The Giant’s Stairs on Bailey Island, Northern Casco Bay, Maine

The nearly kilometer-long stretch of beautiful seaside bedrock exposures along the public path (maintained by the town of Harpswell) along the east side of Bailey Island provide great opportunities for geological exploration and teaching. The namesake of this shoreline walk (Giant’s Stairs) is formed due to differential erosion of a three-meter wide Mesozoic mafic dike that cross-cuts the strongly deformed Ordovician metasedimentary rocks. Below we provide a brief overview of the geologic history of the area with references to the more detailed studies that have been completed. Relevant small-scale geologic maps of the region are provided in the Appendix, as are beautifully detailed drone-generated geologic maps of the outcrops of interest that have been generously provided by Mark Swanson. The original 1:24,000 scale geologic mapping this portion of Casco Bay was completed by Hussey (1971), and subsequent detailed structural, metamorphic, and thermochronological studies in the immediate region are referred to below.

Ordovician Volcanic Arc/Back-arc Protoliths

The steeply dipping stratified rocks exposed at Giant’s Stairs are interlayered mica schist and impure quartzites of the Middle Ordovician (~470 Ma) Cape Elizabeth Formation of the Casco Bay Group. These rocks were originally deposited as volcanogenic sediments flanking an actively eroding volcanic arc/back arc terrane build upon a peri-Gondwanan crustal fragment (Gander) outboard of the Laurentian margin (Fig. 1). Metamorphosed Ordovician volcanic rocks associated with this arc/back-arc sequence are found nearby in the Cushing and Spring Point formations of the Casco Bay Group, and the Yarmouth Island Formation of the East Harpswell Group. Subduction of intervening oceanic lithosphere between Laurentia and Ganderia led to the accretion of the volcanic arc terranes in Late Silurian time (Salinic orogeny). Continued Devonian convergence between these crustal blocks, and the intervening sedimentary basins and volcanic arc/back-arc sequences, led to deep burial, amphibolite facies metamorphism, complex deformation of these belts, along with magma intrusion (Acadian orogeny), as shown in Fig. A1. Details of the pre-accretionary history of these rocks can be found in Hussey et al. (2010), West et al. (2004; 2021), and references therein.

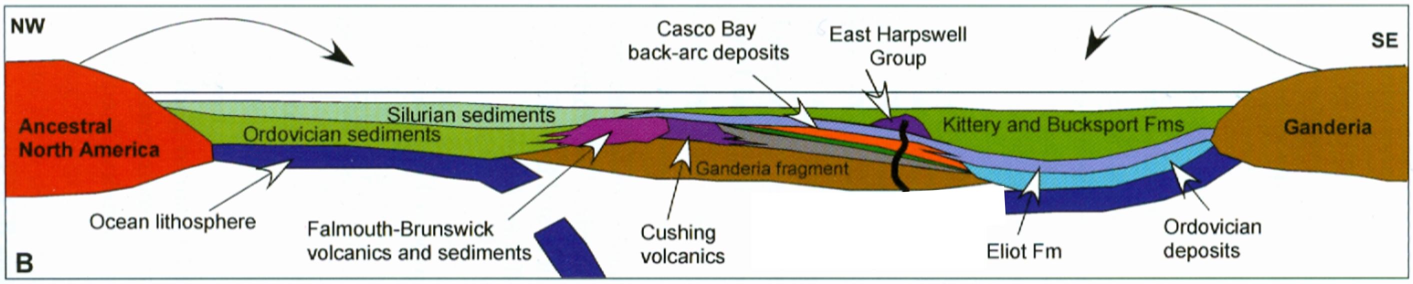


Figure 1. A highly schematic tectonic diagram modified from Hussey (2015) showing the hypothesized tectonic setting in southwestern Maine in Early Silurian time. Note that earlier subduction towards the southeast in Ordovician time produced volcanic arc (Falmouth Brunswick Group) and back-arc (Casco Bay and East Harpswell groups) deposits that were built upon a fragment of Ganderia. In this model, Silurian sediments derived primarily from ancestral North America were deposited northwest of the arc sequence (Central Maine belt) and Silurian sediments derived primarily from Ganderia were deposited southeast of the actively eroding volcanic arc sequence (Kittery and Bucksport formations of the Merrimack and Fredericton belts, respectively).

