Zartman and Naylor (1984)
Biddeford pluton	Rb-Sr	344 ± 12	Gaudette et al. (1982)
Pegmatite, Falmouth area			
Discordant	Rb-Sr	375	Brookins (pers. commun. 1976)
Concordant	Rb-Sr	385	Brookins (pers. commun. 1976)
Sebago batholith	Zr	325 ± 3	Aleinikoff et al. (1985)
Lyman pluton	Rb-Sr	322 ± 12	Gaudette et al. (1982)
Waldoboro pluton	Rb-Sr	367 ± 4	Knight and Gaudette (1987)
Saco pluton	Rb-Sr	307 ± 20	Gaudette et al. (1982)

Waldoboro pluton crop out close to non-rusty schists that are lithically very similar to the Cape Elizabeth Formation in the Boothbay Harbor area (Hussey, 1972). These schists have been traced by Newberg (1979) into the outcrop belt of the Benner Hill sequence of Osberg and Guidotti (1974). As noted above, fossils from this sequence (Boucot et al., 1972; Neuman, 1973) indicate an Ordovician age for these rocks. If this correlation is valid, the Cape Elizabeth Formation would be of Ordovician age.

2) With the Eliot Formation of the Merrimack Group. The Cape Elizabeth Formation at low metamorphic grade in the Saco area is lithologically identical to the Eliot Formation, the middle unit of the Merrimack Group in southwestern Maine. This correlation would suggest a Late Precambrian to Ordovician age for the Cape Elizabeth Formation. This correlation might preclude a correlation with the Benner Hill sequence in view of the seemingly greater age of the Merrimack Group. The Merrimack Group is older than the 473 Ma Rb/Sr age obtained by Gaudette et al. (1983) for the Exeter pluton that intrudes the group in southeastern New Hampshire. Prior to intrusion, the Merrimack Group had been folded first by large-scale (?) recumbent folds and then refolded by upright folds that control the map-pattern of the formations of the group. In view of this structural history and the age of the Exeter pluton, they suggest that the Merrimack Group might be as old as Late Precambrian, and no younger than Middle Ordovician.

3) With the Rye Formation. The high-grade Cape Elizabeth Formation of the Georgetown area is lithically similar to metasedimentary rocks exposed on Appledore Island in the Isles of Shoals offshore of Portsmouth, New Hampshire. These rocks are correlated with the Rye Formation of southwestern Maine and southeastern New Hampshire, and possibly with the Nashoba Formation of eastern Massachusetts. Hepburn and Munn (1984) obtained an Rb/Sr Early Middle Ordovician metamorphic (?) age for the Nashoba Formation, very similar to the age reported by Brookins and Hussey (1978) for the Cape Elizabeth Formation (Table 2).

Upper Part of the Casco Bay Group. Units of the Casco Bay Group above the Cape Elizabeth Formation have been mapped in the Liberty area to the north of the study area by Pankiwskyj (1978) where they are exposed in a syncline southeast of the Norumbega fault. Due to plunge reversals, these rocks cannot be traced into the exposures at the southern end of the Casco Bay synclinorium. The upper units of the Casco Bay Group correlate with no other sequences in adjacent parts of the northern Appalachians. Their stratigraphic position, conformably above the Cape Elizabeth Formation, suggests a similar age for them, i.e., Early to Middle Ordovician at the youngest, and Late Precambrian at the oldest.

Sebascodegan formation of the Boothbay Harbor Area. The biotite and calc-silicate granofels sequence of the Boothbay Harbor area, now mapped as part of the Sebascodegan formation of the Casco Bay Group, closely resembles the Bucksport Formation of east-central Maine. With that formation they heretofore have been correlated (Osberg et al., 1985). These granofels also resemble the Kittery and Berwick Formations of the Merrimack Group and the Vassalboro Formation of the Kearsarge-central Maine synclinorium. Stewart (pers. commun., 1987) notes significant differences in bedding style and the amount of calc-silicate between the Sebascodegan formation rocks of the Boothbay Harbor area and the type Bucksport Formation near the town of Bucksport to the northeast and suggests they are not correlatable. Significantly, the Bucksport-like rocks are overlain conformably by the Cape Elizabeth Formation in the Boothbay Harbor area, just as the Sebascodegan formation is overlain by the Cape Elizabeth Formation in the eastern part of Harpswell, further strengthening the correlation of the calc-silicate and biotite granofels of the Boothbay Harbor area with the Sebascodegan formation. This poses the problem of how to separate the outcrop belt of the Sebascodegan formation from that of the Bucksport Formation on strike with it to the north east. The map pattern of this belt as it is known at this time (Osberg et al., 1985) does not readily allow this interpretation. This raises the question of whether they do correlate and that the Bucksport Formation is not of Silurian to Devonian age but of Late Precambrian to Ordovician age. This remains a major problem for resolution through future mapping and discussion.

Macworth Formation. The Macworth Formation is similar at its highest metamorphic grade to the Vassalboro Formation of the Kearsarge-central Maine sequence, although it is perhaps a bit less feldspathic and quartzose than the latter. It also resembles other calc-silicate and biotite granofels sequences (Berwick, Kittery, and Sebascodegan Formations) of the discussion area. At our present state of understanding, two possible correlations of the Macworth Formation should be entertained (Table 3).

1) The Macworth Formation correlates with the lower part of the Vassalboro Formation, perhaps parts not exposed northwest of the Norumbega fault (Table 3, alternative 1). This correlation would establish the age of the Macworth Formation as Middle to Late Ordovician. Because of the apparent stratigraphic conformity between the Macworth and Jewell Formations described above, a consequence of this correlation would be to establish a depositional continuum between the Casco Bay and Kearsarge-central Maine packages.

2) The Macworth Formation correlates with the Berwick Formation of the Merrimack Group and not the Vassalboro Formation, the latter being equivalent to the type Bucksport Formation to the northeast (Table 3, alternative 2). The Sebascodegan formation in Boothbay Harbor could conceivably be equivalent to the Kittery Formation and the Cape Elizabeth Formation to the Eliot Formation. The units of the Casco Bay Group between the Cape Elizabeth and Macworth Formations would have to pinch out to the southwest inasmuch as none of these lithologies are represented in the outcrop belt of the Merrimack Group. Such a pinch-out, at least for the Spring Point and Diamond Island Formations is already demonstrated (Hussey, 1971a); these two formations are not mapped around the south end of the Saco syncline (Fig. 3). This correlation would not establish any sedimentary relation between the Casco Bay Group and the Kearsarge-central Maine sequence, but would relate the

TABLE 3. PROPOSED STRATIGRAPHIC CORRELATION OF ROCKS OF THE GREATER CASCO BAY AREA.

Alternative 1: Macworth correlates with the Vassalboro Formation.

