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Title: Bedrock Geology of Small Point, Maine: A Fresh Look at the Stratigraphy, Structure, and Metamorphism

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**Cover Credit**

The cover photograph is by Arthur M. Hussey II, to whom this guidebook is dedicated. Arthur Hussey was an accomplished photographer and his numerous photo collections highlighted many aspects of the natural beauty of southwestern Maine. The photo was taken by Arthur at a location about a kilometer south of Lookout Point along the western shore of Harpswell Neck. Arthur first began mapping in this area in 1962, and his 1965 NEIGC field trip visited exposures nearby. The view in the photo is towards the south and the exposures are east-dipping metamorphosed Ordovician volcanic rocks of the Cushing Formation. Arthur's hammer for scale.

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BEDROCK GEOLOGY OF SMALL POINT, MAINE:
A FRESH LOOK AT THE STRATIGRAPHY, STRUCTURE, AND METAMORPHISM

By

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DEDICATION

This trip is dedicated to Professor Arthur Hussey for his lifetime of geologic mapping in Maine, his collegiality
and willingness to share those geologic insights, and his constant reminder to legions of students that all geologic
research starts with sound field observation and attention to detail. We will miss Art and know his legacy of
contributions to the New England geologic community and Maine geology will live on. Eusden would also like to
thank Heather Doolittle, Peter Miller, Jen Lindelof and Haley Sive, all alumni of Bates Geology class of 2012, for
their excellent work in remapping the bedrock geology of Small Point. Thanks also to Maine State Geologist Robert
Marvinney and Henry Berry for supporting this USGS EdMap project.

The mapping crew at Icebox beach, from L to R: Art Hussey, Heather Doolittle, Peter Miller, Haley Sive, Henry
Berry, and Jen Lindelof.
INTRODUCTION

This field trip will examine the Ordovician stratigraphy and Silurian through Permian deformation and metamorphism along the spectacular coastal outcrops of Small Point, Maine. There is one moderate walk along dirt roads and the coastline of about 2.5 miles and three other easy walks of about a mile each. All of the stops are on private land that is very strictly controlled and posted. Figure 1 shows the location of Small Point and the stops for the field trip.

The stratigraphy we present here is a revision of that originally proposed by Arthur Hussey and most recently updated by him in 2012 (Hussey, 2012). Figure 2 shows Hussey's 2012 bedrock geologic map. Our interpretation differs from his in that we mapped the rocks at Small Point as an east younging, structurally overturned section without significant stratigraphic discontinuities. The structural geology was studied well by Hussey and Berry (2002) and Swanson and Bampton (2009). Our five stage structural model for the deformation blends aspects of both previous researchers and focuses on D3 regional folding event and D4 dextral shearing along the Phippsburg Shear Zone. Hussey and Berry (2002) and Grover and Lang (1995) studied the metamorphism at Small Point and the latter pair visited our last stop on their own NEIGC trip. Our interpretation of the metamorphism focuses on the isograd pattern of M3 metamorphism and an older M2 metamorphism with relict mineral assemblages and textures.

Our work to remap the bedrock geology of the Small Point region was a USGS EdMap project supported by the Maine Geological Survey and completed during the field season of 2011. Four Bates students, Doolittle, Lindelof, Miller, and Sive, all participated in the bedrock mapping and then each did a full year senior thesis on a specific aspect of the geology (Doolittle, 2012, metamorphism; Lindelof, 2012, rock-water geochemical interactions; Miller, 2012, Phippsburg Shear Zone and Sive, 2012 geologic map). Tim Grover has joined us on this field trip to offer his insights on the metamorphism as well as the overall geologic setting in a region where he has spent numerous field seasons of mapping.

REGIONAL GEOLOGIC AND TECTONIC SETTING

The bedrock at Small Point is composed of the Middle to Late Ordovician Casco Bay Group, part of the regional Merribuckfred Basin that was deposited on peri-Gondwanan basement in an active plate setting, presumably an arc, of poorly constrained plate geometry (Hussey et al., 2010). The traditional units of the Casco Bay Group are, from oldest to youngest, the Cushing, Cape Elizabeth, Spring Point, Diamond Island, and Scarborough Formations. Figure 3 shows a possible plate tectonic reconstruction for the Casco Bay Group from Hussey et al. (2010) and two stratigraphic correlation charts, one for Maine and New Hampshire (Hussey et al., 2010) and the other for the rocks we mapped at Small Point. We have chosen to use local geographic names (e.g., Aliquippa, Cape Small, etc.) for the revised stratigraphy shown in Figure 3C.

Subsequent to the deposition and eruption of the Casco Bay Group onto a Ganderian fragment, the rocks were impacted by the numerous orogenic cycles. The first was the Early Silurian Salinic Orogeny as the Tadouche-Exploits basin closed reuniting two wayward pieces of Gander (Reusch and van Staal, 2012). This was then followed by an early Acadian Orogenic phase in the latest Silurian as the leading edge of Avalon collided with composite Ganderia (Bradley et al., 2000), and in turn was followed by a later phase of the Acadian (Early to Middle Devonian?) as the oblique collision continued (Hussey et al., 2010). In the Late Devonian to Early Carboniferous, Meguma obliquely collided with everything else to the west initiating the Neo-Acadian Orogeny characterized by dextral strike slip motion along the expanding Norumbega Fault Zone (Swanson, 1999). The culminating Pangea-forming Paleozoic collision was the Alleghanian Orogeny in the Permian when Gondwana collided obliquely with the rest to the west (Wintsch et al., 2014). In the Triassic and Jurassic continental breakup began as Pangea rifted apart. To widely varying degrees, all of these events have left both deformational and/or metamorphic imprints on the rocks at Small Point.