Structural Geology

The style of folding and associated ductile deformational structures in the northern Casco Bay region differ dramatically on either side of the Flying Point fault of the Norumbega fault system (see the schematic cross-section in Fig. A2, and see Fig. 2 of Solar and Tomascak, 2016). 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; 2016) and Solar and Tomascak (2016) have suggested that the relatively flat structures west of the Flying Point fault are consistent with an episode of northwest directed thrusting associated with dextral transpression in the Casco Bay restraining bend of the Norumbega fault system (Fig. 2). In stark contrast, east of the Flying Point fault where the Giant’s Stairs exposures are located, stratified rocks are dominated by steep dipping foliation, sub-horizontal 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 northern Casco Bay (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; 2016). 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.

Included in the Appendix are drone-generated images of the Giant's Stairs outcrops that have been generously provided by Mark Swanson in association with his detailed structural studies of the exposure. What follows is an overview of the structures at the exposure taken directly from Stop 3 of Mark's field trip guide (2016): ***". . . host rock foliation is very steeply-dipping to near-vertical in orientation with gentle SW-plunging stretching lineations. These outcrops exhibit numerous deformed and reoriented quartz-filled boudin partings running oblique across the steep foliation. This consistent geometry suggests initial layer-parallel elongation and the development of orthogonal boudin partings followed by CW rotation due to right-lateral shear. While many of the quartz-filled partings have developed clear asymmetric geometries due to a simple shear component but others show signs of layer-normal shortening in a pure shear component. A single distinctive 30 cm thick amphibolite layer exposed at the base of the outcrop cliff edge has separated into boudin pods along initially-orthogonal partings that have evolved through CW rotation and layer-parallel right lateral simple shear. The resulting boudin geometry has changed from rectangular to parallelogram reflecting the internal layer-parallel shear within the amphibolite."***

