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Bedrock Geology of the Mainland Portion of the Newbury Neck and Salsbury Cove 7.5-minute Quadrangles

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ABSTRACT

The mainland portion of the Newbury Neck and Salsbury Cove 7.5' quadrangles of coastal Maine is underlain predominantly by low grade metamorphic rocks of the Middle Cambrian Ellsworth Schist. The common variety of Ellsworth Schist includes quartz-feldspar-muscovite-chlorite schist, greenstone, and metarhyolite. Two mappable members have been identified. The Morgan Bay Member, of pelitic schist, quartzite, and conglomerate, is exposed only in the western part of the Newbury Neck quadrangle. The Egypt Member of the Ellsworth, exposed in the northern part of both quadrangles, is predominantly a feldspar porphyroblastic schist. Age relationships are indeterminate.

A prominent foliation, with lineation and related asymmetric structures suggestive of top-to-northwest or west kinematics, varies from subhorizontal across much of the Newbury Neck quadrangle to moderately dipping on both limbs of a late, large-scale antiform eastward in the Salsbury Cove quadrangle. At the west edge of the Newbury Neck quadrangle, the Devonian Blue Hill pluton dips gently eastward beneath the Ellsworth Schist, which hosts a contact aureole several kilometers wide. Elsewhere, metamorphic grade is in the lower greenschist facies. Post-metamorphic intermediate to mafic dikes are sparse, considering the proximity of an overlying, large plutonic complex on Mt. Desert Island in the southern part of the quadrangles.

Pervasive bimodal igneous sheets in the Ellsworth Schist suggest rifting, perhaps in a back-arc setting, during the Middle Cambrian. The main deformational fabric may record emplacement of the Ellsworth Schist over the St. Croix sedimentary margin to the northwest prior to the penetration of the Silurian and Devonian magmas, and development of late structures associated with Middle Paleozoic accretion of these rocks to North America.

INTRODUCTION

Location and previous work

The study area is on the mainland portion of the Newbury Neck and Salsbury Cove 7.5' quadrangles which constitute the northern half of the Mount Desert 15' quadrangle; the Ellsworth 15' quadrangle is adjacent to the north (Figure 1). Most of the study area is in the Hancock County towns of Surry, Trenton, and Lamoine. The southern parts of the quadrangles include the northern part of Mt. Desert Island. The geology of Mt. Desert Island, previously mapped by Gilman and Chapman (Gilman and others, 1988), was not included in the present study, though it is shown on the maps (Reusch and Hogan, 2002; Reusch, 2003).

Jackie Delaine McGregor did geologic mapping in the Ellsworth 15' quadrangle at a scale of 1:62,500, which was the basis of his Ph. D. thesis (McGregor, 1964). The western part of the Newbury Neck quadrangle was included in the 1:62,500-scale map of northern Penobscot Bay by Stewart (1998). And Hibbard (1995) did reconnaissance investigations at Lamoine State Park in the Salsbury Cove quadrangle.

Regional geologic setting

The map area lies entirely within the Ellsworth terrane (Stewart, 1998) of coastal Maine. The Ellsworth terrane is bounded by the St. Croix terrane to the northwest and by the Gulf of Maine to the southeast. Early Paleozoic paleomagnetic evidence for high southern paleolatitudes and Middle Paleozoic faunal provinciality indicate that the Ellsworth terrane formed near the Gondwanan supercontinent, across the Iapetus Ocean from Laurentia; hence it is considered a peri-Gondwanan terrane

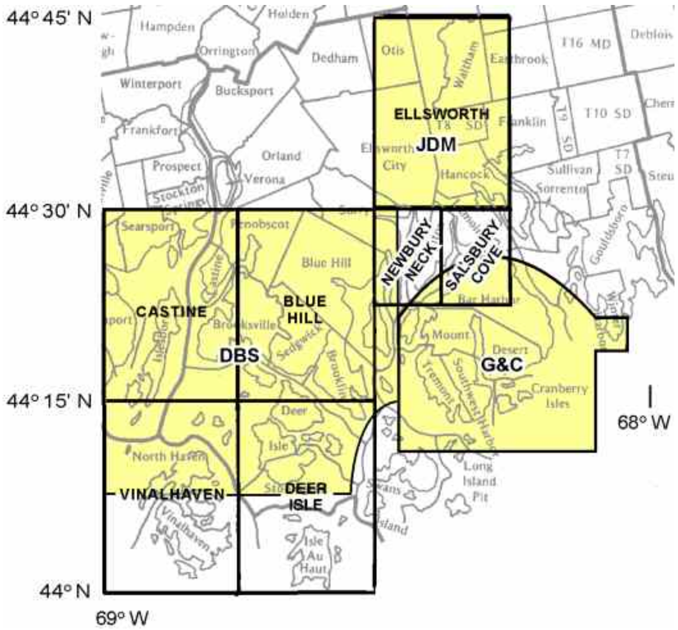

Figure 1. Location of Newbury Neck and Salsbury Cove 7.5' quadrangles and previous work. Names of selected 15' quadrangles are shown. DBS = Stewart (1998); JDM = McGregor (1964); G&C = Gilman and Chapman (1988).

(Brookins and others, 1973; van Staal and others, 1998; Mac Niocaill and others, 1997). It was probably accreted to North America by Devonian time. Questions remain about the origin of the Ellsworth Schist and the regional significance of its deformation.

Basis of study

Thirty visits (179 stations) were made to the Newbury Neck quadrangle between September 5 and December 4, 2000, and sixteen visits (174 stations) to the northern part of the Salsbury Cove quadrangle between September 6 and December 14, 2001. Oriented thin sections were made from around a dozen samples.

The distribution of Quaternary sedimentary deposits controls bedrock exposure. Excellent shoreline outcrops, including wave-cut platforms and cliffs, occur on even low-angle shorelines where wave action is efficient and overburden thin. Thick till and glacial outwash obscure bedrock in several large parts of the map area (Borns, 1974; Thompson and Borns, 1985). For example, there is extensive glaciomarine sediment (Presumpscot Formation) on the Trenton peninsula, in Goose Cove (NN)*, and at the head of Union River Bay (NN); moraine ridges south of the Carrying Place on Newbury Neck and south of Heath Brook on the Trenton peninsula (NN); and till along the south shore of Patten Bay (NN). Along the east shore of Union River Bay, many large slabs of rock are locally derived. A large esker-delta complex hides bedrock east of the Jordan River (SC)* whereas bedrock is almost completely exposed along the Skillings River a few kilometers to the east (SC).

STRATIGRAPHY

Ellsworth Schist

Stratified rocks in the study area are all assigned to the Ellsworth Schist, subdivided into three units (Figure 2). The main portion of the formation consists of metavolcanic and metasedimentary rocks. The Morgan Bay Member consists dominantly of metasedimentary rocks. Distinctive metamorphic rocks at the northern part of the study area are assigned to the Egypt Member. The total thickness of these units is between 4 and 7 km, based on geologic and seismic data (Stewart, 1998). Stratigraphic relationships among the units are uncertain because of a paucity of primary topping indicators, intensity of deformation, and lack of exposure at the contacts.

The Ellsworth Schist was originally defined by Smith and others (1907) from "abundant exposures" in the city of Ellsworth, even though their map area was to the west of Ellsworth, in Penobscot Bay. In the Ellsworth 15' quadrangle, McGregor (1964) subdivided the Ellsworth Schist, applying the name "Lamoine group" to non-porphyroblastic schists, greenstones, and metarhyolites exposed in the southern part of the Ellsworth quadrangle. Since these rocks are indistinguishable from the bulk of the Ellsworth Schist mapped to the west (Stewart, 1998), the name Lamoine group of McGregor is conisdered unnecessary and is not followed here. The rocks at Lamoine are mapped as just Ellsworth Schist, undifferentiated.

