OPEN-FILE REPORT NO. NEIGC16C:C2

Title: Middle Ordovician to Early Silurian Terranes of the Northern Casco Bay Region, Maine

Author: David P. West, Jr., and Arthur M. Hussey II

Date: October 2016

Reprinted in color, by permission, from:

Contents: 18 p. report

Recommended Citation: West, David P., Jr., and Hussey, Arthur M., II, 2016, Middle Ordovician to Early Silurian terranes of the northern Casco Bay region, Maine: in Berry, Henry N., IV, and West, David P., Jr., editors, Guidebook for field trips along the Maine coast from Maquoit Bay to Muscongus Bay: New England Intercollegiate Geological Conference, p. 249-266.
NEW ENGLAND INTERCOLLEGIATE GEOLOGICAL CONFERENCE
108th Annual Meeting

Guidebook for Field Trips along the Maine Coast from Maquoit Bay to Muscongus Bay

Edited by
Henry N. Berry IV and
David P. West, Jr.

Hosted by
The Maine Geological Survey and
The Middlebury College Geology Department

October 14-16, 2016
Copies of this guidebook, as long as they last, may be purchased for $25 from the following address:

Geology Department
Middlebury College
276 Bicentennial Way
Middlebury, VT 05753

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.

The field guides for this Conference are offered under the terms of the Creative Commons Attribution-Non-Commercial 3.0 Unported

DISCLAIMER

Before visiting any of the sites described in New England Intercollegiate Geological Conference guidebooks, you must obtain permission from the current landowners.

Landowners only granted permission to visit these sites to the organizers of the original trips for the designated dates of the conference. It is your responsibility to obtain permission for your visit. Be aware that this permission may not be granted.

Especially when using older NEIGC guidebooks, note that locations may have changed drastically. Likewise, geological interpretations may differ from current understandings.

Please respect any trip stops designated as "no hammers", "no collecting" or the like.

Consider possible hazards and use appropriate caution and safety equipment.

NEIGC and the hosts of these online guidebooks are not responsible for the use or misuse of the guidebooks.

Printed by Reprographics, Middlebury College, Middlebury, VT 05753
This document is printed on recycled paper
It is with a heavy heart that I will be leading this field trip without my mentor, colleague, and friend Arthur Hussey who passed away on July 26, 2016*. Arthur began detailed field studies in the area immediately south of Brunswick, Maine in the summer of 1963, two years after his initial appointment at Bowdoin College. In 1965 he led a NEIGC field trip through the area based on the results of his early mapping and his accompanying NEIGC guidebook article contained numerous hand-drafted geologic maps detailing relationships at individual stops (Hussey, 1965). Arthur continued mapping in the area through the late 1960’s and this work culminated in 1971 with the publication of his classic geologic map of the Orrs Island 7.5’ quadrangle (GM-2) by the Maine Geological Survey (Hussey, 1971). Arthur loved sharing his knowledge of the geology in northern Casco Bay and when one includes instructional trips with students over his teaching career at Bowdoin College, he literally led hundreds of field excursions through the area. Additionally, he always encouraged others to join him in his studies of the area and numerous detailed investigations completed with his assistance have yielded important findings on metamorphic (Lang and Dunn, 1990; Daniel and Spear, 1998; Spear and Daniel, 2001), structural (Swanson, 1992: 1999a,b), thermochronologic (West et al, 1993; West and Roden-Tice, 2003), and igneous (Tomascak et al., 1996a, b; McHone et al., 2014) processes. Although his interpretations of the geologic history of the region evolved over the years with new findings, his 1971 map remains an accurate representation of the spectacular geology exposed along the northern shores of Casco Bay. Thank you Arthur for all of your hard work, and for sharing your love and passion for all aspects of the geology of southwestern Maine.

*Arthur M. Hussey II at his home in Bowdoinham, Maine (Summer, 2012)
**INTRODUCTION**

This field trip provides an opportunity to explore deformed and metamorphosed stratified rocks within three different lithotectonic terranes exposed in the northern Casco Bay region of Maine. Each of these terranes (Falmouth-Brunswick sequence, Casco Bay Group, and East Harpswell Group) contains a wide variety of complexly deformed sedimentary and volcanic rocks that have been metamorphosed to amphibolite facies conditions. Hussey et al. (2010) interpreted all of these rocks to have been deposited in association with an evolving Middle to Late Ordovician volcanic arc/back-arc sequence built on a fragment of non-North American crust (a portion of the peri-Gondwanan Ganderia terrane). The field guide that follows will highlight the stratigraphy of the individual lithotectonic belts, and introduce aspects of the structural geology, metamorphic petrology, and plutonic rock history preserved in the bedrock of the northern Casco Bay region.

As mentioned above, Arthur Hussey first began working in the area of this field trip in the early 1960’s. His first formally published ideas on the stratigraphy, structure, and age relationships of the rocks exposed in Casco Bay were in the classic “Billings Volume” on northern Appalachian geology (Hussey, 1968). It is safe to say that the geologic relationships in this region were never far from his mind over the next 50 years. His final published views on the geology can be found in Hussey et al. (2010) where detailed regional relationships are presented, and in Hussey (2015) which presents a comprehensive overview of the geology of southwestern Maine for the educated layperson. Those interested in exploring the geology of the region are encouraged to refer to these publications, as well as the 1:24,000 scale geologic maps of Hussey (1971), and Hussey and West (in review). Hussey et al. (1971) illustrates relationships on the Harpswell peninsula, and Sebascodegan, Orrs, and Bailey islands, while Hussey and West (in review) portrays relationship in the Brunswick, Topsham, and Cooks Corner areas.

Hammers should not be used on any of the outcrops described in this guidebook article. Not only do we want to preserve these sites for future study and teaching, but nearly all of the geologic features exposed at these localities are enhanced by weathering processes and so fresh surfaces produced by hammering rarely provide better observations. Please note that many of the stops on this field trip are located on private property, and arrangements to visit these sites apply only to this specific trip. Later access to these locations is not implied and future visits will require permission of landowners prior to visiting.