STRATIGRAPHY

Our new bedrock geologic map is shown in Figure 4. We have interpreted the metasedimentary units as younging to the east but overturned in the inverted limb of an early D1 or D2 nappe-scale fold with poor structural control. Though there are preserved primary bedding features in many places, typified by interbedded schists and
Figure 1. Location of the Small Point area, Maine. The third panel from the left shows the entire Small Point 7.5 minute quadrangle and the lower GoogleEarth image shows the region covered by the trip, the numbered STOPS, parking locations for each STOP, and walking routes as red lines. Roads shown as white lines.
Figure 2. A) Regional geologic setting of the Casco Bay Group from Hussey et al. (2010). Small Point region shown in box. B) Bedrock geologic map and legend (C) of Small Point, Maine by Hussey (2012).
**Figure 3.**

A) Correlation chart of stratified units in Maine and New Hampshire from Hussey et al. (2010). B) Stratigraphic correlation of units mapped by us at Small Point to the Casco Bay Group of Maine. C) Possible Ordovician plate tectonic setting for the Casco bay Group from Hussey et al. (2010).
quartz-rich granofels, there was only one convincing topping indicator; a reversed (via metamorphism), inverted, graded bed (STOP 5). This lack of topping control makes lithologic correlation to other sections of the Casco Bay Group the only way to establish stratigraphic order. The new stratigraphy uses local names that we have correlated to the traditional formational names in the region. Nearly all of the contacts between the units are somewhat gradational. From oldest to youngest the stratigraphy consists of the following units:

Cape Small Formation with its two main members, the Cape Small Silver Schist and the Cape Small Rusty Schist. These units are all correlated to the Cape Elizabeth Formation.

*Cape Small Silver Schist* (Ocsss), a schist with the submembers *Singing Sands Schist* a staurolite-rich silver schist (Ossss) and the quartz-rich granofels member (Ocsss-g). Thin calc-silicate units are infrequently found throughout these units.

*Cape Small Rusty Schist* (Ocsrs), a deeply rusty weathering schist and with numerous interlayered horizons of *Icebox Amphibole-rich Calc-silicate* (Oiacs).

Aliquippa Formation a moderately rusty weathering schist (Oars) with members *Aliquippa Amphibolite* (Oaa) and *Aliquippa Marble* (Oam). These units are correlated to the Spring Point Formation.

Graphitic Phyllite (Ogp), a black, rusty weathering, phyllitic schist that is correlated to the Diamond Island Formation.

West Marsh Formation with its six different members that are all correlated to the Scarboro Formation. *West Marsh Rusty Schist* (Owmrs), *West Marsh Schist* (Owms), *muscovite-rich West Marsh Schist* (Owms-m), *garnet-rich West Marsh Schist* (Owms-g), *West Marsh Amphibolite* (Owma), and *West Marsh Granofels* (Owmg).

The West Marsh Formation is found in the northeast portion of the map (Fig. 4). This is one area where our map differs significantly from Hussey's 2012 map (see Fig 2B). He correlated most of these rocks to the Cape Elizabeth Formation (Oqs on Fig 2C). Our recognition of the granofels and amphibolite members within the *non-rusty schists* of the West Marsh Formation makes this section very different lithologically from the Cape Small Formation that both Hussey and us agree are correlative to the Cape Elizabeth Formation. Amphibolites and calc-silicate granofels in the Cape Small Formation are typically within deeply rusty weathering schists. Juxtaposition of the West Marsh Formation against the Graphitic Phyllite (yellow unit in the middle of the map, Fig. 4), a very good correlative to the Diamond Island Formation, further justifies our interpretation. Our interpretation that there are several different amphibole-rich calc-silicate units in the Cape Small Formation at Ice Box Beach (Oiacs on Fig 4) is also significantly different from Hussey (2012) who interprets these as a single unit repeated by isoclinal folding (Obc on Fig 2B). The different outcrop expressions and internal characteristics of the units led us to believe these were different horizons. We also did not find any evidence of early, macroscopic, isoclinal fold hinges that would repeat these units, supporting our interpretation of a more complex stratigraphy and simpler structure. The remainder of our map (Fig 4) and Hussey's 2012 map (Fig 2B) are quite similar in both shape and stratigraphic correlation, give or take a few structural details here and there.

**STRUCTURAL GEOLOGY**

The history of deformation at Small Point is complex and multi-phase. All previous researchers have recognized this and we offer here a revision to the deformation sequence by combining our observations with those of Hussey (Hussey, 1988 and 2012; Hussey and Berry, 2002) and Swanson (Swanson, 1999; Swanson and Bampton, 2009). We interpret the deformation as having formed in a 5-stage model, D1 through D5.