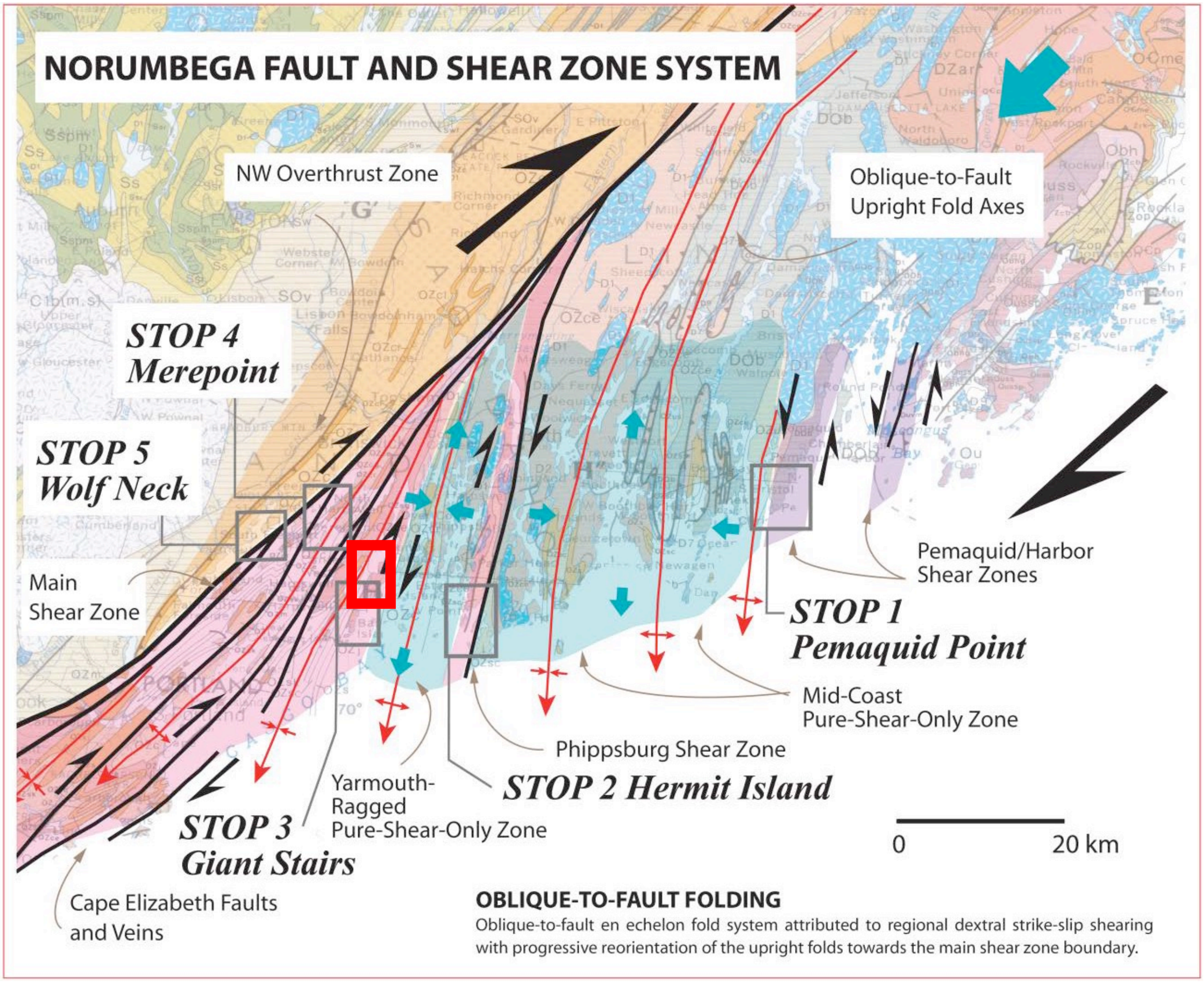


Figure 2. This is a reproduction of Figure 1 of Mark Swanson's regional field trip through the region in 2016. The location of Giant's Stairs within the southeastern flank of the Norumbega fault system is highlighted in the red box. The geologic base map is modified from Osberg et al. (1985).

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 Al_2SiO_5 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 (see Fig. A2), 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 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}Ar/^{39}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. ***The more aluminous layers of Cape Elizabeth Formation at Giant's Stairs 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.***

Thermochronology

In addition to making an abrupt change in structural style, the Flying Point fault of the Norumbega fault system marks a major thermochronological discontinuity (Fig. 3). Rocks east of the Flying Point fault last experienced high-grade metamorphism in the Late Devonian and had cooled below ~ 200^{o}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^{o}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.