**GEOLOGIC SETTING**

The stratified rocks exposed in the northern portions of Casco Bay can be divided into four tectonostratigraphic sequences based on similarities in the ages and types of rocks exposed within each belt (Fig. 1). From west to east these include (1) Late Ordovician (?) to Silurian metasedimentary rocks of the Central Maine belt, (2) Ordovician metasedimentary and metavolcanic rocks of the Falmouth-Brunswick sequence, (3) Ordovician metasedimentary and metavolcanic rocks of the Casco Bay Group, and (4) Late Ordovician to Early Silurian metasedimentary and metavolcanic rocks of the East Harpswell Group. A brief summary of each of these belts is provided below, but the reader is referred to Hussey and Berry (2002), and Hussey et al. (2010; 2016) for the details of rock types present, constraints on protolith ages, and interpretations of the contact relationships between the different belts. Note that subsequent to original deposition, all of these stratified rocks were complexly deformed, metamorphosed to upper greenschist - amphibolite facies conditions, and intruded by a diverse range of igneous rocks.

Hussey et al. (2010) and Hussey (2015) provide a discussion of possible tectonic environments associated with the original formation of the stratified rocks in an actively evolving middle Paleozoic oceanic setting between Laurentia on the western side and a peri-Gondwanan terrane called Ganderia on the eastern side (directions relative to present day coordinates). Summarizing from this work and illustrated in Figure 2, sedimentary rocks of the Central Maine basin (derived largely from Laurentian sources to the west) and Merrimack-Fredericton basin (derived largely from Ganderian sources to the east) are separated by Ordovician volcanic arc/back-arc rocks of the Falmouth-Brunswick sequence and Casco Bay Group (FBCB arc of Hussey et al., 2010). Volcanic activity continued into earliest Silurian time as represented by rocks of the East Harpswell Group. Eventually, continued
Figure 1a. Generalized geologic map of the field area. Map legend and schematic cross section are on the next page. Map based on the work of Hussey (1971), Hussey and Marvinney (2002), and Hussey and West (in review).
Figure 1b. Schematic cross-section along A-A’ from the map on the previous page.

**Intrusive Rocks**

- **Dhh**
  - Hornbean Hill Granite
  - Gneiss (394 Ma)
- **Dg**
  - Devonian granite

**Stratified Rocks**

**Central Maine Sequence**
- **SOv**
  - Vassalboro Group (undivided)
  - Contact relations unclear
  - Falmouth-Brunswick Seq.
    - **Oma**
      - Mt. Ararat Fm.
    - **Onp**
      - Nehumkeag Pond Fm.

**East Harpswell Group**
- **SOs**
  - Sebascodegan Fm.
- **SObp**
  - Bethel Point Fm.
- **SOyi**
  - Yarmouth Island Fm.

**Flying Point fault**

**Pre-metamorphic thrust**

**Casco Bay Group**
- **Ouc**
  - Upper Casco Bay Group
    - (Spring Pt., Diamond Isl., Scarborough Spurwink, Jewell fms.)
- **Oce**
  - Cape Elizabeth Fm.
- **Oc**
  - Cushing Fm.
convergence between Laurentia and Ganderia in Late Silurian time led to the head-on collision of these crustal blocks, with the intervening sedimentary basins and volcanic arc/back arcs becoming deeply buried, complexly deformed, metamorphosed, and periodically intruded by magmas.

The Late Silurian–Early Devonian orogenic activity derived from the largely head-on collision of Laurentia with various peri-Gondwanan terranes was followed by a long period of time (Late Devonian to Permian) dominated by right-lateral transcurrent tectonism. This resulted in both widespread penetrative ductile dextral shear deformation (Swanson, 1992; 1999a,b; 2016), and more localized zones of brittle strike-slip faulting associated with the Norumbega fault system (Hussey, 1988). Kuiper (2016) has recently suggested this period of dextral transpression was initiated in response to the subduction of an oceanic ridge and associated transform fault. Regardless as to the tectonic causes, during the Permian rocks to the west of the Flying Point fault were metamorphosed to amphibolite facies conditions (West et al., 1993) and intruded by granitic pegmatites (Tomascak, 1996a,b; West and Cubley, 2006).

Thermochronological studies of rocks exposed on opposite sides of the Norumbega fault system in the Bath-Brunswick area reveal a significant time-temperature discontinuity that persisted across the structure into Mesozoic time (West et al., 1993). Differences in apatite fission track ages in this region are likely the result of kilometer-scale east-side-down vertical displacement along this portion of the Norumbega fault system in Late Cretaceous time (West and Roden-Tice, 2003). In addition to this Mesozoic faulting, numerous fine-grained mafic dikes of Mesozoic age can be found throughout the field area. Although most of these dikes are less than a few meters wide, the Christmas Cove dike is up to 30 meters across (Hussey, 1971). \(^{40}\)Ar/\(^{39}\)Ar ages from this dike (in McHone et al., 2014) indicate an emplacement age of about 200 Ma which is similar to ages from other dikes and basaltic lava flows in the Central Atlantic Magmatic Province (CAMP). This period of intense mafic magmatism has been linked to the mass extinction event near the Triassic-Jurassic boundary (Schoene et al., 2010; Blackburn et al., 2013).

**Figure 2.** Schematic diagram from Hussey (2015) showing the hypothesized tectonic setting in southwestern Maine in Early Silurian time. Note that earlier subduction towards the southeast in Ordovician time produced volcanic arc (Falmouth-Brunswick sequence) and back-arc (Casco Bay Group) deposits associated with the FBCB arc which was built upon a fragment of Ganderia. Silurian sediments derived from ancestral North America were deposited northwest of the FBCB arc (Central Maine belt) and Silurian sediments derived from Ganderia were deposited southeast of the FBCB belt (Kittery and Bucksport fms. of the Merrimack and Fredericton belts, respectively).