Southwestern Maine			Greater Portland Area		Harpswell	Boothbay Harbor	
Shapleigh Group			Vassalboro Fm Macworth Fm				Early Silurian to Late Ordovician
(fault)			Jewell Fm Spurwink Metals. Scarboro Fm Diamond Island Fm Spring Point Fm Cape Elizabeth Fm Cushing Fm (of Saco-Harpswell sequence)	CASCO BAY GROUP	Jewell Fm Spurwink Metals. Scarboro Fm Spring Point Fm Cape Elizabeth Fm Sebascodegan fm Cushing Fm (of Saco-Harpswell sequence)	Cape Elizabeth Fm Sebascodegan fm (fault) Cross River fm	Ordovician
			(fault)				
Berwick Fm Eliot Fm Kittery Fm	MERRIMACK GROUP	(fault)	Cushing Fm (of Falmouth-Brunswick sequence)				Ordovician to Late Proterozoic

Alternative 2: Macworth correlates with the Berwick Formation.

Southwestern Maine			Greater Portland Area		Harpswell	Boothbay Harbor	
Shapleigh Group			Vassalboro Fm				Early Silurian
(fault)			(fault)				
Berwick Fm Eliot Fm Kittery Fm	MERRIMACK GROUP		Macworth Fm Jewell Fm Spurwink Metals. Scarboro Fm Diamond Island Fm Spring Point Fm Cape Elizabeth Fm Cushing Fm (of Saco-Harpswell sequence)	CASCO BAY GROUP	Jewell Fm Spurwink Metals. Scarboro Fm Spring Point Fm Cape Elizabeth Fm Sebascodegan fm Cushing Fm (of Saco-Harpswell sequence)	Cape Elizabeth Fm Sebascodegan fm	Late Proterozoic to Early Ordovician
			(fault)			(fault)	
			Cushing Fm (of Falmouth-Brunswick sequence)			Cross River fm	Ordovician

Casco Bay Group to the Merrimack sequence. A choice between these two alternative correlations must await further field work and regional synthesis.

A correlation of the Vassalboro Formation with the Berwick Formation now appears to be untenable. Available information suggests that the Vassalboro Formation underwent both recumbent and upright deformation during the Acadian orogeny in Early Devonian time, whereas the Merrimack sequence was similarly deformed prior to the Middle Ordovician emplacement of the Exeter pluton.

Cushing Formation. Radiometric ages obtained by Gaudette et al. (1983) for the Mount Ararat member of the Cushing Formation (Table 2) indicate an Early Ordovician or older age for the Falmouth-Brunswick sequence.

The relations between the Cushing members of the Falmouth-Brunswick sequence and Cushing members of the Saco-Harpswell sequence is uncertain. Two alternatives must be entertained.

1) The two sequences are unrelated in space and perhaps, but not necessarily, in time to each other. As noted earlier, no correlations or evidence of stratigraphic superposition have been deduced that establish either a facies or relative time relationship between them. However, on a very speculative and tenuous basis, units of the Falmouth-Brunswick sequence, particularly the Mount Ararat member, show strong lithic similarities to several pre-Silurian metavolcanic sequences to the northwest and southwest including the stratified core rocks of the Oliverian domes and overlying Ammonoosuc volcanics of the Bronson Hill anticlinorium in western New Hampshire (Naylor, 1968), parts of the Massabesic Gneiss of southeastern New Hamsphire (Bothner et al., 1984), and the Monson Gneiss of the Pelham dome (Robinson et al., 1986). These rocks are also similar to Ordovician bimodal volcanics of the Miramichi anticlinorium in central western New Brunswick (Fyffe, 1982). The Falmouth-Brunswick sequence might then be a part of one of these sequences thrust in from the west over units of the Saco-Harpswell sequence.

2) The Falmouth-Brunswick sequence constitutes a basement terrane on which the Saco-Harpswell sequence was deposited. Contamination of subduction-produced intermediate volcanics by a felsic basement could account for the dominantly felsic nature of the volcanic rocks of the Saco-Harpswell sequence. The volcanic rocks in the Cushing Formation of the Saco-Harpswell sequence might conceivably be equivalent to the Ammonoosuc Volcanics, or be a separate sequence, depending on subduction models for Early Ordovician time.

These speculations naturally raise questions about the evolution of the area in terms of plate-tectonic activity – subduction, volcanic arc, and trench development, back-arc basin spreading, etc. It is, however, premature to develop these ideas further in view of uncertainties about ages of the rocks.

Cross River formation. The Cross River formation is correlated with either the Penobscot Formation or the rusty schist of the Benner Hill sequence, both of which are exposed on the east side of the St. George fault (Figs. 2 and 3). This would indicate a Cambrian to Ordovician age for the Cross River formation. The two exposures of the Cross River formation are windows through the Boothbay thrust, a major low-angle, west-dipping folded thrust, not the St. George fault (see section following).

STRUCTURE

Introduction

Major folds and faults that affect the rocks of the Casco Bay Group and surrounding sequences are shown in Figure 3. All sequences have been multiply folded, thrust-faulted, and normally faulted. Various interpretations for the major structure of the Casco Bay Group have been proposed in the past. North of the study area, Osberg (1974) referred to the belt as the Liberty-Orrington anticlinorium on the basis that older rocks (the Casco Bay Group) occur in the center of the structure. On the other hand, the structure of the south end of the belt, in the Portland-Boothbay Harbor area, was referred to as the Casco Bay synclinorium (Hussey, 1968) on the basis of the overall synclinorial pattern of the upright folds of the Casco Bay Group. The presence of older rocks supposedly surrounded by younger sequences was explained by postulating a major synclinorially folded klippe for the Casco Bay Group (Hussey, 1985; Osberg et al., 1985). Now, in light of the seismic reflection studies across the northern part of the study area (Stewart et al., 1986), the regional structure of this belt is herein reinterpreted to be dominated primarily by several major west-dipping thrust faults. This regional picture is complicated by normal and strike-slip faulting of the Norumbega fault system and multiple folding of the stratified rocks.