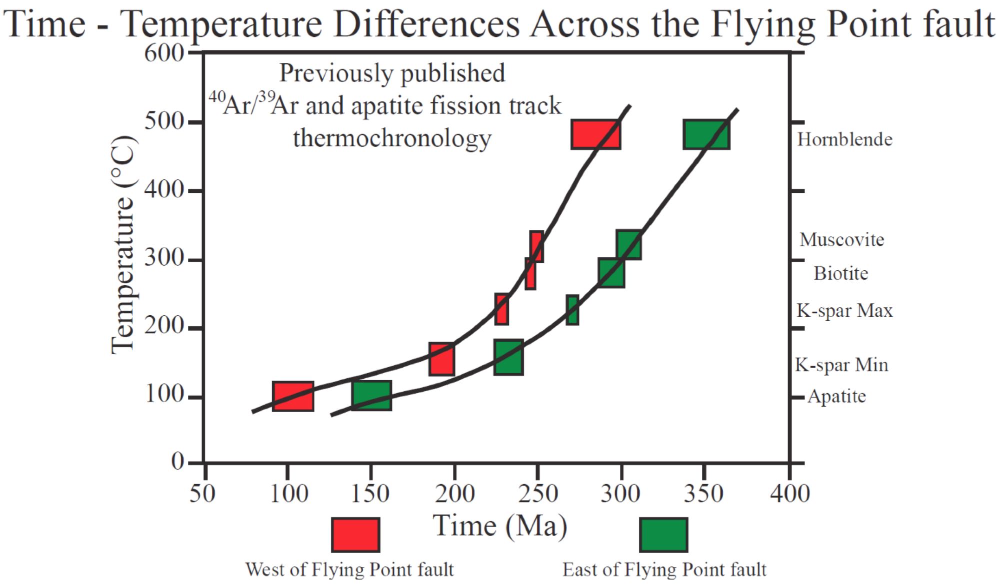


Figure 3. Previously determined ^{40}Ar/^{39}Ar (West et al., 1993) and fission track (West and Roden-Tice, 2003) mineral ages reveals a major time-temperature discontinuity across the Flying Point fault in the Brunswick-Bath area. The thermochronology indicates throughout the Late Paleozoic, Mesozoic, 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.