**Tectonostratigraphic Belts**

*Central Maine belt*

The Central Maine belt contains a thick Late Ordovician (?) to Early Devonian assemblage of metamorphosed wacke, shale, and minor limestone (Osberg, 1988) that underlies much of central portion of the state. This field trip is along the eastern margin of this wide belt and includes undifferentiated rocks of the Vassalboro Group (Marvinney et al., 2010) – mostly thin-bedded biotite granofels with lesser amounts of calc-silicate granofels and rusty weathering schist. The original sediments were deposited in latest Ordovician to Early Silurian time and presumably derived from a Laurentian source region to the west (Hussey et al., 2010).
**Falmouth-Brunswick sequence**

Metamorphosed Ordovician aged sedimentary and volcanic rocks of the Falmouth-Brunswick sequence in the Brunswick-Topsham area consist of the Nehumkeag Pond and Mount Ararat formations. These units, first introduced by Hussey (1985), were initially included in the Casco Bay Group (Hussey, 1988). Hussey and Berry (2002) later separated these rocks from the Casco Bay Group and lithologies correlated with the Falmouth-Brunswick sequence have now been mapped continuously from Falmouth to just north of Brooks, Maine – a distance of over 125 kms. All of the units included within the Falmouth-Brunswick sequence have been interpreted to represent deformed and metamorphosed rocks associated with Ordovician arc and back-arc volcanic activity (the FBCB volcanic arc complex of Hussey et al., 2010).

The Nehumkeag Pond Formation is dominated by felsic gneisses and granofels, but locally mappable members north of Topsham include amphibolite, pelitic schist, rusty schist, and impure marble. These rocks have been interpreted to represent metamorphosed volcanic rocks and volcanogenic sedimentary rocks deposited in association with an evolving arc to back-arc tectonic setting (Hussey et al., 2010). Hussey et al. (2010) report a U-Pb SHRIMP zircon age of 472 ± 7 Ma obtained from a felsic gneiss collected from the Nehumkeag Pond Formation in the Brunswick 7.5’ quadrangle. These authors interpret this age to reflect the timing of felsic volcanism.

The Mount Ararat Formation consists of thin (< 10 cm) alternating layers of dark gray amphibolite and light gray felsic gneiss and granofels. These layers have been interpreted to represent alternations of mafic and felsic volcanic material (ash?). Mapping to the north of Topsham shows these rock types occur at different stratigraphic levels within the Nehumkeag Pond Formation (West and Cubley, 2006). Hussey et al. (2010) report a U-Pb SHRIMP zircon age of 471 ± 6 Ma from a felsic granofels layer within the Mount Ararat Formation which they interpret to represent the age of timing of felsic volcanism in the unit.

**Casco Bay Group**

The Casco Bay Group consists of a conformable sequence of metavolcanic and metasedimentary units of Middle to Late Ordovician age. Although not all of the individual formations are present everywhere along strike, rocks assigned to the Casco Bay Group can be found continuously along a 150 km long northeast-trending belt extending from the Portland area to the south, through to just south of Bangor (see Osberg et al., 1985). Mapping by Hussey (1971) has shown that all formations of the Casco Bay Group (Cushing, Cape Elizabeth, Spring Point, Diamond Island, Scarboro, Spurwink, and Jewell) are present on Harpswell Neck. All of these rocks have been interpreted to represent volcanism and associated sedimentation in a back-arc tectonic setting influenced by Ganderian crust (West et al., 2004; Hussey et al., 2010; Hussey, 2015). Whole rock geochemical signatures and detrital zircon age populations are supportive of a correlation between the Casco Bay Group in Maine and the Bathurst Supergroup in the Miramichi belt of New Brunswick (West et al., 2004, 2008).

The Cushing Formation, the oldest unit in the Casco Bay Group, is dominated by metamorphosed felsic to intermediate volcanic rocks. U-Pb SHRMP zircon age of 465 ± 4 Ma has been interpreted to represent the eruptive age (Hussey et al., 2010). The Wilson Cove member of the Cushing Formation is a distinctive metamorphosed iron- and manganese-rich lithology that West et al. (2008) have interpreted to represent a mixture of hydrothermal exhalatives and peri-Gondwanan terrigenous clastic sediment. The overlying Cape Elizabeth Formation, the most laterally persistent formation within the group, is a metasedimentary unit dominated by interbedded mica schist and quartz-feldspar rich granofels. The metavolcanic Spring Point Formation overlies the Cape Elizabeth and a 469 ± 3 Ma U-Pb zircon age from felsic volcanic rocks in this unit (Tucker et al., 2001) support a Middle to Late Ordovician age for the Casco Bay Group. Relatively thin metasedimentary formations (Diamond Island, Scarboro, Spurwink, and Jewell) make up the upper part of the Casco Bay Group.

**East Harpswell Group**

The East Harpswell Group contains, from oldest to youngest, the Yarmouth Island, Bethel Point, and Sebascodegan formations (Hussey and Berry, 2002). These units were originally mapped as members of the Cushing Formation (Hussey, 1971), however unpublished U-Pb zircon ages from the Yarmouth Island Formation
(referred to in Hussey and Berry, 2002) are 20 million years younger than the age of the Cushing Formation. This age discrepancy necessitated separating the Yarmouth Island, Bethel Point and Sebascodegan units from rocks of the Casco Bay Group and creating the East Harpswell Group. Hussey et al. (2010) and Hussey (2015) suggest rocks of the East Harpswell Group represent a younger period of volcanism (Early Silurian) associated with a subduction polarity reversal beneath the earlier formed FBCB volcanic arc complex.

The Yarmouth Island Formation is dominated by metamorphosed felsic to intermediate volcanic rocks. The presence of orthoamphibole+cordierite+staurolite assemblages in some rocks within the unit are suggestive of sea-floor alteration prior to metamorphism. The overlying Bethel Point Formation is a distinctive strongly rusty weathering schist. The Sebascodegan Formation, the upper-most unit in the group, is dominated by calcareous metasedimentary rocks, including mappable members of both pure and impure marble.

Contacts between the Tectonostratigraphic Belts

The contact between rocks of the Central Maine belt and Falmouth-Brunswick sequence has been the subject of controversy for decades (conformable, unconformable, thrust fault). Unfortunately, relationships in the greater Brunswick area do not shed light on the issue. However, it should be noted that structural styles and the conditions of metamorphism do not change across the boundary in this region and thus juxtapositioning of these belts via a "late structure" can be ruled out. Further research will be required to discern whether rocks of the Vassalboro Group were conformably or unconformably deposited directly on rocks of the Falmouth-Brunswick sequence, or whether an early pre-metamorphic thrust fault is responsible for their current juxtaposition.

