Alleghanian deformation of Cambrian metasedimentary rocks on Avalonia in south-central Rhode Island, USA

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ABSTRACT

Lower greenschist-facies metasedimentary rocks of the Middle Cambrian Conanicut Group occur in and around Beavertail State Park, Rhode Island. Detailed structural mapping (1:1000-scale) and petrology of these rocks indicate an early fold generation (F_1) and axial planar metamorphic foliation (S_1). F_1 is folded by a more prominent, E-verging, NNE- to NNW-trending, non-coaxial fold generation (F_2) and an associated pressure solution-enhanced crenulation cleavage (S_2). A third map-scale fold generation is inferred from NNE-trending broad folding of F_2 and S_2. N-S extension resulted in boudins that deformed S_2 on a scale of 1–10 m, whereas late planar quartz veins indicate NW-SE extension. All structures are cross cut by faults striking N- to NE- and ENE- to ESE that show dominantly normal motion with minor sinistral or dextral components. Kink bands associated with faulting trend NNE to ENE with WNW to NNW side up. The vertical Beaverhead shear zone juxtaposes the Cambrian rocks with Pennsylvanian rocks of the Narragansett Basin, and deflects S_2 in a dextral sense, consistent with motion recorded elsewhere.

The Cambrian rocks record the same deformation and metamorphism as the adjacent Narragansett Basin rocks. No evidence was found for pre-Alleghanian deformation or for northwest- or north-directed thrusting and accretion of a Meguma-like terrane during the Alleghanian orogeny. If the Beaverhead shear zone was a pre-existing terrane boundary within Avalonia, both the Cambrian and Pennsylvanian Narragansett Basin sediments were deposited after terrane accretion.

RÉSUMÉ

Des roches profondes métasédimentaires du faciès des schistes verts, que l'on retrouve dans le groupe Conanicut du Cambrien moyen, sont présentes dans le Beavertail State Park, au Rhode Island, et dans les environs. Une cartographie structurale détaillée (à l'échelle 1:1 000) et la pétrologie de ces roches indiquent la formation précoce d'un pli (F_1) et une foliation métamorphique (S_1) de plan axial. Le F_1 est causé par la formation d'un pli (F_2) non coaxial plus dominant, à vergence est et d'orientation NNE-NNO ainsi que par une schistosité de crénulation (S_2) amplifiée en raison d'une dissolution par pression connexe. La formation d'un troisième pli à l'échelle cartographique est provoquée par un vaste plissement du F_2 et de la S_2 d'orientation NNE. Une extension N-S a produit des boudins qui déforment la S_2 sur l'échelle de 1 à 10 m, tandis que des veines de quartz planes formées ultérieurement indiquent une extension NO-SE. Toutes les structures sont traversées par des failles orientées N-NE et ENE-ESE montrant un mouvement normal dominant accompagné de composantes senestres et dextres peu importantes. Les bandes froissées associées à ces failles sont orientées NNE-ENE et présentent une tangente verticale ONO-NNO. Dans la zone de cisaillement verticale de Beaverhead, les roches du Cambrien sont juxtaposées aux roches de la Pennsylvanie du bassin Narragansett, et la S_2 dévie en un mouvement dextre, ce qui concorde avec le mouvement enregistré ailleurs.

Les roches du Cambrien montrent la même déformation et le même métamorphisme que les roches du

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bassin Narragansett adjacent. On n'a trouvé aucune donnée appuyant la création d'une déformation avant l'orogenèse alléghanienne ni celle d'un chevauchement et d'une accrétion orientés vers le nord ou le nord-ouest d'un terrane semblable à la zone de Meguma lors de l'orogenèse alléghanienne. Si la zone de cisaillement verticale de Beaverhead constituait une limite de terrane qui existait avant l'orogenèse de l'Avalonien, les sédiments cambriens et pennsylvaniens du bassin Narragansett se sont déposés après l'accrétion du terrane.

[Traduit par la redaction]

INTRODUCTION

New England is composed of tectonic blocks, microcontinents, and/or terranes accreted to eastern Laurentia primarily during the Silurian-Devonian Salinic, Acadian, and Neoacadian orogenies, and the Pennsylvanian-Permian Alleghanian orogeny (O'Hara and Gromet 1985; Goldstein 1989; Skehan and Rast 1990; Wintsch et al. 1992, 2007; Rast and Skehan 1993; Hepburn et al. 1995; van Staal 2005; Hibbard et al. 2006, 2007). Over the last three decades, the number and extent of these terranes and the timing of their accretion and juxtaposition have been debated. To constrain plate tectonic reconstructions of Laurentia and accreted peri-Gondwanan blocks it is necessary to thoroughly understand the deformational histories of these terranes.