**First Deformation - D1**

D1 is characterized by a penetrative early S1 schistosity and very rare F1 isoclinal folds of relict bedding (S0). Though the timing is poorly constrained, this deformation event seems most likely to be related to the Salinic orogeny sometime in the early Silurian.
Figure 4. New bedrock geologic map and cross sections of Small Point, Maine. *1 STOP locations
Second Deformation - D₂
D₂ is characterized by a second penetrative schistosity, S₂, and fairly common, but infrequent F₂ isoclinal folds of especially metamorphic quartz veins, S₁ schistosity, and less so relict bedding (S₀). S₂ schistosity is seen cutting S₁ schistosity in many thin sections from Small Point and we will hopefully see it in outcrop at STOP 5. Hussey (1988) recognized these two structural fabrics referring to them as F₁ and F₁ₐ. As with D₁, the timing of D₂ deformation is poorly constrained and hypothesized to be part of the earliest Acadian Orogeny in the latest Silurian. The deformation created by the combined effects of D₁ and D₂ most likely produced what we interpret to be an overturned stratigraphy, albeit poorly constrained by one graded bed.

Third Deformation - D₃
D₃ folding in turn strongly deforms the earlier fabrics and is characterized by widespread folding at the meso and macro-scales. Most folds that you will see on the trip are of D₃ age. Four macro-scale folds are easily recognized by regional changes in the attitude of the composite fabric S₀/S₁/S₂. From east to west the macroscopic folds are: Seal Island antiformal syncline; Cape Small synformal anticline; Head Beach antiformal syncline; and Hermit Island synformal anticline. The fold form of these macro-scale structures changes progressively from tight, upright folds in the north (cross sections A-A’ and B-B’ Fig 4) to broad, open to gentle folds in the south (cross section C-C’ on Fig 4).

All mesoscopic folds, with a few exceptions, plunge gently to the south (ave. F₃ trend and plunge = 188, 28) with predominately west, but many east, steeply dipping axial surfaces striking N-S (ave. S₃ axial plane = 181, 71). The axial plane is defined by a spaced S₃ cleavage and rarely a weak S₁ schistosity. Meso-scale folds are quite variable in their distribution and intensity in the Small Point area. In general the most abundant meso-scale folds occur in trains with 3-4 anticline crests per every .5 meter. These zones of abundant F₃ folds are mostly limited to the Cape Small Formation and especially the Cape Small Silver schist (Ocsss), which we will see at STOPS 4 and 5. This is in stark contrast to the fold density of the West Marsh Formation where few if any meso-scale F₃ folds are found. We speculate that these units may exhibit different multilayer rheologic properties where the West Marsh Formation, with mostly just massive schist and no rigid interbeds, folds less, and the Cape Small Formation, with thin rigid interbedded quartz-rich granofels and garnet coticule layers in the schists, folds the most.

Hussey’s (2012) map of the Cape Small synformal anticline (Fig 2B) is nearly identical to ours (Fig. 4), however our map pattern of the other three macroscopic D₃ folds differs in location of the axial traces. The other major difference between our map and Hussey’s (2012) is his use of multiple D₃ macroscopic fold hinges on the east side of Small Point near STOP 3. In these places Hussey (2012) connects his units Oma, Ogr, Ors, and Obc (see Fig 2B) together with isoclinal hinges that are shown folding around either underwater or in thick woods with little outcrop and thus poor control. Because we did not see any evidence for D₃ macroscopic fold hinges, we favor a more complex stratigraphy with fewer repetitions by folding in an overall less complex structure dominated by D₃ macroscopic folding. The age of D₃ is poorly constrained but likely records the culminating effects of the Early to Middle Devonian Acadian Orogeny.

Fourth Deformation - D₄
D₄ is restricted to the western part of Small Point and in particular Hermit Island. It is part of the Phippsburg Shear Zone, a dextral-oblique, ductile transitioning to brittle, shear zone that is probably a splay off of the Norumbega Fault. Figure 5A shows a structural model for the entire shear zone width in the vicinity of Small Point. As one moves west across Small Point and approaches Hermit Island, the composite fabric S₀/S₁/S₂ changes orientation from that dominated by D₃ folding (with both east and west dips of S₀/S₁/S₂), to an east-only dipping domain of S₀/S₁/S₂ at Hermit Island (STOP 6). The boundary between dip domains is sharp and shown on Figure 5C. A south plunging quartz rod lineation, some exhibiting sheath fold-like properties, also increases in intensity as one approaches Hermit Island and the east dipping S₀/S₁/S₂ domain.

Open and gentle D₃ folds transition to tight to isoclinal folds with a stronger S₃/S₄ axial plane schistosity in the shear zone. In places west of Hermit Island (e.g. STOPS 4 and 5) mineral lineations defined by aligned sillimanite, quartz, and mica, parallel to F₁ hinge lines fill the gaps between pieces of boudined andalusites. This may record the transition from D₃ to D₄ as hinge parallel extension possibly related to regional extrusion begins (Swanson and Bampton, 2009). A structural model showing the transition from D₃ to D₄ is shown in Figure 5B.
Figure 5. Structural geology at Small Point. A) Phippsburg Shear Zone model showing regions of varying shear strain and deformation. B) Deformation model for Hermit Island showing $D_3$ through $D_5$ deformation. C) Dip domain map of $S_0/S_1/S_2$ at Hermit Island. Red lines show east dipping domain defining the edge of the Phippsburg Shear Zone. D) Shear strain map calculated from rotated granitic veins intruded initially orthogonal to $S_0/S_1/S_2$. E) Region of crustal extrusion indicated by the large single arrow pointing south (Swanson and Bampton, 2009). Regional, south plunging, $D_3$ folds and subsidiary shear zones are linked to a restraining bend on the dextral Norumbega Fault Zone (bold black line). F) Swanson’s (1999) model for dextral rotation and folding of granitic and quartz veins which were initially orthogonal to shear zone foliation. S-shaped folds with boudined limbs are produced by dextral shear.
Shear strain values, as measured using quartz and granitic veins that were emplaced orthogonal to S₀/S₁/S₂ and then dextrally rotated, range from zero in the west to shear strain values of 5-10 at Hermit Island. A map of shear strain values for Hermit Island is shown in Figure 5D. These veins and intrusions are now oblique by about 20° to S₀/S₁/S₂ and exhibit excellent forward rotated boudinage. Dextral kink bands infused with tourmaline (schorl) mineralization accompanied the intrusion and formed during rotation of the granitic veins. Enigmatic S-shaped folds of some of these granitic veins developed by dextral rather than sinistral shear as the veins rotated through the shortening field and then became extended and boudined. A model of how this might work from Swanson (1999) is shown in Figure 5F. As exhumation progressed during shearing, late stage, bookshelf style, sinistral brittle faults developed in some of the granites, again in an overall dextral strain regime. Taken together these D₄ structures record a continuous and protracted period of ductile to brittle-ductile to brittle, dextral shearing during exhumation.