The Flying Point fault of the Norumbega fault system separates the Falmouth-Brunswick sequence from the Casco Bay Group. Both late Paleozoic ductile dextral shear deformation (Swanson, 1992; 1999a), and Mesozoic brittle dip-slip displacements (West et al., 1993; West and Roden-Tice, 2003) have been associated with the Flying Point fault. In addition to forming the boundary between these two sequences, the Flying Point fault also marks an abrupt change in structural style (see below), and thermal history (Fig. 3). Rocks east of the Flying Point fault last experienced high-grade metamorphism in the Late Devonian and had cooled below ~ 200°C by the end of the Paleozoic. In stark contrast, west of the Flying Point fault, rocks last experienced high-grade metamorphic conditions in the Permian and did not cool below ~ 200°C until 50 to 75 m.y. after those to the east. The findings are consistent with the rocks currently juxtaposed along Flying Point fault having experienced radically different metamorphic and structural histories in middle to late Paleozoic time, and radically different thermal histories persisted until the Late Cretaceous. Final juxtapositioning and contemporaneous cooling of the Falmouth-Brunswick sequence and Casco Bay Group did not occur until after the Cretaceous and was accomplished through significant displacement along the Flying Point fault.

The contact between the Casco Bay Group and the East Harpswell Group has been interpreted to be a pre-metamorphic thrust fault based on differences in the ages of the rocks in the two sequences (~ 465-470 Ma for the Casco Bay Group and ~ 445 Ma for the structurally underlying East Harpswell Group). This thrusting may have been associated with the Boothbay thrust to the east which juxtaposes rocks of the Casco Bay Group with those in the Fredericton Trough (Hussey and Berry, 2002).

Plutonic Rocks

Intrusive igneous rocks ranging in age from Middle Devonian to Early Jurassic can be found in the greater Brunswick area. These rocks can generally be divided into four general groups based on crystallization age and their relationships to deformational and metamorphic events. These include, from oldest to youngest:

1. Middle Devonian tonalitic to dioritic rocks of the Hornbeam Hill gneiss exposed to the north of Topsham along the contact between the Central Maine and Falmouth-Brunswick belts (West and Cubley, 2006). An igneous crystallization age of 393 ± 4 Ma from the Hornbeam Hill gneiss (Gerbi and West, 2007) is important because the intrusion seals the contact between the two stratigraphic sequences AND it contains
relatively flat fabrics (see below) that are associated with the deformation that is prevalent on the western side of the Flying Point fault.

(2) Late Devonian granites and granitic pegmatites that are particularly abundant east of the Flying Point fault in the area around and south of Bath (Hussey and Marvinney, 2002). Both the larger mappable bodies and the smaller pegmatite have mineral assemblages (accessory muscovite and/or garnet ± tourmaline) that suggest peraluminous granitic compositions. The larger of these bodies have elongate map patterns that are concordant with fabrics preserved in the surrounding stratified rocks, and most of these rocks contain a weak to moderate foliation. Although radiometric ages are not available from these rocks, their apparent syn-kinematic relationships to dated Late Devonian deformational and metamorphic events in the area (West et al., 1993) are strongly suggestive of Late Devonian emplacement.

(3) A generally north-northeasterly trending belt of Permian aged granite (Brunswick granite of Tomascak et al., 1996), and distinctive graphic texture pegmatites are found west of the Flying Point fault in the Brunswick, Topsham, and Bowdoinham areas. The pegmatite intrusions, up to several hundred meters across, tend to be found in elongate north to northwest trending bodies within the Falmouth-Brunswick sequence (West and Cubley, 2006; Hussey and West, in review). Many of these pegmatite bodies have been the sites of past, relatively small-scale quarrying activity, mainly for feldspar (Shainin, 1948; Cameron et al., 1954), but beryl, and Nb-Ta oxides are present in many (Francis, 1987). Tomascak et al. (1996) report U-Pb monazite ages ranging from 268-275 Ma for pegmatites in the Topsham area, suggesting a Permian age of intrusion.

(4) Post-deformational, relatively narrow, fine-grained, mafic dikes of Mesozoic age can be found throughout the northern Casco Bay region. Petrographic examination of selected samples reveals microphenocrysts of orthopyroxene set in a finer grained matrix of plagioclase, clinopyroxene, and magnetite. $^{40}$Ar/$^{39}$Ar whole rock ages from the largest of these dikes, the Christmas Cove dike (McHone et al., 2014), are ~200 Ma and suggest many of these small-scale intrusions are Late Triassic to Early Jurassic in age.

**Figure 3.** Previously determined $^{40}$Ar/$^{39}$Ar (West et al., 1993) and fission track (West and Roden-Tice, 2003) mineral ages reveals a major time-temperature discontinuity across the Flying Point fault in the Brunswick-Bath area. The thermochronology indicates throughout the Late Paleozoic, Mesozoic, and Early Cenozoic, a significant thermal contrast existed in the rocks currently juxtaposed across the Flying Point fault, suggesting significant displacement (km-scale) along the Flying Point fault must have occurred within the last 100 million years.
Structural Geology

The style of folding and associated ductile deformational structures in the greater Brunswick area differs dramatically on either side of the Flying Point Fault (see cross-section in Fig. 1b, and the fabric data in Fig. 4). Stratified rocks exposed west of the Flying Point fault are dominated by moderately east-dipping foliation, moderate northeast plunging mineral lineations, and recumbent to gently inclined minor folds. Swanson (1999a, b) suggested the relatively flat structures west of the Flying Point fault are consistent with an episode of northwest directed thrusting associated with late Paleozoic dextral transpression in the Casco Bay restraining bend of the Norumbega fault system. In stark contrast, east of the Flying Point fault, stratified rocks are dominated by steep east dipping foliation, subhorizontal mineral lineations, and upright to steeply inclined minor folds. At a larger scale, this style of folding is responsible for the distribution of map units across the peninsulas of the northern Casco Bay region (i.e., the map-scale Hen Cove, Harpswell Sound, and Merepoint folds of Hussey, 1971).

In addition to these earlier episodes of folding and associated fabric development, the rocks east of the Flying Point fault have been subjected to significant ductile dextral simple shear deformation (Swanson, 1992; 1999a; this volume). Dextral shear deformational features (e.g., shear bands, asymmetric folding, asymmetric boudinage, etc.) are both widely distributed across the region east of the Flying Point fault, and also concentrated into high strain zones (Swanson, 1992; 1999a, 2016). Swanson (1999b; 2016) has attributed this dextral shear deformation to have been associated with a restraining-bend geometry that developed in late Paleozoic time along the Norumbega fault system in the Casco Bay area.