Field, geochronological, geochemical, and geophysical investigations have addressed the timing of accretion of both Avalonia and Meguma, the two most outboard peri-Gondwanan blocks, to eastern Laurentia (e.g., Keppie and Dallmeyer 1987, 1994; Hutchison *et al.* 1988; Keen *et al.* 1991; Waldron *et al.* 1996; Hibbard *et al.* 2007). Avalonia extends north from Rhode Island, USA, into eastern Canada (southeastern New Brunswick, northwestern Nova Scotia, and eastern Newfoundland) whereas the outboard Meguma terrane is juxtaposed to Avalonia along the Minas fault zone in Nova Scotia and inferred extensions in offshore areas (Fig. 1a) (Hutchinson *et al.* 1988; Keen et al. 1991; Murphy *et al.* 2011).

The mainly Neoproterozoic sedimentary, volcanic, and plutonic rocks and overlying Cambrian-Ordovician sedimentary rocks of Avalonia experienced a period of tectonic quiescence until a tectonothermal event in the Silurian-Devonian, evidence for which is preserved in rocks in parts of Avalonia in New Brunswick and northern mainland Nova Scotia (e.g., Nance and Dallmeyer 1994; Waldron *et al.* 1996). Although the precise timing of accretion of Avalonia to composite Laurentia is still debated, it has been postulated to have been accomplished by the Early Devonian (e.g., van Staal and Barr 2012).

The Meguma terrane is composed of stratified Paleozoic rocks that overlie unknown continental basement material. It accreted to eastern North America during the mid-Devonian Neoacadian orogeny, with further juxtaposition during the Alleghenian (Waldron *et al.* 2009, 2011; Murphy *et al.* 2011; White and Barr 2012; White *et al.* 2012).

One area of Avalonia that remains poorly understood is the part of the southeastern New England (SENE) Avalon (Thompson *et al.* 2010, 2012) on which the Pennsylvanian Narragansett Basin lies. The SENE Avalon block is separated from the Putnam-Nashoba terrane to the west by the Bloody Bluff, Lake Char, and Honey Hill fault zones (Fig. 1b) (Goldstein 1989; Hepburn *et al.* 1995). It is a composite terrane structurally subdivided into the penetratively deformed Hope Valley terrane and the less deformed Esmond-Dedham terrane, separated by the inferred Pennsylvanian Hope Valley shear zone in western Rhode Island (Fig. 1b) (O'Hara and Gromet 1985; Goldstein 1986, 1989; Skehan and Rast 1990; Gromet 1991; Walsh *et al.* 2011). Rast and Skehan (1990) further subdivided the Esmond-Dedham terrane and defined a 'Bulgarmarsh terrane' located southeast of the Narragansett Basin and separated from the basin by the Beaverhead shear zone (Fig. 1b). Skehan and Rast (1990) correlated the Cambrian Conanicut Group rocks of the Bulgarmarsh terrane with dark phyllite of the Cambrian-Ordovician Halifax Formation (now Group; White *et al.* 2012) of the Meguma terrane in Nova Scotia. Skehan and Rast (1990) suggested that the Bulgarmarsh terrane may have been thrust northwestward over the Pennsylvanian Narragansett Basin along the Beaverhead shear zone during the Alleghenian orogeny. However, based on its fossil assemblages, Landing (1996) correlated the Conanicut Group with lower to upper Cambrian stratigraphic units characteristic of Avalonia and discounted the existence of a separate Bulgarmarsh terrane.

