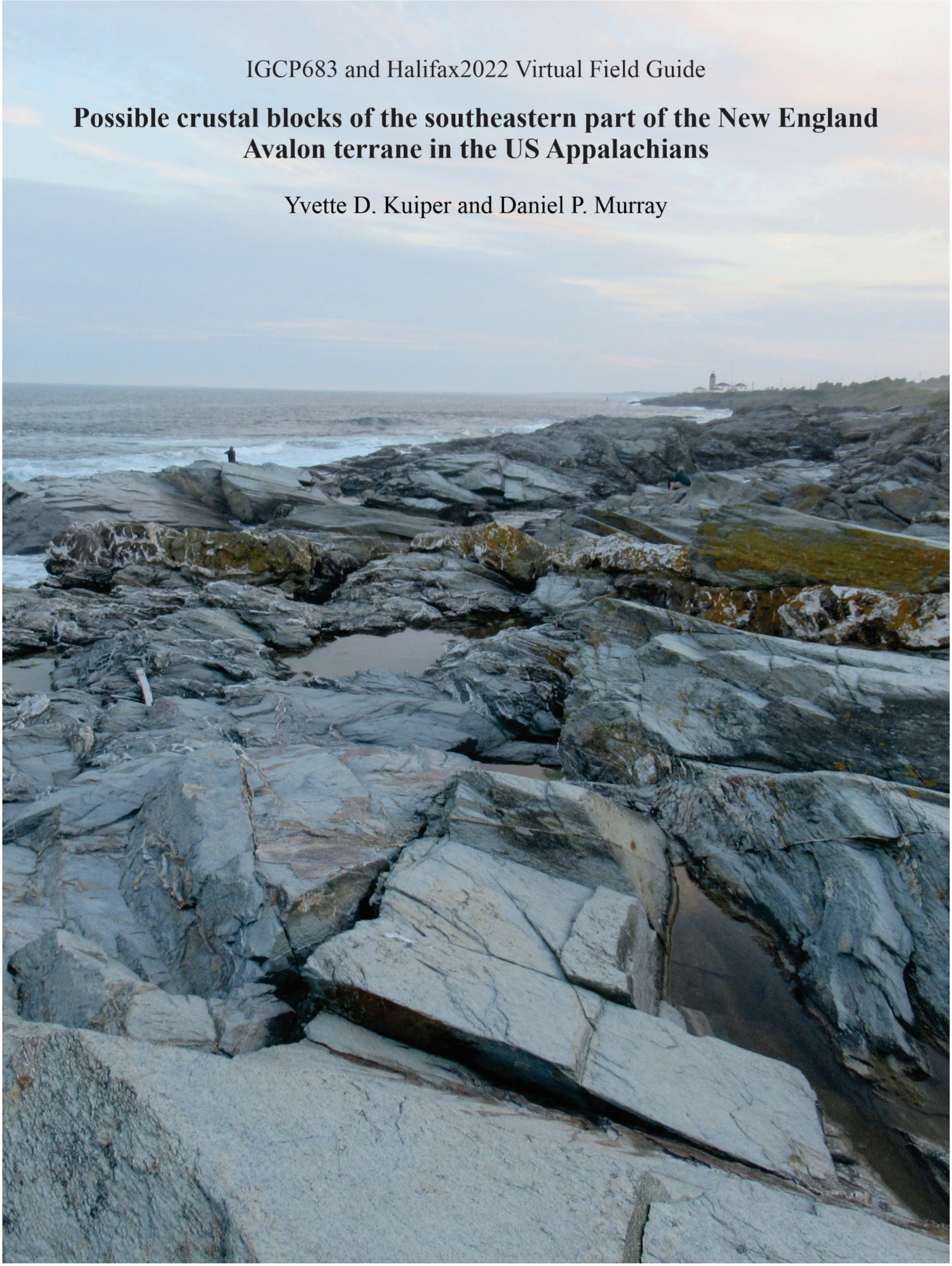
IGCP683 and Halifax2022 Virtual Field Guide

Possible crustal blocks of the southeastern part of the New England Avalon terrane in the US Appalachians

Yvette D. Kuiper and Daniel P. Murray



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Possible crustal blocks of the southeastern part of the New England Avalon terrane in the US Appalachians

Part of field trip "Correlations and comparisons of crustal blocks in eastern North America with northwest Africa and Iberia", May 19-23, 2022

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OVERVIEW

On this field trip, participants are introduced to possible crustal blocks of the southeastern part of the New England Avalon terrane. This field trip primarily builds on recent results from a U–Pb detrital zircon geochronology investigation by the field trip leaders and collaborators that revealed the Neoproterozoic Newport Group around Newport, Rhode Island (RI), as a possible non-Avalonian block. The potential exotic nature and history of the Newport Group, as well as structural and petrologic intricacies of the southeastern part of the New England Avalon terrane will be discussed.

We first visit rocks of the northern and western parts of the Southeastern New England Avalon terrane that correlate well with Avalonian terranes in Newfoundland, Nova Scotia and New Brunswick, Canada, based on rock types and ages, U–Pb detrital zircon signatures of metasedimentary rocks, and Sm–Nd isotope geochemistry data. Stops include: (1) a quartzite of the Neoproterozoic Blackstone Group (2) a quartzite of the Cambrian North Attleboro Formation, and (3) the Conanicut Group of Beavertail State Park, RI, all of which show or hint at correlations with the Avalon terrane based on U–Pb detrital zircon analysis. An enigmatic pillow basalt is exposed in what has been interpreted as the Blackstone Group, but may be as young as its youngest, latest Devonian zircon. If so, it may correlate with the basal Wamsutta Formation of the latest Devonian to Permian Narragansett Basin that overlies parts of the Southeastern New England Avalon terrane, which contains the only known other undeformed basalt in the area.

We then visit the Price Neck and Newport Neck formations of the Neoproterozoic Newport Group in southern Rhode Island, which, based on U–Pb detrital zircon analyses, have a likely northwest African affinity. The Newport Group may thus represent a subterrane, terrane or other crustal block with a different origin and history than the southeastern New England Avalon terrane to the northwest. The boundary of this Newport Block may be restricted to the boundaries of the Newport Group, or it may extend as far north as Weymouth, Massachusetts (MA), as far northwest as (but not including) the North Attleboro Formation quartzite and associated rocks in North Attleboro, MA, and as far west as Warwick, RI, where eastern exposures of the Blackstone Group quartzite exist. Its eastern limit is most of the New Bedford region, where granitic and gneissic rocks have Avalonian affinities.

We finish our trip with the New Bedford area, where, unlike the areas described above, the metamorphic grade is high and structures trend west, as in the southwestern part of the New England Avalon terrane. This is in contrast with the greenschist and lower metamorphic grades, and northerly-trending structures of the domains described above. Preliminary detrital zircon analysis suggests an Avalonian affinity for this area.

GEOLOGICAL BACKGROUND

Avalonia comprises a ~20–200 km wide zone of subterranes that define the eastern flank of the northern Appalachians between Newfoundland, Canada, and southeastern New England in the USA. These terranes are considered to represent the remnants of a microcontinent that rifted from supercontinent Gondwana in the Ordovician (e.g. Nance et al., 2008; Pollock et al., 2012) and accreted to Laurentia during the latest Silurian to Middle Devonian Acadian orogeny (e.g., Skehan and Rast, 1990; Nance et al., 2008; van Staal et al., 2009; Hatcher, 2010). The southeastern New England Avalon terrane in southeastern Massachusetts (MA), Rhode Island (RI) and southeastern Connecticut (CT) is comparable with Avalonian terranes in Newfoundland, Nova Scotia and New Brunswick, Canada (Fig. 1a), and collectively these are called Avalonia, or West Avalonia to distinguish it from East Avalonia in Europe (Williams and Hatcher, 1982, 1983; Rast and Skehan, 1993; van Staal, 2005; Hibbard et al., 2007).

The southeastern New England Avalon terrane is bounded to the northwest by the Honey Hill — Lake Char — Bloody Bluff fault system (Fig. 1c), and is characterized by tectonostratigraphic relationships between Proterozoic to Permian rocks that are distinct from those in the rest of New England. The Avalon terrane of southeastern New England consists of Proterozoic rocks including widespread Ediacaran granitoid rocks and Cambrian sedimentary and volcanic rocks (Hepburn et al., 1993; Thompson et al., 1996, 2007, 2010; cf. Zartman and Naylor, 1984; Kuiper et al., 2022; Severson et al., 2022) and Ediacaran to Devonian alkaline plutons (Hermes and Zartman, 1985, 1992; Thompson et al., 2018) (Fig. 1c, d). In the Late Devonian to Carboniferous, graben sediments of the Narragansett and Norfolk basins (Fig. 1c) were deposited (e.g., Mosher, 1983; Skehan et al., 1986; Thompson and Hermes, 2003; Murray et al., 2004 and references therein). Metamorphism throughout much of the Avalon terrane in southeastern New England is no higher than greenschist facies, but locally reached the amphibolite facies (Grew and Day, 1972; Goldsmith, 1991c; Wintsch et al., 1992, 2014; Fetherston et al, 2014). Much, if not all, of the ductile deformation and metamorphism in the southern part of the Avalon terrane of southeastern New England may be attributed to the Alleghanian orogeny (e.g., Wintsch et al., 2014), which resulted from the formation of Pangea.

The northern part of the southeastern New England Avalon terrane (Fig. 1c) correlates with Avalonian terranes in Canada, based on rock types and ages, and U–Pb detrital zircon signatures of metasedimentary rocks (Hepburn et al., 2008; Thompson and Bowring, 2000; Thompson et al., 2012, 2014; Kuiper et al., 2022). The Newport area, and possibly adjacent areas, has previously been interpreted as part of Avalonia. However, recent U–Pb detrital zircon data suggest a northwest African origin (Kuiper et al., 2022). The southeasternmost tip of MA and adjacent offshore regions, southeast of the Nauset magnetic anomaly (Fig. 1a) have previously been interpreted as the Gondwanan-derived Meguma terrane, based on seismic reflection, gravity and magnetic surveys, and K–Ar dates (e.g., Hutchinson et al., 1988; Stewart et al., 1993; van Staal et al., 2009; White and Barr, 2010). The Meguma terrane departed from Gondwana in the early Silurian (MacDonald et al., 2002) and accreted to Laurentia during the Middle Devonian to Earliest Carboniferous (e.g., van Staal et al., 2009; White and Barr, 2010). The terrane is exposed in Nova Scotia, Canada (Fig. 1a), but not in southeastern MA. The presence of an Ediacaran granite in southeastern MA, southeast of the Nauset magnetic anomaly (Leo et al., 1993; CC2 in Fig. 1c) is not consistent with the Meguma terrane in Nova Scotia, which does not contain Precambrian rocks. The area southeast of the Nauset magnetic anomaly is more likely to be part of the Avalon terrane, or alternatively part of a northwest African crustal block, as is present below the Georges Bank, 143 km east-southeast of Nantucket, MA, near the