Metamorphism

The conditions of metamorphism recorded in stratified rocks of the northern Casco Bay region vary significantly and an abrupt change is present across the Flying Point fault. It should be noted that while peak metamorphic temperatures vary, pressures are believed to have been consistently below that of the Al₂SiO₅ triple point for all of the metamorphism recorded in the area (i.e., low pressure, or Buchan metamorphism). West of the Flying Point fault in the Falmouth-Brunswick sequence and Central Maine belt, the rocks are extensively migmatized and metamorphosed to upper amphibolite facies conditions. $^{40}$Ar/$^{39}$Ar hornblende cooling ages from rocks of the Falmouth-Brunswick sequence indicate the last cooling below amphibolite facies conditions occurred in the Permian (West et al., 1993).
Peak metamorphic temperatures recorded in rocks east of the Flying Point fault in the Casco Bay and East Harpswell groups varies considerably. These rocks, particularly in the Orrs Island and Harpswell Neck areas have been the subject of several detailed metamorphic studies (Dunn and Lang, 1988; Lang and Dunn, 1990; Grover and Lang, 1995; Dunn and Spear, Daniel and Spear, 1998; Spear and Daniel, 2001). Here, a single episode of low pressure metamorphism (2 to 3 kilobar) increases in intensity from southwest to northeast, from garnet zone in the southern parts of Harpswell Neck to sillimanite zone in the northern parts of Orrs Island and adjacent Sebascodegan Island (Hussey 1971; Dunn and Lang, 1998). $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende ages from this area are Late Devonian and indicate the time of cooling following this low pressure metamorphic event (West et al., 1993). Lang and Dunn (1990) indicate this metamorphism was largely synchronous with the major episode of regional deformation (i.e., upright folds and associated steeply dipping foliation) in the area.

**SUMMARY OF THE TECTONIC HISTORY OF THE NORTHERN CASCO BAY REGION**

The earliest recorded activity preserved in the bedrock underlying the northern portion of Casco Bay is Middle Ordovician volcanism and associated sedimentation preserved in the Falmouth-Brunswick sequence. Hussey et al. (2010) suggested this volcanic activity was the result of the eastward subduction of oceanic lithosphere beneath a fragment of non-North American crust (an isolated sliver of Ganderia) within an ocean basin east of Laurentia - referred to by these authors as the Merribuckfread Basin. Subduction continued during the latter part of the Ordovician and eventual spreading behind the FBCB arc led to the volcanism and sedimentation that is preserved in the Casco Bay Group. In the Early Silurian, the polarity of subduction reversed and volcanism and sedimentation associated with the East Harpswell Group resulted in the deposition of rocks proximal to the FBCB arc/back-arc complex (Fig. 2). Additionally, during the latest Ordovician and into the Silurian, thick accumulations of sediment derived from both Laurentian sources to the west (Central Maine basin sediments) and Ganderian sources to the east (Merrimack and Fredericton basin sediments) were deposited and eventually buried the older arc sequence.

Beginning in Late Silurian time, the convergence of Laurentia and Ganderia led to the closing of the Merribuckfread Basin, and widespread orogenesis associated with the Acadian orogeny began (Bradley et al., 2000; Tucker et al., 2001). In the northern Casco Bay area this began with the thrust faulting of the Casco Bay rocks over the East Harpswell Group, obscuring their original contact relationships. This was followed in Middle to Late Devonian time by abundant folding and fabric development associated with compressional deformation, as well as regional low pressure metamorphism, and granite intrusion. Later in the Paleozoic, tectonic stresses became transpressional and ductile dextral shear features and brittle strike-slip faults developed in the Casco Bay area in association with the regionally extensive Norumbega fault system (Swanson, 1992; 1999a). West of the Flying Point fault, this lead to burial, high-grade metamorphism, and intrusion of granitic magmas (West et al., 1993; Tomascak et al., 1996). Finally, in the Mesozoic, stresses became extensional prior to the opening of the North Atlantic Ocean basin and this resulted in decompression melting at depth and localized intrusions of mafic dikes that were likely feeding basalt flows in nearby basins (McHone et al., 2014). Later in the Mesozoic, kilometer scale dip-slip displacement along the Flying Point fault led to the final juxtaposition of the Falmouth-Brunswick sequence and Casco Bay Group, and resulted in the contrasting structural styles and thermal histories seen across this structure at the present erosional surface (West and Roden-Tice, 2003).

**ACKNOWLEDGMENTS**

A trademark of all Arthur Hussey publications was a sincere acknowledgement of those who worked before him, and those who supported his field work. In this regard, this would include the early 20th century mapping of portions of southwestern Maine by Frank Katz of the U.S.G.S. who Arthur always acknowledged as laying the groundwork for all of his geological studies in the region. Additionally, Arthur always acknowledged the support and encouragement of the Maine State Geologists whom he worked under – Jack Rand, Robert Doyle, Walter Anderson, and Robert Marvinney. Additionally, in the context of his work in the northern Casco Bay area, Arthur
frequently referred to ideas he received from Henry Berry, Wally Bothner, and Mark Swanson as being particularly helpful as he wrestled with trying to put it all together.

Dave West would like to acknowledge the support of the Maine Geological Survey (MGS) STATEMAP program for providing funding for his field work in the Brunswick quadrangle in 2014. Arthur had previously mapped most of the quadrangle, but there were some “holes” and the MGS funding allowed me to work closely with Arthur to fill in these holes. Previous MGS STATEMAP funding for field work in the adjacent Bowdoinham (2004, 2005), and Richmond quadrangles (2008) also helped me become familiar with the geology of the area along strike.

I first met Arthur in the fall of 1986 as I began field work in the northern Casco Bay area that would eventually evolve into my Master’s thesis project at the University of Maine. Art served on my thesis committee, and over the next 30 years I constantly drew knowledge and inspiration from him. I am not alone in this regard as I’m sure his long legacy of Bowdoin College students and many close colleagues can attest.