Appendix Figures

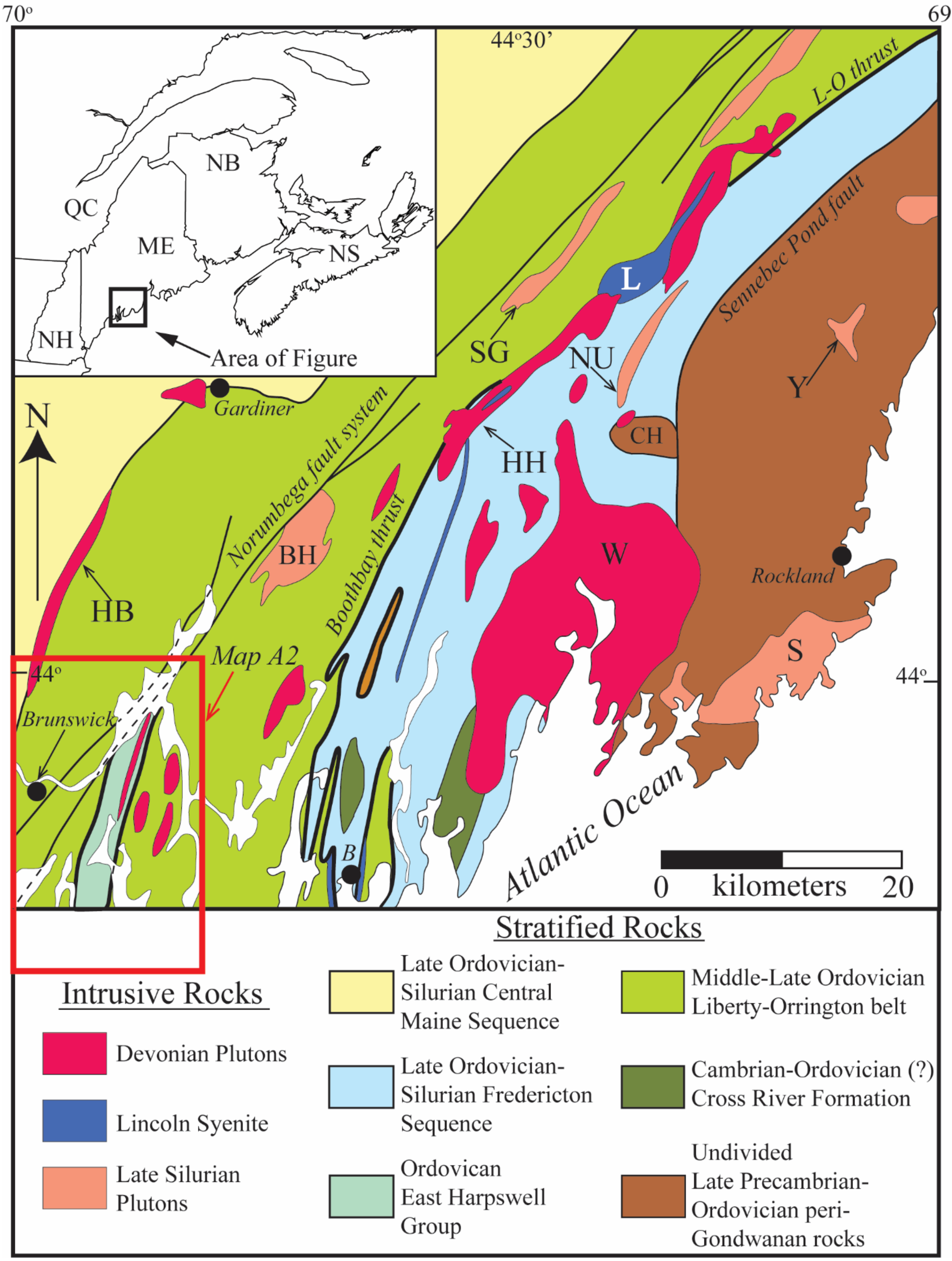
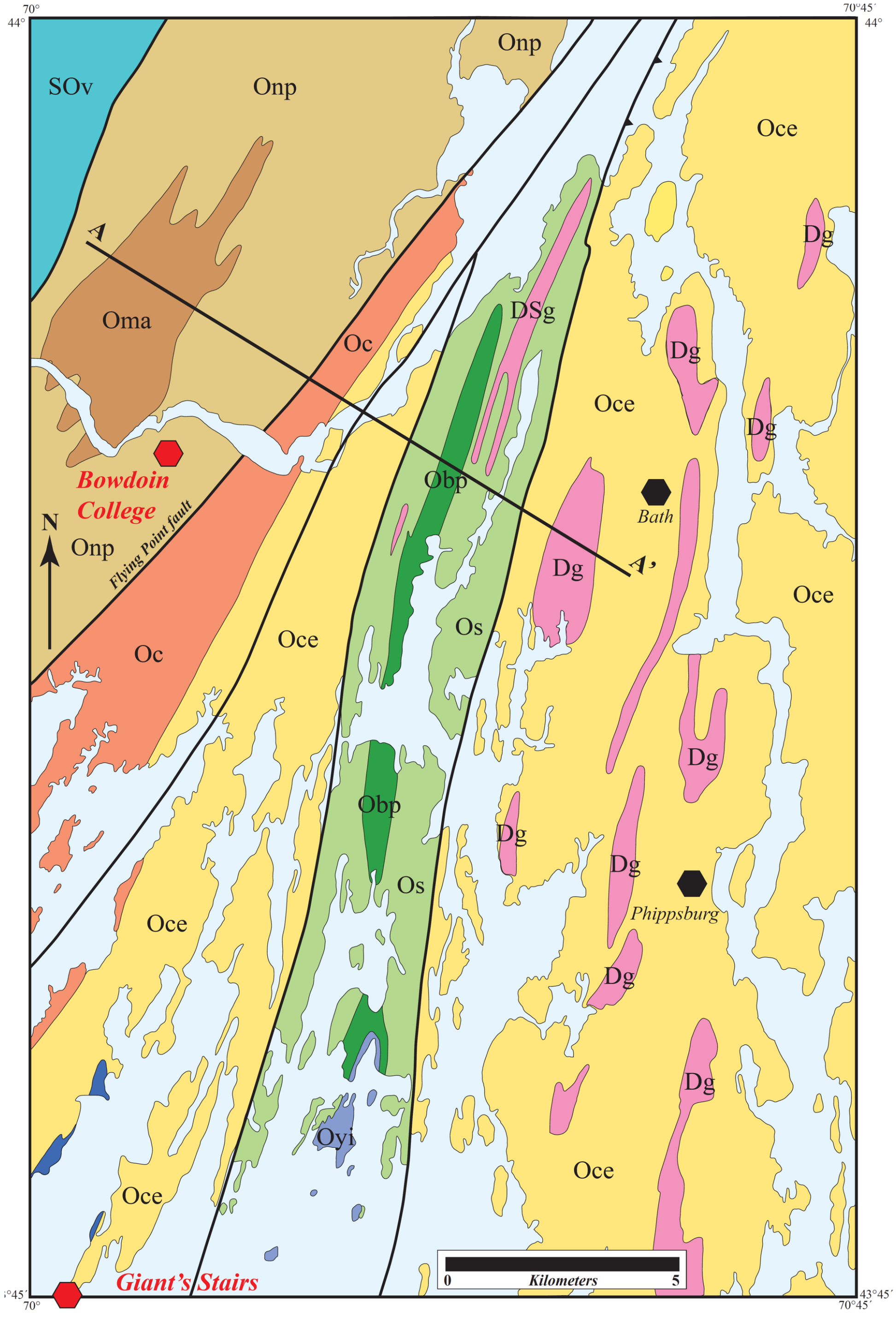