We support the transpressional model presented by Swanson and Bampton (2009) and shown in Figure 5E calling for crustal scale extrusion of a midcoast block bounded on the west by the dextral Phippsburg Shear Zone and on the east by the sinistral Pemaquid Shear Zone. We offer a wrinkle to this model and suggest that at least the tail end of the shearing was transtensional. This is supported by the overall dextral motion, the east dipping domain of the S₀/S₁/S₂ shear zone fabric, and the south plunge of the shear zone quartz rod lineations. These suggest a kinematic model dominated by strike slip but with a subordinate normal component of dip slip created by transtension (see Fig 5B cartoon d). Though poorly constrained, D₄ shearing most likely began at the very end of the Acadian Orogeny, and continued through both the NeoAcadian (Late Devonian-Carboniferous) and Alleghanian (Permian) Orogenies. Hussey (2012) does map a shear zone at Small Point but not at Hermit Island. His zone of "highly deformed rocks" lies to the east near the Sprague Marsh (Fig 2B). This shear zone has no kinematic information reported and is drawn based on map-scale truncations of units. We did not see evidence to support this shear zone.

**Fifth Deformation - D₅**

D₅ is characterized by a late brittle fault seen north of Icebox Beach (thin red line near STOP 3 on Fig. 4) and is probably associated with normal faulting perhaps at the end of the Alleghanian (Permian) and into the initial breakup of Pangea in the Triassic. There is truncation of the amphibolite-calc-silicate units in the Cape Small Rusty Schist and widespread development of cm-scale crenulations (axial plane of 193°, 15°; hinge line trend and plunge of 196°, 9°). The relationship between D₄ shearing and D₅ faulting associated with these crenulation is unclear as they appear in geographically separate areas. Hussey (2012) maps similar late faults in the same region though with a different spatial pattern, and another late fault he named the Phippsburg Fault near Head Beach that we did not see.

**METAMORPHISM**

Two Buchan-style (low P, moderate T) metamorphic events, M₂ and M₃, have been found in the area (Dunn and Lang, 1988; Lang and Dunn, 1990; Grover and Lang, 1995). M₁ has been reported by West et al. (2008) and Guidotti (1989) in coastal and western Maine, but not found by us at Small Point. D₁ is probably synchronous with M₁, M₂ and D₂ are synchronous, and D₃ develops before M₃, which is synchronous with D₄. A schematic PT diagram showing the path of metamorphism linked with the deformation at Small Point is shown in Figure 6D.

**M₂ Event**

The first of these metamorphic events at Small Point (M₂) occurred during D₂ isoclinal folding in the Early Acadian Orogeny and developed the dominant S₂ foliation defined by an early biotite + muscovite foliation and inclusion-rich, poikiloblastic garnet cores. Relict staurolite-andalusite grade assemblages typify M₂ in the entirety of Small Point, and as such no isograd maps can obviously be made. Pseudomorphs of M₂ andalusite by M₃ muscovite and inclusions of relict M₂ staurolites preserved as inclusions in the larger M₃ andalusites are the typical manifestations of the M₂ staurolite-andalusite grade. M₂ has been strongly overprinted by M₃, which is slightly higher in metamorphic grade. The M₂ biotite foliation, S₂, is clearly folded by D₃ establishing its pre-D₃, syn-D₂ relative order in the sequence of geologic events at Small Point. Grover and Lang (1995) and Hussey and Berry (2002) previously recognized M₂.