ROAD LOG

Meeting point: (UTM: 0421490 m E, 4865335 m N: NAD 27) The 8:30 am meeting point for the field trip will be at the Hannaford Supermarket parking lot at the Topsham Fair Mall in Topsham, Maine. This is located just off I-295 at exit 31 (Rt. 196 East) in Topsham. After exiting I-295, proceed East on Rt 196 East towards Topsham and turn right almost immediately onto the Topsham Fair Mall Road at the McDonalds restaurant. The Hannaford Supermarket will on the right about 150 meters from McDonalds and we will convene in the northeastern corner of the parking lot (away from the grocery store) for a brief overview of the trip. Note all GPS coordinates listed in this field guide are NAD 1927 datum.

Mileage
0.0 Depart the Hannaford grocery store parking lot and turn right onto Topsham Fair Mall Road
0.8 Turn left onto Park Drive (note signs for “Goodwill”).
0.9 Turn right into the Goodwill Parking lot and proceed to the east side of the parking lot where large road-cut exposures are found.

Stop 1: NEHUMKEAG POND FM. OF THE FALMOUTH-BRUNSWICK SEQUENCE IN TOPSHAM. (0421492 m E, 4864505 m N).

These relatively freshly blasted exposures provide great examples of rocks that are representative of the Nehumkeag Pond Formation of the Falmouth-Brunswick sequence. Additionally, the outcrop displays fabrics that are characteristic of rocks immediately west of the Flying Point fault (see Fig. 4a). Exposures here are dominated by plagioclase-quartz-biotite gneisses, occasional layers that also contain muscovite, garnet, and sillimanite, and cross-cutting pegmatite dikes. Rusty weathering, sulfidic muscovite schist, a common subordinate rock type within the Nehumkeag Pond Formation, can be found at the southern end of the exposure. These rocks have been interpreted by Hussey et al. (2010) to represent metamorphosed volcanogenic sedimentary rocks associated with the early (Middle Ordovician) development of the FBCB volcanic arc on a sliver of Ganderian crust.

Compositional layering and the dominant foliation within the gneisses is oriented approximately N35°E, 35°SE, and most foliation surfaces show a strong mineral lineation that gently rakes towards the northeast. This pervasive fabric can be found over a large area west of the Flying Point fault in rocks of both the Falmouth-Brunswick sequence and adjacent Central Maine belt. Swanson (1999b) interpreted these fabrics to represent northwest directed thrusting associated with dextral transpression related to a restraining bend along the Norumbega fault system in late Paleozoic time (Swanson, 1999b). Return to vehicles and return to the Topsham Fair Mall Road.

1.2 Turn left on Topsham Fair Mall Road
1.3 Turn left into parking lot and park next to outcrops on the east side.
Stop 2: RECUMBENT FOLDS IN THE FALMOUTH-BRUNSWICK SEQUENCE.  
(0421435 E, 4864302 N).

The exposure in the blasted wall of this parking lot reveals a relatively thick (10’s of meters thick) amphibolite within the Nehumkeag Pond Formation which is interpreted to represent metamorphosed mafic igneous rock within the unit. However, the most prominent aspect of this exposure are the spectacular recumbent folds that are representative of the folding style on the western side of the Flying Point fault in this region. In addition, the rocks are cut by a late pegmatite that is likely Permian in age. $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende ages from similar amphibolites nearby have ages that range from 265 to 295 Ma and indicate latest cooling below amphibolite facies condition did not occur until the Permian (West et al., 1993). Note just above the outcrop is an old “working” within the pegmatite intrusion. There are literally hundreds of these small scale “workings” scattered through a roughly north-south trending corridor between Topsham and Bowdoinham. We will see larger scale quarrying activity in these pegmatites at the next stop. Return to cars and return to the Topsham Fair Mall road.

1.4 Turn right onto Topsham Fair Mall road.  
2.4 Intersection with Rt. 196, turn right and proceed east on Rt. 196.  
2.9 Intersection with Rt. 201, continue straight on Rt. 196 East.  
3.4 Turn left onto Village Drive and into the Highland Green subdivision  
4.2 Turn right into the parking lot of the Highland Green Community Center, park, and secure permission to access quarry exposures. Parking lot is located at 0423458 m E, 4866147 m N. Note the large blasted blocks of isoclinally folded mafic and felsic gneiss of the Mount Ararat Formation at the entrance to the Community Center. Upon securing permission, walk back to Mountain Road (cross road just before the Community Center) and turn left (east). Walk several hundred meters through a gate as the road becomes unpaved. Walk another several hundred meters and abandoned quarries will be on the left (north).

Stop 3: PERMIAN PEGMATITE QUARRY IN THE FALMOUTH-BRUNSWICK SEQUENCE.  
(0423700 m E, 4866206 m N)

Significant mining of pegmatite bodies in the Topsham-Bowdoinham area began in the 1850’s (King and Ashton, 2009) and continued until the 1950’s. The principal economic interest in these rocks was white potassium feldspar for use in the ceramics industry and these pegmatites contain both large feldspar crystals and spectacular examples of the graphic intergrowth of feldspar and quartz. In addition to the past mining activity, these pegmatites have been of keen interest to mineral collectors since the days of Bowdoin College Professor Parker Cleaveland in the early 1800’s. Many museum quality specimens of garnet, beryl, topaz, columbite, uraninite, and other minerals have been obtained from these rocks (Francis (1995) provides an overview of the mineralogy). Detailed investigations of the Topsham pegmatites were first made by Shainin (1948) and Cameron et al. (1954), and more modern geochemical and geochronological studies of these rocks have been presented by Tomascak et al. (1995a, b). Tomascak and Francis (1995) provide a nice summary of the earlier work on these rocks, as well as options for field trips to other pegmatite bodies in the area. Finally, Thompson et al. (2000, p. 378) provides a map showing over 30 different significant mineral localities in pegmatite bodies in the Topsham-Bowdoinham area.

This particular stop is in an old water filled quarry of the Consolidated Feldspar Company (#2) that operated in the Topsham area in the first half of the 20th century. Although much of the original relationships are obscured, this particular pegmatite body is intrusive into rocks of the Falmouth-Brunswick sequence and is one of the largest in the area. Tomascak et al. (1996a) report U-Pb monazite ages from the Topsham pegmatites range from 269-275 Ma and this Permian age of intrusion coincides with the timing of amphibolite facies metamorphism west of the Flying Point fault (West et al., 1993). Detailed petrologic and geochemical studies by Tomascak et al. (1995a, b) indicate peraluminous, REE-rich compositions, but accessory mineral assemblages are intermediate between those of the classically defined Niobium-Yttrium-Fluorine (NYF) and Lithium-Cesium-Tantalum (LCT) pegmatites (e.g., Cerny, 1992). Although finding gem quality specimens of exotic minerals requires significant patience, great examples of
extremely coarse grained muscovite and biotite are easily obtained – as are spectacular examples of quartz-feldspar graphic texture. Walk back to vehicles and return to Rt. 196 via Village Road.