In the Newbury Neck and Salsbury Cove quadrangles, undifferentiated Ellsworth Schist (**Ce**) extends from the east side of the Skillings River (SC) south of Young's Point, southwestward to the south end of Newbury Neck (NN). The characteristic rock is a white-weathering, dark green quartz-feldspar-muscovite-chlorite schist that consists of 1-20 mm-thick quartz and feldspar-rich laminations alternating with films and lenses of muscovite-chlorite schist (Figure 3). The quartz-feldspar laminations have an equigranular (on average 0.3 mm) polygonal texture. A typical ratio of quartz and feldspar to phyllosilicates (QF:PS) is 2:1 (McGregor, 1964), which may be compatible with a rhyolite ash or immature volcaniclastic sedimentary protolith (see further discussion below). The compositional layering, of quartz-feldspar laminations alternating with phyllosilicates, is considered to be metamorphic in origin, formed at lower greenschist conditions. Features such as graded or cross-beds that are diagnostic of primary stratification are absent; rather, segregated metamorphic minerals define the layers. (See opposite view presented by Bouley, 1978.) Quartz veins, lenses, pods, and irregular masses are abundant. The rocks are poorly stratified, although medium-bedded feldspathic sand-

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* In this report, (NN) indicates places in the Newbury Neck quadrangle, and (SC) indicates places in the Salsbury Cove quadrangle.

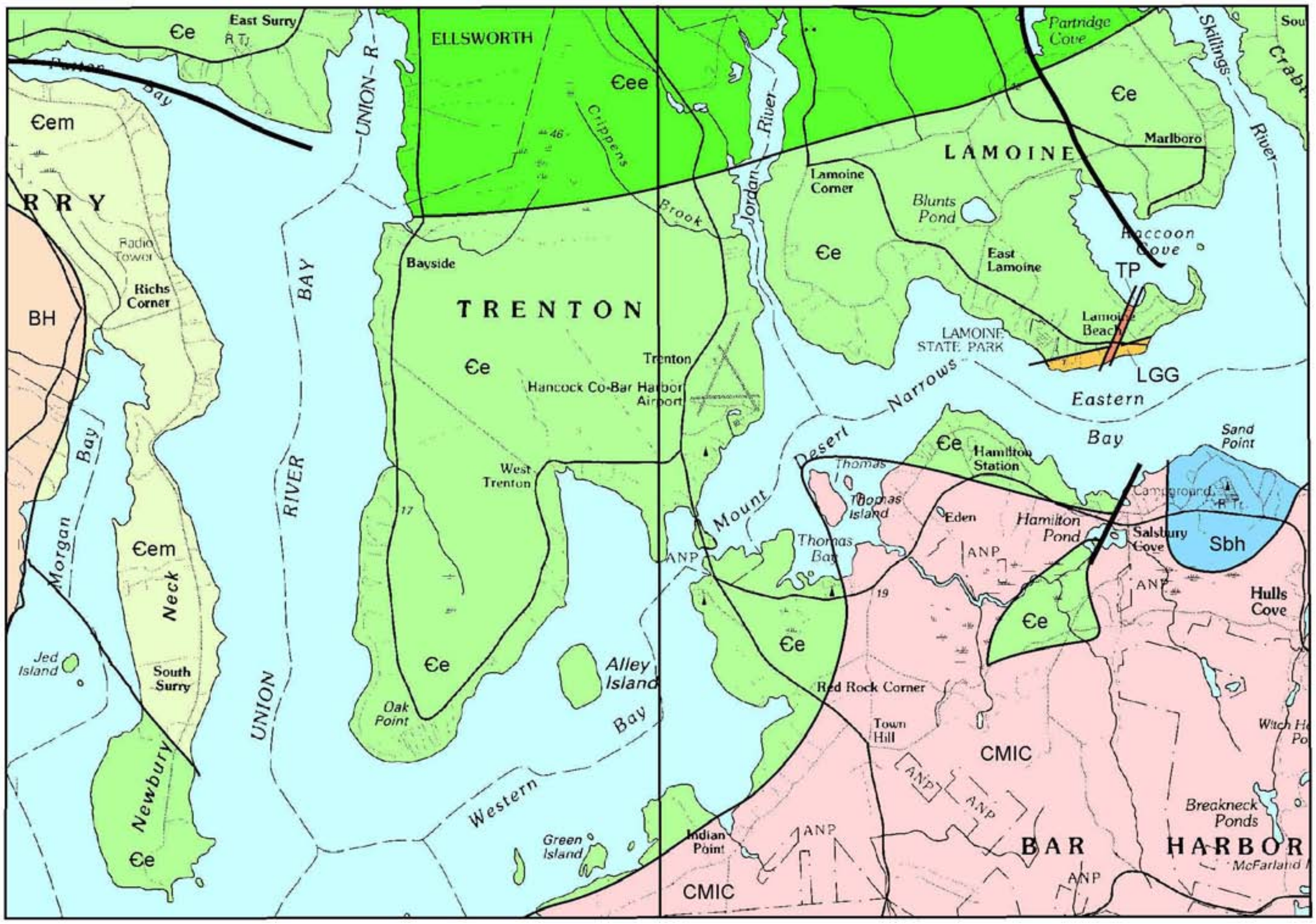

Figure 2. Generalized geologic map of the Newbury Neck and Salsbury Cove 7.5' quadrangles. Stratified units: Ce = Ellsworth Schist; Cem = Morgan Bay Member of the Ellsworth Schist; Cee = Egypt Member of the Ellsworth Schist; Sbh = Bar Harbor Formation. Plutonic rocks: LGG = Lamoine Granite Gneiss; CMIC = Cadillac Mountain Intrusive Complex; BH = Blue Hill pluton; TP = dike at Timber Point. *(Adapted from Reusch and Hogan, 2002; and Reusch, 2003)*

Figure 3. Thinly interlayered white quartz-feldspar rock and grayish-green muscovite-chlorite schist typical of the Ellsworth Schist. *(Photo 1 of Reusch, 2003)*

stones are present on Goose Rock (NN) and northwest of Alley Island (NN), which two occurrences are possibly the same horizon. An extensive unit of phyllosilicate-rich schist occurs along High Head (NN).

Igneous sheets within the Ellsworth Schist are ubiquitous and comprise a strongly bimodal assemblage of greenstone (metabasalt) and metarhyolite (Figure 4). These layers range in thickness from several centimeters to several meters, but are typically 0.1-1 m thick. They are presumably tuffs, rather than flows or sills, because they lack chilled margins, bases, or tops, and many are too thin to be flows. They are internally foliated, and thus were clearly affected by the same thermal and mechanical events as the enclosing schist, but behaved more rigidly. Greenstones typically contain mm-sized feldspars, which are commonly broken and define a mineral lineation. The green color is caused by chlorite, actinolite, and minor epidote. Metarhyolites are gray, weather cream to white, invariably contain