Folds

Two fold systems of regional extent affecting the Saco-Harpswell sequence are recognized. The older system, designated F_1, is characterized by nearly isoclinal recumbent folds. The younger, designated F_2, deforms the older folds and consists of upright to slightly overturned tight to open folds, locally with well-developed axial planar schistosity. Although large-scale recumbent folds such as postulated by Osberg (1980) and Eusden et al. (1987) for the Kearsarge-central Maine synclinorium cannot be demonstrated, mesoscopic-scale recumbent folds are locally observed in outcrop. At Chimney Rock in Cape Elizabeth, downward-facing F_2 folds (D. W. Newberg, pers. commun., 1982), deform the Cape Elizabeth-Peaks Island contact. This locality clearly establishes the stratigraphic sequence between these units; graded beds in the Cape Elizabeth Formation within a half meter of the contact indicate that the Cape Elizabeth Formation was deposited on top of the Cushing Formation. On the eastern side of Small Point, tight recumbent F_1 folds of thin calc-silicate and biotite granofels beds have been refolded by relatively open, upright F_2 folds. The Cape Elizabeth Formation at Two Lights State Park in Cape Elizabeth is deformed by tight F_1 recumbent isoclines and gentle, open F_2 folds (Fig. 5). On the west side of Small Point thin calc-silicate beds in the Cape Elizabeth Formation show small, mesoscopic-scale, recumbent F_1 folds with a well-developed fracture cleavage deformed by small-scale F_2 upright folds (Fig. 6a). The fracture cleavage of the calc-silicate beds and adjacent psammitic beds of the Cape Elizabeth Formation are deformed by an intermediate set of small-scale, tight, recumbent folds. The limbs of these tight isoclines (Fig. 6b) show marked pressure-solution thinning of the quartz-rich bands between cleavage planes. The relatively thicker quartz laminae in the hinges give a pseudo-bedded appearance. Quartz veins in adjacent mica schists of the Cape Elizabeth Formation at Small Point preserve evidence of similar stages of multiple deformation (Fig. 6c).

The map pattern of the formations of the Casco Bay Group is controlled by F_2 folds in addition to the various faults. F_2 folds are much larger in scale than any observed or mapped

recumbent folds. F_2 parasitic folds are most commonly preserved in the Cape Elizabeth Formation. In the Small Point area, F_2 folds are relatively open and deform the schistosity defined by muscovite. Locally, biotite is developed parallel to F_2 axial planes. In the Harpswell area, F_2 parasitic folds are tighter than at Small Point, and they have a well-developed biotite as well as muscovite schistosity (Hussey, 1971b). In the Portland and Cape Elizabeth areas, F_2 folds are locally very gentle, open structures (Hussey, 1971a).

Fold systems of the Falmouth-Brunswick sequence are not as well known, due in part to the scarcity of outcrop of units of the sequence and in larger part to the fact that much of the sequence is strongly migmatized. F_1 and F_2 fold systems are inferred from the map pattern of the units of the Cushing Formation west of the Flying Point fault. F_1 folds are represented by the refolded hinges of marble and sulfidic gneiss mapped by Newberg (1981) in the Bowdoinham area (Fig. 3). F_2 folds are the north-northeast-trending folds (Fig. 3) that are generally congruent with F_2 fold systems of the Kearsarge-central Maine sequence (Osberg et al., 1985). In the area of most extensive migmatization, mesoscopic folds are strongly overturned

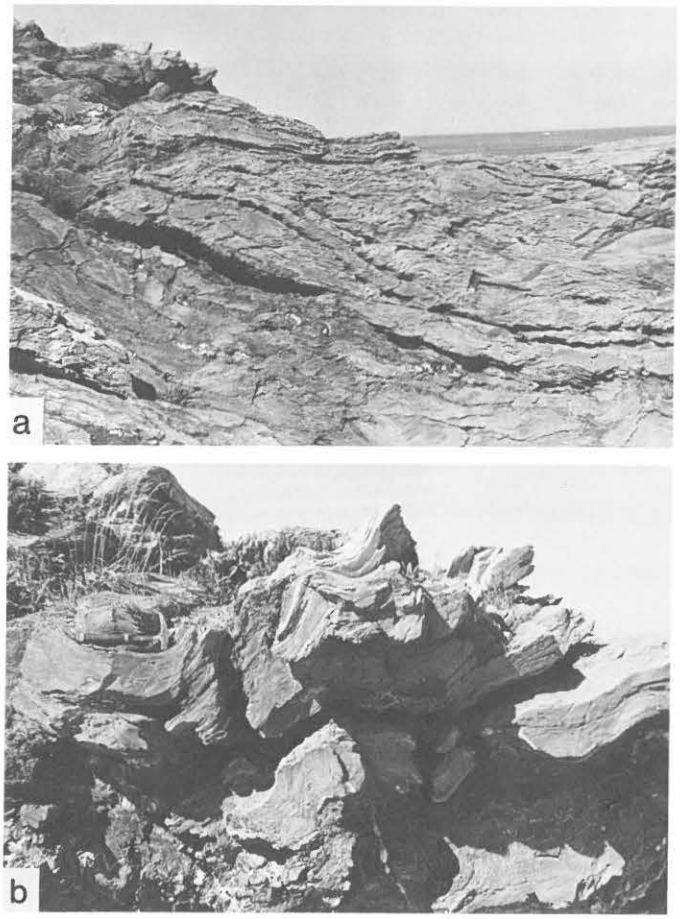

Figure 5. Multiple deformation of the Cape Elizabeth Formation, Two Lights State Park, Cape Elizabeth. (a) Recumbent F_1 fold. (b) Slightly overturned F_2 folds that refold bedding and spaced cleavage of F_1 folds.