5.0 Intersection with Rt. 196, Turn left (east) onto Rt. 196.
6.2 Bridge over the Androscoggin River, get in the left lane and merge onto Rt. 1 north
7.0 **Crossing the Flying Point fault.** The rocks on the east side of the fault belong to a different stratigraphic sequence (Casco Bay Group), have a different structural style, and different thermal history.
8.2 Exit onto Rt. 24 at Cooks Corner. Immediately get in the left lane and prepare to turn left
8.5 Turn left onto the Bath Road and proceed toward the east.
9.3 Crossing the thrust fault contact between the Casco Bay Group (west) and East Harpswell Group (east).
9.5 Turn right onto the Medical Center Drive at the entrance to the Midcoast Hospital.
10.0 Turn right into the Employee Parking area and park (Area H employee parking lot).

**Stop 4: BETHEL POINT FM. OF THE EAST HARPSWELL GROUP AT MIDCOAST HOSPITAL.**

(0428311 m E, 4861839 m N)

The freshly blasted exposures around the margins of the parking lot are very rusty-weathering quartz-mica-graphic schist of the Early Silurian Bethel Point Formation of the East Harpswell Group. This locality is in the axial region of the Hen Cove anticline and younger carbonate-bearing metasedimentary rocks of the Sebascodegan Formation can be found within a few hundred meters across strike on either side of this location. Underlying metavolcanic rocks of the Yarmouth Island Formation are exposed to the south farther down the axial region of the plunging fold (Hussey, 1971). Numerous granite sills up to several 10’s of meters across, presumably of Late Devonian age, generally underlie the high ground in the area. Stilplaminate can be found on some foliation surfaces and attests to the high-grade of Late Devonian metamorphism found here. Protoliths of this rock were probably black shales deposited in an anoxic basin. Return to cars and return to the Bath road via Medical Center Drive.

10.6 Turn left onto the Bath Road and drive back towards Cooks Corner
11.5 Turn left onto Rt. 24 South.
13.3 Pull over the side of the road adjacent to the low outcrops on the west side of the road.

**Stop 5: DYER COVE AMPHIBOLITE OF THE SEBASCODEGAN FORMATION ALONG Rt. 24.**

(0426920 m E, 4859178 m N)

This will be a quick stop, mainly because it was one of Arthur’s favorite “petrologic outcrops” in the area (Hussey, 1965, Stop #4). The rocks exposed in the low outcrops are thinly banded, carbonate-bearing amphibolites of the Dyer Cove member of the Sebascodegan Formation (uppermost unit of the East Harpswell Group). The thrust fault contact (not exposed) between these rocks and older rocks of the Cape Elizabeth Formation is less than two hundred meters to the west of this location. Arthur liked these rocks because thin sections from some layers contain three different amphiboles: hornblende, gedrite, and cummingtonite. The association with these minerals with thin calc-silicate layers led Arthur to believe the protoliths of these amphibolites were impure carbonate rocks rather than mafic igneous rocks. However, other amphibolites within the East Harpswell Group have a mineralogies and textures suggestive of mafic igneous origins. Return to cars and continue south on Rt. 24.

13.5 Note the low, light-colored outcrops on the east side of the road – which include a relatively pure marble layer over a meter thick. Several relatively narrow north-south oriented trenches in the area attest to the early 1800’s mining of thin marble horizons within the Sebascodegan Formation (Hussey, 2014).
15.1 Cross bridge onto Sebascodegan Island
20.2 Cross small bridge onto Orrs Island. The route from here down to Orrs Island will be parallel to the strike of nearly vertically dipping schists and quartzites of the Cape Elizabeth Formation.
24.2 Pull into the unpaved parking lot on the right (west) side of the road immediately before the Bridge to Bailey Island.

STOP 6: SPRING POINT FORMATION OF THE CASCO BAY GROUP AT THE CRIBSTONE BRIDGE.  
(0420437 m E, 4844412 m N)

The low dark colored outcrops immediately west of the bridge near the water’s edge are garnet-bearing amphibolites of the Spring Point Formation exposed along the eastern limb of the Harpswell Sound syncline (Hussey, 1971). Abundant large stretched garnets can be found in many horizons (Beane and Prior, 2002), and beautiful “fish-mouth boudinage” structure (Swanson, 1992) within the amphibolite is also common. Low relatively inconspicuous outcrops beneath the wall just to the north of this exposure are interlayered schists and quartzites of the underlying Cape Elizabeth Formation. The contact between the two formations is exposed here, and again on the south end of the bridge (east side). A better look at the Cape Elizabeth Fm. will be provided at the next stop.

The amphibolites of the Spring Point Formation are interpreted to represent metamorphosed mafic volcanic rocks and geochemical studies to the north indicate generation in a back-arc basin influenced by Ganderian crust (West et al., 2004). Additionally a U-Pb zircon age of 469 ± 3 Ma obtained from felsic meta-volcanic rocks of the Spring Point Formation in south-central Maine have been interpreted to represent the age of this volcanism (Tucker et al., 2001) in the Casco Bay Group.

24.4 Cross the very narrow Cribstone Bridge to Bailey Island. This historic bridge, constructed in the late 1920’s is one of only a few of this design in the world. The granite pillars used to construct the bridge were obtained from quarries just north of the village of Yarmouth, Maine.

25.9 Turn left onto Washington Ave. and proceed very cautiously as the road is very narrow

26.1 Washington Ave. takes a hard right turn and Ocean St. begins. At this intersection, park in the very small parking lot in front of the “All Saints by the Sea Episcopal Church” (except on Sunday mornings). Walk due east down Ocean Street to the shore and proceed to the south (right) along exposures

STOP 7: CAPE ELIZABETH FORMATION AT GIANT STEPS.  
(Beginning of seaside outcrops = 0419990 m E, 4841704 m N)

The nearly kilometer-long stretch of beautiful sea-side exposures along the public path provide great opportunities for geological exploration and teaching! The steeply dipping stratified rocks exposed here are interlayered mica schists and impure quartzites of the Cape Elizabeth Formation. The schists contain both garnet and staurolite and the isograd map of Dunn and Lang (1988) indicates the location is just to the south (low-grade side) of the sillimanite isograd. However, it should be noted that many of the quartz veins here contain pink andalusite and occasional sillimanite. Close examination also reveals numerous small-scale isoclinal upright folds and examples of boudinage.