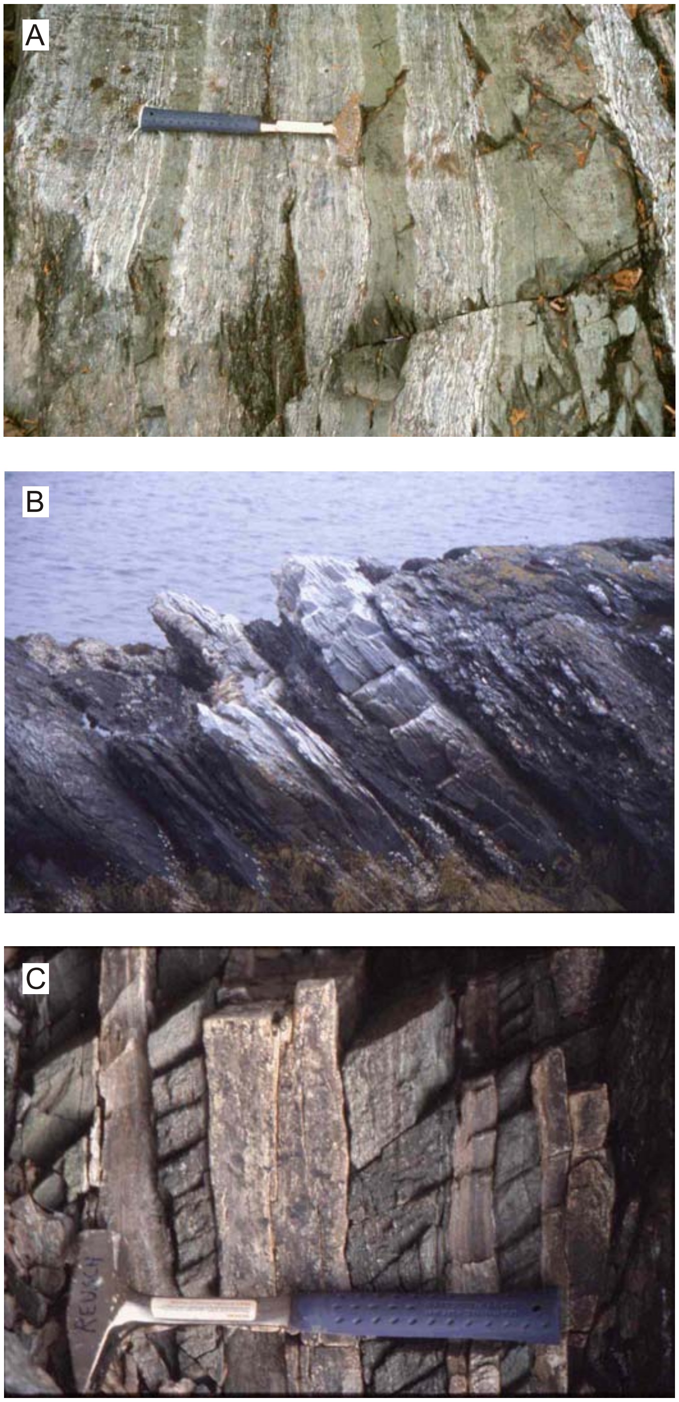

Figure 4. Igneous sheets in the Ellsworth Schist. A. Thin greenstone sheets. B. Two rhyolite sheets of medium thickness. C. Interleaved mafic and felsic rocks within a bimodal igneous layer several meters thick.

traces of mm-sized pyrite, and vary from aphyric to quartz and/or feldspar-phyric. Conspicuous white-weathering rocks with quartz and/or feldspar phenocrysts are thought to be crystal tuffs (e.g., High Head); a pumice fragment confirms a pyroclastic origin at location 164 southeast of South Surry (NN) (Figure 5).

Figure 5. Pumice fragment in the Ellsworth Schist, demonstrating an extrusive pyroclastic origin.

Evidence constraining the depositional environment of the Ellsworth Schist is sparse. Stewart (1998) proposed that typical Ellsworth rocks accumulated in a marine environment within a continental rift. Iron-manganese precipitates elsewhere in the Ellsworth Schist suggest marine conditions. If the thin laminations that are here considered to have a metamorphic origin were instead derived from primary siliceous ooze and pelagic clay (Bouley, 1978), then a distal marine setting is implied. Alternatively, in the present map area, rare massive layers possibly represent welded tuffs, which would suggest subaerial deposition.

The quartz content of the Ellsworth Schist, which ranges from 30-45% (McGregor, 1964), most likely reflects a felsic igneous protolith, here interpreted to be felsic pyroclastic materials of rhyolitic composition. This composition implies melting of sialic crust. The alternative origin of the schist as metamorphosed siliceous ooze and pelagic clay would not carry this implication. Regardless of the interpretation of the schist itself, the intercalated bimodal igneous sheets reflect partial melting of both the mantle and sialic crust, which points strongly to origin in an extensional tectonic setting, either in a continental rift (Stewart, 1998) or a back-arc setting.

*Morgan Bay Member (new name) (**Cem**)*. The Morgan Bay Member, here named for Morgan Bay in the Newbury Neck quadrangle, is exposed along Morgan Bay and Newbury Neck north of High Head. Previously, it was not differentiated from the Ellsworth Schist (Osberg and others, 1985; Stewart, 1998). It comprises pelitic schists, impure quartzites, and minor conglomerate together with greenstones and metarhyolites that may be sills (Figure 6). Pelitic layers are conspicuous in the field where andalusites have grown within the contact aureole of the Blue Hill pluton. It is typically medium-bedded (10-30 cm). The Smelt Brook Conglomerate, a prominent 30 cm-thick conglomerate bed exposed on either side of Morgan Bay, contains a few discernible clasts of felsic igneous rocks (Figure 7). It is mappable at 1:24,000 scale only because its nearly horizontal dip produces a significant breadth of outcrop.

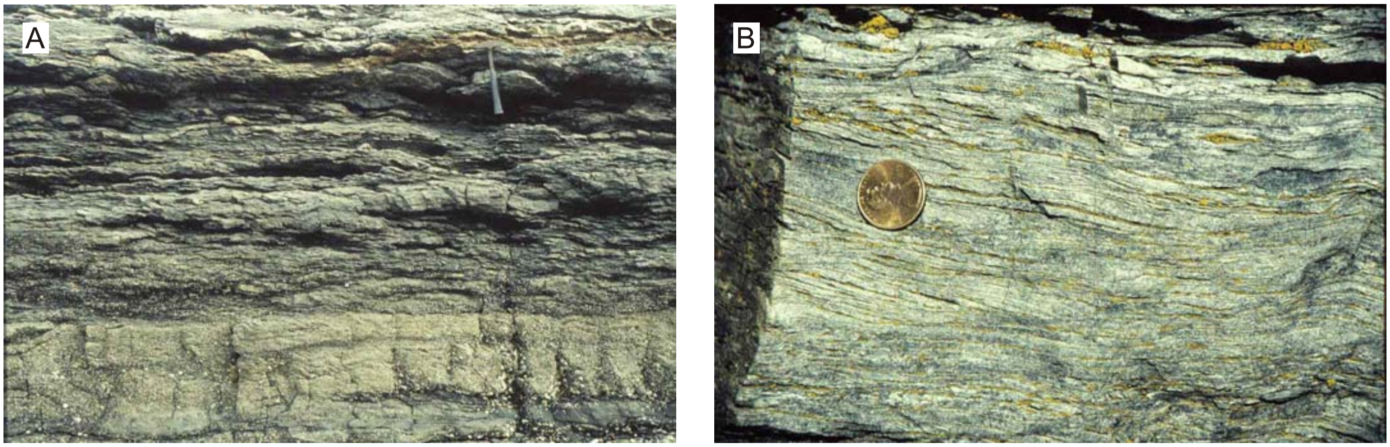

Figure 6. Rocks of the Morgan Bay Member of the Ellsworth Schist. A. Compositional layers of schist and quartzite. Note hammer for scale. B. Thick quartzite bed with deformational S-C structure.