**M₃ Event**

The next event (M₃) was syn-D₄ shearing (Phippsburg Shear Zone) in the NeoAcadian and Alleghanian Orogenies and shows a second generation of less to non-foliated biotite and muscovite, clear garnet rims, fresh staurolite
Figure 6. Metamorphism at Small Point, Maine. A) Isograd map from Hussey and Berry (2002) showing staurolite-out isograd and migmatite front. Small Point region is outlined by the box. B) Isograds and mineral assemblages in the Harpswell-Small Point region by Grover and Lang (1995). All of their samples in the Small Point region are in the sillimanite zone with the assemblage Grt+Bt+Sil+And+/-St. Box shows the Small Point area. C) Our isograd map for the Small Point region. We refined the position of the M3 staurolite-out isograd and drew the M3 andalusite-out isograd. M1 assemblages are all within the andalusite-staurolite zone and variably overprinted by M3, STOPs = *1. D) Possible P-T path and metamorphic reactions with phases of deformation D1-D4 and metamorphic events M1-M3, labelled along the path. Phase boundaries from Theriak Domino.
showing a later staurolite out reaction, $F_3$ hinge parallel fibrolitic sillimanite filling between boudined andalusite, and fibrolite pseudomorphic lenses of $M_2$ and/or $M_3$ staurolite or andalusite. $M_3$ sillimanite is present in all thin sections we studied which is why Grover and Lang (1995) placed the entire $M_3$ assemblage at Small Point in the sillimanite zone (Fig 6B). We were able to map three $M_3$ metamorphic zones: a staurolite+andalusite+sillimanite zone (Zone I) terminating against the staurolite-out isograd; an andalusite+sillimanite zone (Zone II) stopping at the andalusite-out isograd; and a sillimanite zone (Zone III). The isograd map for Small Point (Fig 6c) shows the grade increasing from the SW to the NE, towards the map-scale Morse Mountain granite in the northeast. This compares well to the map shown by Hussey and Berry (2002) with the exception that they did not map the andalusite+sillimanite zone and andalusite-out isograd (Fig 6A).

**DRIVING AND WALKING LOG FOR STOPS**

**MEETING POINT FOR TRIP:** (43.745037°, -69.837317°) 8:00 am at the Bates-Morse Mountain Public Parking Lot. From Bath, drive south on Rte. 209, continue straight on Rte. 216 at the left turn to Popham Beach (Rte. 206 veers off to the left) and drive .8 miles where you take a left on Morse Mountain Road (dirt) to the nearby parking lot .1 mile down the road. Assemble here for an overview of the trip and logistics. Please pack your lunch and water as there are no options to pick up food along the trip. There are no bathrooms except at the very last stop at Hermit Island in the mid-afternoon. Ticks and poison ivy are prevalent and the best strategy is to cover up with long pants and long sleeve shirt. Though the driving distance for this trip is only about 3 miles, the cumulative walking distance is about 5 miles along trails, the slippery intertidal region, and rugged rocky coastline. We will need to consolidate vehicles here as well.

**Mileage**

- **STOP 1 – Sprague Marsh:** (43.743299°, -69.832685°; 1 hour)

  **Stratigraphy:** The upper section of the stratigraphy is exposed here in low woods outcrops with poison ivy and mosquitoes. There are no topping controls here and in most of the quad (we will show you THE one graded bed we found later in the day!) so the stratigraphic order is by correlation to other known sections. Exposed from youngest to oldest and east to west in a structurally inverted (?) section are the following: West Marsh Granofels (Owmg); West Marsh Amphibolite (Owma); West Marsh Garnet-ric Schist (Owms-g); Mica-rich West Marsh Schist (Owms-m); and West Marsh Schist (Owms). All contacts are gradational and a few scattered, undeformed pegmatites, granites, and/or aplites of the Morse Mountain Granite are found across the causeway to the east.

  The three varieties of West Marsh schist could easily be lumped as one unit; they were simply subdivided by variations in the mode of muscovite and/or garnet. The Amphibolite has nicely aligned amphiboles in thin section as well as quartz/plagioclase porphyroblasts with symmetric tails. The granofels has granoblastic texture with the assemblage quartz-plagioclase-muscovite-biotite. We would correlate all of these rocks to variations of the Scarboro Formation. We interpret the section to young to the east. This is differs significantly from the interpretation by Hussey (2012) where these same rocks are less subdivided and correlated by him to the Cape Elizabeth Formation.

  **Structure:** The attitude (right hand rule) of bedding/layering $S_0$ (which is nearly always parallel to the principal foliation $S_1$ and $S_2$) is $160-180°$, $50-70°$. There is a conspicuous absence of any minor $D_1$ folding here. The west dips and our stratigraphic assignment suggest that this is an inverted section, which, in theory, is on the limb of a regional $D_1$ or $D_2$ nappe-scale fold of unknown vergence. The overall structure is controlled by a $D_3$ synform as these outcrops are on the east limb of the south plunging Cape Small synformal anticline. There is no topping control, so lots of room for future reinterpretations, both stratigraphic and structural! As an example of this, Hussey (2012) recognizes a zone west of STOP 1 of “highly deformed rocks” that he interprets to be an unspecified shear zone that would juxtapose the Scarboro Formation to the west against the Cape Elizabeth Formation. We did not see this zone in the field nor the apparent truncations along it to the south and hence do not support its existence on our map.

  **Metamorphism:** These schists are without andalusite and staurolite placing them on the high-grade side of the $M_3$ andalusite-out isograd with an overall assemblage of bio+gar+/- sill. $M_3$ is a local event likely caused by contact metamorphism associated with the Morse Mountain Granite and other plutons to the east and northeast. Garnets in
these schists are texturally zoned with relatively narrow, clear, inclusion-free rims, yielding to wider, inclusion-rich (ilmenite and/or graphite) cores. Overall in the quadrangle, texturally zoned garnets occur to the east while unzoned garnets occur to the west and at lower M3 grades. Our interpretation is that the texturally zoned garnets record two episodes of garnet growth, first M2 (cores), then later during M3 (rims). M3 is an earlier regional event that developed during the Acadian Orogeny and throughout the quadrangle is at andalusite-staurolite grade, but here overprinted completely by the higher M3 assemblages.