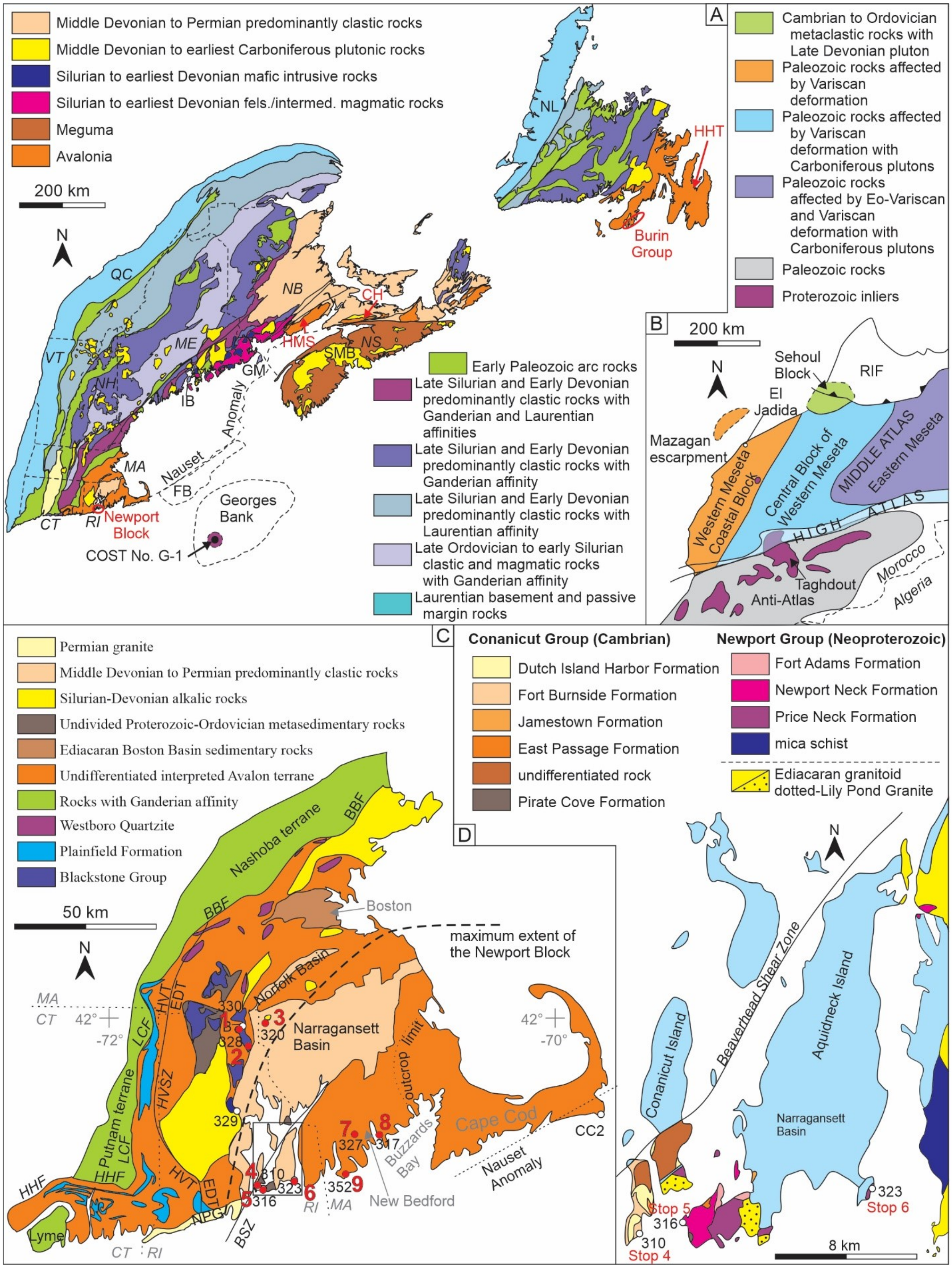

A
Middle Devonian to Permian predominantly clastic rocks
Middle Devonian to earliest Carboniferous plutonic rocks
Silurian to earliest Devonian mafic intrusive rocks
Silurian to earliest Devonian fels./intermed. magmatic rocks
Meguma
Avalonia
200 km
N
QC
VT
NH
ME
NB
NS
MA
CT
RI
NL
HHT
Burin Group
CH
HMS
SMB
GM
IB
Anomaly
Nauset
FB
Georges Bank
Newport Block
COST No. G-1
Early Paleozoic arc rocks
Late Silurian and Early Devonian predominantly clastic rocks with Ganderian and Laurentian affinities
Late Silurian and Early Devonian predominantly clastic rocks with Ganderian affinity
Late Silurian and Early Devonian predominantly clastic rocks with Laurentian affinity
Late Ordovician to early Silurian clastic and magmatic rocks with Ganderian affinity
Laurentian basement and passive margin rocks
Cambrian to Ordovician metaclastic rocks with Late Devonian pluton
Paleozoic rocks affected by Variscan deformation
Paleozoic rocks affected by Variscan deformation with Carboniferous plutons
Paleozoic rocks affected by Eo-Variscan and Variscan deformation with Carboniferous plutons
Paleozoic rocks
Proterozoic inliers
B
200 km
N
Sehoul Block
RIF
El Jadida
Mazagan escarpment
Western Meseta Coastal Block
Central Block of Western Meseta
MIDDLE ATLAS
Eastern Meseta
HIGH ATLAS
Taghdout
Anti-Atlas
Morocco
Algeria
C
Permian granite
Middle Devonian to Permian predominantly clastic rocks
Silurian-Devonian alkalic rocks
Undivided Proterozoic-Ordovician metasedimentary rocks
Ediacaran Boston Basin sedimentary rocks
Undifferentiated interpreted Avalon terrane
Rocks with Ganderian affinity
Westboro Quartzite
Plainfield Formation
Blackstone Group
50 km
N
Nashoba terrane
BBF
Boston
maximum extent of the Newport Block
Norfolk Basin
Narragansett Basin
outcrop limit
Cape Cod
CC2
Nauset Anomaly
Buzzards Bay
New Bedford
Putnam terrane
LCF
HVSZ
HVT
EDT
HHF
NPG
BSZ
Lyme
42°
-72°
-70°
330
328
320
329
327
317
310
316
323
352
Conanicut Group (Cambrian)
Dutch Island Harbor Formation
Fort Burnside Formation
Jamestown Formation
East Passage Formation
undifferentiated rock
Pirate Cove Formation
Newport Group (Neoproterozoic)
Fort Adams Formation
Newport Neck Formation
Price Neck Formation
mica schist
Ediacaran granitoid dotted-Lily Pond Granite
D
N
Beaverhead Shear Zone
Conanicut Island
Aquidneck Island
Narragansett Basin
Stop 4
Stop 5
Stop 6
8 km

Figure 1. Generalized geology and location maps. (a) Geological map of the northern Appalachians (modified after Hibbard et al., 2006). Abbreviations: CH—Cobequid Highlands; FB—Franklin Batholith; GM—Grand Manan; HHT—Hawke Hills Tuff; HMS—Hammondvale Metamorphic Suite; IB—Islesboro; SMB—South Mountain Batholith. Possible sources for or correlative units with the Newport Group in RI in red. States/provinces: CT—Connecticut; MA—Massachusetts; ME—Maine; NB—New Brunswick; NL—Newfoundland; NS—Nova Scotia; NH—New Hampshire; QC—Quebec; RI—Rhode Island, VT—Vermont. COST No. G-1 is a well location. (b) Geological map of northern Morocco (modified after Michard et al., 2010). (c) Geological map of the southeastern New England Appalachians (modified after Zen et al., 1983; Rodgers, 1985; Hermes et al., 1994; Hepburn et al., 2008; Thompson et al., 2012). Sample numbers indicated with locations (white circles). Field trip **Stops 1-9** indicated in red. Box outlines location of (d). Fault/shear zones (italic): BBF—Bloody Bluff Fault; BSZ—Beaverhead Shear Zone; HHF—Honey Hill Fault; HVSZ—Hope Valley Shear Zone; LCF—Lake Char Fault. State abbreviations as in (a). Terranes: EDT—Esmond-Dedham subterrane; HVT—Hope Valley subterrane. NPG—Narragansett Pier Granite. (d) Geological map of south-central Rhode Island after Hermes et al. (1994) with sample locations and **Stops 4-6** indicated.

eastern continental boundary of North America (Fig. 1a; Kuiper et al., 2017). The detrital signature of these rocks is most consistent with the Paleoproterozoic Taghdout quartzite of the Anti-Atlas of Morocco (Fig. 1b), which is part of a Paleoproterozoic passive margin sequence that exists directly on top of the Archean–Paleoproterozoic West African Craton (e.g., Abati et al., 2010). Because the Anti-Atlas was adjacent to MA at the time of Pangea, the simplest interpretation is that the crustal block remained behind after the breakup of Pangea (Kuiper et al., 2017). Alternatively, it may have arrived earlier as the other Gondwanan terranes described above and below. The Newport Group may or may not be part of this same crustal block and its potential history will be discussed.

Blackstone Group

The Blackstone Group as shown on the bedrock geologic map of RI (Hermes et al., 1994; Fig. 1c, 2) represents a diverse suite of northwest-trending metaigneous and metasedimentary rocks that primarily occur in northeastern RI in the vicinity of the Blackstone River (Quinn, 1971; Quinn et al., 1949). It consists of the following map units (Hermes et al., 1994, and references therein): (1) greenstone (formerly called the Hunting Hill greenstone by Quinn, 1971), amphibolite, serpentinite, (2) quartzite (formerly called the Quinnville quartzite by Quinn, 1971) and marble, (3) epidote and biotite schist (formerly called the Sneech Pond schist and Mussey Brook schist by Quinn (1971), and (4) undifferentiated rock. Although there are no radiometric or fossil dates from the Blackstone Group it is presumed to be the oldest sequence in RI, as the 599 ± 2 Ma Esmond Granite (Thompson et al., 2010) truncates an early schistosity (Dreier, 1985), and contains roof pendants of the Blackstone Group. Subsequent Permian metamorphism and deformation related to the Alleghanian orogeny overprint these features, making it difficult to determine the extent to which they are evidence of widespread Neoproterozoic 'Avalonian' tectonism that affected the southeastern New England Avalon terrane (Dreier, 1985; Bailey et al., 1989; cf. van Staal et al., 2020).

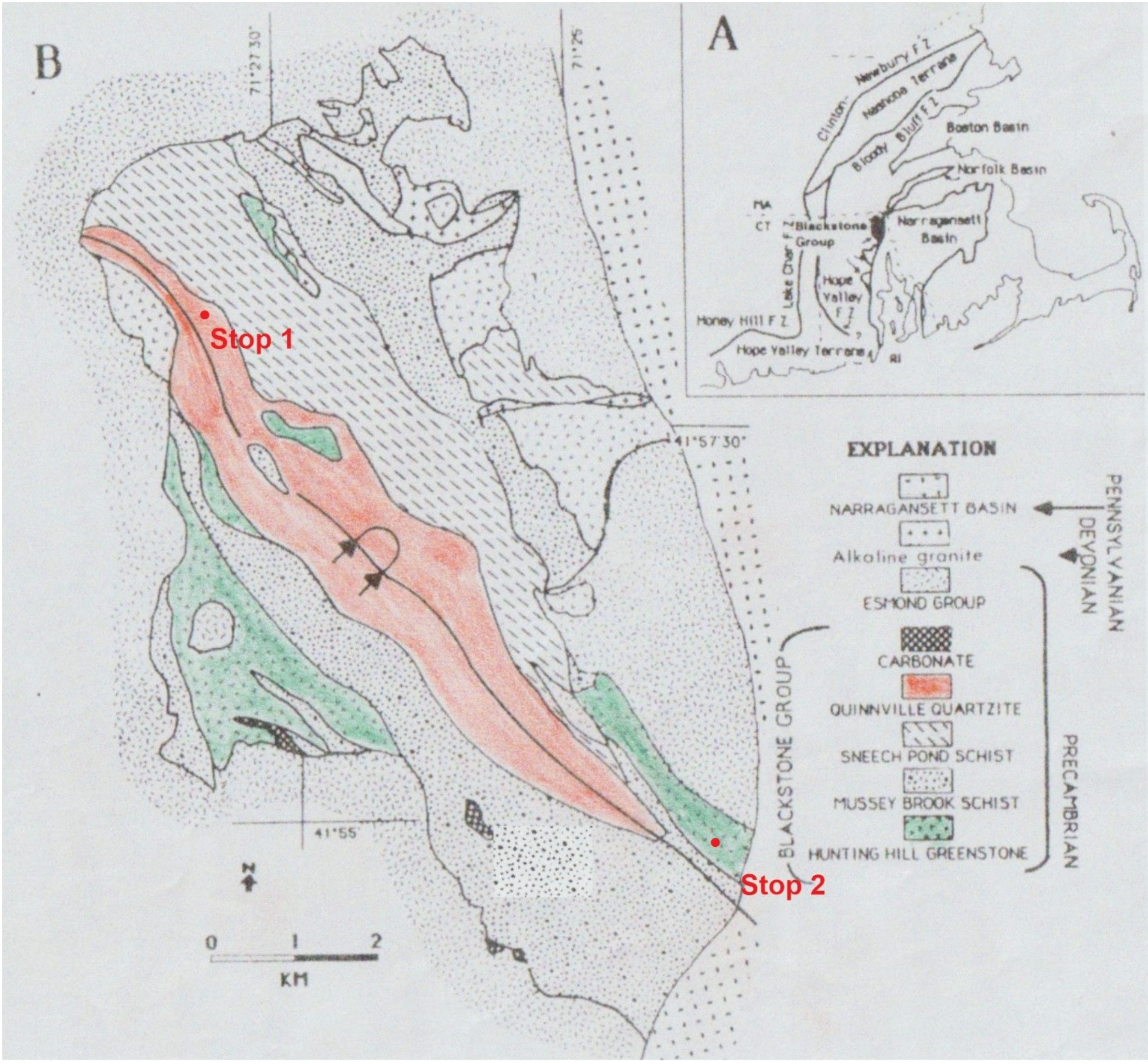


Figure 2. (a) Blackstone Group outcrop location in eastern Rhode Island in its regional setting (from Bailey et al., 1989; modified from Dreier, 1985). (b) Geologic map of the Blackstone Group in northeastern Rhode Island (from Bailey et al., 1989). The red dots mark the approximate location of **Stops 1 and 2**.

Attempts to define a coherent stratigraphy within the Blackstone Group have proven difficult, as mafic volcanic rocks are tectonically interleaved with mature continental sedimentary rocks. However, based on mapping and structural analysis, Dreier (1985) identified a stratigraphy with the Hunting Hill Greenstone at the base, and the Quinnville quartzite at the top. As described by Dreier (1985) and Bailey et al. (1989), the Quinnville quartzite occurs as lenses and layers of quartz arenite interbedded with mudstone, and all units of the Blackstone Group display evidence of soft-sediment deformation. They consider that at least in the Blackstone River Valley region, where the Blackstone Group is best exposed (Fig. 2), the tectonostratigraphic relationships represent an olistostrome that formed as part of the early stages of the Neoproterozoic Avalonian orogeny (Dreier, 1985; Bailey et al., 1989; Fig. 3). The

Plainfield Formation in eastern CT and western RI and adjacent MA, and the Westboro Formation of MA may be correlated with the Blackstone Group, based upon similarities in detrital zircon age patterns (Kuiper et al, 2022).

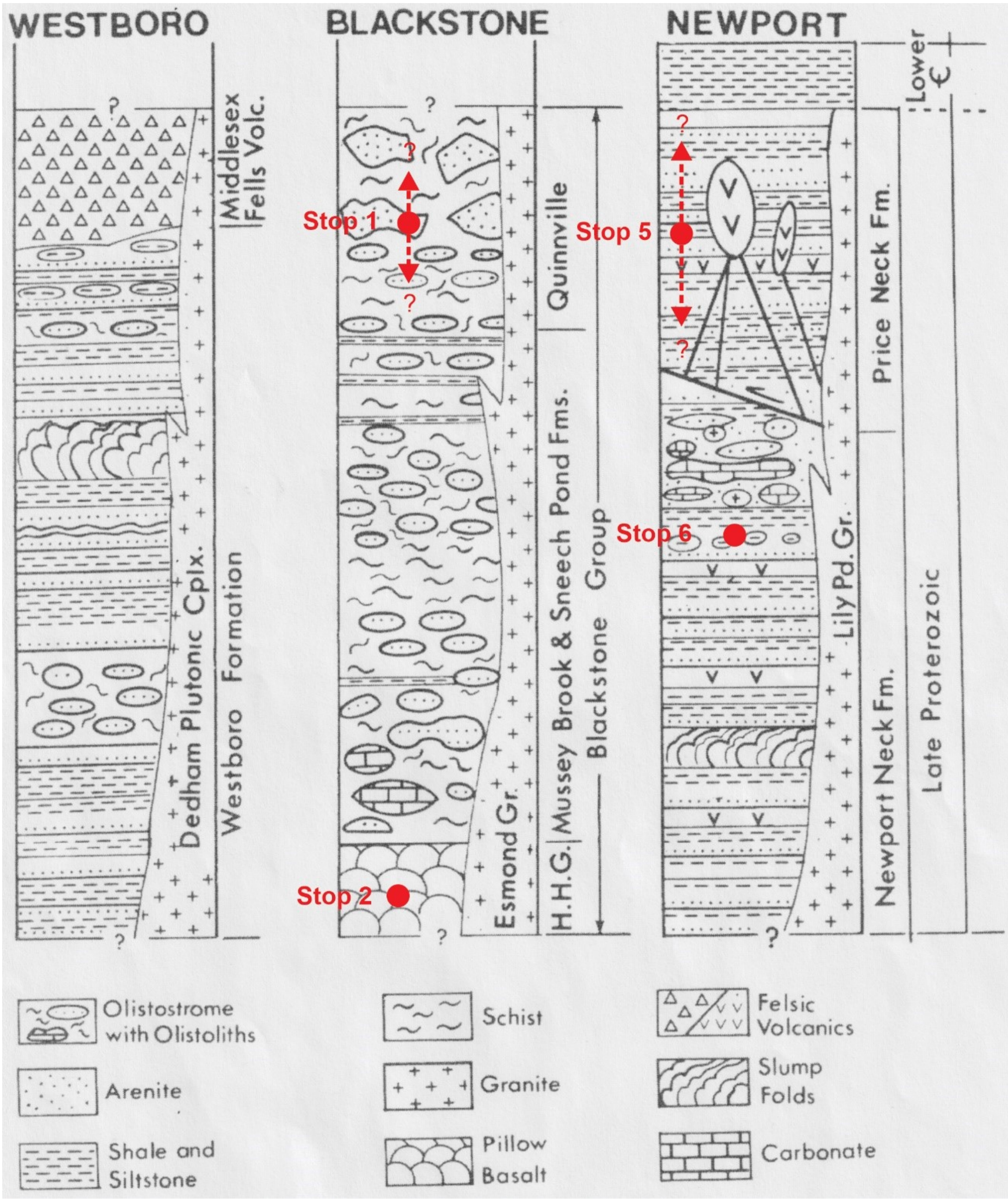


Figure 3. Schematic comparative stratigraphic columns showing the distribution of olistostromes and associated rocks. Hunting Hill Greenstone labeled H.H.G. Thicknesses not to scale; approximate thickness of Westboro Formation is 1,100 m, Blackstone Group 2,000 m, Newport Neck Formation 525 m. From Bailey et al. (1989). The Blackstone (modified from Dreier, 1985) and Newport (modified from Webster, 1986) columns pertain to **Stops 1, 2, 5 and 6** (indicated in red) on this field trip.