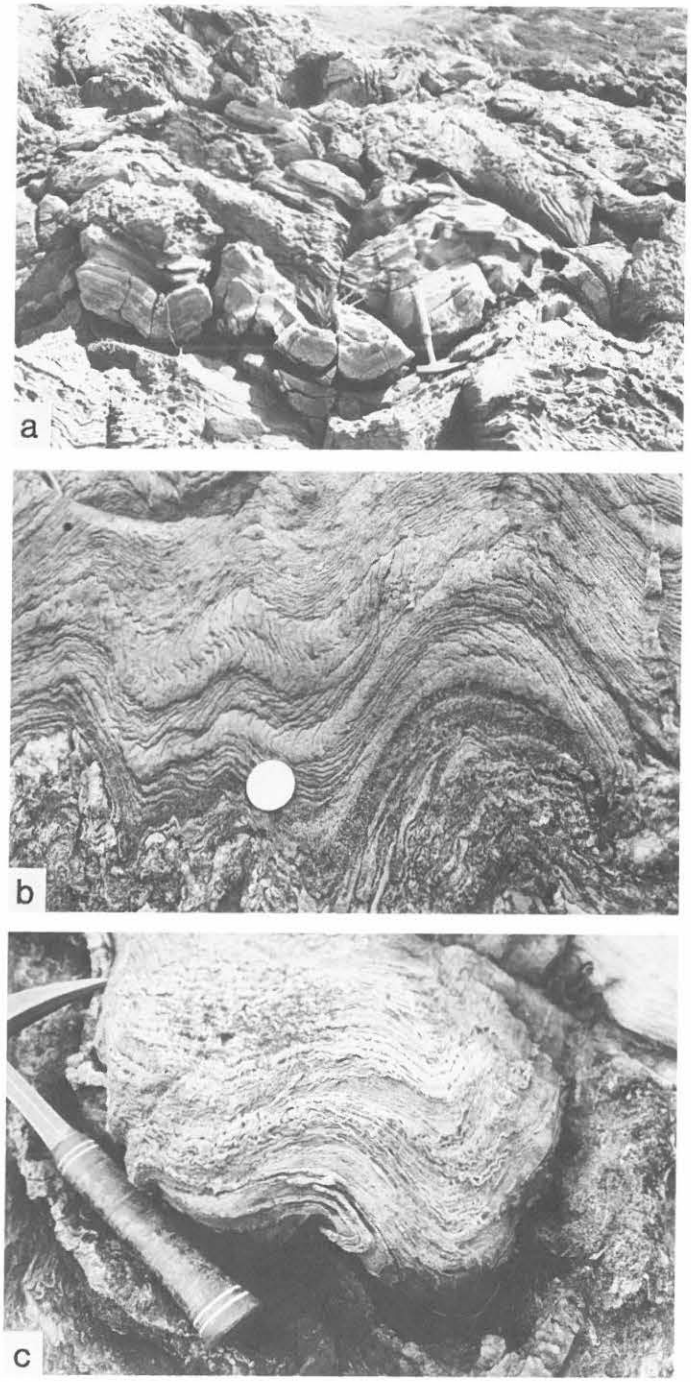

Figure 6. Multiple deformation of the Cape Elizabeth Formation, Small Point, Phippsburg. (a) Mesoscopic-scale recumbent fold (F_1) of calc-silicate bed refolded by relatively open upright F_2 folds. (b) Small-scale open upright F_2 folds. Spaced cleavage (originally parallel to the axial planes of F_1 recumbent folds) has been intensely and recumbently folded by an intermediate deformation (designated F_{1A}) seen only at this locality. Pressure solution has resulted in the removal of quartz in, and hence extreme attenuation of, the limbs of F_{1A}. At a distance the relatively thickened hinges of F_{1A} folds have the appearance of thin psammitic beds. Note dime for scale. (c) Multiply folded quartz vein in metapelite shows two stages of recumbent folding (F_1 and F_{1A}) openly refolded by F_2.

to recumbent or reclined (Fig. 7). Most commonly, these folds deform the migmatite stringers and thin concordant pegmatite lenses suggesting that rather than being older F_1 structures, they are younger structures related possibly to local gravity flattening during migmatization. These folds are very similar to late F_3 folds developed around the northeastern margin of the Sebago batholith during its emplacement (Lux and Guidotti, 1985) and around the northeast edge of the Mooselookmeguntic pluton in the Rangeley area for which Moench and Zartman (1976) suggested an origin by gravitational flattening due to heating as the pluton was emplaced. Some of the reclined and recumbent folds of the Falmouth-Brunswick sequence are strongly compressed and may represent older F_2 or possibly F_1 folds flattened during migmatization.

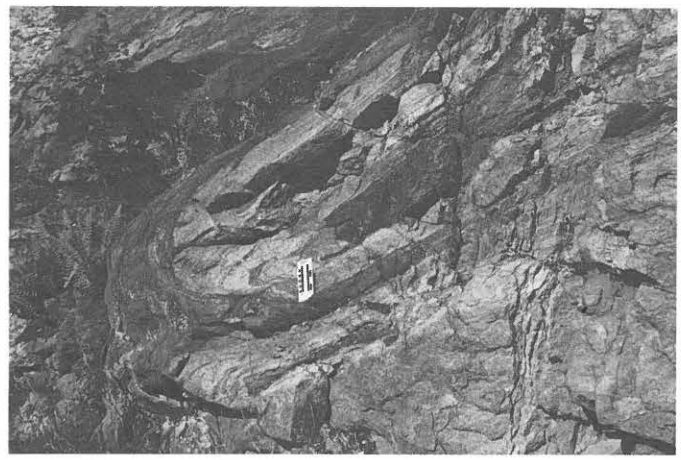

Figure 7. Recumbent F_3 folds of the Mount Ararat member of the Cushing Formation (Falmouth-Brunswick sequence), I-95 roadcut near the Bowdoinham exit.

Faults

Major faults in the study area are shown on Figure 3. They include normal and strike-slip faults associated with the Norumbega fault zone, and major thrust faults that juxtapose rocks of contrasting depositional environments against one another.

The major thrust faults include the Hackmatack Pond and Beech Pond faults, (Pankiwskyj, 1978; Newberg, 1985), the Boothbay thrust here named for its exposure in two windows in the Boothbay-Bristol area, and the St. George fault (Bickel, 1976). The Beech Pond and Boothbay thrusts are represented as distinct reflectors on the seismic reflection survey across the Kearsarge-central Maine synclinorium and coastal lithotectonic belt (Stewart et al., 1986). All dip gently to the northwest. The Hackmatack Pond fault brings the Siluro-Ordovician Vassalboro Formation, the lowest unit of the Kearsarge-central Maine sequence, eastward over the Late Proterozoic-Ordovician rocks of the Falmouth-Brunswick sequence. The Beech Pond fault brings the Falmouth-Brunswick sequence eastward over the Late Proterozoic-Ordovician Cape Elizabeth Formation of the Casco Bay Group. The Boothbay thrust brings the Late Proterozoic-Ordovician units of the Casco Bay Group, including the Sebascodegan formation, eastward over rusty schist and migmatite of the Ordovician(?) age Cross River formation. This fault surfaces in two antiforms only in the Boothbay-Bristol area and is cut out by the St. George fault. The St. George fault thrusts the Penobscot and Benner Hill sequences westward over the the Sebascodegan formation and the Bucksport Formation north of the the study area.

The Norumbega fault system is represented in the study area by the Cape Elizabeth, Flying Point, and Nonesuch River faults. These are post-metamorphic faults, the major movement on which, however, predates intrusion of the Devonian-Mississippian Lyman, Biddeford and Saco plutons. The Nonesuch River fault is traced from its junction with the Flying Point fault southwest of Portland to the Maine-New Hampshire border near Rochester, New Hampshire where it can be traced into the Campbell Hill fault of Lyons et al. (1982). The Nonesuch River fault is marked by the straight course of the upper Nonesuch River, silicified zones with drusy quartz boxwork, offset metamorphic isograds, and local contortion of schistosity of the Cape Elizabeth Formation. Hussey and Newberg (1978) suggest right-lateral strike-slip movement of up to 30 km. Movement may, however, have been left-lateral as suggested below for the Flying Point and Cape Elizabeth faults. This movement occurred prior to the intrusion of the Saco and Lyman plutons in Mississippian time inasmuch as these plutons are not significantly offset along the faults. Renewed minor dip-slip movement after pluton emplacement is suggested by a drainage and topographic lineament that does not offset the pluton-wall rock contacts. This lineament extends at least 8 km northeast of where the Flying Point fault meets the Nonesuch River fault.