In order to determine the structural relationships between these proposed terranes, their timing of accretion and juxtaposition, and their possible correlation with distal terranes, a better understanding of the deformational history of the basement blocks within the SENE Avalon terrane is fundamental. Toward this goal, we present the results of detailed structural mapping and fabric analysis of trilobite-bearing Middle Cambrian rocks in Beavertail State Park and along the western coastline between Beavertail and Fort Getty state parks in Rhode Island (Fig. 1c). These rocks form part of the hypothesized Bulgarmarsh terrane,

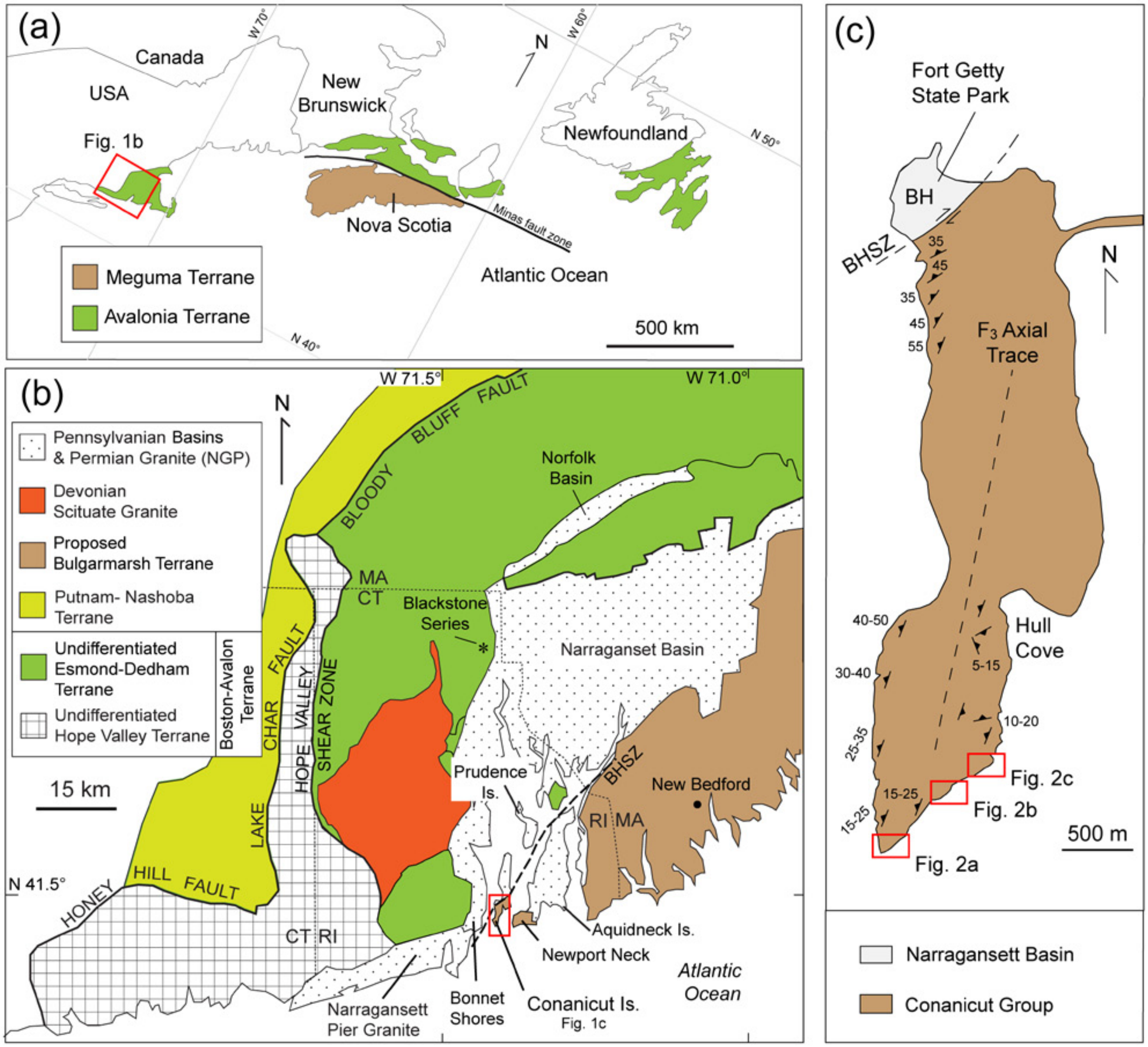

Figure 1. (a) Location of Avalonia and Meguma in northeastern North America (modified from Hibbard *et al*. 2007). Location of Fig. 1b shown by red box. (b) General geologic map of southeastern New England showing undifferentiated rocks of the Hope Valley and Esmond-Dedham terranes that comprise the southeast New England Avalon terrane (modified from O'Hara and Gromet 1985). The Putnam-Nashoba terrane, the proposed Bulgarmarsh terrane, and the Scituate granite are also indicated (O'Hara and Gromet 1985; Getty and Gromet 1988; Skehan and Rast 1990). The dashed line (Beaverhead shear zone - BHSZ) separates Pennsylvanian rocks of the Narragansett Basin from Cambrian rocks of the Conanicut Group on Conanicut island. Location of Fig. 1c is shown by the red box. (c) Map of the field area including Beavertail State Park (peninsula south of Hull Cove), Cambrian and Pennsylvanian rocks across the BHSZ at Beaverhead (BH), where Fort Getty State Park is located. The orientation of S_2 near the Beaverhead shear zone (motion indicated in NW corner) is consistent with dextral motion. To the south, the general change in S_2 orientation across the island recording F_3 is shown, and the inferred F_3 axial trace is noted. Detailed map locations for Figs. 2a, b, c are indicated

immediately southeast of the proposed boundary with the Esmond-Dedham terrane (Skehan et al. 1978, 1981; Skehan and Rast 1990; Landing 1996; Geyer and Landing 2001). At this important locality, the well-layered Cambrian rocks lie adjacent to Pennsylvanian strata of the Narragansett Basin along the Beaverhead shear zone (Fig. 1c). The Pennsylvanian rocks exclusively record the Alleghanian orogeny.

We compare the timing of deformation and metamorphism, as well as structural relationships, between the Cambrian and Pennsylvanian rocks. If earlier structures are preserved in the Cambrian rocks, it would suggest that Avalonia had accreted to Laurentia prior to the Alleghanian orogeny, and may record Acadian (or earlier) deformation. However, if the structural and metamorphic styles in the Cambrian rocks are similar