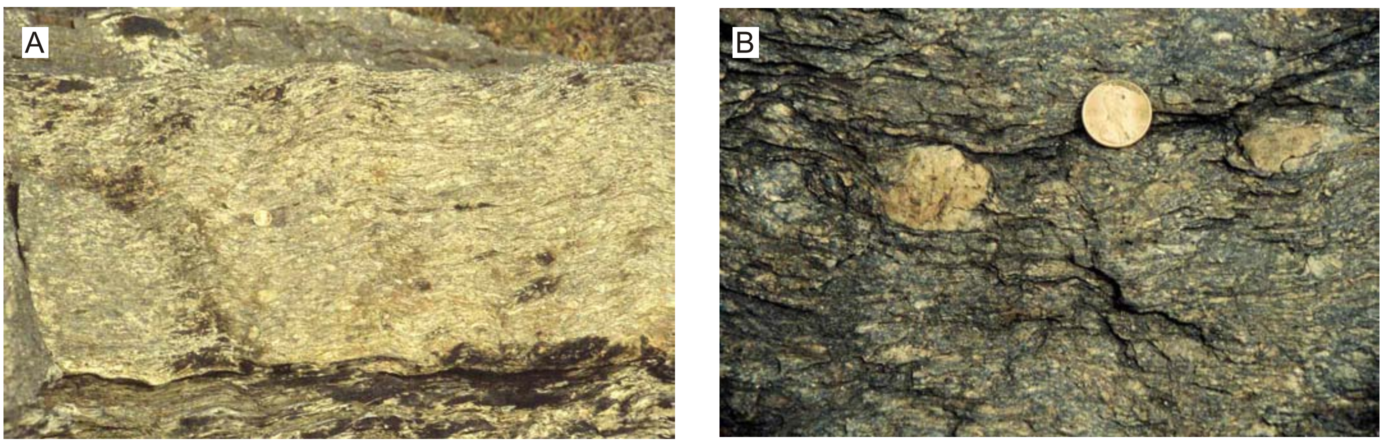

Figure 7. Rocks of the Smelt Brook Conglomerate. A. Entire bed resting on schist. B. Close-up of granite pebble in conglomerate. *(Webber Cove, **NN**)*

Between the head of Morgan Bay and Browns Point (NN), there are greenstone and metarhyolite sheets which may intrude the formation. They locally display (foliated) gabbroic texture (Figure 8) and possible chilled margins (Figure 9). They are typically 10 cm thick, but range from several centimeters to as much as a few meters. Arguably, these igneous sheets in the Morgan Bay Member represent feeders to very similar igneous sheets elsewhere in the Ellsworth Schist that are considered extrusive.

The contact between the the Morgan Bay Member and undifferentiated Ellsworth Schist is poorly located and possibly gradational. The rest of the Ellsworth may be younger than the Morgan Bay Member if igneous sheets, which appear to be extrusive deposits in ordinary Ellsworth, constitute sills within the Morgan Bay Member.

The single conglomerate bed in the Morgan Bay Member indicates moderate proximity to an eroding source area which in-

Figure 8. Relict gabbroic texture in mafic sheet from the Morgan Bay Member, suggesting it was an intrusive rock. The curved foliation is a younger deformational feature. *(Photo 4 of Reusch and Hogan, 2002)*

Figure 9. Mafic dike in the Morgan Bay Member with darker margins interpreted as a finer-grained, chilled texture. *(Browns Point, NN)*

cluded felsic intrusive rocks. If the igneous sheets are sills, then the Morgan Bay Member represents a dominantly sedimentary sequence. No other indicators diagnostic of depositional environment have been recognized.

Rhyolite of Goose Cove (**Cer**). Locally, metarhyolite of the undifferentiated Ellsworth Schist crops out sufficiently to be shown as a separate map unit. The poorly exposed Rhyolite of Goose Cove is gray, weathers cream to buff, contains traces of pyrite, and carries the same fabric as adjacent schists. McGregor (1964) correlated this unit with the Lamoine granite gneiss, which here is viewed as the high-level intrusive equivalent.

Egypt Member (new name) (**Cee**). The Egypt unit was one of the informal subdivisions of the Ellsworth Schist proposed by McGregor (1964) for feldspar-porphyroblastic schists, greenstones, and amphibolites preserved in the core of a late synform east of Ellsworth. The name is here adopted as a member of the Ellsworth Schist. It is named for the coastal village of Egypt, about 7 miles east of Ellsworth near the Hancock-Franklin town line. Some of these rocks, north of the present study area, are indicated on the state bedrock map as a volcanic member of the Ellsworth Schist (Osberg and others, 1985, their map symbol OZev).

The Egypt Member crops out in the northern part of the Salsbury Cove sheet and northeastern part of the Newbury Neck sheet (Figure 2). Meter-sized and larger slabs of this unit are common along the east shore of the Union River north of Mill Cove (NN). Its thickness is on the order of a kilometer.

In the map area, the Egypt Member consists of dark, feldspar-phyric schists (Figure 10). Initially, I thought the feldspars were crystals in crystal-vitric tuffs, however I now view them as porphyroblasts based on the presence of garnet and tourmaline porphyroblasts elsewhere in this unit (McGregor, 1964) and on feldspar concentrations that are locally too high for a pyroclastic origin. The matrix is chlorite-rich. Thin (1-5 mm), gently undulating, smeared quartz veins are common. The ratio of quartz and feldspar to phyllosilicates (QF:PS) is commonly in the 1.0-1.5 range (McGregor, 1964), making it darker than normal Ellsworth Schist. Biotite is present in thin section, and McGregor considered the base of the Egypt unit to coincide with the biotite isograd. North of the map area, the Egypt unit includes greenstones and an occurrence of black, fine-grained amphibolite.

McGregor (1964) reported a greater intensity of small-scale isoclinal folds in the Egypt Member than in ordinary Ellsworth Schist. Along the east shore of the Union River, rocks near the base of the Egypt Member display a pronounced lineation on a subhorizontal foliation; also, slickensides are common in the large slabs near Mill Cove (NN). In one of the few outcrops in this area (location 00-171), sigmoidal quartz veins step up to the northwest, indicating top-to-northwest kinematics. The apparent localization of strain near the southern contact of the Egypt Member suggests a thrust relationship based on the occurrence of biotite and higher-grade rocks above chlorite-grade rocks. The contact near Youngs Point (east side of Skillings River just north of the Salsbury Cove quadrangle), previously the best exposure, is reported to be concordant with layering (McGregor, 1964). Unfortunately, this location now appears to be smack in the middle of a fish processing plant. In Mill Cove and along the western shores of the Jordan and Skillings Rivers, I cannot rule out the possibility of a late, steeply-dipping fault at the southern margin of the Egypt Member.

Stewart (1998) considers the Egypt Member to be younger than the Ellsworth Schist based on its structural position above the latter. It is, however, likely to be older or the same age as the adjacent Ellsworth Schist if its lower contact is a thrust fault. In a consistent fashion, Stewart also correlates greenstones of the Egypt Member with a mafic unit at the south end of Long Island in Blue Hill Bay and with the North Haven Greenstone in Penobscot Bay (Stewart, 1998). In support of this correlation, a glacial boulder at Lamoine Beach, presumably derived from the Egypt Member to the north, is lithologically identical to certain greenstones at the south end of Long Island in that they both contain distinctive horizons of white, felsic lapilli.

Figure 10. Feldspar porphyroblasts in chlorite-muscovite schist characteristic of the Egypt Member of the Ellsworth Schist.

The depositional environment of the Egypt Member is possibly more distal than that of the underlying Ellsworth Schist based on its greater abundance of phyllosilicates. In addition, whereas the Egypt Member also contains mafic layers, it does not contain the rhyolite layers common elsewhere in the Ellsworth (McGregor, 1964) suggesting the absence of a sialic basement. If the arguments above hold and if the depositional site of the Egypt Member lay to the southeast, then the sediment source area may have lain to the northwest.

Age and correlation of the stratified rocks

The Morgan Bay Member has no known correlatives, though it may be that equivalent sedimentary rocks elsewhere are currently mapped within the Ellsworth Schist.