The Flying Point fault extends from its junction with the Nonesuch River fault northeast through Flying Point in Freeport, to the Bowdoinham area where it merges with the Cape Elizabeth fault to form the Norumbega fault. It separates rocks of the Vassalboro Formation and the Falmouth-Brunswick sequence on the west from the Saco-Harpswell sequence on the east. It forms the boundary between high-grade migmatized members of the Cushing Formation of the Falmouth-Brunswick sequence on the west and significantly lower-grade units of the upper part of the Casco Bay Group on the east. This is traceable as far north as the southern end of Merrymeeting Bay. The fault offsets the migmatization front by approximately 40 km suggesting a major component of left-lateral strike-slip movement. The amount is unknown due to uncertainties as to the dip of the migmatite front. If very gentle, the major movement may actually be dip-slip normal, with the east side of the fault down-dropped. Splays of the fault are exposed at Johns Point on Flying Point, Freeport. Here rocks of the Cushing Formation of both sequences have been brecciated, and the foliation contorted and cut by numerous slickensided surfaces. The latest movement suggested by the slickensides is dip-slip normal.

The Cape Elizabeth fault has been traced by Hussey (1971a,b)

and Newberg (1981) from the Old Orchard Beach area to the Dresden Mills area where it merges with the Flying Point fault. Pankiwskyj (1978) traces a single fault from there to the northeast into the Norumbega fault of Stewart and Wones (1974) in the Bangor area. Near its southern end, along the shore in Cape Elizabeth, the Cape Elizabeth fault is actually a kilometer-wide zone of high-angle fault slices, locally filled with gouge and breccia. The principal break is marked by a series of 5 to 10 m wide pods of milky quartz traceable for about 2 km. In the area of Harpswell Neck, Harpswell, the contact between the Cape Elizabeth and Cushing Formations and the sillimanite/staurolite isograd are offset about 4 to 5 km suggesting left-lateral strike-slip movement, but as with the Flying Point fault, this may be significantly less, and possibly mostly dip-slip, if the contact and isograd surfaces are both very gentle in overall dip.

Numerous normal faults have been mapped in the study area, the larger of which are shown in Figure 3. They are of three general trends: 1) north to northeast, parallel to regional strike of the the metasedimentary rocks; 2) northwest; and 3) east-northeast. Faults of the latter two directions are generally traceable for less than a kilometer, and result in offsets of a few tens of meters. Normal faults parallel to regional strike may involve dip-slip movement of a few hundred meters. Among the more prominent of these north-northeast-trending faults are the Phippsburg, South Portland, and Back River faults (Fig. 3) and the boundary fault on the southeast side of the Macworth outcrop belt. The existence of the Back River fault is clearly demonstrated by the offset of a thin amphibolite lens within the Cape Elizabeth Formation and a granite orthogneiss, and by the retrograding of biotite to chlorite in exposures of the Cape Elizabeth Formation along the trace of the fault.

Small, unmapped faults are numerous throughout the region. Along the shore, these frequently control small-scale topographic indents of the shoreline. They are commonly marked by thin, very rusty-weathering gouge and breccia zones, the susceptibility of which to wave erosion and frost action produces the indentations.

METAMORPHISM

The stratified rocks of the the study area have been metamorphosed in a low-pressure (Buchan-type) facies series with grades of metamorphism ranging from low greenschist facies to upper amphibolite facies. Pelitic rocks are characterized at intermediate grade by the presence of andalusite, cordierite, and staurolite. At lower grades, the biotite zone is only poorly developed, biotite appearing in abundance essentially with the appearance of almandine garnet. At the highest grades of metamorphism, the pelitic rocks are strongly migmatized with a mineral assemblage characteristic of the sillimanite-K-feldspar grade of metamorphism. To the north of the study area in lenses of metapelite associated with the Falmouth-Brunswick sequence, Pankiwskyj (1978) reports the presence of microscopic kyanite, suggesting transition to a medium-pressure facies series in that area. Kyanite also occurs in rocks of the Kearsarge-central Maine sequence just southeast of Sebago Lake (Thomson and Guidotti, 1986).

Pelitic rocks of the Small Point area, now at andalusite to sillimanite grades of metamorphism, preserve 2 to 4 cm long pseudomorphs of muscovite after chiastolite(?) (Fig. 8). This suggests an earlier, intermediate grade, low-pressure facies series metamorphism. The present assemblage includes poikiloblastic fresh andalusite up to 5 cm in diameter, twinned staurolite, biotite porphyroblasts, minor cordierite, and sillimanite in small quantities intergrown with the biotite, in addition to the muscovite pseudomorphs.

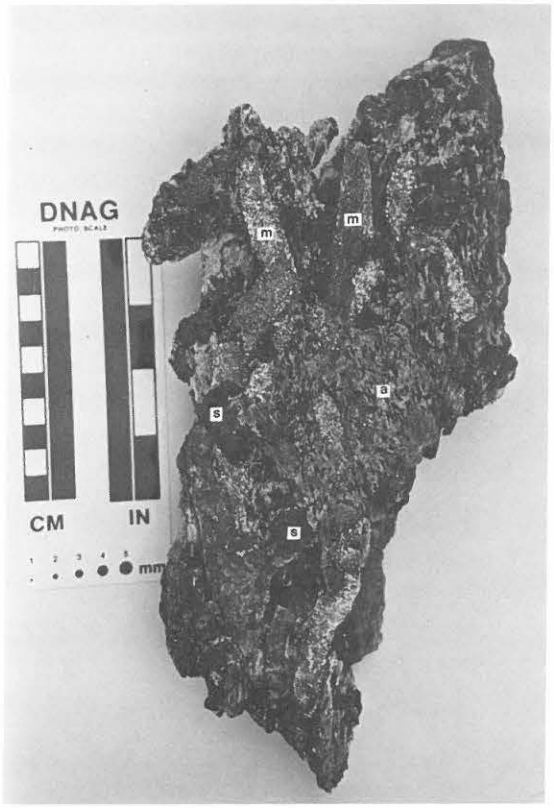

Figure 8. Multiple metamorphism of metapelite, Cape Elizabeth Formation, Small Point, Phippsburg. m: pseudomorphs of muscovite after first generation chiastolite; (a) second generation poikiloblastic pink andalusite with biotite inclusions; s: second generation staurolite porphyroblasts.

Retrograde metamorphism has variably affected the entire study area, and is expressed in the partial to locally complete chloritization of biotite, garnet, and staurolite, and the replacement of chiastolite by muscovite. Chloritization is particularly strong in the quartzo-feldspathic rocks of the Cushing Formation of both sequences, and the Cape Elizabeth Formation adjacent to the Flying Point, Back River, and Cape Elizabeth faults.