The M3 isograds presented here are modified and expanded from those of Hussey and Berry (2002) and Grover and Lang (1995). M2 assemblages have never been mapped in this region but have been discussed previously by Hussey and Berry (2002) and Grover and Lang (1995).

Retrace walking route back to vehicles.

0.3 Drive back to Rte. 216 and proceed left (south) down the road for .3 miles. Take a right (west) on Aliquippa Rd.

0.6 Drive another .3 miles to the boat landing and the end of Aliquippa Rd. There is very limited parking here so we’ll have to be creative!

STOP 2 – Aliquippa Landing: (43.741472°, -69.843853°; 1 hour) We will examine the rocks (low tide mostly) to the west and south of the boat landing.

Stratigraphy: The next lower units in the stratigraphy are exposed here. Exposed from youngest to oldest (?) are the following units: West Marsh Rusty Schist (Owms-r); and the Aliquippa Rusty Schist (Oars). The difference between the rusty schists of the Owms-r and Oars is subtle and mostly based on the increased abundance of calc-silicate and amphibolite horizons in the Oars. The rusty weathering is moderate in both units.

We would correlate these rocks to the Scarboro Formation (Owms-r) and Spring Point Formation (Oars). This agrees mostly with the interpretation of Hussey (2012) who correlates these rocks to the same formations.

Structure: This is one of the rare places in the quad where one can see an early D2 fold refolded by a D3 fold. We have mapped this as a north plunging D2 macroscopic antiform refolded by a D3 antiform with a somewhat anomalous southeast trend. Due to the complex folding, bedding/layering is more variable, ranging from typical attitudes (RHR S&D) of 190-160°, 45-80° to less common attitudes of 10°, 80°. Minor D3 folds are present but not as abundant as the exposures we will see later to the south. Due to the complex interaction of D2 and D3 fold generations, the D3 minor folds have both north and south plunges and as a result are somewhat atypical of D3 minor structures elsewhere which uniformly plunge southerly. D3 folds are also characterized by a smaller interlimb angle here and are classified as tight folds. This D3 fold parameter progressively changes to the south where the fold form changes to a much more open style. Overall in the quadrangle, D2 deformation is much less well constrained but is always characterized by a strong, pervasive, early foliation (S2) and in rare instances like this, isoclinal folds of bedding/layering and, in other places, quartz veins.

The overall fold style and age is much the same as portrayed by Hussey (2012), however he maps the Phippsburg fault through here based on apparent stratigraphic offsets. We did not see this structure and would not support its existence.

Metamorphism: As with STOP 1, these schists are without andalusite and staurolite placing them on the high-grade side of the M3 andalusite-out isograd with an overall assemblage of bio+gar+/- sill. These garnets also exhibit textural zoning from core to rim again indicating complex metamorphic growth during both M2 and M3.
south of the clubhouse turn right and ascend a set of concrete stairs to the top. Take the trail to the left at
the top of the stairs that goes along the ledges overlooking the ocean, the Cliff Trail (no sign), hugging the
water's edge until you arrive at the first private beach (Icebox Beach) a distance of about .3 miles.

STOP 3 – Icebox Beach: (43.715366°, -69.836023°; 2 hours including walking time) We will examine the outcrops
just above the high tide line as we walk generally south on Icebox beach.

Stratigraphy: Exposed here are three units: the Cape Small rusty schist (Ocsrs); Icebox amphibolite and calc-silicate
(Oiacs); and Cape Small Silver Schist (Ocsss) which is found both above and below the Ocsrs and Oiacs. The high
cliffs to the east are made up of Cape Small Silver Schist (Ocsss) where original bedding (?) can be seen as layers of
schist alternate with thin layers of quartz-rich granofels. Garnet occurs as both porphyroblasts and as thin
discontinuous coticles. Along the remaining length of Icebox Beach to the south are the deeply rusty weathering
Ocsrs schists. These are in places slightly magnetic due to pyrrhotite. Interlayered in many different locations are 1-
4 m wide amphibolites with or without calc-silicate. These resistant layers are featured prominently in these
outcrops. Each layer is unique in its appearance and thickness, suggesting to us that these are individual units in the
stratigraphy. We would correlate all of these rocks to the Cape Elizabeth Formation, as does Hussey (2012).

Structure: The attitude of bedding/layering ranges from 180, 60 in the north section of the beach, to 130, 20 towards
the southeast part of the beach as the layers fold through a regional D3 fold (east limb of the Cape Small synformal
anticline or west limb of the Seal Island antiformal syncline). This is an area where the D3 macro-scale structures
dominate and south plunging D3 meso-scale folds are less common. We mapped a late, normal (?) fault that
truncates the amphibolites to the east and is seen as a brittle structure in outcrop sometimes with associated local
crenulations. We’ve termed these D3 features and they would represent the youngest deformation (aside from late
joints) in the quad.

Our interpretation of the stratigraphy and structures here differs significantly from Hussey (2012). He interpreted
the amphibolites and rusty schists as being repeated by D2 (?) isoclinal folding. We mapped a more complex
stratigraphy and simpler structure. This was based on two things: 1) each amphibolite unit appeared to be
lithologically unique; and 2) we did not see any early fold hinges repeating these units. Hussey (2012) also mapped
several inferred faults here, one of which is similar to the location of the late fault described in the previous
paragraph.