Figure A1. Generalized geologic map of mid-coastal Maine showing the major lithotectonic belts, bounding faults, and Paleozoic intrusive rock bodies (modified from Osberg and others, 1985; Hussey and Marvinney, 2002; Gerbi and West, 2007). BH = Blinn Hill granite gneiss (424 ± 2 Ma); HB = Hornbeam Hill granite gneiss (393 ± 4 Ma: Gerbi and West, 2007); HH = Haskell Hill granite gneiss (408 ± 5 Ma); SG = Lake St. George granite gneiss (422 ± 2 Ma); L = Lincoln syenite (418 ± 1 Ma); L-O = Liberty-Orrington thrust; NU = North Union granite gneiss (422 ± 2 Ma); S = Spruce Head granite (421 ± 1 Ma); W = Waldoboro granite (368 ± 2 Ma); Y = Youngtown granite (420 ± 2 Ma). *B* = Boothbay Harbor; *SP* = Small Point located ~10 kilometers south. Unless otherwise indicated, all quoted ages are U-Pb zircon ages from Tucker and others (2001). The red box outlines the area of Figure A2.



Stratified Rocks

Central Maine Sequence

SOv	Vassalboro Group (undivided)

Falmouth-Brunswick Seq.

Oma	Mt. Ararat Fm.
Onp	Nehumkeag Pond Fm.

Flying Point fault

Casco Bay Group

Ouc	Upper Casco Bay Group (Undivided)
	Cape Elizabeth Fm.
Oc	Cushing Fm.

East Harpswell Group

Os	Sebascodegan Fm.
Obp	Bethel Point Fm.
Oyi	Yarmouth Island Fm.

Highly Schematic Cross Section

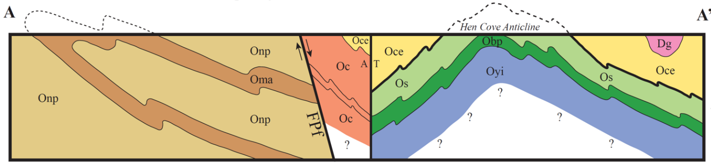


Figure A2. Generalized geology of the northern Casco Bay area showing the distribution of the major rock units and prominent fault locations. **Note that the Giant's Steps field site is just off the southwestern corner of the map and is entirely within the Cape Elizabeth Formation.** The highly schematic cross-section shown above is located along the A-A' line indicated on the map to the right. Note the relatively moderate east-dipping orientation of structures west of the Flying Point fault (FPf), versus the upright nature of structures to the east of the fault. The geology portrayed on the map is modified from Hussey (1971), Hussey and Marvinney (2002), and Hussey and West (2018). The cross-section is modeled after Hussey and Marvinney (2002), and Hussey and West (2018).

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