PLUTONISM

Intrusive rocks constitute about 25% of the outcrop in the study area. Plutons range in size from the Sebago batholith, areally the largest in the state of Maine, to the small elongate to irregular shaped plutons of the Phippsburg-Georgetown area (Fig. 3). Most are calc-alkaline biotite granite and two-mica granite. Two small quartz diorite plutons are present in Georgetown. Diorite forms the Saco pluton in the Saco area and a small unnamed pluton at the south end of the Sebago batholith northwest of Portland. Minor intrusives include granitic pegmatites which are very common in the areas of extensive migmatization, and diabase or basalt dikes. Pegmatites occur as irregular masses, lenses, and dikes. Some are folded and have a moderate foliation; others are massive. Exotic minerals (e.g., gemmy tourmaline, spodumene, purple apatite, rose quartz, etc.) characteristic of pegmatites in the central Maine area are lacking in most of the pegmatites of the Topsham-Georgetown area, notable exceptions being the large pegmatites of the Consolidated Feldspar Company quarry in Georgetown and the Fisher quarry in Topsham (Rand, 1957). The diabase and basalt form post-metamorphic dikes and sills up to 30 meters in thickness. They are ubiquitous throughout the area, although not abundant.

A few premetamorphic dikes have been mapped. They are mostly of felsic to intermediate composition, are unfolded, but are metamorphosed in harmony with the country rock. One dike consisting of light green, buff-weathering, calcite-green mica granofels, possibly representing an altered ultrabasic, intrudes the Cape Elizabeth Formation at the southern end of Bailey Island in Harpswell. Conformable lenses of chlorite-hornblende schist and occasionally anthophyllite-cummingtonite amphibolite occur sporadically in the Cape Elizabeth Formation. They are characteristically boudined and probably represent basic to ultrabasic sills intruded prior to both metamorphism and deformation.

TIME OF DEFORMATION, METAMORPHISM, AND PLUTONISM

Plutonism

Intrusion of plutons (other than the minor premetamorphic sills and dikes and post-tectonic basic dikes and sills) occurred from Early Devonian to Pennsylvanian time. Radiometric ages reported by Gaudette et al. (1982) and Aleinikoff et al. (1985) (Table 2) indicate intrusion of the Biddeford pluton (Fig. 3) during Middle Mississippian time, the Lyman pluton and Sebago batholith during late Mississippian time, and the Saco pluton possibly during the Pennsylvanian. The Pennsylvanian age of the Saco pluton is unusual because of the very strong pervasive lineation and foliation throughout the pluton and the metamorphic alteration of the primary igneous mineralogy. The pluton had earlier been interpreted to be a syntectonic premetamorphic Acadian intrusive (Hussey, 1985). The Webhannet pluton, which intrudes the Merrimack Group just to the south of the study area, was intruded during Early Devonian time. Pegmatites of the Falmouth-Yarmouth area were intruded during Late Devonian time. Granite and granodiorite plutons in the Augusta area north of the study area give radiometric ages indicating emplacement during Middle Devonian time (Dallmeyer and Van Breeman, 1981). McHone and Trygstad (1982) report a Middle Jurassic K/Ar age for a dolerite dike in Harpswell (Table 2). They indicate that similar dikes in New England give ages ranging from Late Triassic to Cretaceous.

Thrust-Faulting

The Hackmatack Pond fault which separates the Late Ordovician-Early Devonian Kearsarge-central Maine sequence from the Late Proterozoic-Ordovician Falmouth-Brunswick sequence is a result of the Acadian orogeny in Early Devonian time. The Boothbay thrust and the St. George fault are both locked by the Late Devonian age Waldoboro pluton. The youngest sequence affected by the Boothbay thrust is the Cross River formation of probable Ordovician age. Thus, although it may have formed during the Acadian orogeny, the Boothbay thrust may be as old as Ordovician. The St. George fault just east of the study area offsets the Penobscot Formation of Ordovician(?) age, and probably the Ordovician Benner Hill sequence (although the actual relations are obscured by the Waldoboro pluton). The continuation of this fault to the northeast into eastern Maine cuts the Flume Ridge Formation of possible Siluro-Devonian age. The St. George fault would appear to be an Acadian structure. The Beech Pond fault, which thrusts the Late Proterozoic-Ordovician Falmouth-Brunswick sequence eastward over similar age units of the Saco-Harpswell sequence, is either of Acadian or older age.

Normal and Strike-Slip Faults

Major movement on strike-slip faults of the area occurred between Early Devonian and Late Mississippian time. Strike-slip movement predates the emplacement of Mississippian to Pennsylvanian age plutons. The Nonesuch River fault, which merges with the Flying Point fault (Fig. 3) is locked by the Lyman pluton. The Cape Elizabeth fault is locked by the Biddeford and Saco plutons. However, since the Nonesuch River and Flying Point faults involve movement of the Late Ordovician-Early Devonian Kearsarge-central Maine sequence against pre-Silurian rocks of the Falmouth-Brunswick and Saco-Harpswell sequences, movement must post-date the Early Devonian.

Movement on northwest- and east-northeast-trending cross faults is inferred to post-date development of Acadian structures. However, no critical data are available to refine more closely the age of this movement.

Folding

The Vassalboro Formation is the oldest unit of the conformable formations of the Kearsarge-central Maine sequence that

includes units as young as Early Devonian. Clearly, then, both F_1 and F_2 fold systems of the Kearsarge-central Maine sequence were produced during the Acadian orogeny in Early Devonian time. Times of deformation of the rocks of the Falmouth-Brunswick and Saco-Harpswell sequences are not critically constrained by existing field relations, stratigraphic and structural interpretation, or radiometric age determinations. If, as previously discussed, the Macworth Formation, which is the uppermost unit of the Casco Bay Group, is conformable or disconformable to the Kearsarge-central Maine sequence, then both F_1 and F_2 of the Casco Bay sequence correlate with F_1 and F_2, respectively, of the Kearsarge-central Maine sequence. They would thus be of Acadian age. If, on the other hand, the Macworth Formation correlates with the Berwick Formation, the age of the deformation would be Late Precambrian to Early Ordovician. The constraint here is the 473 Ma age of the Exeter pluton which Gaudette et al. (1984) regard as having been post-tectonically intruded into the Merrimack Group.

Strongly overturned folds (F_3) of the Falmouth-Brunswick sequence developed in the areas of intensive migmatization are interpreted to be younger than the F_2 folds of adjoining sequences. They have a similar geometry to the northwest-trending late folds around the northeast side of the Sebago batholith for which Hussey et al. (1986) and Aleinikoff et al. (1985) suggest a Mississippian age. The latter folds are interpreted to have been formed synchronously with the migmatization of the Kearsarge-central Maine sequence and emplacement of the batholith. The ages of F_1 recumbent folds and F_2 upright folds of the Falmouth-Brunswick sequence are unclear. F_2 folds appear to be generally conformable with F_2 folds of the Kearsarge-central Maine sequence which are clearly effects of the Acadian orogeny in Early Devonian time. This suggests that F_2 folding of the Falmouth-Brunswick sequence is likewise related to the Acadian orogeny.

No evidence of regionally extensive Alleghenian deformation has been noted.