to those in the Pennsylvanian rocks, it is likely that both experienced the same deformational event (i.e. the Alleghenian orogeny). Additionally, if NW-directed thrusting of the proposed Bulgarmarsh terrane is responsible for deformation in both Cambrian and Pennsylvanian rocks, then NW-verging folds and thrust faults would be expected in these rocks. The results of this study allow us to test previously proposed models for accretion and/or juxtaposition of the proposed Bulgarmarsh terrane and its relationship to Meguma terrane (Skehan and Rast 1990; Rast and Skehan 1990), as well as help constrain the timing of deformation and accretion of Avalonia to composite Laurentia.

GEOLOGICAL SETTING

The Pennsylvanian Narragansett Basin, located on the Esmond-Dedham terrane (Fig. 1b), was deformed during the Alleghanian orogeny (e.g., Mosher 1983; Snoke and Mosher 1989). In contrast, Neoproterozoic and early Paleozoic rocks surrounding the basin show variable deformation ranging from Neoproterozoic to Permian (e.g., Skehan *et al.* 1981; Hermes and Zartman 1985, 1992; Dreier 1985; Goldstein 1986; Getty and Gromet 1988; Murray *et al.* 1990).

Neoproterozoic (Avalonian) basement rocks

Surrounding the Narragansett Basin are basement rocks that show varying effects of Alleghanian and/or older deformation. Adjacent to the northwestern part of the Narragansett Basin, the Neoproterozoic Blackstone Group (Fig. 1b) was deformed and metamorphosed syn-tectonically with the intrusion of the 599 ± 2 Ma Esmond Plutonic Suite (Thompson *et al.* 2010), indicating Neoproterozoic tectonism (Dreier 1985). The Blackstone Group also shows younger deformation and associated metamorphism that affected the ~370 Ma Rhode Island Quincy Granite (Hermes and Zartman 1985), indicating Alleghanian tectonism (Dreier 1985). Alleghanian structures recorded in rocks of the Blackstone Group include NNE-trending folds with axial planar biotite-grade foliation and superimposed ENE-trending folds and crenulations (Dreier 1985). Further west of the Narragansett Basin, the Devonian Scituate Granite (Fig. 1b), which intruded the Esmond-Dedham terrane, is deformed only at its western margin along the proposed Hope Valley shear zone (Goldstein 1986; Getty and Gromet 1988).

East of the Narragansett Basin in the area of New Bedford, MA (Fig. 1b), Murray *et al.* (1990) documented penetratively deformed rocks that are lithologically similar to Hope Valley terrane rocks, and suggested that Hope Valley terrane may also be exposed east of the Narragansett Basin in that area. If so, the Esmond-Dedham terrane on which the Narragansett Basin was deposited would be a thrust slice. However, Hermes and Zartman (1992) concluded that most of the deformation in this area is Neoproterozoic.