The Pillow Basalt Problem: Pillow basalts have long been recognized as one of the most distinctive players in the Avalonian narrative. They are ubiquitous within the Blackstone Group (Rose, 1985; Dreier, 1985; Bailey et al., 1989), where they occur as massive to pillow basalts that are interlayered with mafic volcaniclastic and epiclastic rock. U-Pb LA-ICPMS of zircon from a pillow basalt from one of the classic occurrences of the lithology (Stop 2; Fig. 2) yielded not only Proterozoic ages, but also late Silurian to Early Devonian and one Late Devonian age (see Stop 2). The age of this youngest zircon is not surprising, as there are Devonian alkalic basalts in the region (Maria and Hermes, 2001), but it raises the question as to whether other putatively Neoproterozoic basalts in the Blackstone Group may in fact be Devonian. Stay tuned!

North Attleboro Formation quartzite

At Hoppin Hill (in North Attleboro, MA; see location of sample 320 in Fig. 1c), massive to cross-bedded quartzite nonconformably overlies Ediacaran Dedham Granite, and in turn is overlain by fossiliferous red shale with shell hash limestones at several horizons (Fig. 4). Shaler et al. (1899) described early Cambrian fauna from here, and since then additional studies documented the presence of a siliciclastic stratigraphy with affinities to Cambrian rocks of the Avalon platform. Detailed maps showing measured stratigraphic sections and descriptions of the paleontology and paleoenvironmental setting for this site are given in Antsey (1979), Landing (1988, 1996), and Goldsmith (1991a). The units seen at this locale were called the Hoppin Formation on the Massachusetts Bedrock Geologic Map (Zen, ed., 1983), but subsequently the quartzite was named the North Attleboro Formation and the shale plus limestone were referred to as the Weymouth Formation (Landing, 1988, 1996). Further discussion of the Cambrian section at Hoppin Hill, in terms of its depositional setting and relationship to other contemporaneous Avalonian successions, are given in Landing (1988, 1996; Landing et al., 2022) and Goldsmith (1991a). One sample of North Attleboro Formation quartzite was analyzed. Data are presented below with the field stops.

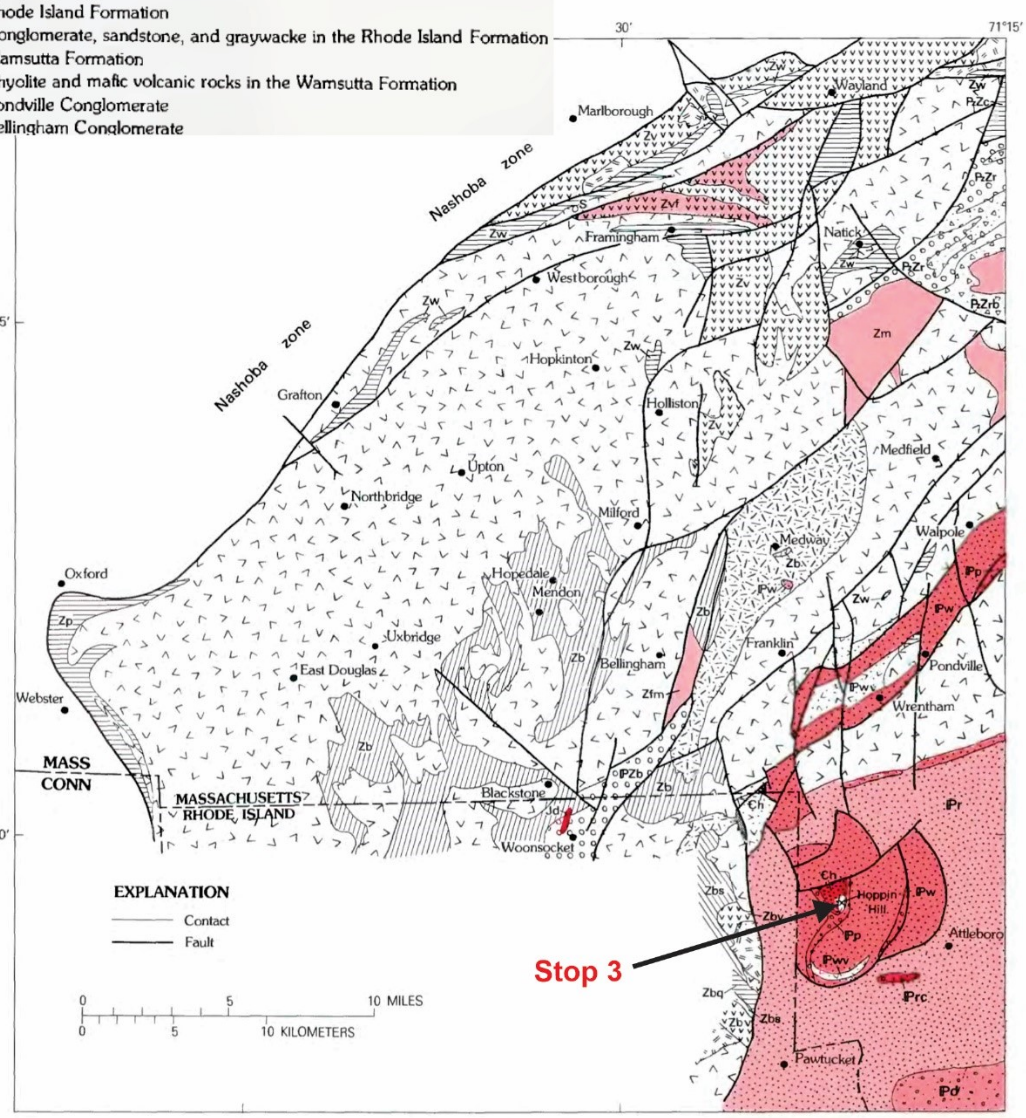
Conanicut Group

Figure 5 shows the location of Stops 5 and 6 on a geologic map of southern Narragansett Bay. Stop 5, the southern half of Conanicut Island in RI, includes the most complete and well exposed occurrences of Cambrian Avalonian metasedimentary rocks in the USA Appalachians (Fig. 6), and this trip examines the continuous shoreline exposure of these rocks at Beavertail State Park. Beginning in the mid-1970's there was increased interest in the geology of Beavertail, with the emphasis placed on the documentation of the multiple episodes of deformation (Murray and Skehan, 1979) and the trilobite fossils that proved diagnostic in the assignment of a Cambrian age to the section. Moreover, the Beavertail trilobite fauna display Acado-Baltic affinities, and on that basis have been correlated with similar-aged trilobite fossils in Avalonian terranes in Europe (Skehan et al., 1978).

Structural relationships: The results of these efforts have appeared in a variety of field guides (e.g., Skehan et al., 1981) and references therein (Skehan and Rast, 1990), and were incorporated in the bedrock geology of Rhode Island (Hermes et al., 1994). Recently, Matthew Carter carried out a detailed mapping and structural analysis of the Cambrian metasedimentary rocks in Beavertail State Park (Carter, 2008; Carter and Mosher, 2013; Carter et al., 2014). The observation that these metasedimentary rocks contain evidence of multiple episodes of penetrative deformation is not disputed, but whether that deformation can be attributable solely

ℙd	Dighton Conglomerate
ℙr	Rhode Island Formation
ℙrc	Conglomerate, sandstone, and graywacke in the Rhode Island Formation
ℙw	Wamsutta Formation
ℙwv	Rhyolite and mafic volcanic rocks in the Wamsutta Formation
ℙp	Pondville Conglomerate
ℙZb	Bellingham Conglomerate

A



Alkalic granitic rocks

Includes Peabody Granite (Dpgr); Wenham Monzonite (Dwm); Cherry Hill Granite (Dcygr); granite of Rattlesnake Hill pluton (Drgr)

Alkalic granitic and gabbroic rocks

Includes Blue Hills Granite Porphyry (SObgr); Cape Ann Complex (SOcgr, SOcsm, SOcb); Quincy Granite (SOqgr); alkalic granite in Franklin (DOgr); Nahant Gabbro (Ongb)

u Serpentinite

Batholithic rocks

Includes biotite granite (Zgr), Milford Granite (Zmgr, Zmgd); Hope Valley Alaskite Gneiss (Zhg); alaskite (Zagr); Scituate Granite Gneiss (Zsg); Esmond Granite (Zegr); Topsfield Granodiorite (Ztgd); Grant Mills Granodiorite (Zgmgd); Dedham Granite (Zdgr, Zdngr); Westwood Granite (Zwgr); fine-grained granite and granite porphyry (fgr); granite of the Fall River pluton (Zfgr); Ponaganset Gneiss (Zpg); porphyritic granite (Zpgr); granite, gneiss, and schist, undivided (Zgg)

Mafic rocks

Includes diorite at Rowley (Zrdi); diorite (Zdi); diorite and gabbro (Zdigb); gabbro (Zgb); Sharon Syenite (Zssy)

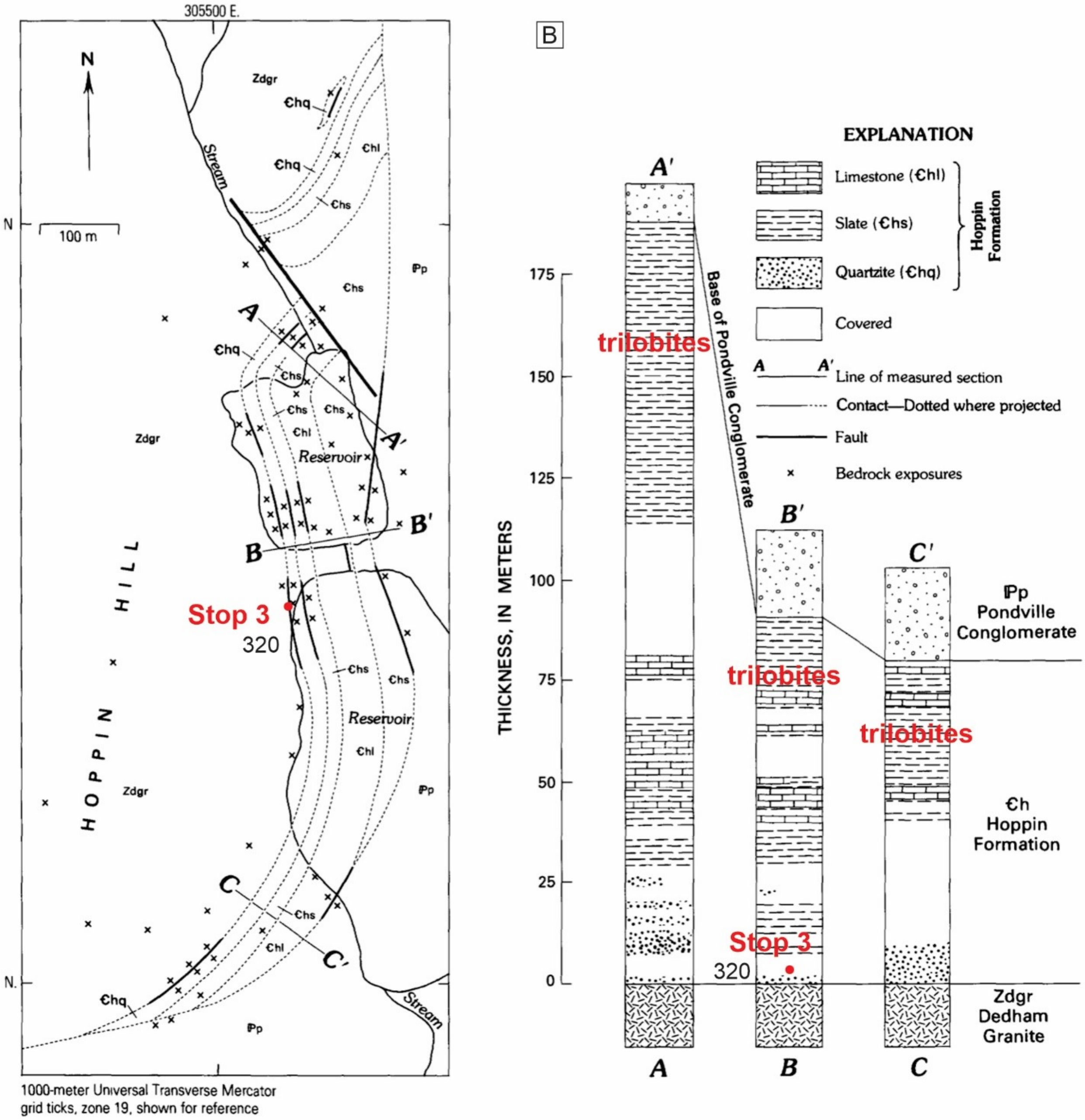


Figure 4. (a) Geologic map of **Stop 3**, the North Attleboro Formation quartzite at Hoppin Hill MA., as displayed on the Bedrock Geologic Map of Massachusetts (Zen et al., 1983) and in Figure 4b (Antsey, 1979; Fig. 4 of Goldsmith, 1991a). Note the location of Hoppin Hill in the lower right corner of the map. The fossiliferous Cambrian rocks are labeled "Ch". (b) Detailed map of the field relationships at **Stop 3** (Antsey, 1979; Fig. 11 of Goldsmith, 1991a). The red dot marks the location of the dated sample.

to the Alleghanian orogeny is unclear. Carter and Mosher (2013) argue that it is, and the basis for their assertion is summarized in Table 1, where they show that all of the episodes of penetrative deformation recorded in the Cambrian units can be correlated with Alleghanian structural events seen in nearby Pennsylvanian rocks. At Stop 4 we will see a sampling of the mesoscopic features at Beavertail State Park outcrops for which this locale is famous.