Metamorphism

Regional metamorphism of the Kearsarge-central Maine sequence was accomplished in several stages during the Acadian orogeny (Guidotti, 1985). Mississippian ages for metamorphic minerals of rocks in the area north and northeast of the Sebago batholith reported by Lux and Guidotti (1985) are probably best interpreted as the age of a relatively extensive thermal aureole around the Sebago batholith. In a similar but much narrower aureole in the Vassalboro Formation around the Lyman pluton, also of Mississippian age, the Vassalboro Formation has been recrystallized. In particular, a schistosity defined by biotite has been recrystallized parallel to the contacts with the pluton, and to axial planes of small-scale F_3 folds. Approximately 1 km away from the pluton, outside the aureole, the schistosity has its normal north-northeast trend parallel to axial planes of F_2 folds. These relations argue for an Acadian age for the regional metamorphism of the Kearsarge-central Maine sequence.

The age of metamorphism of the Saco-Harpswell sequence is very uncertain, and parallels the arguments for age of folding discussed above. If the Macworth Formation is part of the Vassalboro Formation, the age of metamorphism is Acadian. If it is correlated with the Berwick Formation of the Merrimack Group, then metamorphism would predate the intrusion of the Exeter pluton, and would be Early Ordovician or older. The Early Middle Ordovician Rb/Sr ages (Table 2) for the Cape Elizabeth and Cushing Formations are subject also to varying interpretations, consequently not giving clear-cut constraints for time of metamorphism. They may represent ages of deposition/diagenesis and volcanism (Brookins and Hussey, 1978), or they may represent ages either completely or partially reset by metamorphism (H. E. Gaudette, pers. commun., 1986).

ACKNOWLEDGMENTS

I gratefully acknowledge the support over the past 30 years of the Maine Geological Survey. I am particularly appreciative of the encouragement and interest in my work given by former State Geologists, John Rand and Robert Doyle, and particularly the present State Geologist, Walter Anderson. I also thank the many colleagues who have visited with me in the field and with whom I have had many lively discussions, in particular Donald Newberg, Wallace Bothner, Philip Osberg, David Stewart, Olcott Gates, Richard Gilman, Gary Boone, and Allan Ludman. This paper has benefited from review of an earlier draft by Robert Moench, Robert Marvinney, and an anonymous reviewer.

REFERENCES CITED

Aleinikoff, J. N., Moench, R. C., and Lyons, J. T., 1985, Carboniferous U-Pb age of the Sebago batholith, southwestern Maine: Metamorphic and tectonic implications: Geol. Soc. Amer., Bull., v. 96, p. 990-996.

Bickel, C. E., 1976, Stratigraphy of the Belfast quadrangle, Maine, *in* Page, L. R. (ed.), Contributions to the stratigraphy of New England: Geol. Soc. Amer., Mem. 148, p. 97-128.

Bothner, W. A., Boudette, E. L., Fagan, T. J., Gaudette, H. E., Laird, J., and Olszewski, W. J., Jr., 1984, Geologic framework of the Massabesic anticlinorium and the Merrimack trough, southeastern New Hampshire, *in* Hanson, L. S. (ed.), New England Intercollegiate Geological Conference guidebook for field trips in the coastal lowlands, Boston, MA, to Kennebunk, ME: p. 186-206.

Boucot, A. J., Brookins, D. G., Forbes, W., and Guidotti, C. V., 1972, Staurolite-zone Caradoc (Middle-Late Ordovician) age Old World province brachiopods from Penobscot Bay, Maine: Geol. Soc. Amer., Bull., v. 83, p. 1953-1960.

Brookins, D. G., and Hussey, A. M., II, 1978, Rb-Sr ages for the Casco Bay Group and other rocks from the Portland-Orrs Island area, Maine: Geol. Soc. Amer., Abs. with Prog., v. 10, no. 2, p. 34.

Dallmeyer, R. D., and Van Breeman, O., 1981, Rb-Sr whole rock ages of the Togus, Hallowell, and Three Mile Pond plutons: Contrib. Min. and Petrol., v. 78, p. 61-73.

Eusden, J. D., Bothner, W. A., and Hussey, A. M., II, 1987, The Kearsarge - central Maine synclinorium of southeastern New Hampshire and southwestern Maine: stratigraphic and structural relations of an inverted section: Jour. Sci., v. 287, p. 242-264.

Fyffe, L. R., 1982, Taconian and Acadian structural trends in central and northern New Brunswick, *in* St-Julien, P., and Beland, J. (eds.), Major structural zones and faults of the northern Appalachians: Geol. Assoc. Canada, Spec. Paper 24, p. 117-130.

Gaudette, H. E., Bothner, W. A., Laird, J., Olszewski, W. J., Jr., and Cheatham, M. M., 1984, Late Precambrian/Early Paleozoic deformation and metamorphism in southeastern New Hampshire – confirmation of an exotic terrane: Geol. Soc. Amer., Abs. with Prog., v. 16, p. 516.

Gaudette, H. E., Kovach, A., and Hussey, A. M., II, 1982, Ages of some intrusive rocks, southwestern Maine, USA: Can. Jour. Earth Sci., v. 19, p. 1350-1357.

Gaudette, H. E., Olszewski, W. J., Jr., and Cheatham, M. M., 1983, Rb/Sr whole rock ages of gneisses from the Liberty - Orrington anticline, Maine: the oldest (?) basement complex of the eastern margin, northern Appalachians: Geol. Soc. Amer., Abs. with Prog., v. 15, p. 579.

Guidotti, C. V., 1985, Generalized map of regional metamorphic zones, *in* Osberg, P. H., Hussey, A. M., II, and Boone, G. M. (eds.), Bedrock geologic map of Maine: Maine Geol. Surv., scale 1:500,000.

Hepburn, J. C., and Munn, B., 1984, A geologic traverse across the Nashoba Block, Eastern Massachusetts, *in* Hanson, L. S. (ed.), New England Intercollegiate Geological Conference guidebook for field trips in the coastal lowlands, Boston, MA, to Kennebunk, ME: p. 103-123.

Hussey, A. M., II, 1968, Stratigraphy and structure of southwestern Maine, *in* Zen, E-an, White, W. S., Hadley, J. B., and Thompson, J. B., Jr. (eds.), Studies of Appalachian geology, Northern and Maritime, Wiley - Interscience, New York, p. 291-301.

Hussey, A. M., II, 1971a, Geologic map of the Portland 15′ quadrangle, Maine: Maine Geol. Surv., Map GM-1, 19 p.

Hussey, A. M., II, 1971b, Geologic map and cross sections of the Orrs Island 7.5′ quadrangle and adjacent area, Maine: Maine Geol. Surv., Map GM-2, 18 p.

Hussey, A. M., II, 1972, Reconnaissance bedrock geologic map of the Friendship 7.5′ quadrangle, Maine: Maine Geol. Surv., Open File No. 71-9.