A Middle Cambrian age is assigned to the Ellsworth Schist, based on a high-precision U-Pb zircon age of 509 ± 1 Ma from two layers of rhyolite tuff collected approximately 10 km southwest of the map area (R. D. Tucker *in* Stewart and others, 1995; Stewart, 1998). The Ellsworth Schist may grade laterally into, or underlie, the pre-Silurian North Haven Greenstone of Penobscot Bay.

West of the map area, the Castine Volcanics overlie the Ellsworth Schist (Smith and others, 1907; Stewart, 1998). Pebbles of schist in the basal conglomerate of the Castine Volcanics suggest an angular unconformity (Stewart and Wones, 1974; Stewart, 1998). Late Cambrian ages of 503 ± 4 (Ruitenberg and others, 1993) and 502 ± 4 (R. D. Tucker *in* Stewart, 1998) have been determined for the Castine Volcanics, which is consistent with its interpreted position above the Ellsworth Schist.

INTRUSIVE ROCKS

Lamoine Granite Gneiss (SClg)

A foliated granite sill extends from Lamoine State Park to Lamoine Beach (SC). It is on the order of a hundred meters thick, carries the same fabric as the enclosing Ellsworth Schist, and dips moderately south (Figure 11). Quartz and feldspar crystals are uniformly several millimeters in diameter. Exposed surfaces weather light gray, and fracture surfaces are commonly very rusty. This sill is probably an intrusive equivalent of the extrusive rhyolites of the Ellsworth Schist. In particular, it may be a feeder for the Rhyolite of Goose Cove (Reusch and Hogan, 2002), which is exposed 7 km to the west-southwest (NN).

Undeformed greenstone dikes

Two examples of unstrained greenstone dikes which appear to truncate the main foliation of the Ellsworth Schist were identified in the Newbury Neck quadrangle, one at High Head, and the other at Weymouth Point. These dikes resemble the Ellsworth greenstones in their degree of metamorphism, but seem to postdate the main fabric development. North of Weymouth Point, the greenstone appears to truncate the main foliation. At High Head, the post-deformation age of a greenstone dike is less certain because it is a large, competent body in weak matrix. Possibly, these dikes were feeders for the weakly metamorphosed and little-deformed Castine Volcanics.

Gabbro of Thompson Island (DSgb)

A previously unmapped small gabbro body occupies the northwest half of Thompson Island (SC). It is equigranular and becomes diabasic in texture towards its margins. It is most likely related to extensive igneous rocks exposed nearby on Mt. Desert Island and is considered to be Late Silurian.

A small northwest-trending dike of undeformed diabase to gabbro is located in the tidal zone east and south of Crippens Brook (SC). It has a chilled margin against granite to the west. Its extensions have not been located either to the northwest or southeast.

Granite at Crippens Brook (Sgr)

A 200-meter-wide body of granite is poorly exposed on the west shore of the Jordan River south of Crippens Brook (SC). It is medium-grained equicrystalline granite and appears not to be deformed. Its northwestern contact trends northeast. McGregor (1964) and Osberg and others (1985) viewed this granite as a felsic layer in the Ellsworth Schist, but its relatively undeformed state suggests it may be Silurian-Devonian.

Timber Point dike (DOr)

A rhyolite dike several meters wide extends north-northeastward from Lamoine Beach to Timber Point (SC). Flow

Figure 11. Foliated granite of the Lamoine Granite Gneiss. *(East of boat ramp, Lamoine State Park)*

laminations are generally parallel to the margins and locally folded. It intrudes the Lamoine Granite Gneiss (Figure 12). This dike is the only candidate in the map area for a feeder to the large overlying granite mass on Mt. Desert Island. If so, then its age is Late Silurian.

Blue Hill pluton (Dge, Dgs, Dgl)

The Blue Hill pluton, at the western edge of the Newbury Neck quadrangle, comprises two varieties of coarse-grained syenogranite (**Dge, Dgs**). A related leucogranite sill (**Dgl**), capped with pegmatite, crops out on the west side of Morgan Bay, in Webber Cove and up the hill to the west. The pegmatite contains tourmaline and muscovite (Figure 13). It is on the order of tens of meters thick and dips gently southeast beneath Morgan Bay parallel to the main foliation of the Ellsworth Schist. Its contacts are sharp.

In the contact aureole of the pluton, pelitic layers of the Ellsworth Schist contain cm-sized andalusites (Figure 14), and small, elliptical shapes suggest possibly cordierite also. Outward from the pluton, the color of the Ellsworth Schist changes from gray above the biotite isograd to green in the chlorite zone below. Tourmaline is present near Browns Point. Heat from the pluton probably further dehydrated the overlying schists, but the abundant deformed quartz veins are clearly related to an event that predates the contact metamorphism.

Late dikes

Unmetamorphosed late dikes are uncommon. They are present in the Newbury Neck quadrangle at the north end of Morgan Bay, Browns Point, north of Alley Island (these three may be connected), and High Head, and in the Salsbury Cove quadrangle at Lamoine and the north end of the Skillings River. Most of these dikes are on the order of a meter wide. They have mafic to intermediate compositions and are fine-grained with chilled margins indicating high-level emplacement into cold rocks. Most dip steeply. The age of the dikes is inferred to be either Silurian-Devonian, associated with the large plutons of these periods, or Mesozoic, associated with rifting of the Gulf of Maine. Prior to mapping, I expected to find clear examples of granite dikes that fed the Mt. Desert Island magmas. The scarcity of granite dikes suggests that there might have been post-intrusion fault displacement in the intervening, largely submerged area.

METAMORPHISM

The contact aureole of the Blue Hill pluton overprints a low grade regional metamorphism that affects all the stratified rocks. The Ellsworth Schist is regionally metamorphosed to lower greenschist facies.

McGregor (1964) reports fine-grained biotite in thin section from the Egypt Member of the Ellsworth, and he considered the southern contact of the Egypt Member to coincide with the

Figure 12. Unmetamorphosed rhyolite dike of Timber Point with flow laminations (lower part of photo) intrudes rusty-weathering rocks of the Lamoine Granite Gneiss.

Figure 13. Pegmatite with black tourmaline and muscovite from the Blue Hill pluton. (*Photo 10 of Reusch and Hogan, 2002.*)

Figure 14. Andalusite porphyroblasts in pelitic rock of the Ellsworth Schist. In the contact aureole of the Blue Hill pluton. (*Photo 11 of Reusch and Hogan, 2002.*)

biotite isograd. Additional work is needed to test whether this is indeed the southern limit of biotite, and if so whether it is a true reaction isograd or merely a "first occurrence" isograd, reflecting a bulk composition in the Egypt Member with slightly higher Fe to Mg ratio, for example. Parts of the Egypt Member to the north of the map area include fine-grained black amphibolites, but the petrologic significance of these rocks is also uncertain.

The foliation in the Lamoine Granite Gneiss is defined by muscovite and chlorite, indicating that it was metamorphosed at greenschist facies together with the enclosing Ellsworth Schist.

STRUCTURAL GEOLOGY

The main fabric of the metamorphic rocks

The main fabric comprises several elements: compositional layers (quartz-rich vs. phyllosilicates), the main foliation (Hibbard, 1995) consisting of aligned phyllosilicate minerals, mineral lineation, small-scale folds, sigmoid-shaped quartz bodies, and S-C fabric.

The main foliation is almost everywhere parallel to the compositional layers. Nowhere was I able to discern a clear axial-planar relationship between aligned phyllosilicates and folded compositional layers, such as a high angle between the foliation and layers at fold hinges. The main foliation was therefore operationally measured on a plane parallel to either the schistosity in phyllosilicate-rich sections or the alternating quartz/feldpar-phyllosilicate layers. Bouley (1978) described a similar relationship in the Ellsworth Schist to the west of the map area. Tentatively, the metamorphic foliation formed prior to the small-scale asymmetric folds.