South of the Narragansett Basin, Neoproterozoic metasedimentary rocks that crop out on Newport Neck (Fig. 1b) show several phases of Neoproterozoic and some possibly younger deformation (Skehan and Rast 1990). The Price Neck Formation records two generations of ENE-trending folds (Skehan and Rast 1990), which are Neoproterozoic based on the relationship to the 595 ± 12 Ma Cliff Walk Granite (Smith 1978). Within the adjacent Proterozoic Newport Neck Formation, NW- to N-trending, tight to isoclinal, west-verging F_1 folds with slaty S_1 cleavage have been refolded by N-trending F_2 folds with an associated dominant S_2 cleavage and N-trending broad upright F_3. The age of these structures has been interpreted as either Neoproterozoic (Skehan *et al.* 1981) or post-Cambrian (Skehan and Rast 1990). The latter interpretation is based on the observation that the Cambrian rocks were overthrust by the Neoproterozoic rocks prior to F_2; however, Webster *et al.* (1986) and Landing (1996) interpreted the boundary as an overturned unconformity rather than a thrust.

Cambrian rocks

In previous work on the Cambrian rocks in Beavertail State Park, three formations were recognized in the Conanicut Group, from oldest to youngest, the Jamestown, Fort Burnside and Dutch Island Harbor formations (Skehan *et al.* 1981; Skehan and Rast 1990). The Jamestown Formation contains the Beavertail Point, Hull Cove, and Lionhead members, and the Fort Burnside Formation contains the Short Point and Taylor Point members; no members were recognized in the Dutch Island Harbor Formation. Earlier workers considered these rocks to be of Pennsylvanian age (e.g., Nichols 1956; Quinn 1971), until the discovery of Middle Cambrian trilobites of Acado-Baltic affinities in the basal Jamestown Formation (Skehan *et al.* 1978). Dikes in the area were described by Nichols (1956) as lamprophyre (see also Skehan and Rast 1990).

Previous field research by Murray and Skehan (1979) recognized NE-trending, tight to isoclinal F_1 folds with axial planar, slaty cleavage refolded by NNE-trending, open and overturned F_2 folds. A dominant, W-dipping S_2 axial planar cleavage transects F_1 folds. Murray and Skehan (1979) also postulated later NE-trending F_3 folds, and describe a NW-trending mineral lineation on S_2 and kink bands. Skehan *et al.* (1981), however, interpreted the earliest folds and numerous "tectonic slides" as soft sediment slump-related structures. Skehan and Rast (1990) repeated this interpretation and further proposed that thrust faults with eastward transport occur on west-dipping S_2 cleavage planes that offset upright F_1 folds and likely caused the folding and boudinage of quartz veins. Most authors (e.g., Murray and Skehan 1979; Burks 1981; Skehan and Rast 1990) attributed all but the first generation structures to the Alleghanian orogeny. Skehan and Rast (1990) suggested that the Cambrian rocks were thrust northwestward over the Pennsylvanian rocks along the BHSZ during D_1 and that NW- to N-directed thrusting was responsible for the deformation of both the Cambrian rocks and Pennsylvanian rocks of the Narragansett Basin.

Narragansett Basin

The southern part of the Pennsylvanian Narragansett Basin (southern Rhode Island) shows multiple phases of deformation and Barrovian-type metamorphism that ranges in grade from sillimanite in the west to chlorite and biotite in the east (Mosher 1983). The metasedimentary rocks of the northern part of the basin (northern Rhode Island and Massachusetts) and adjacent Norfolk Basin (Massachusetts) are at a lower metamorphic grade and less intensely deformed with upright, open, ENE-trending folds that parallel the northern basin margins (Quinn and Oliver 1962; Lyons *et al.* 1976; Cazier 1987).