Metamorphism: We have moved to slightly lower M3 grades at this STOP. Icebox Beach lies just west of, or on the
low grade side of, the M3 andalusite-out isograd. In thin sections from the Cape Small Silver Schists at this locality
coexisting andalusite and sillimanite can be found. In places the andalusite is partially to completely replaced,
reflective of the proximity to the andalusite-out isograd. Relict M2 staurolites, preserved as inclusions in the larger
M3 andalusites, are seen in thin section here. Garnets here continue to exhibit the textural zoning seen at the previous
STOPs.

At the south end of the Icebox Beach traverse we will follow a short 50 yd. walking trail to join Gun Club Rd. (dirt).
Follow this road for .7 miles past the last houses on the Point via a grassy path to Navy Rd., go left down Navy Rd.
about 50 yds, then right on a path through the dunes to Bald Head Cove, another private beach. Pending the time,
we’ll eat lunch either before or after looking at the rocks; enjoy the awesome view!

STOP 4 – Singing Sands Beach: (43.705502°, -69.840564°; 2.5 hours including walking time and lunch) We will
examine the outcrops just west of the Singing Sands beach by walking west across the ledges to the next beach.

Stratigraphy: Exposed here are the oldest units (?) in the stratigraphy: Singing Sands Silver Schist (Ossss) and Cape
Small Silver Schist (Ocsss). The “host” rock here is the Cape Small Silver Schists (Ocsss) which we saw at STOP 3.
It has the relict bedding in the form of interlayered schists, granofels, rare calc-silicate layers, and discontinuous
garnet coticle layers. The Singing Sands Silver Schist (Ossss) which forms 1-5 m thick bands of schist interlayered
with the Ocsss and rendered mappable by the increase mode of coarse staurolite porphyroblasts. These rocks are
correlated to the Cape Elizabeth Formation, in agreement with the stratigraphic assignment of Hussey (2012).
Structure: Bedding (S₀) is again parallel to foliation (S₁ and S₂) and has attitudes of 90-110°, 30-40°. We are just about on the axial trace of the macro-scale D₃ Cape Small synformal anticline that plunges gently south. If we had time to walk the entire length of the beach to both the west and east, one would see the attitudes of S₀/S₁/S₂ progressively changing defining the fold with an impressive wavelength of approximately 2 kms. Meso-scale D₃ folds are pretty much everywhere with about 3 anticlines per every .5 meters. These folds are mostly open, upright, and all plunging to the south. S₃ is a spaced axial planar cleavage here. The overall structure presented here is in good agreement with that described by Hussey (2012).

Metamorphism: These outcrops should be in the “Shrine to Polymetamorphism”. Spectacular coarse-grained porphyroblasts of staurolite, andalusite, garnet, and biotite are found. These rocks are slightly lower grade than those we’ve seen at the previous STOPs and lie just about on the M₃ staurolite-out isograd. The M₃ mineral assemblage is staur+and+sill+gar+bio. M₃ staurolite can be as large as a 1-3 cm across and often exhibit cruciform twinning. M₃ andalusite occurs in strikingly large somewhat rectangular lumps ranging from 2-10 cm in length that in the correct light show a cleavage “flash” indicating these are single crystals. In thin section M₃ staurolite inclusions are found in these M₃ andalusites. An unusual texture exhibited by some of these M₃ andalusite porphyroblasts is boudinage with the gaps filled with aligned M₃ quartz, sillimanite, and muscovite. The extension direction implied by these boudined andalusites is parallel to the D₃ meso-scale fold axes. One of the harder to find features here are the M₃ andalusite pseudomorphs that nicely record the relict M₂ andalusite-staurolite regional grade. These porphyroblasts are completely replaced by muscovite yet preserve the andalusite shape. We have not seen convincing relict or fresh chiastolite crosses in either the M₂ or M₃ andalusites (Help us find one!). M₃ garnets are both texturally zoned and unzoned and are typically up to .5 mm in size.

At the west end of the ledges in east corner of the next beach we’ll pick up a trail (watch the poison ivy) taking us to Navy Rd. Follow the trail for about .2 miles, then head north on Navy Rd to the junction with Seal Cove Rd. Go downhill (southeast) on Seal Cove Rd. to Icebox Beach (about 100 yds) and retrace our steps on the Cliff Trail and Club Rd to the vans, a distance of about 1.4 miles.

2.7 Drive the vehicles .5 miles south on Rte. 216 and take a right for Hermit Island Campground on Head Beach Rd.

2.9 Drive about .2 miles and park at the Head Beach Parking lot (43.719185°, -69.849865°), about .1 mile before the Hermit Island campground complex. Walk to the beach and proceed south down the shoreline a distance of about .3 miles from the van parking lot.

STOP 5 – South Head Beach: (43.716011°, -69.850185°; 1 hour) We will examine the outcrops of Cape Small Silver Schist (Ocsss) and on the way, very quickly, an exposure of Icebox amphibolite calc-silicate (Oiacs). 

Stratigraphy: The exposure of Oiacs connects to those we saw earlier at Icebox Beach (STOP 3) and serves to demonstrate the extent of these amphibolite-calc-silicate units. Though we didn’t really appreciate it at the time, the outcrop of Ocsss south of Head Beach turns out to have the ONLY reliable topping indicator in the entire quad! Bedding grain size is reversed due to metamorphism and we’ll show you one pretty convincing reverse graded bed that indicates tops are inverted. We can debate at the outcrop the topping direction but this was “blessed” as inverted by preeminent geo-heavy weights Henry Berry and Arthur Hussey. The grading is likely preserved here due to the thicker-than-normal quartz-rich granofels interbeds in the schist. D₁ and D₂ isoclinal folding is very difficult to see but most likely present in these rocks. As such, regional extrapolation of the significance of this single inverted bed should be done with appropriate caution! All of these rocks are correlated to the Cape Elizabeth Formation by us and also by Hussey (2012).