A mineral lineation is weakly to strongly developed within the plane of the main foliation. It is most clearly defined by elongate quartz crystals on the tops of metarhyolite sheets (Figure 15) and by trains of broken feldspars on the surfaces of some greenstones. In rhyolites, this lineation may also be expressed by trains of pyrite. In one outcrop near Heath Brook (NN), the pyrite has pressure shadows, with quartz extension fibers. In schists, quartz rods are present locally, some of which seem to be thickened very small-scale fold hinges. The lineation is generally poorly developed in the phyllosilicate layers.

In large areas of the Newbury Neck quadrangle, the main foliation dips gently southeast and the main lineation plunges gently southeast (Figure 16). In the Salsbury Cove quadrangle, these have been folded on a late east-northeast-trending antiform but initially seem to have had the same subhorizontal orientation (Figure 17).

Several elements of the main fabric are potential kinematic indicators. These include pervasive cm-scale, tight to isoclinal folds, sigmoid-shaped quartz veins, and S-C fabrics (present locally in quartzites) (Figure 18). The folds are most commonly developed in thin quartz laminations; again, it has not been possible to demonstrate an axial-planar relationship with the main foliation. The hinge lines, which are mostly at acute angles to the lineation, define a great circle (Figure 16) that is coincident with the main foliation. This spread of hinge lines around the lineation suggests random exposures through sheath folds. Vergence ranges from north through west to southwest, which is consistent with top-to-northwest kinematics.

Figure 15. Mineral lineation in the foliation plane of a rhyolite sheet in the Ellsworth Schist.

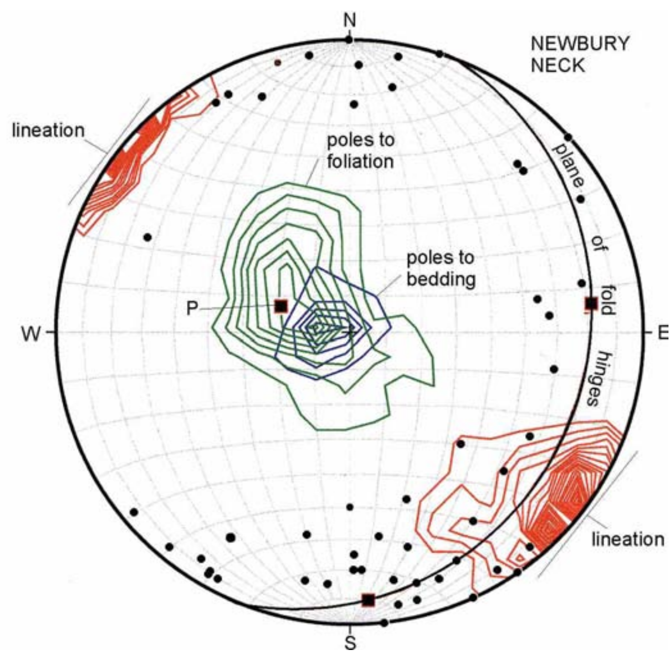

Figure 16. Orientation of structural elements in the Newbury Neck quadrangle. Poles to bedding are contoured in blue (N=81, contour interval 5% per 1% area). Poles to main foliation are contoured in green (N=198, C.I.=2% per 1% area). Main stage lineations are contoured in red (N=86, C.I.=2% per 1% area). Individual fold hinges, plotted in black dots (N=56), fall along a best-fit great circle whose pole (P) closely approximates the average pole to foliation. (All stereograms are lower hemisphere, equal area projections.)

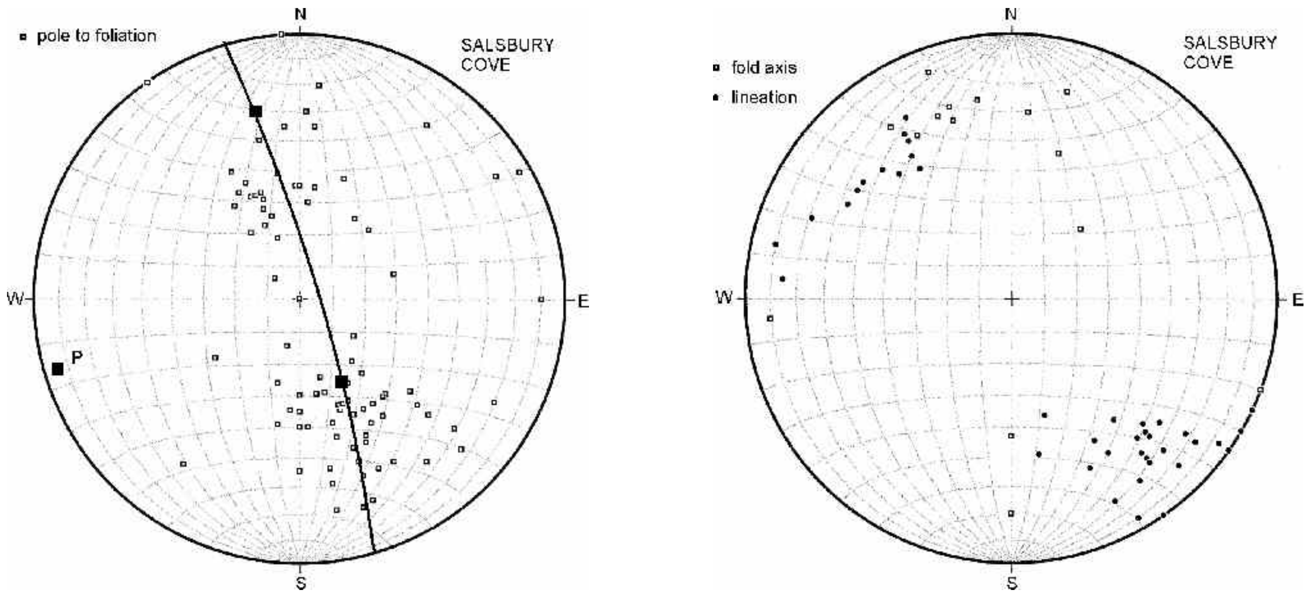

Figure 17. Orientation of main stage features in the Salsbury Cove quadrangle. A. Poles to main foliation (N=92). Best fit great circle has a pole at P, the approximate axis of the Trenton-Hancock antiform. B. Lineations (black dots, N=42) and minor fold axes (open squares, N=15) plunge gently to the northwest or to the southeast on opposite limbs of the antiform.