The namesake of this shoreline walk (Giant Steps) is formed due to the differential erosion of a cross-cutting three-meter wide Mesozoic mafic dike (with chilled margins). Additionally, also cut by the dike, is a greenish-gray, talc-bearing sill within the stratified rocks. Hussey (2015, p. 125) discusses other occurrences of this metamorphosed ultramafic rock type within the Cape Elizabeth Formation, but an explanation for their origins remains elusive (they’ve never been studied). Return to vehicles and return to Rt. 24 via Washington Avenue.

26.2 Intersection of Washington Ave. with Rt. 24. Turn right onto Rt. 24 North.
27.8 Cross the very narrow Cribstone Bridge, returning to Orrs Island.
31.9 Cross bridge and return to Sebascodegan Island.
32.4 Turn left onto Mountain Road (signs for Harpswell)
33.2 Carefully pull over to the right side of the road in front of prominent outcrop
STOP 8 (OPTIONAL): CHRISTMAS COVE DIKE OF MESOZOIC AGE ON MOUNTAIN ROAD.  
(0424332 m E, 4850702 m N)

This optional stop is intended for those interested in Mesozoic igneous activity as it provides an exposure of one of the largest dikes in New England. The Christmas Cove dike (McHone et al., 2014), up to 35 meters in width, has been mapped discontinuously for nearly 200 kilometers across southern coastal Maine (e.g., see Hussey and Berry, 2000). Whole rock $^{40}$Ar/$^{39}$Ar ages from the dike indicate a crystallization age near the Triassic-Jurassic boundary (~200 Ma) and whole rock geochemistry suggests this and other large dikes in New England (e.g., Higganum dike in southern New England) were probably feeders to Mesozoic basin lava flows (McHone et al., 2014). At this location, the exact width of the dike cannot be determined because its contacts with adjacent rocks of the Cape Elizabeth Formation cannot be observed. Petrographic examination of the Christmas Cove dike here reveals micro-porphyritic textures that include larger crystals of orthopyroxene set in a finer grained matrix dominated by plagioclase, clinopyroxene and Fe-Ti oxides.

34.2 Cross bridge over to Harpswell Neck.
35.0 Turn left onto Rt. 123 South.
36.7 Turn right onto Lookout Point Road and proceed west.
37.4 Road ends, park vehicles in the parking area opposite the boat launch. Permission to visit the outcrops should be secured from the people who live in the house at the western tip of the point.

STOP 9: CUSHING FORMATION, INCLUDING WILSON COVE MEMBER, AT LOOKOUT POINT.  
(Parking area = 0420065 m E, 4850831 m N)

The outcrops of interest, Stop #9 of Hussey (1965, his figure reproduced below), are on the two islands just to the west of the boat launch and can be accessed, without getting wet, at low to mid-tide. Be aware of the tidal cycle when visiting as the water rises quickly during the incoming tide, and you could find yourself stranded!

Figure 5. Hand-drawn map of Hussey (1965) showing the rock types exposed at Lookout Point (Stop 9)
The light colored rocks on the islands are deformed and metamorphosed Ordovician volcanic rocks of the Cushing Formation. These include what Hussey (1965; 2014) has interpreted to represent volcanic breccia, and tuffaceous rocks of felsic to intermediate composition. The dark colored rocks exposed in the open synform on the northern of the two islands are metamorphosed iron- and manganese-rich rocks of the Wilson Cove member of the Cushing Formation (now garnet- and amphibole-rich granofels and gneiss). Small islands offshore to the west in Middle Bay with the names “Irony Island”, “Black Rock”, and “Little Iron Island” have exposures of these same rocks (Hussey, 1971). Detailed studies of the Wilson Cove unit farther to the north (West et al., 2008) indicate the protoliths represent a mixture of hydrothermal exhalatives and peri-Gondwanan terrigenous clastic sediment. Importantly, detailed work by Hussey at various locations around Casco Bay indicate a conformable contact relationship between the volcanic rock dominated Cushing Formation and the overlying meta-sedimentary rocks of the Cape Elizabeth Formation. Return to cars and drive back to Rt. 123 via Lookout Point Road (the only way out).

38.0  Turn right on to Rt. 123 South
43.0  Arrive at Estes Lobster House (just before the narrow causeway.  Park in the unpaved parking lot on the left.

**STOP 10: JEWELL FORMATION IN SOUTH HARPSWELL.**

(Parking area = 0418057 m E, 4843367 m N; Outcrop = 0418235 m E, 4843318 m N)

The outcrop of interest, Stop #8 of Hussey (1965), is located on the prominent point east of the parking area beyond the beach. The rocks exposed here are well bedded, garnet-bearing phyllites of the Jewell Formation, the upper-most unit of the Casco Bay Group. This locality is near the axial trace of the Harpswell Sound syncline (Hussey, 1971) – an upright, map-scale F2 fold that controls the distribution of various units within the Casco Bay Group on Harpswell Neck. These pelitic rocks are in the garnet zone, immediately south of the staurolite-in isograd (Dunn and Lang, 1988). Metamorphic conditions at the location have been estimated to be ~ 450-500°C at pressures of 2-3 kbars (Dunn and Lang, 1988; Daniel and Spear, 1998). Several detailed studies aimed at understanding garnet nucleation and growth in metamorphic rocks have focused on the rocks here (Lang and Dunn, 1990; Daniel and Spear, 1998; Spear and Daniel, 2001).

**End of Field Trip**

Return to Brunswick via Rt. 123 North. It is ~ 13 miles back to Brunswick, and ~ 15 miles back to Topsham.

**REFERENCES CITED**


Hussey A.M. II, and West, D.P., Jr., in review, Bedrock geology of the Brunswick 7.5’ quadrangle, Maine: Maine Geological Survey Map, Scale = 1:24,000.