Structure: In the Ocsss outcrop, bedding/foliation (S₀/S₁/S₂) have attitudes of 50-90°, 30-40° to 270°, 30°. The exposure is located on the west limb of the D₁ Cape Small synformal anticline and the east limb of the Head beach antiformal syncline. Minor D₁ folds with meter-scale wavelengths are common and fold the earlier fabric elements S₀/S₁/S₂. We’ll try to find the exposure here that shows S₂ foliation oblique to and cutting the early S₁ foliation. This argues for the existence of an early D₁ and a late D₂ set of isoclinal nappe-stage folds. We’ve seen this in scattered thin section and Hussey (2012 and 1988) shows this relationship in outcrop photographs from this area. The outcrop of Oiacs has a nice set of meso-scale D₁ folds exposed.
Metamorphism: These rocks are at staurolite-andalusite M3 grade, the lowest we’ve seen today and the lowest in the quadrangle. M3 staurolite and andalusite are found but as abundant as at STOP 4. Thin sections here did not reveal very good relict M2 porphyroblasts.

Retrace the walking route back to vehicles.

3.0 Drive about .1 miles west toward Hermit Island Campground and park (43.720033°, -69.851566°). Walk .5 miles northwest along the dirt Hermit Island campground road to the Bathtub.

STOP – 6 Phippsburg Shear Zone at the Bathtub: (43.724535°, -69.857311°; 1 hour) We will examine a variety of structures at the Bathtub. Please be mindful of the poison ivy!

Stratigraphy: As we walk west we remain in either the Ocsss or the Ocsrs with similar lithologies to what we have seen at other STOPS. The Bathtub is in the Cape Small Silver Schist (Ocsss) all correlated to the Cape Elizabeth Formation. Note that the number of granitic intrusions and quartz veins has increased in this region.

Structure: These outcrops should be in the “Structure Hall of Fame!” The D4 Phippsburg Shear Zone is exceptionally well exposed here and shows a protracted period of post-D3 ductile through brittle-ductile dextral shearing that transforms the structures we have seen earlier. The overall dip of bedding/foliation is incredibly uniform with average attitude 15-30°, 60-80°. This discrete and mappable east dipping domain is a hallmark of the shear zone. D3 folds have been transformed into tight to isoclinal shapes and now have a weak S3 schistosity. A strong quartz rod lineation has also developed in the earliest quartz veins trending circa 200°, 20°. Some of these veins exhibit sheath-like fold forms where the plunge steepens sharply, indicating ductile conditions and high strains. Intrusion of quartz veins continued after the quartz rod lineations formed as did intrusion of M3 quartz-andalusite-sillimanite veins and coarse granites and pegmatites. These likely intruded steeply oblique or orthogonal to the principal bedding/foliation and, as shearing progressed, became forward rotated boudins trains showing dextral motion. The boudin trains remain oblique by about 20° to the principal bedding/foliation. Dextral kink bands that are similarly oblique to bedding/foliation are directly associated with these granitic boudins and have tourmaline mineralization on their flanks. Some of the granites, and less so the kink bands, are folded into S-shapes suggestive of sinistral shear. Nevertheless, these likely formed in a dextral system as they initially rotated clockwise through the shortening field, became symmetrically folded, then subsequently had their limbs attenuated into the asymmetric S-shapes. In a few places late, brittle, left-handed bookshelf gliding style, brittle faults developed in the boudined granites yet still in an overall dextral shear environment. Taken together these structures record a continuous and protracted period of ductile to brittle-ductile to brittle, dextral shearing as exhumation stripped off the overlying rocks during shearing and deformation conditions changed.

We agree with the work done here by Mark Swanson (Swanson and Bampton, 2009) who suggested that the Phippsburg Shear Zone was caused by south-directed extrusion of the midcoastal Block due to transpression from the Casco Bay restraining bend along the Norumbega Fault. We would modify this interpretation and propose a period of local extension that allowed for the intrusion of granite and metamorphic veins of quartz and aluminosilicates orthogonal to bedding/foliation. The overall dextral shear sense, the steep (but not vertical) east dips of bedding/foliation, and the gentle, south plunges of the quartz rod lineations suggest that the oblique component of dip slip here was normal. This suggests that the shear zone was of transtensional style.

Metamorphism: The rocks here are at the same M3 staurolite-andalusite grade as we saw in STOPS 4 and 5. In addition, thin sections show excellent relict M2 assemblages, in particular M2 staurolite inclusions in M3 andalusite. Though not quite as spectacular as the coarse Singing Sands Schist exposures of STOP 4, these rocks make up for it with an incredible set of M3 quartz-andalusite-sillimanite veins. These are now boudined by D4 shearing in the Phippsburg Shear Zone and are found up to a meter in length and about 10-20 cm wide. Andalusite makes up the coarsest part of the assemblage, comprising the bulk of the veins, and giving them a nice pink color. Sillimanite and muscovite are interstitial to the andalusite. The boudins are surrounded by concentrations of tourmaline and biotite.

Return to vehicles. END OF TRIP! Safe travels.
REFERENCES CITED


http://scarab.bates.edu/honorstheses/18


http://scarab.bates.edu/geology_theses/2