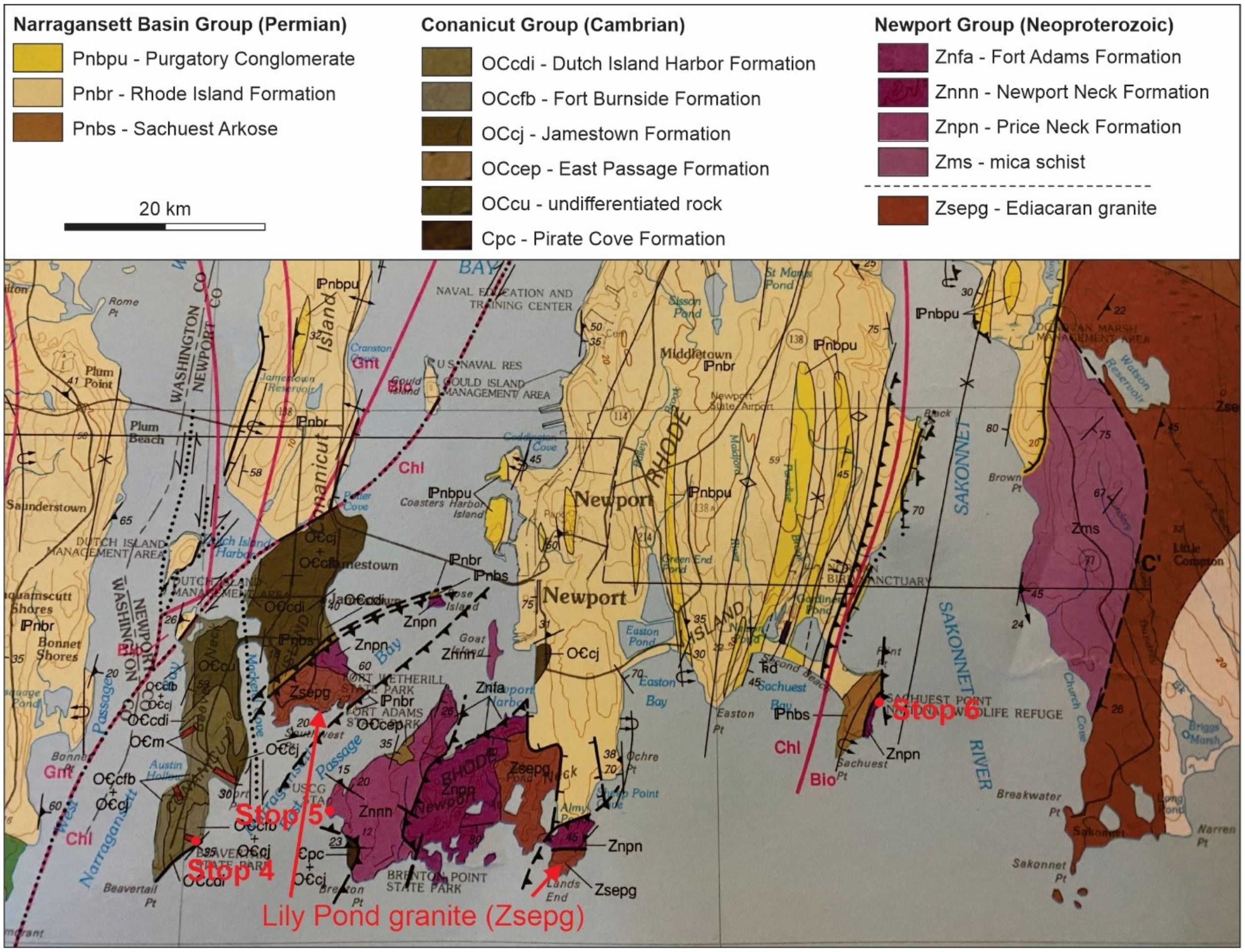


Figure 5. Bedrock geology of the southern Narragansett Bay area, as shown on the Bedrock Geologic Map of Rhode Island (Hermes et al., 1994). **Stops 4, 5** and **6** indicated in red.

Cambrian rocks: Previously, three distinct stratigraphic formations were recognized within the Cambrian Conanicut Group of Beavertail State Park (Skehan et al., 1978; 1981; Skehan and Rast, 1990). As shown on the bedrock geological map of Rhode Island (Hermes et al., 1994), from oldest to youngest, these units include: 1) the **Jamestown Formation** with the basal Beavertail Point member, the medial Hull Cove and the upper Lion Head members; 2) the **Fort Burnside Formation** with the lower Short Point member and the upper Taylor Point member; and 3) the **Dutch Island Harbor Formation.** Table 2 summarizes the stratigraphic relationships for these rocks (Carter et al., 2014), based on the published stratigraphic relations (Hermes, 1994). However, based on detailed mapping of the metasedimentary Cambrian rocks, Matt Carter (personal communication, 2014) suggested a more plausible stratigraphy. From oldest to youngest, it is: 1) Jamestown Formation, Lion Head member; 2) Fort Burnside Formation, Short Point member; 3) Burnside Formation, Taylor Point member; 4) Dutch Island Harbor Formation; and 5) Jamestown Formation, Beavertail Point member. The justification for the change comes from a consideration of the map pattern, for the new stratigraphy resolves several inconsistencies that had become apparent in previous maps of Beavertail. In any case, the trilobite fauna still resides in the Jamestown Formation, Lion Head member.

These greenschist facies rocks are cut by minette or lamprophyre dikes (Nichols, 1956) that have contact metamorphosed Cambrian rocks at Beavertail, and in turn are deformed by the structural events listed in Table 1. The dikes are undated, and their age is bracketed as no older than Cambrian and no younger than the Alleghanian orogeny.

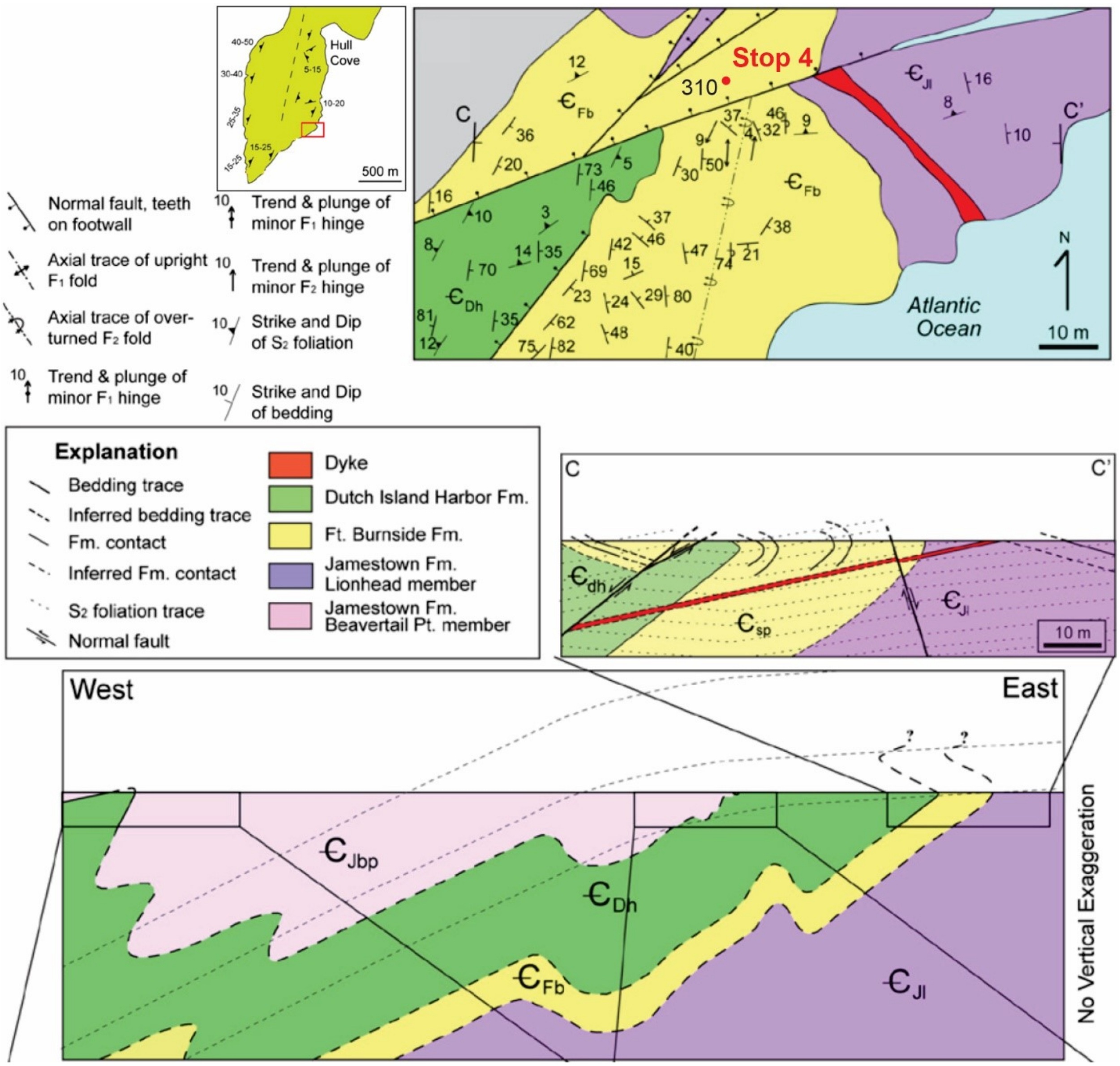


Figure 6. Detailed map and cross section from east side of Beavertail State Park from Carter and Mosher (2013; see Carter, 2008 for complete maps). Location of **Stop 4** and sample 310 indicated.

	CAMBRIAN	PENNSYLVANIAN	
Location	Beavertail State Park	North Conanicut Island	Aquidneck Island
D_1	Open to isoclinal F_1 folds with variable orientations and plunges. Early faults. S_1 defined by aligned muscovite and chlorite	F_{1A} folds and NNE-trending, WNW-verging, tight to isoclinal and shallowly plunging F_{1b} folds. S_{1a} and S_{1b} are defined by aligned chlorite, muscovite, and pressure solution	NNE-trending, WNW-verging, tight to isoclinal and shallowly plunging F_1 folds. S_1 is defined by aligned chlorite, muscovite, and pressure solution
D_2	NNW to NNE-trending, open to tight, E-verging to recumbent, shallowly plunging F_2 folds. S_2 is a pressure solution cleavage with microstylolites	NNE-trending, ESE-verging, open to tight, shallowly plunging F_2 folds. S_2 is a pressure solution cleavage	NNE-trending, ESE-verging, open to tight, shallowly plunging F_2 folds. S_2 is a pressure solution cleavage
D_3	NNE-trending, gentle, shallowly plunging F_3 fold. Multiply oriented crenulation cleavages (S_c)	NE-trending, upright to recumbent, shallowly plunging F_3 folds. NNE-trending sinistral oblique-slip faults	E-trending kink bands.
D_4	N-S trending boudinage	N-S trending, dm-scale boudinage	Minor N-S trending boudinage
Late-Stage	NNE-ENE trending kink bands and normal faults	N-trending, steepyly dipping brittle normal faults	N-trending, steepyly dipping brittle normal faults

Table 1. **Stop 4**: Summary and comparison table for deformational events in Pennsylvanian rocks of the Narragansett Basin that are most proximal to the Cambrian Conanicut Group rocks in Beavertail State Park (Carter and Mosher, 2013; Carter et al., 2014).

Formation	Member	Lithologies	Comments
Dutch Island Harbor		Dark-gray rhythmically bedded phyllite	Abundant carbonate concretions
Fort Burnside			
	Taylor Pt.	Dark gray phyllite and tan siltstone	Fluidization structures common
	Short Pt.	Interlayered tan siltstone and dark gray phyllite	Siltstone more abundant than in other units
Jamestown			
	Lion Head	Massive gray phyllite	Middle Cambrian trilobites present
	Hull Cove	Gray and green phyllite	Minor trilobite fragments and ichnofossils
	Beavertail Pt.	Primarily green phyllite,	Locally tan siltstone abundant
Pirate Cave	*Occurs only on Aquidneck Is., and is not seen on this field trip.*	Basal limestone overlain by phyllite	Lower Cambrian hyoliths present

Table 2. **Stop 4**: Summary of stratigraphic relationships of Conanicut Group rocks in southern Narragansett Bay, from Carter et al. (2014). Modified from Skehan et al., (1978, 1981, 1987) and Murray and Skehan (1979).

Newport Group

The Newport Group, as shown on the bedrock geologic map of RI (Hermes et al., 1994) and on Figures 3 and 5, represents a suite of Neoproterozoic metasedimentary and metavolcanic rocks in southeastern RI. These multiply deformed greenschist facies rocks are truncated by the 595 ± 12 Ma Newport (currently known as the Lily Pond; Fig. 1d, 7) Granite (Rb-Sr whole-rock date; Smith, 1978). The Newport Group consists of three formations: the Price Neck Formation, the Newport Neck Formation, and the Fort Adams Formation (Fig. 1d, 5, 8). Although sedimentary structures such as graded bedding allow younging directions to be determined within formations, lack of outcrop or faults prevents age relationships among formations to be established. Based on the presence of a variety of soft-sediment structures in the Newport Neck Formation and olistoliths in the Fort Adams Formation, the Newport Group is considered to have preserved a record of Neoroterozoic rifting of a continental margin (Rast and Skehan, 1981a; Bailey et al., 1989; Fig. 3, 5). It is less clear what the relative ages of the formations within the Newport Group are, and whether only the Price Neck Formation, or the entire Newport Group, is older than the Lily Pond Granite. On this field trip we will visit the Price Neck and Newport Neck Formations. The following descriptions of them are drawn from Skehan et al. (1998), Rast and Skehan (1981b) and Webster (1986).