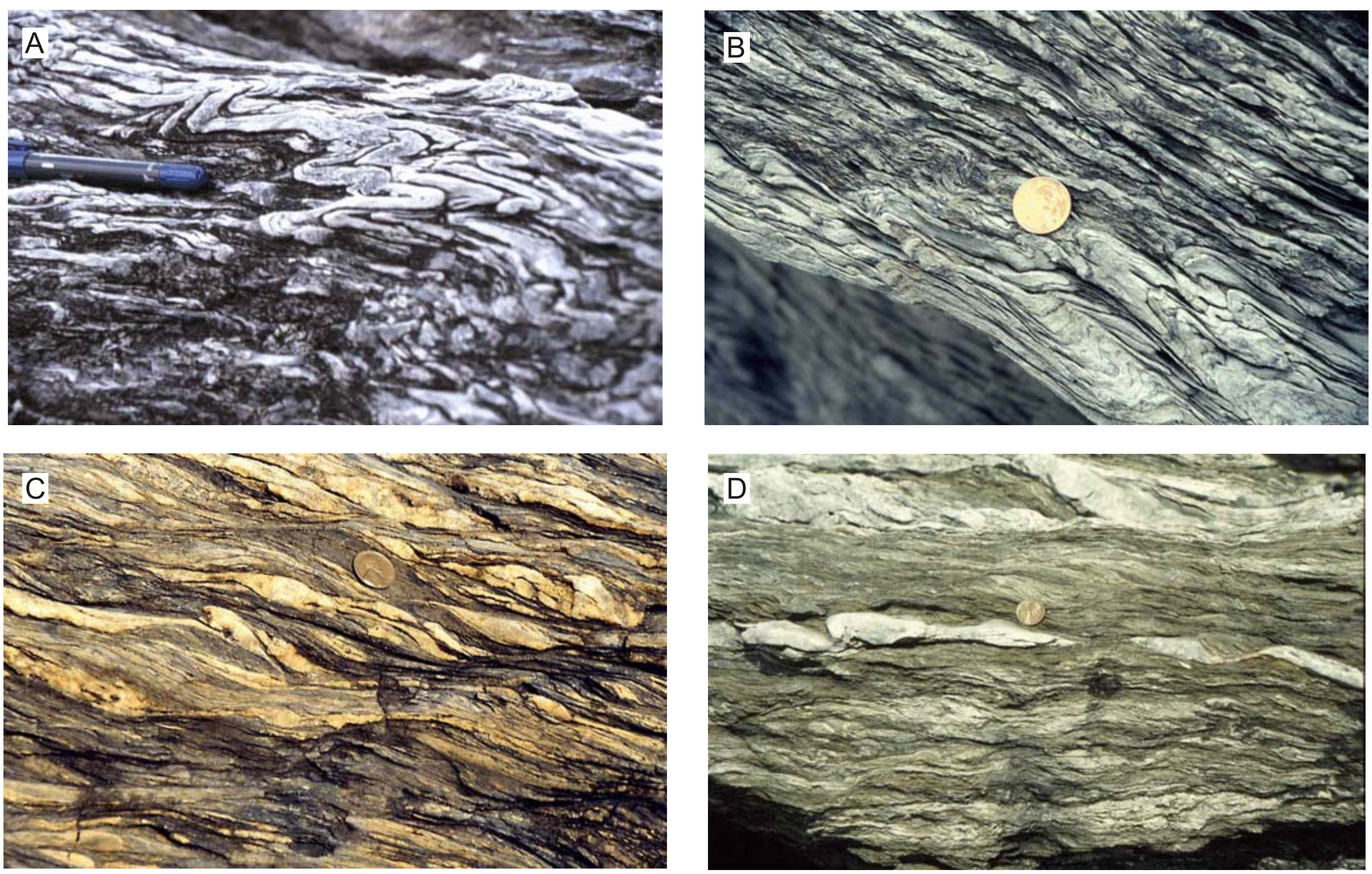

Figure 18. Kinematic indicators related to the main metamorphic fabric consistently show top-to-the-northwest movement. A. Asymmetric minor folds overturned to the northwest (right). B. Asymmetric folds overturned to the northwest (left). C. Asymmetric quartz veins in top-to-the-northwest (left) shear fabric. D. A single quartz layer is affected by folding and by step-up structure with consistent asymmetry. *(Bluff Point, NN)*

Figure 19. Minor fold in which the overturned limb has been thinned. This geometry may be similar to the larger-scale structure of the Newbury Neck quadrangle. *(Contention Cove, NN)*

Figure 20. Foliation surface showing two lineations. The main phase lineation trends northwest (parallel to the pen). The crenulation cleavage, which trends east-west, is well developed in the upper left and right-center parts of the photo. *(East of Contention Cove, NN)*

Sigmoid-shaped features, most commonly quartz lenses, step up to the northwest, consistent with the asymmetry of the folds (see photo of same quartz layer affected by fold and step-up) (Figure 18D). The S-C fabrics in quartzites agree with these kinematics. Small-scale structures, especially folds, are locally well-developed along the contacts between igneous sheets and adjacent schist, presumably due to a competency contrast.

Northeast-striking extensional quartz veins in metarhyolite sheets may have formed after the peak or towards the end of the main deformation event. They clearly cut the main fabric, but seem spatially related to it. Locally, the conjugate fractures intersect at a small angle and are nearly perpendicular to the extension direction, which suggests low lithostatic pressure and a high structural level (Twiss and Moores, 1992, p. 175).

Two occurrences of mélange, one on High Head and the other just north of Curtis Cove (NN), consist of greenstone blocks in pelitic matrix. These occurrences indicate intense deformation and large ductility contrast, features typical of accretionary complexes, though not diagnostic. The thinned overturned limb on a small-scale fold north of Patten Bay (Figure 19) may be a geometrical model for a much larger-scale nappe structure.

The overall character of the main deformation implies shortening and thickening and suggests an accretionary wedge setting. Local mélange development and abundant quartz veins are consistent with this tectonic setting. Strongly deformed metamorphic layers and quartz veins indicate continued movement following the achievement of greenschist conditions, irrespective of whether these conditions were caused by primary hydrothermal activity, sedimentary burial, or tectonic burial. Inherently reactive materials are likely to have promoted this metamorphism. An independent metamorphic event most likely related to Silurian magmatism caused the equigranular-polygonal textures within quartz-feldspar laminations.

Crenulation cleavages were noted locally, but their significance is unclear. On Burnt Point (NN), a locally-developed crenulation cleavage, which is axial planar to folds with southeast-dipping limbs, seems to be kinematically related to the main fabric. In the Skillings River area (SC), a crenulation cleavage is locally developed; it is a spaced cleavage with microlithons several millimeters thick, and dips gently northeast. Heterogeneous development of crenulation intersection lineation on foliation surfaces are common (Figure 20).

Late folds

The main fabric is affected by a variety of late folds that are not penetrative and are generally difficult to interpret.

Meter and larger-scale southeast-vergent folds are present in a few locations, such as the west-central shore of Newbury Neck. These "backfolds" are more open and larger-scale than the main generation folds. On the southeast shore of the Skillings River (SC) near the eastern edge of the map area, however, the style of southeast-vergent folds is not significantly different from those of the main generation.

The Trenton-Hancock antiform was first identified by McGregor (1964). Its subhorizontal axis trends roughly east-west through Hancock Point (just east of the study area) and the Lamoine and Trenton peninsulas; it may loosely connect with the antiform at High Head (NN). The Trenton-Hancock antiform is several kilometers wide, is open and upright in the Salsbury Cove quadrangle and becomes more asymmetric to the southwest in the eastern Newbury Neck quadrangle, where it has a moderately-dipping southeast limb and gently-dipping northwest limb. The late folds at High Head include a complex series of NNE-trending antiforms and synforms. For example, northwest of Curtis Cove, the main foliation dips and the lineation plunges anomalously northwest. In this area, the crumpling is

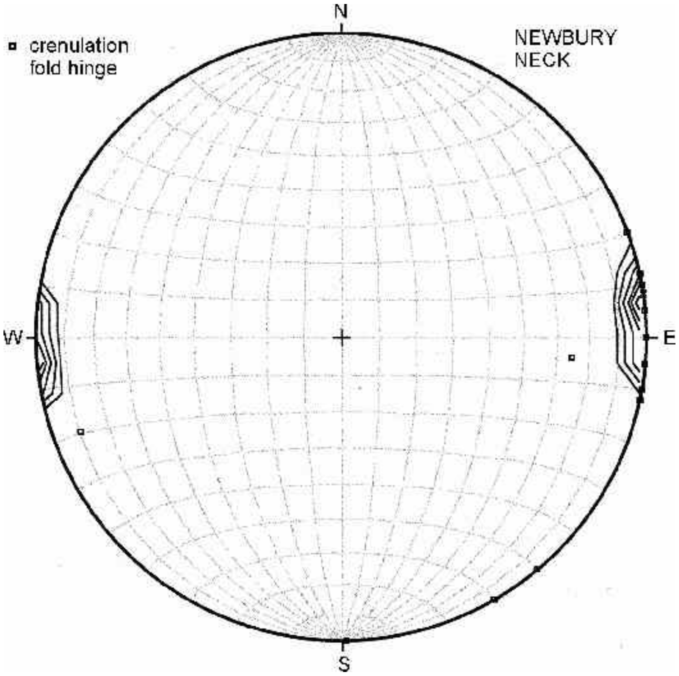

Figure 21. Orientation of hinge lines of crenulation folds (N=32) in the Newbury Neck quadrangle. Contour interval is 10% per 1% area.

localized to a zone approximately ½ km wide. Meter-scale asymmetric folds weather prominently with narrow spines between flat limbs; the hinge lines are anastomosing in plan view.