Hussey, A. M., II, 1985, The bedrock geology of the Bath and Portland 2 degree map sheets, Maine: Maine Geol. Surv., Open File No. 85-87, 82 p.

Hussey, A. M., II, 1986, Stratigraphic and structural relationships between the Cushing, Cape Elizabeth, Bucksport, and Cross River Formations, Portland-Boothbay area, Maine, *in* Newberg, D. W. (ed.), New England Intercollegiate Geological Conference guidebook for field trips in southwestern Maine, p. 164-183.

Hussey, A. M., II, Bothner, W. A., and Thomson, J. A., 1986, Geological comparisons across the Norumbega fault zone, southwestern Maine, *in* Newberg, D. W. (ed.), New England Intercollegiate Geological Conference guidebook for field trips in southwestern Maine, p. 53-79.

Hussey, A. M., II, and Newberg, D. W., 1978, Major faulting in the Merrimack synclinorium between Hollis, N. H., and Biddeford, Maine: Geol. Soc. Amer., Abs. with Prog., v. 10, no. 2, p. 48.

Katz, F. J., 1917, Stratigraphy in southwestern Maine and southeastern New Hampshire: U.S. Geol. Surv., Prof. Paper 108, p. 165-177.

Knight, D. R., and Gaudette, H. E., 1987, Rb-Sr age of the Waldoboro two-mica granite, coastal Maine: Geol. Soc. Amer., Abs. with Prog., v. 19, p. 23.

Lux, D. R., and Guidotti, C. V., 1985, Evidence for extensive Hercynian metamorphism in western Maine: Geology, v. 13, p. 696-700.

Lyons, J. B., Boudette, E. L., and Aleinikoff, J. N., 1982, The Avalonian and Gander zones in central New England, *in* St-Julien, P., and Beland, J. (eds.), Major structural zones and faults of the northern Appalachians: Geol. Assoc. Canada, Spec. Paper 24, p. 43-66.

McHone, J. G., and Trygstad, J. C., 1982, Mesozoic mafic dikes of southern Maine: Geol. Soc. Maine, Bull. 2, Shorter Contributions to the Geology of Maine, p. 16-32.

Moench, R. H., and Zartman, R. E., 1976, Chronology and styles of multiple deformation, plutonism, and polymetamorphism in the Merrimack synclinorium of western Maine, *in* Lyons, P. C. and Brownlow, A. H. (eds.), Studies in New England geology: Geol. Soc. Amer., Mem. 146, p. 203-238.

Naylor, R. S., 1968, Origin and relationsips of the core rocks of the Oliverian domes, *in* Zen, E-an, White, W. S., Hadley, J. B., and Thompson, J. B., Jr. (eds.), Studies of Appalachian geology, Northern and Maritime: Wiley - Interscience, New York, p. 231-240.

Neuman, R. B., 1973, Staurolite-zone Caradoc (Middle-Late Ordovician) age Old World province brachiopods from Penobscot Bay, Maine: (discussion): Geol. Soc. Amer., Bull., v. 48, p. 1829-1830.

Newberg, D. W., 1979, Bedrock geology of the Waldoboro East and Waldoboro West 7.5′ quadrangles, Maine: Maine Geol. Surv., Open File No. 79-19, 16 p.

Newberg, D. W., 1981, Bedrock geology and structure of the Gardiner 15′ quadrangle, southwestern Maine, *in* New England Seismotectonic Study Activities in Maine during Fiscal Year 1981: Maine Geol. Surv., p. 57-66.

Newberg, D. W., 1985, Bedrock geology of the Palermo 7.5′ quadrangle, Maine: Maine Geol. Surv., Open File No. 85-84, 14p.

Osberg, P. H., 1974, Foreward, *in* New England Intercollegiate Geological Conference guidebook for field trips in east-central and north-central Maine, p. iii-xii.

Osberg, P. H., 1980, Stratigraphic and structural relations in the turbidite sequence of south-central Maine, *in* Roy, D. C. (ed.), New England Intercollegiate Geological Conference guidebook for field trips in northeastern Maine and neighboring New Brunswick, p. 48-60.

Osberg, P. H., and Guidotti, C. V., 1974, The geology of the Camden-Rockland area, *in* Osberg, P. H. (ed.), New England Intercollegiate Geological Conference guidebook for field trips in east-central and north-central Maine, p. 47-60.

Osberg, P. H., Hussey, A. M., II, and Boone, G. M., 1985, Bedrock geologic map of Maine: Maine Geol. Surv., scale 1:500,000.

Pankiwskyj, K. A., 1978, Bedrock geology of the Coopers Mills-Liberty area, Maine: Geol. Soc. Maine, Guidebook for field trip 3; reprinted in Geol. Soc. Maine, Bull. 3, p. 19-25.

Perkins, E. H., and Smith, E. S. C., 1925, Contributions to the Geology of Maine, no. 1: a geological cross-section from the Kennebec River to Penobscot Bay: Am. Jour. Sci, v. 209, p. 204-228.

Rand, J. R., 1957, Maine pegmatite mines and prospects and associated minerals: Maine Geol. Surv., Minerals Resources Index No. 1, 43 p.

Robinson, P., Tracy, R. J., Hollocher, K. T., Schumacher, J. C., and Berry, H. N., IV, 1986, The central Massachusetts metamorphic high, *in* Robinson, P., and Elbett, D. C. (eds.), Regional metamorphism and metamorphic phase relations in northwestern and central New England, Guidebook, Trip B-5, 14th General Meeting, Int. Min. Assoc., p. 195-288.

Ruitenburg, A. A., and Ludman, A., 1978, Stratigraphy and tectonic setting of Early Paleozoic rocks of the Wirral - Big Lake area, southwestern New Brunswick and southeastetn Maine: Can. Jour. Earth Sci., v. 15, p. 22-33.

Stewart, D. B., and Wones, D. R., 1974, Bedrock geology of the northern Penobscot Bay area, *in* Osberg, P. H. (ed.), New England Intercollegiate Geological Conference guidebook for field trips in east-central and north-central Maine, p. 223-239.

Stewart, D. B., Unger, J. D., Phillips, J. D., Goldsmith, R. R., Poole, W. H., Spencer, C. P., Green, A. G., Loiselle, M. C., and St-Julien, P., 1986, The Quebec-western Maine seismic reflection profile: setting and first year results: Amer. Geophys. Union, Geodynamics Series, v. 14, p. 189-199.

Thomson, J. A., and Guidotti, C. V., 1986, The occurrence of kyanite in southern Maine, and its metamorphic implications: Geol. Soc. Amer., Abs. with Prog., v. 18, p. 72.

Zartman, R. E., and Naylor, R. S., 1984, Structural implications of some new radiometric ages of igneous rocks in southeastern New England: Geol. Soc. Amer., Bull., v. 95, p. 522-539.