Figure 7. Lily Pond Granite along Cliff Walk at Lands End in Newport, RI, looking northeast.

Price Neck Formation: The Price Neck Formation is best seen along Ocean Drive between Brenton Point State Park to the west and the Lilly Pond Granite to the east, where the former is contact metamorphosed by the latter. Other smaller occurrences are shown on the bedrock geological map of Rhode Island (Hermes, et al. 1994) and the dated sample came from the shoreline exposure at Sachuest Point (Stop 6). There it consists of massive to finely bedded felsic volcaniclastic turbidites and sedimentary rocks.

Newport Neck Formation: The Newport Neck Formation occurs primarily in the southwestern corner of Newport, along Ocean Drive. From oldest to youngest, it consists of three members (Webster, 1986; Skehan et al, 1998): the Brenton Point member, the Graves Point member, and the Castle Hill member. Figure 8 presents a stratigraphic column for this unit. The unit consists of graded beds of feldspathic granule conglomerate and slate. The dated sample came from the Castle Hill member (Stop 5).

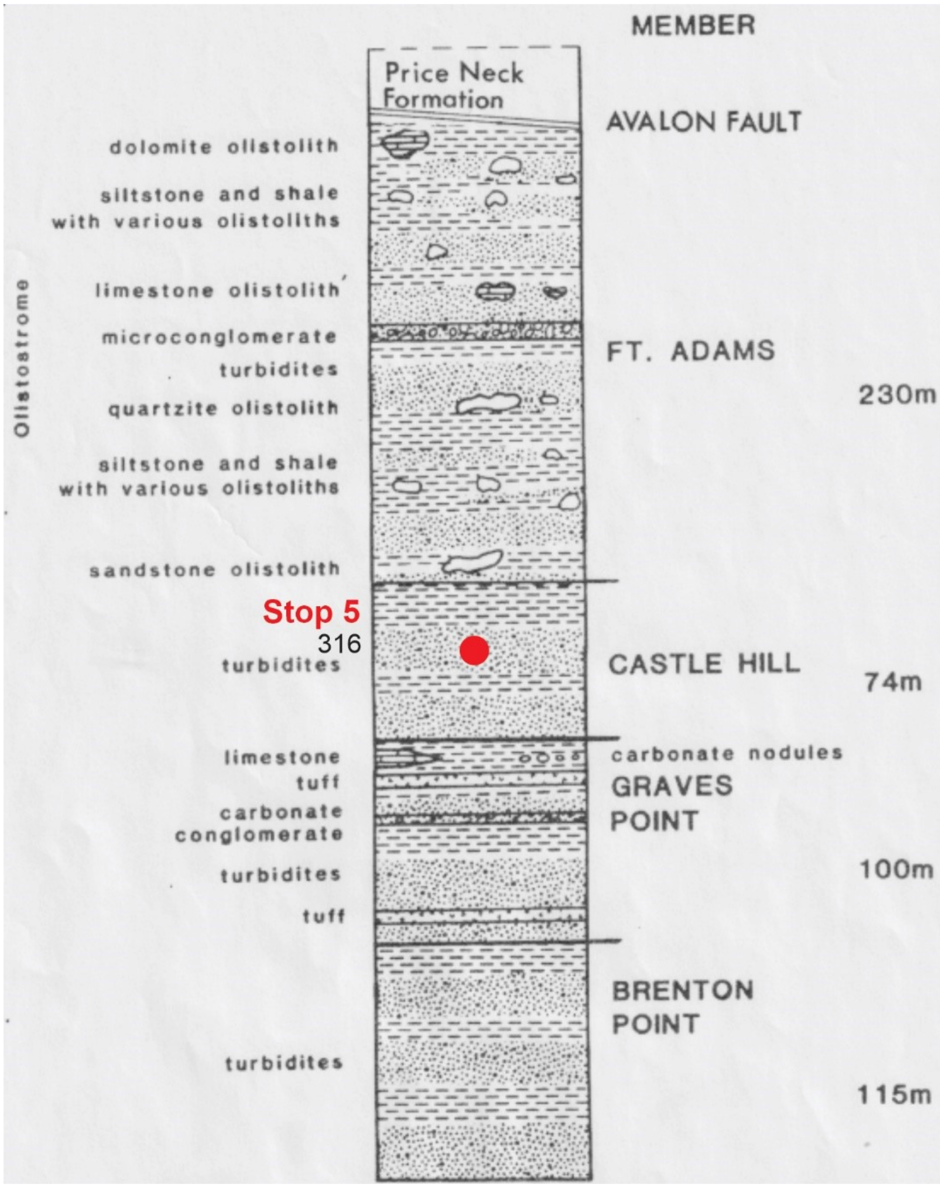


Figure 8. Stratigraphy of Newport Neck Formation, Newport Group. **Stop 5** and sample 316 indicated (from Bailey et al., 1989; as modified from Webster, 1986).

New Bedford area

We have a nearly complete picture of the segment of the New England Avalon zone that extends from the Narragansett basin to Boston. We know much less about the tectonic setting of the region between the Narragansett Basin and Cape Cod, primarily because of lack of outcrop and a paucity of distinctive lithologies. The most comprehensive description of the stratigraphy and structure of this region remains the reconnaissance mapping of Richard Goldsmith (1991a, 1991b) that was done for the Geological Map of Massachusetts (Zen, 1983).

The New Bedford area (Fig. 9) is bounded by the Narragansett Basin to the north and west, Buzzards Bay to the south, and Cape Cod to the east. Based on petrographic and geochemical relationships presented in Murray et al. (1990, 1998) the lithologies can be divided into two categories. Group I occurs in the northern and western parts, and consists of variably

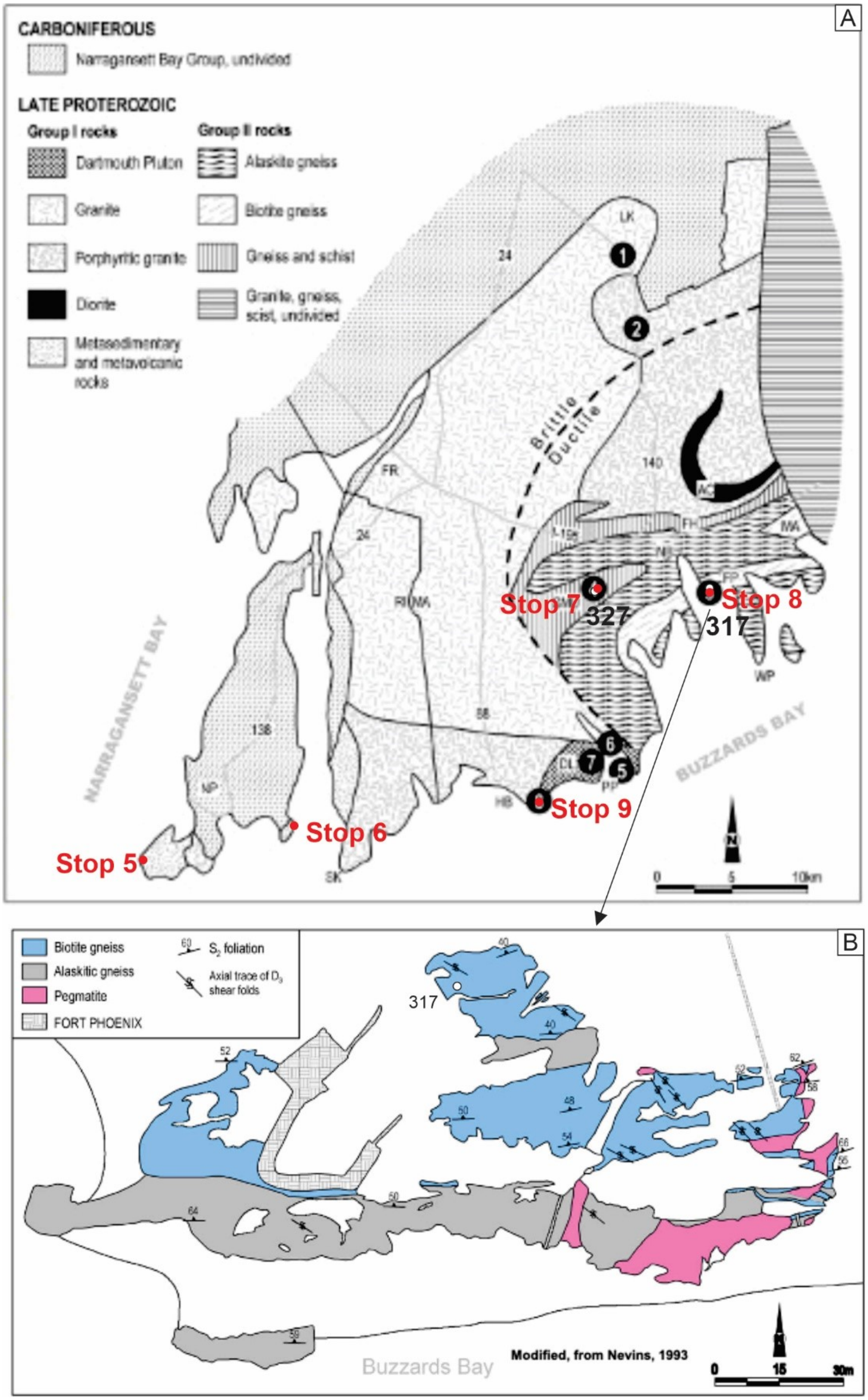


Figure 9. (a) Simplified geologic map of the New Bedford area (Goldsmith, 1991a). **Stops 5-9** indicated in red. Black numbers refer to field trip stops of Murray et al. (1998). Sample numbers indicated in black. (b) Sketch map of **Stop 8**, Fort Phoenix (Murray et al., 1998). Location of sample 317 indicated.

deformed granitoids and related mafic igneous rocks that are contiguous with the Esmond – Dedham terrane. Group II occurs to the southeast in the vicinity of New Bedford and is characterized by alaskitic granitic gneisses and biotite gneisses that are reminiscent of gneisses in southwestern Rhode Island and southeastern Connecticut. The nature of the contact between these groups is unclear, as nowhere is it exposed. The dominant structural feature in the New Bedford area is a steeply north-dipping to vertical, east-west trending foliation that becomes more pervasive to the south, and which is subparallel to brittle and ductile shear zones. This pattern is shown on the Tectonic Map of Massachusetts (Zen, ed., 1983), as the division of the region into "BRITTLEY DEFORMED TERRANE" and "GNEISSIC TERRANE" regimes. To a first approximation this boundary coincides with the contact between Group I and Group II rocks.

Figure 9 presents a simplified map of the area. There are three suites in this region that merit consideration in any model for the evolution of this part of Avalonia in New England, and we will visit stops in all of them.

The Dartmouth Pluton: The composite Dartmouth Pluton is an Ediacaran alkalic igneous complex in the vicinity of South Dartmouth, MA. It includes a diverse variety of granitic, monzonitic, to dioritic rocks that are intrusive into older granites and gneisses of the Avalon basement. A variety of mingling and mixing features caused by felsic and mafic magma interactions are well preserved. It is pertinent for several reasons. First, at 595 Ma (Hermes and Zartman, 1992; Thompson et al., 1996), it is the oldest alkalic granite in New England Avalonia. Second, although it is within the "Gneissic Terrane", at least at first glance it shows none of the ductile deformation that characterizes other rocks in this region, implying that the effect of the Alleghanian tectonism was milder. Third, based on field relationships, a series of brittle to ductile shear zones may have been active during the suite's emplacement. If so, they record Neoproterozoic Avalonian tectonism. This intriguing pluton is briefly visited on Stop 9, and described more fully in Murray et al. (1990, 1998).

Metasedimentary rocks at the University of Massachusetts at Dartmouth: Metasedimentary rocks are rare in the area southeast of the Narragansett Basin, and only one occurrence of a pelitic schist is documented. It consists of staurolite schist outcrops on the UMass Dartmouth campus, and will be visited at Stop 7.

The gneisses at Fort Phoenix, MA: On the state geological map, the New Bedford area consists of Proterozoic alaskitic (Zagr) and biotite (Zgn) gneiss, which are especially well displayed along the coast at Fort Phoenix on New Bedford Harbor. There, both units are discordantly to concordantly cut by medium- to coarse-grained, undeformed muscovite granite. The foliation is defined by segregations of oriented micas and feldspar laths. The dominant fabric is a moderately to steeply north-dipping foliation. The biotite gneiss contains intrafolial rootless folds and concordant, boudinaged seams of granite that grade, without truncation, into discordant granite (Stop 8). These field relationships are reminiscent of those in late Paleozoic granitoids west of the Narragansett Basin, where Gromet et al. (1998) documented textures that suggest melt segregation and redistribution of a deforming crystal mush. Preliminary textural analysis confirms that this interpretation applies to the gneisses at Fort Phoenix as well, as both biotite and alaskitic gneisses show little evidence of crystal plastic deformation (Stop 8). U-Pb ID-TIMS monazite analyses from Fort Phoenix alaskitic and biotite gneisses show highly concordant U-Pb ages of 278±2 Ma and 267±2 Ma respectively, and preliminary analysis of one zircon separate from alaskitic gneiss shows complex discordance (Murray et al., 2002; L. Peter Gromet, personal communication, 2001).

FIELD STOPS

Stop 1 – Blackstone Group quartzite - 41°58.508'N, 71°28.511'W

As described earlier, based on rare younging criteria and structural arguments, Dreier (1985; cf. Bailey et al., 1989) recognized the stratigraphy shown in Figures 2 and 3. For the purpose of this field guide it may be simplified as follows, from oldest to youngest: 1) Hunting Hill greenstone, 2) Mussey Brook and Sneech Pond schists, and 3) Quinnville quartz arenite. Both samples chosen for dating were from the Quinnville quartz arenite.

The northern sample (328) was collected from a quarry in Cumberland, RI that is located in the core of a synform shown in (Fig. 2). The quartzite (Fig. 10) is interbedded with phyllite, and the contacts are gradual. Detailed sample, thin section, zircon and U-Pb LA-ICPMS data descriptions can be found in Kuiper et al. (2022). In summary, the youngest population and interpreted maximum depositional age are 1053 ± 19 Ma, and two younger grains are 1002 ± 18 Ma and 952 ± 38 Ma. The main peak is at ~1.22 Ga and older peaks are up to ~3.07 Ga with a small age gap at ~2.4–2.3 Ga (Fig. 11a; Kuiper et al., 2022).