Crenulated phyllosilicates, common throughout the map area, are most obvious when viewed normal to the main fabric. Most hinge lines trend east-west (Figure 21), which suggests a relationship with the larger-scale late folds; locally, more than one set of crenulations is present. At Contention Cove (NN) and at several other sites, conjugate sets of asymmetric kinks afford the possibility of inferring the paleostress orientation. Still other sets of late folds describe symmetrical, open "crumples." Finally, subtle broad, map-scale "warps" are recognized by slightly different orientations of the main fabric; despite a similarity in style, these have no obvious relationship with the crumples.

Late faults

Late, brittle faults are present in a few places in the map area. They almost certainly formed at a high level in the crust and are probably the youngest structural features in the area.

On the shoreline northwest of Alley Island (NN), slickensides indicate top-to-west movement on a southeast-dipping thrust fault. At Weymouth Point (NN), numerous anastomosing steep faults trend approximately east-west to north-northwest (Figure 22). McGregor (1964) independently noted these faults. They provide some of the justification for proposing a late east-west fault through Patten Bay. The other argument for this fault relies on apparently truncated isograds of the Blue Hill contact aureole.

A few hundred meters north of Heath Brook (NN), along a northeast-trending fault (030, 60SE), beds are displaced in a normal sense. This fault and similar ones north of Weymouth Point (Figure 22) and in Morgan Bay may be associated with Gulf of Maine rifting in Mesozoic time. Minor north-trending late faults are inferred in Raccoon Cove and Berry Cove to explain left-lateral offsets of the Trenton-Hancock antiform.

SPECULATIONS ON A GEOLOGIC HISTORY

The oldest information-carrying materials are pebbles in the conglomerate of the Morgan Bay Member. They are felsic igneous rocks similar to ones found in other parts of the Ellsworth Schist, although conceivably they might have been eroded from some unexposed Ellsworth basement.

As the contact relationships among mapped units are highly uncertain, the following scenario should be considered highly speculative. Possibly, the Egypt member is allochthonous on the undifferentiated Ellsworth Schist based on its slightly higher metamorphic grade and the intense deformation near the contact. If so, then the entire package, Morgan Bay member included, may represent a sedimentary-volcanic margin that faced southeast. The Morgan Bay Formation contains the coarsest sediment, albeit a single conglomerate and several quartzite beds. The Egypt Member may have accumulated in the most distal position as suggested by its lower QF:PS ratio (1-1.5) compared to typical Ellsworth Schist (around 2) and its near absence of felsic igneous rocks. The Lamoine Granite Gneiss intruded the Ellsworth Schist as a high-level pluton while the Rhyolite of Goose Cove erupted and became interstratified with the schist. Regionally, if the Ellsworth Schist underlies, rather than grades laterally into, the North Haven Greenstone, then a deepening and widening-

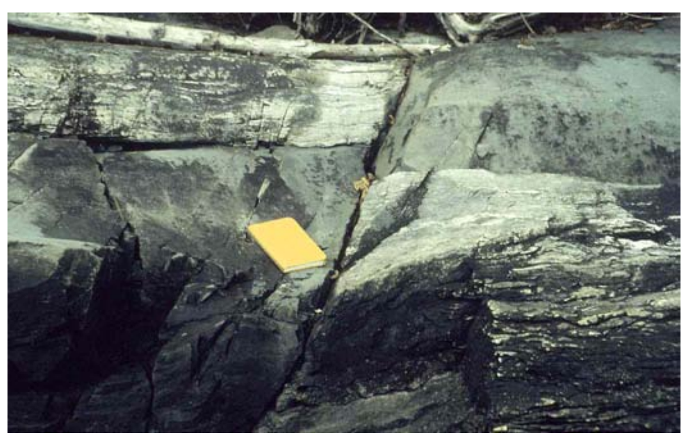

Figure 22. Greenstone sheet cut by high angle normal fault. Fault is oriented N65E, 65 SE (view toward the southwest). *(Photo 9 of Reusch and Hogan, 2002)*

upwards facies sequence would be indicated, with the Ellsworth Schist recording the initial rifting event.

The main fabric of the Ellsworth Schist has been ascribed to a thrusting event (Hibbard, 1995; also, Osberg and others, 1985) that would have telescoped the Morgan Bay-Ellsworth-Egypt margin. The greenschist minerals formed in response to burial either at the base of a many kilometer-thick, warm volcano-sedimentary pile or thrust stack. The regional metamorphism and deformation may be broadly contemporaneous because metamorphic features such as quartz veins are clearly deformed yet greenschist facies minerals define the main fabric.

The mineral lineation formed parallel to the northwesterly transport direction, and, if the sheath fold interpretation is correct, initially perpendicular small-scale fold hinges rotated towards the transport direction. Abundant small-scale folds demand horizontal shortening and vertical thickening as do the sigmoid step-up structures and S-C fabrics. Extensional veins in competent rhyolite layers formed nearly perpendicular to the transport direction; the low angle between conjugate fractures suggests a high level in the crust. This was likely a protracted event, and local crenulation cleavage and southeast-vergent backfolds may reflect late stages of a single top-to-northwest orogenic event.

The timing of thrusting and metamorphism was pre-Middle Silurian based on a probable unconformity on North Haven Island (Smith and others, 1907; Gates, 2001). Conceivably, the timing could have been contemporaneous with the youngest Tremadocian rocks in the adjacent St. Croix terrane, in which case this event marks the local expression of the Penobscot orogeny (van Staal and others, 1998). If, however, sedimentation was continuous in the St. Croix terrane through the Caradocian Kendall Mountain Formation, then the two terranes were not juxtaposed until the Late Ordovician.

During Late Silurian time, the region became the site of arc magmatism above a subduction zone that dipped either southeast (Bradley and others, 2000) or northwest (McLeod and others, 2001). In the latter view, the strong thermal overprint at this time, especially west of Penobscot Bay, reflects high heat flow in an arc environment rather than regional metamorphism in the roots of an orogen. The Timber Point rhyolite dike and the gabbro of Thompson Island could be of this age. Stewart (1998) has demonstrated that steep faults in Penobscot Bay were contemporaneous with the Late Silurian igneous rocks.

More granitic magma was intruded during the Devonian. At this time, the contact aureole around the Blue Hill pluton was imprinted on the Ellsworth Schist.

The late folds are post-Late Silurian if they correlate with similarly-oriented folds in the Ames Knob Formation on North Haven Island. Hibbard (1995) related these to sinistral displacements on the Ellsworth-St. Croix boundary fault because they appear to increase in intensity towards the fault and indicate north-south compression (which would cause sinistral slip on a northeast-trending fault).

Evidence for dextral strike-slip related to the Norumbega fault was not recognized. Late normal faults and mafic dikes, if not associated with earlier magma systems, may be related to extension in the Gulf of Maine/Bay of Fundy rift during the Mesozoic, followed by less than a few kilometers of erosion to the present.

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