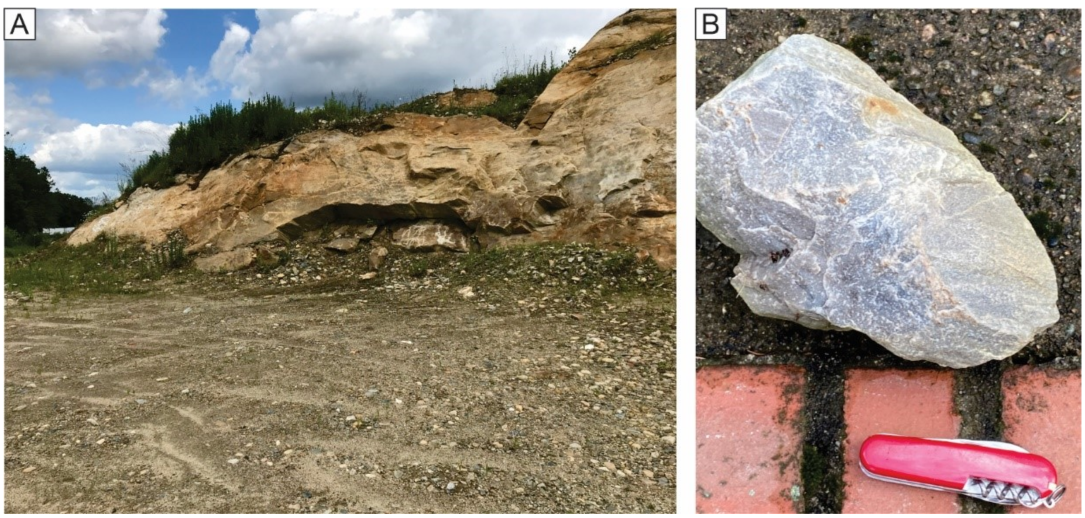


Figure 10. **Stop 1**: (a) Blackstone quartzite looking east in quarry at sample 328 location. (b) Hand specimen of quartzite.

Another sample of the same quartzite was taken from an outcrop at Winman Jr. High School in Warwick, RI (Sample 329, Fig. 1; 41°42.396'N, 71°29.086'W; Kuiper et al., 2022) from an outlier that has been correlated with the main body of the Blackstone Group (Hermes et al., 1994). The youngest zircon population is 997 ± 12 Ma, and one younger grain is 949 ± 25 Ma. The largest age population is ~1.22 Ga (Fig. 11b), and there is a spread of populations up to ~3.17 Ga, except ~2.6–2.3 Ga. Data of both quartzites are similar to other quartzites of the Avalon terrane of southeastern New England and Avalonia in Canada (Severson et al., 2022; Fig. 11f).

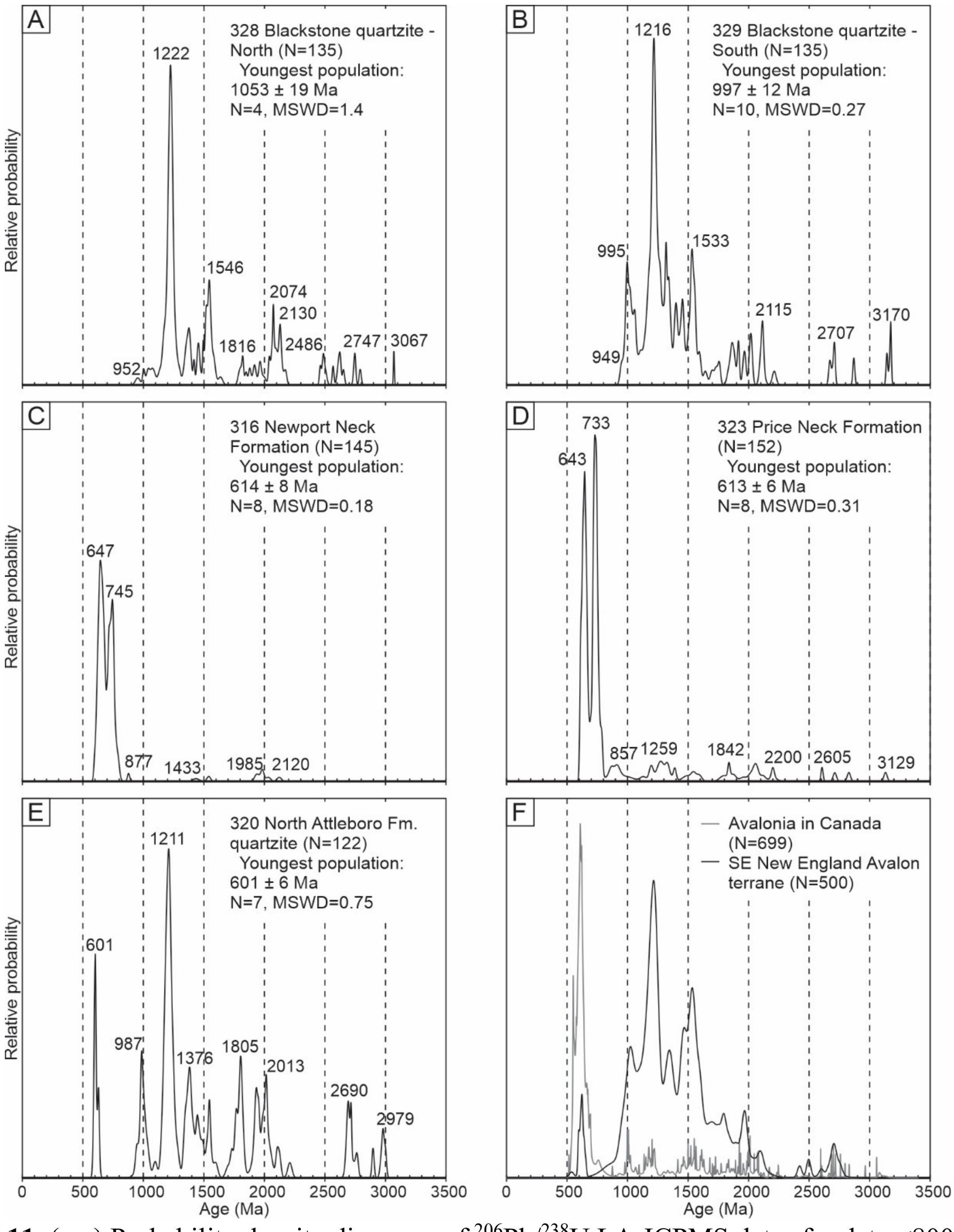


Figure 11. (a-e) Probability density diagrams of $^{206}Pb/^{238}U$ LA-ICPMS dates for data <800 Ma and $^{207}Pb/^{206}Pb$ dates for analyses >800 Ma for samples presented in Kuiper et al. (2022). (f) Compilation of data for the southeastern New England Avalon terrane and Avalonia in Canada (from Severson et al., 2022). Data from Keppie et al. (1998), Barr et al. (2003, 2019), Murphy et al. (2004), Hepburn et al. (2008), Pollock et al. (2009), Satkoski et al. (2010), Thompson et al. (2012), Severson et al. (2022). See Kuiper et al. (2022) for methods.

Stop 2 – Pillow basalt of the Blackstone Group - 41°54.933'N, 71°24.100'W

A sample of Hunting Hill Greenstone (Fig. 2) was collected from a road cut in Cumberland, RI. This unit is characterized by basalt, commonly with pillow structures, and mafic volcaniclastic rocks. At this locale greenish grey pillow basalt (Fig. 12) is cut by discrete shear zones, and calcite veins. Blackstone basaltic rocks are widespread, and commonly ductilely deformed (Dreier, 1985; Rose, 1985). Interestingly, the basaltic rocks at this stop are relatively little deformed, despite being within ten kilometers of the terrain that is penetratively deformed by the Alleghanian orogenesis. Furthermore, they are not far from the well documented (Maria and Hermes, 2001) basaltic rocks of the Late Devonian Wamsutta Formation.

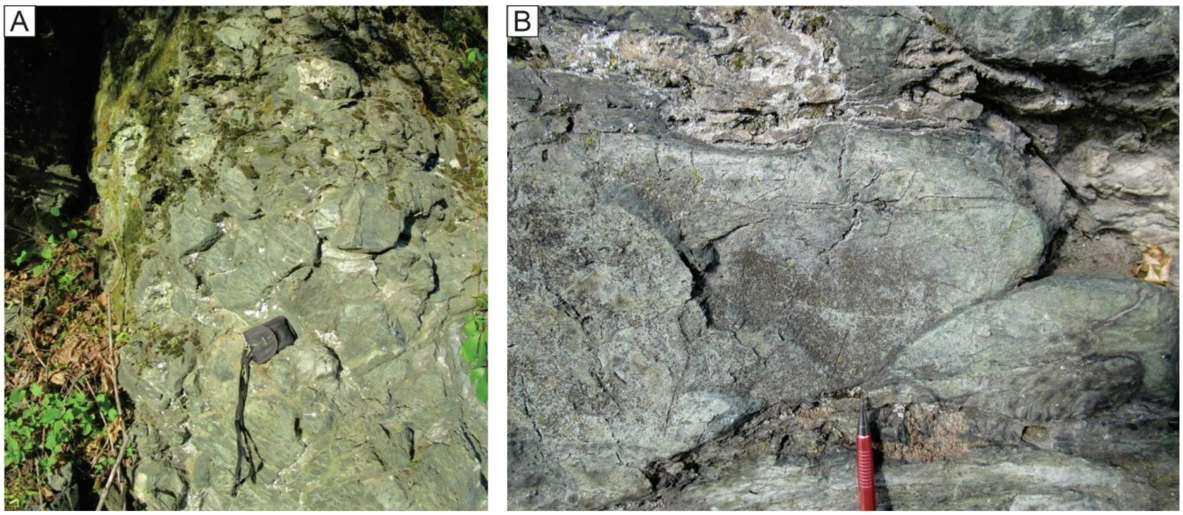


Figure 12. **Stop 2**: (a, b) Blackstone Formation pillow basalt looking east.

A 16 kg sample (330) yielded a few zircon grains with various Proterozoic dates (Fig. 12a) consistent with inheritance from Avalonian basement. Five dates are latest Silurian and Devonian and one is Devonian-Mississippian, 359 ± 12 Ma (Fig. 13a), and is high in U with a low Th/U ratio. It may be metamorphic, but metamorphism of that age has not been recorded in the area and the pillow basalt and metamorphism in the basalt was no higher than greenschist. If the date is igneous it is consistent with the age of the basal Wamsutta Formation of the Narragansett Basin. While we do not put much confidence in one grain, the five other Silurian-Devonian grains are also perplexing and suggest the need for reinterpretation of the area.

Stop 3 – North Attleboro Formation quartzite - 41°57.978'N, 71°20.753'W

The North Attleboro Formation quartzite, or quartzitic arenite, was sampled from the western edge of the southern Hoppin Hill Reservoir, North Attleboro, MA (Fig. 4), when the reservoir was low enough to access the outcrops of North Attleboro Formation quartzite. While low water is not common, on this virtual field trip the water is always low, and our spirits are always high. The sample is from massive quartz arenite at the base of the Cambrian section, immediately east of an arkosic sandstone/phyllite unit, presumably close to the unconformity with the overlying Narragansett basin deposits. It has mm- to cm-scale elongate clasts of quartzite and gray phyllite within an otherwise quartz-rich, white-tan quartzitic arenite (Fig. 14). The sample was taken from loose rocks that are still within their original layer configuration. Detailed descriptions can be found in Kuiper et al. (2022). The youngest detrital zircon age population and maximum age of deposition are 601 ± 6 Ma. The biggest peaks are at ~601 Ma

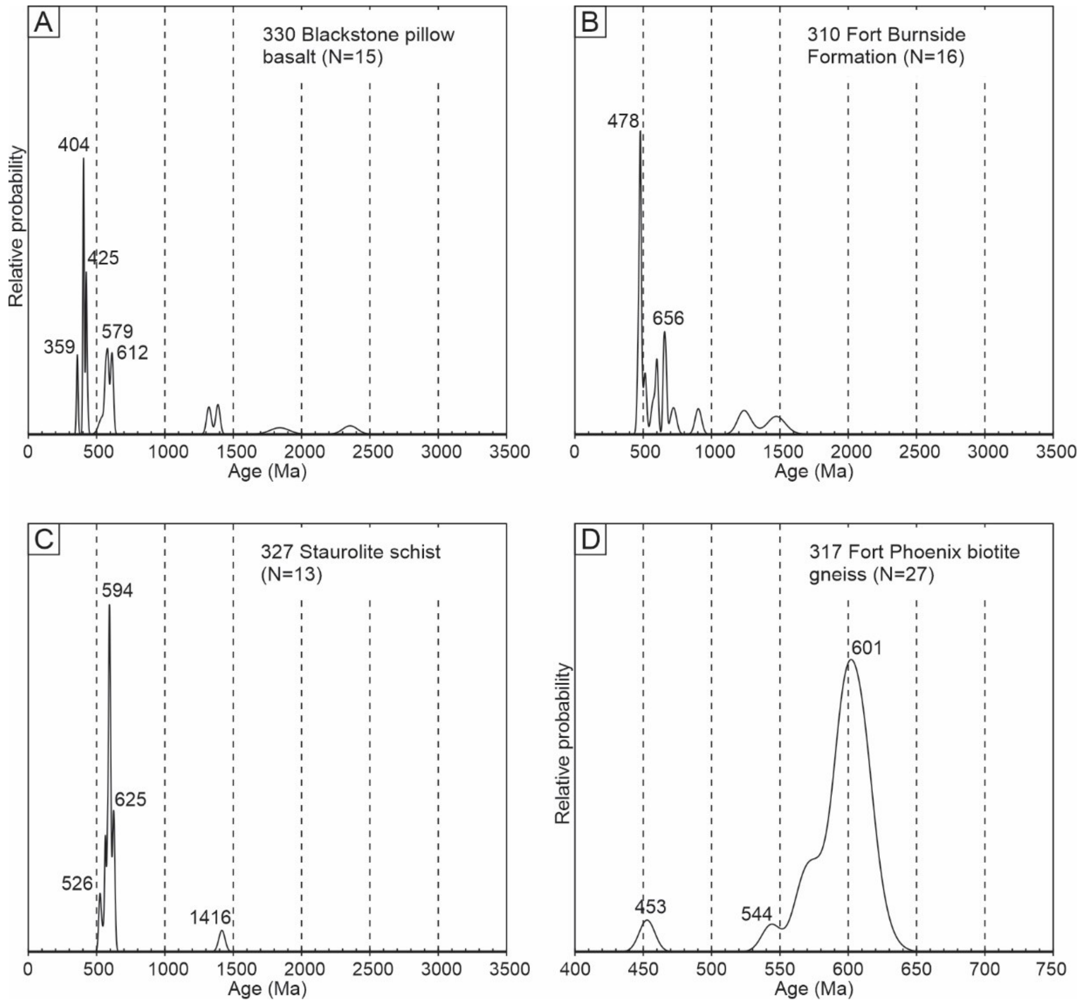


Figure 13. Probability density diagrams of preliminary $^{206}Pb/^{238}U$ LA-ICPMS dates for data <800 Ma and $^{207}Pb/^{206}Pb$ dates for analyses >800 Ma for (a) the pillow basalt in the Blackstone Formation, (c) the staurolite schist, and (d) the Fort Phoenix biotite gneiss, analysed at Boise State University. (b) The same for the Fort Burnside Formation of the Conanicut Group, analysed at Texas Tech.

Figure 14. **Stop 3**: North Attleboro Formation quartzite looking west (a) and close-up (b) at the location of sample 320 along the west side of the Hoppin Hill Reservoir, MA.

and ~1.21 Ga (Fig. 11e), with others between ~2.98 Ga and ~987 Ma. Data are comparable with other quartzites of the Avalon terrane of southeastern New England and Avalonia in Canada (Severson et al., 2022; Fig. 11f).

Stop 4 – Conanicut Group - 41°27.266'N, 71°23.497'W

The Taylor Point member of the Fort Burnside Formation (Figs. 5, 6) consists of alternating buff colored siltstone and phyllite that are part of the inverted limb of a gently NNE-plunging recumbent fold (Carter and Mosher, 2013; Carter et al., 2014; Fig. 6). The sample chosen for geochronology comes from the coarsest layer (Fig. 15c, d), where refracted cleavage is at highest angle with the bedding, on the east side of Beavertail State Park. The structural relationships of this locale are described in detail in several field guides (Murray and Skehan, 1979, Skehan et al., 1981; Carter et al., 2014 and references therein). Figure 15 shows examples of the distinctive isoclinal folds that occur here, and the approximate location of the sample. Mineral separation of some 15 kg of rock yielded a total of four zircons, which yielded mostly discordant dates. Preliminary U-Pb dates of *in situ* zircon in thin section are shown in Fig. 13b, and automated mineralogy images in Figure 16a, b. Interestingly, the youngest zircon age population of 5 zircon is 478 ± 8 Ma (N=5, MSWD=0.37), implying that the rocks are Ordovician or younger. This is younger than the Cambrian age based on trilobites in the Lion Head member of the underlying Jamestown Formation in the Conanicut Group. Moreover, it implies that the lamprophyre dikes are no older than Ordovician.

Stop 5 – Newport Neck Formation, Newport Group - 41°27.613'N, 71°21.737'W

The Newport Neck Formation consists of three members, and from oldest to youngest they are: 1) Brenton Point, 2) Graves, and 3) Castle Hill (Skehan et al., 1998; Figs. 3, 5). (Note: this sequence of units is the opposite of what was presented in a previous field guide; Skehan and Rast, 1981b). Stop 5 visits the Castle Hill member, which is characterized by turbiditic sedimentary rocks. As described by Skehan et al., (1998), this member consists of thickly bedded maroon to blue graded sandstone, now seen as metasandstone and slate. Figure 8 presents a stratigraphic column for the Newport Neck formation showing the member from which the dated sample was collected**,** a shoreline exposure at Ragged Point, near the Castle Hill Inn in Newport, RI (Fig. 17). The sample was taken from multiple coarsest-grained layers (Fig. 17). The youngest population and maximum depositional age are 614 ± 8 Ma and the main age peaks are at ~647 and ~745 Ma (Fig. 11c; Kuiper et al. (2022). Two grains are ~1.54–1.43 Ga, and the oldest four grains are ~2.12–1.98 Ga. This signature does not resemble the typical Avalonian signature (Fig. 11f).

Stop 6 – Price Neck Formation, Newport Group (323) - 41°28.829'N, 71°14.312'W

As described by Skehan et al. (1998) and references therein, the Price Neck Formation consist of felsic volcaniclastic rocks — including graded tuffs, lapilli agglomerates and lahars — preserved as lower greenschist facies phyllites and metasandstones. The dated sample is a tan-gray phyllite, collected from the shoreline at Sachuest Point in Middletown, RI (Figs. 3, 5, 18). The unit is generally fine grained with a few conglomeratic layers, and the sample was taken from a mix of both. The youngest population is 613 ± 6 Ma, and is the maximum depositional age (Kuiper et al., 2022). The main age peaks are at ~643 and ~733 Ma, smaller populations are up to ~2.20 Ga and four older grains are between ~2.61 and ~3.13 Ga (Fig. 11d). One concordant grain is 412 ±

9 Ma. It is unclear whether this is a result of contamination, and therefore is excluded from figures and interpretation. The detrital zircon age signature is similar to that of the Newport Neck Formation, suggesting that the two samples and formations, and perhaps the entire Newport Group, are part of a crustal block that is different from the southeastern New England Avalon terrane. This 'Newport Block' (Kuiper et al. 2022) may be as small as parts of the Newport Group, or extend as far northwest as shown in Figure 1c. Possible interpretations for its tectonic history are discussed by Kuiper et al. (2022).

Figure 15. **Stop 4**: Field photographs of outcrops along the southeastern part of Beavertail State Park. (a, b) Dutch Island Harbor Formation showing F_1 folds, looking north. (c, d) Fort Burnside Formation looking east. Hammer on sampled layer of coarsest material (sample 310). Dashed red line shows refracted cleavage. (e, f) Lionhead member of the Jamestown Formation with trilobite fragments, on eastern tip of island (Lionhead) east of sample 310. (g, h) Beavertail Point member of the Jamestown Formation near the lighthouse at the southern tip of the island (Beavertail Point), showing folds.

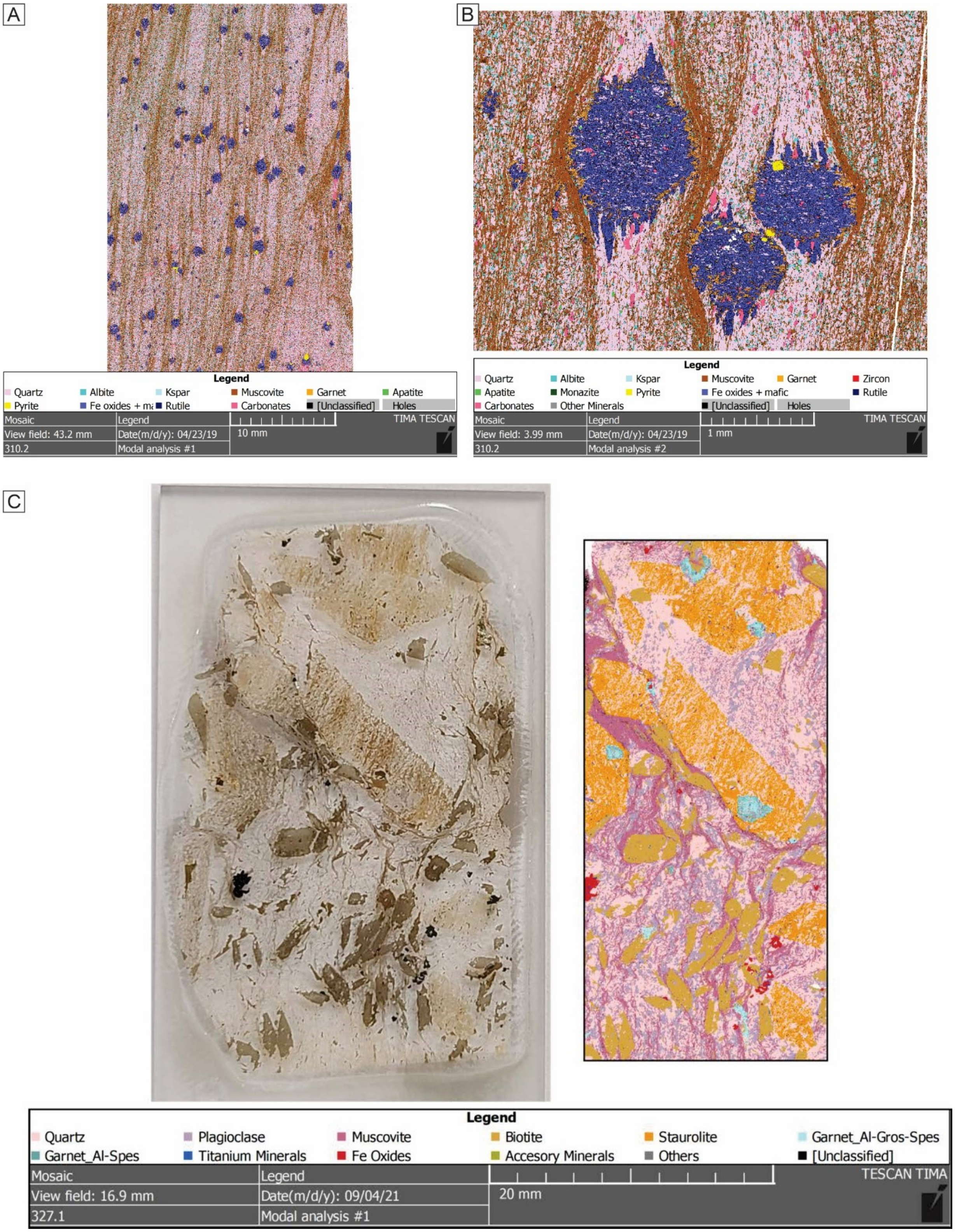


Figure 16. Automated mineralogy images of the analysed thin section of the Fort Burnside Formation (a, b) for which data are shown in Figure 13b and for the staurolite schist (c, with plane polarized light image of the thin section) for which data are shown in Figure 13c.

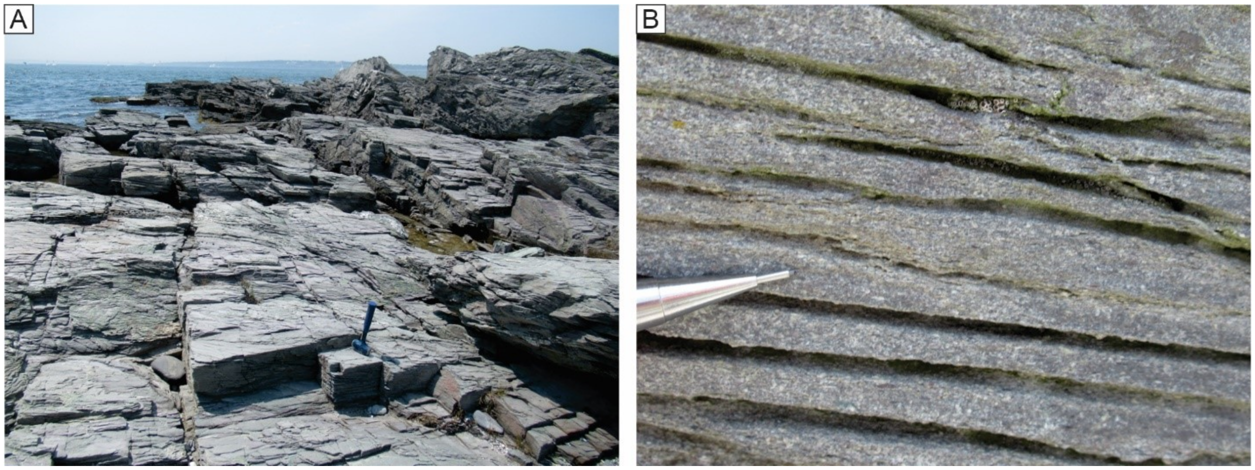


Figure 17. **Stop 5**: (a, b) Newport Neck Formation at Castle Hill, RI, at location of sample 316, looking north.

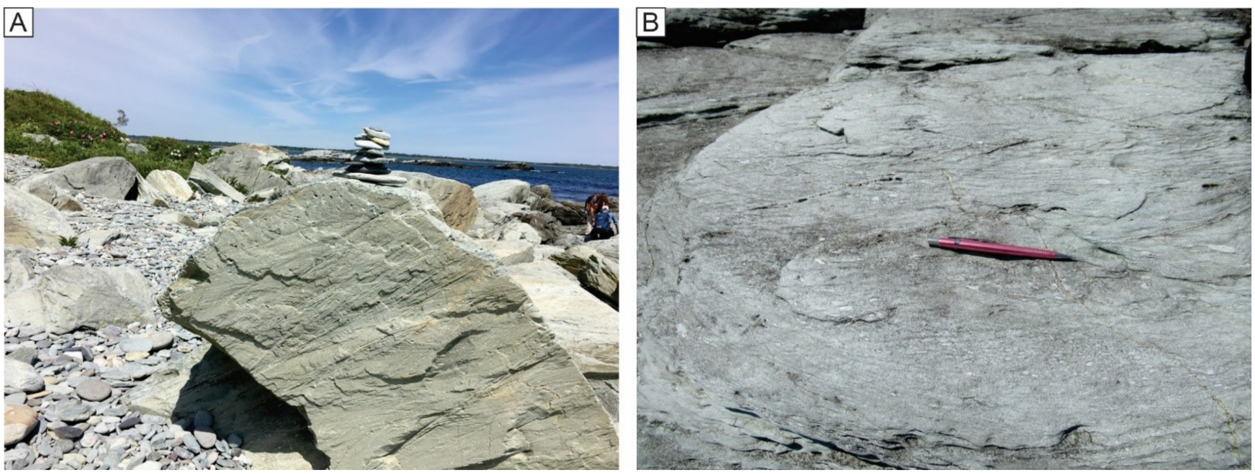


Figure 18. **Stop 6**: Price Neck Formation at Sachuest Point, RI, at sample location 323, looking north (a) and close-up looking west (b).

Stop 7 – UMass Dartmouth garnet staurolite schist - 41°37.801'N, 70°59.869'W

The region south and east of the Narragansett Basin is poorly understood, in part because there are only variably deformed granitoids that reveal their history reluctantly. We sampled the only known pelitic metasedimentary rock in the area, an outcrop of staurolite schist on the UMass Dartmouth campus (Figs. 9, 19). The sample has a greenschist facies crenulated quartz-mica fabric overgrown by coarser grained muscovite, biotite, garnet and porphyroblasts of staurolite (up to five cm. in length). Quartz veins within the schist are folded. Outcrops of circa 600 Ma (?) alaskitic gneiss occur within 200 meters of the outcrop and plausibly could have contact metamorphosed the schist

This ~10 kg sample was collected from an outcrop at UMass Dartmouth. The sample is a garnet staurolite muscovite schist with 0.5-3 cm long staurolite and 2-5 mm garnet crystals (Fig. 16c, 19). It has a steeply north-dipping foliation and down-dip lineation. Zircon grains are euhedral to subhedral. They are relatively uniform in CL brightness, with some grains slightly darker or lighter, and some grains with darker or lighter cores. Most grains have oscillatory zoning, and some grains have sector zoning. Sample 327 yielded 13 concordant detrital zircon analyses (Fig. 13c). The weighted mean of the youngest population is 624.0 ± 6.5 Ma (MSWD = 0.87, n=3), and the youngest grain is ~524 ± 19 Ma. The largest probability density date population is ~595 Ma (Fig. 13c), with smaller populations at ~565 Ma and ~625 Ma. One grain is ~1.42 Ga. While data are sparse, this signature is consistent with the Avalonian signature (Fig. 11f)

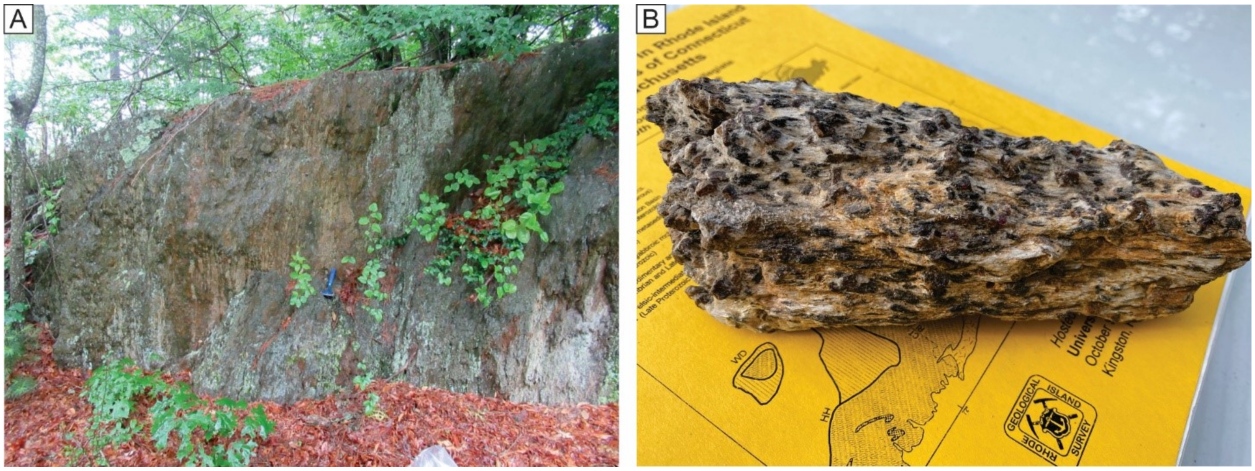


Figure 19. **Stop 7**: (a) Outcrop of Staurolite schist at the University of Massachusetts at Darthmouth, MA, campus looking east. This is the location of sample 327. (b) Hand specimen of the schist.

Stop 8 – Fort Phoenix biotite gneiss - 41°37.467'N, 70°54.102'W

The stop (Fig. 9) consists of the outcrops which form the base of a Revolutionary War naval fortification, at the east end of the New Bedford harbor hurricane storm barrier. There are additional outcrops along the beach, several hundred meters to the east. Figure 9b provides a simplified map of the outcrop, and Figure 20 shows meso- and microphotographs of the granitoids seen at this stop.

The exposures consist of north-dipping Group II gneisses that parallel the coast (Fig. 9b). Proceeding northward (i.e., landward), the following field units are encountered:

- **Alaskitic gneiss**: The unit consists massive to weakly foliated quartz-alkali feldspar gneiss. Field relations suggest this unit is intrusive into the next unit.
- **Biotite gneiss**: The unit consists of roughly equal amounts of millimeter- to centimeter biotite-quartz-feldspar gneiss, and quartz-alkali feldspar gneiss. At Fort Phoenix, the biotite gneiss is migmatitic (Fig. 20). Earlier layering is considered to represent original heterogeneities and/or subsequent solid-state modification. This unit contains the best evidence for multiple episodes of ductile deformation. Elsewhere the biotite gneiss is more massive.
- **Alaskitic gneiss**: As shown on Figure 9a, continuing northward beyond the extent of Figure 9b, the alaskitic gneiss reoccurs.

Garnet-muscovite-quartz-microcline-plagioclase pegmatitic granite: This unit is intrusive both along and across the S_2 foliation, and is boudinaged where parallel to the foliation. We interpret the granite to have been emplaced during the waning stages of the development of the S_2 fabric.

Ongoing mapping indicates at least two generations of folds in the banded gneiss. D_1 structures occur as rootless folds, variably transposed into D_2 folds. S_2, the pervasive E-W trending north dipping foliation seen in the outcrop (Fig. 20), is axial planar to them. S_2 is geometrically similar to the east-west trending shear zones observed in the Group I rocks. Abundant asymmetric folds of S_2 (labeled D_3 shear folds in Fig. 16) are consistently "S" folds, with axes that plunge to the northwest. Interestingly, these fabric elements are similar in style and orientation to those observed along the Honey Hill Fault of southeastern Connecticut (Lundgren and Eblin, 1972; Gromet et al., 1998; Fleischer and Kuiper, 2022). Fort Phoenix gneisses are intruded by pegmatitic S-type granite reminiscent of the white facies of the Narragansett Pier Granite observed on the west side of Narragansett Bay, apparently synchronous with the development of D_2 and D_3 structures. The pegmatite both truncates and is deformed by D_2—D_3 structures. Veins of granite that obliquely truncate S_2 do so in a manner consistent with extension, during E-W trending, noncoaxial, sinistral shear.

Figure 20. **Stop 8**: Fort Phoenix gneiss at Fort Phoenix, MA, where sample 317 was taken. (a) Pegmatite with diffuse boundaries with leucosome. (b) Leucosome with local diffuse boundaries with the host rock, suggesting it was locally derived, and isoclinal folds. (c) close-up of (b). The foliation dips moderately north (to the left in a and b, and up in c). (d) Thin section of the Fort Phoenix gneiss showing biotite foliation and statically recrystallized quartz and feldspar (and/or high-temperature grain boundary migration?).

A ~2.5 kg sample was collected from the shoreline at Fort Phoenix State Beach, Fairhaven, MA. It is a foliated biotite gneiss with a moderately north-dipping foliation and north-side-up asymmetric folds. Zircon grains are euhedral and faceted. Nearly all grains have oscillatory zoning, and a few have sector zoning. A few grains have overgrowths, and a few grains have darker or lighter cores that could be inherited, but cores are not significantly older than rims. Sample 317 yielded 27 concordant igneous zircon analyses. One concordant date is much younger than the others. The probability density date peak of $^{206}Pb/^{238}U$ dates is ~601 Ma (Fig. 13d), and the weighted mean of those dates with two young dates omitted is 597.1 ± 5.8 Ma (MSWD = 3.5, n=25). One grain yielded a 453 Ma $^{206}Pb/^{238}U$ date. While one date may be meaningless, the Ordovician date is similar to the ~478 Ma population in the Fort Burnside Formation.

Stop 9 (optional) – Horseneck Beach Dartmouth Pluton - 41°30.400'N, 71°01.233'W

The outcrops at Horseneck Beach define the western limit of exposures of the Dartmouth Pluton. Figure 21a presents a sketch of the field relationships there, and the location of sample 352 to be dated. The growth of the Dartmouth Pluton reflects the complex interplay between commingled felsic, mafic and 'hybrid' magmas. The following summary of the field relationships at Horseneck Beach draws from detailed petrographic and geochemistry that are presented in Murray et al. (1990, 1998) and references therein.

Field relationships suggest a three-stage sequence of events: l) mixing of older quartz diorite magma with an unknown more mafic magma represented by the cognate mafic enclaves within the quartz diorite, 2) emplacement of alkali-feldspar granite free of mixing features, and 3) interaction of younger quartz monzonite and diorite magmas to generate the intimately preserved pillowed features, and the composite monzonite-diorites hybrid magma and dikelets. Figure 21b shows the location of the alkali-feldspar granite and the quartz diorite that was collected for dating.

The tectonothermal signature at this locale is variable. A disturbed $^{40}Ar/^{39}Ar$ release pattern was obtained from primary hornblende from the massive diorite (Murray and Dallmeyer, 1991). The simplest interpretation is that it represents a Neoproterozoic age partially reset during the late Paleozoic. This diorite retains igneous textures, and, except for discrete brittle shear zones, is massive. Elsewhere in the outcrop, finer grained diorite is deformed into tight folds, the age of which is unclear. The metamorphic grade of the late Paleozoic (?) deformation is middle greenschist, as indicated by epidote- and chlorite-bearing shear zones.

DISCUSSION

We discussed a variety of rocks of the southeastern New England Avalon terrane. While most data are consistent with existing data and descriptions, three observations are worth emphasizing. First, the Price Neck and Newport Neck formations of the Newport Group show a detrital zircon signature that is very different from other samples analyzed in the southeastern New England Avalon terrane in this and previous studies. These are most consistent with a northwest African origin, and possible tectonic histories are discussed by Kuiper et al. (2022). Second, a pillow basalt in the otherwise Proterozoic Blackstone Group may be Devonian, possibly correlative to the basal Wamsutta Formation of the latest Devonian to Permian Narragansett Basin. Third, the Fort Burnside Formation of the Conanicut Group contains a ~478 Ma zircon population, suggesting it is Ordovician and much younger than the underlying

Cambrian Jamestown Formation. We will continue to add pieces of the southeastern New England Avalonian puzzle in the future!

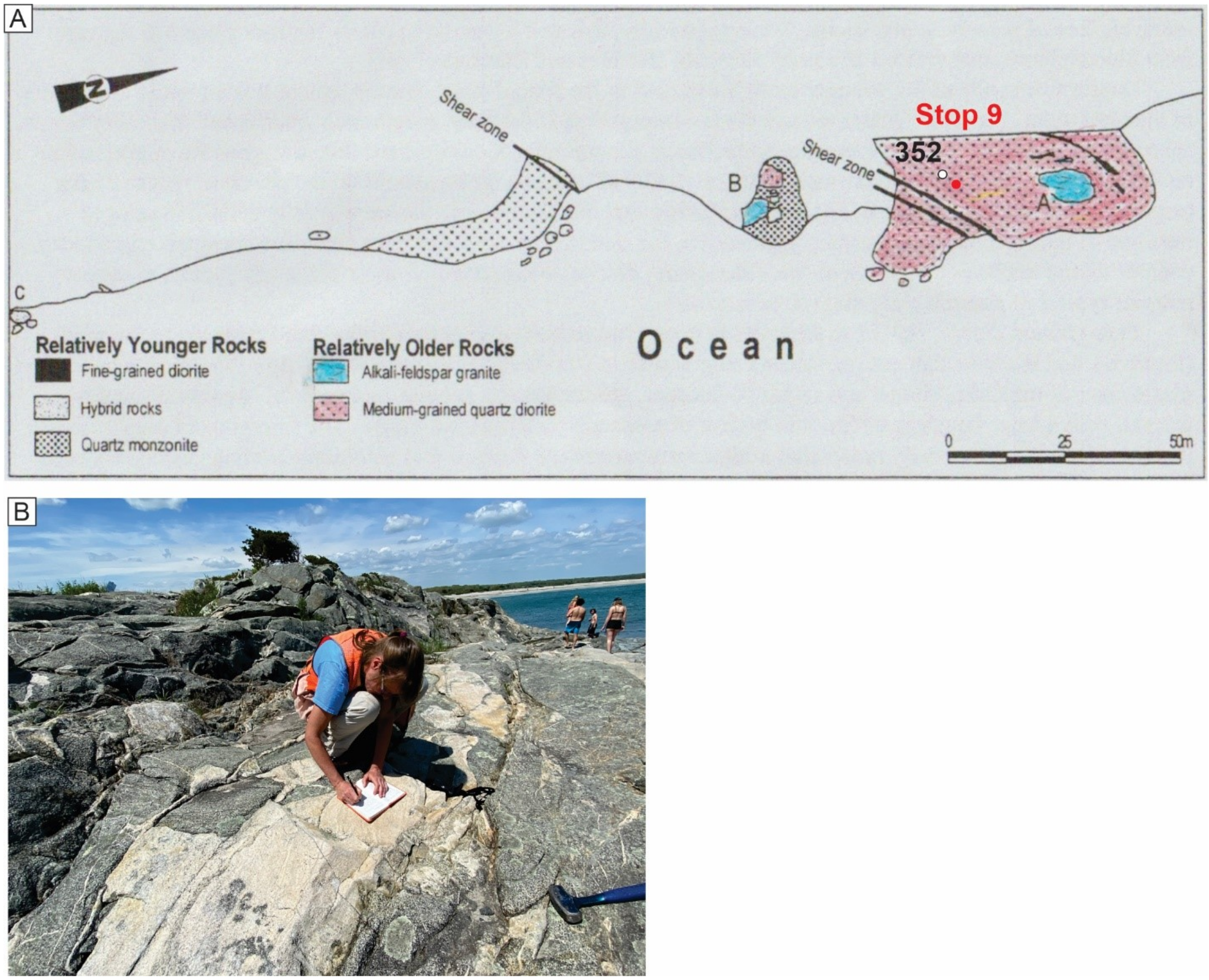


Figure 21. **Stop 9**: (a) Geologic sketch map for relationships at Horseneck Beach (Murray et al., 1998). Letters (A, B, C) refer to specific localities discussed in Murray et al. (1998). Sample 352 (location shown) was collected from a granodioritic part of the "relatively older" quartz diorite. (b) Northeast end of Horseneck Beach, MA, where 352 was collected.

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