In the southern part of the basin, the first phase of deformation (D_1) formed open to isoclinal F_1 folds and an axial planar fabric (S_1). F_1 folds generally trend NNE (to N) and verge westward; associated NNE-striking thrusts show westward transport (Mosher 1983, 1987). Rocks deformed at high metamorphic grades preserve two distinct fold generations, F_{1a} and F_{1b}, and axial planar foliations, S_{1a} and S_{1b}, respectively (Henderson and Mosher 1983; Reck and Mosher 1988; Snoke and Mosher 1989; Mahler-Cogswell and Mosher 1994). S_{1A} and S_{1B} are penetrative foliations observed across the basin. At high metamorphic grades the foliations are defined by parallel muscovite, biotite, and elongate, ductilely deformed quartz (Mahler-Cogswell and Mosher 1994) and at low metamorphic grades by pressure-solution cleavage with fine-grained, parallel muscovite and chlorite and elongate pressure-solved quartz (Farrens 1982). The second phase of deformation (D_2) formed open to tight F_2 folds of bedding, S_{1A} and $_{1B}$, and an axial planar S_2 crenulation cleavage enhanced by pressure solution. F_2 folds trend NNW to NNE and verge eastward (Farrens 1982; Mosher 1983). Peak metamorphism occurred after D_1, and generally prior to D_2 (Mosher 1983; Snoke and Mosher 1989).

D_3 and D_4 are primarily developed in the NE-trending, vertical Beaverhead shear zone (BHSZ) (Mosher 1983; Mosher and Berryhill 1991; Burks and Mosher 1996), although the effects are also more broadly distributed in the high-grade metamorphic rocks (Reck and Mosher 1988; Mahler-Cogswell and Mosher 1994). Within the zone, NNE-trending sinistral strike-, oblique-, and dip-slip shear zones and faults are related to D_3. F_3 folds generally trend NE to E, and an associated S_3 foliation was observed only at the highest grades (Mosher 1983; Mosher and Berryhill 1991; Mahler-Cogswell and Mosher 1994). During D_3, clockwise-younging superposed crenulations and mesoscopic folds formed in discrete zones (Mosher 1983; Mosher and Berryhill 1991; Burks and Mosher 1996). Kink bands displaying normal motion are spatially related to faults striking N to NNE, and are overprinted by D_4 structures (Mosher and Berryhill 1991).

Dextral NE-striking strike-slip and ENE-striking oblique- and dip-slip shear zones and faults are related to D_4. During D_4, pre-existing fabrics and structures are rotated into the BHSZ, and superposed anti-clockwise-younging crenulations and mesoscopic folds formed within the BHSZ and overprint D_3 structures (Mosher 1983; Mosher and Berryhill 1991; Burks and Mosher 1996). At the highest metamorphic grades, N- to NE-trending open F_4 folds were observed to reorient S_2 and F_3 folds (Reck and Mosher 1988; Mahler-Cogswell and Mosher 1994). Kink bands spatially related to E- to ESE-trending faults show normal motion (Mosher and Berryhill 1991). All across the southern part of the basin, centimetre- to decametre-scale boudins record N-S extension late during D_4. This boudinage likely formed synchronously with the ENE-striking dip-slip fault motion (Farrens 1982; Mosher 1983; Mosher and Berryhill 1991). Additionally, NNW- to NNE-striking normal faults related to D_3 and D_4, or to Triassic rifting, juxtapose rocks of different metamorphic grades (Mosher 1983).

RESULTS

Based on the present study, Cambrian rocks along the coasts in Beavertail State Park and along the western coastline between Beavertail and Fort Getty state parks (Fig. 1c) are interpreted to have undergone an early contractional stage of deformation that involved three phases of folding (F_1, F_2, and F_3), and the formation of two penetrative fabrics (S_1 and S_2). Later deformation produced boudins, kink bands, crenulations, fractures, and faults. Our results are based on detailed mapping at a scale of 1:1000 (Figs. 1c, 2) which included both coastlines from the southern tip of the island to Hull Cove, 2.5 km north along the eastern coastline, and to Fort Getty State Park, 4 km north along the western coastline, as well as the examination of 45 oriented thin sections.

S_0 and F_1/S_1 structures

On a map scale, bedding locally changes dip over 10–20 m and forms upright folds and monoclines that are transected by S_2 (Figs. 2, 3). Because these folds and monoclines were not observed to fold S_2, they are interpreted to be the earliest fold phase (F_1). Map-scale F_1 folds and monoclines deform bedding on a wavelength of 3–15 m and amplitude of 1–2 m; some axial planes dip moderately to the east. F_1 interlimb angles range from open to isoclinal as a result of refolding by the later F_2 fold phase. The range of F_1 inter-limb fold angles (0–90°) is locally dependent on the relative size and position of individual F_1 and F_2 fold hinges and limbs.

In outcrop, the first fold generation (F_1) consists of symmetrical and asymmetrical folds that deform bedding (S_0). F_1 folds are typically observed on S_2 surfaces that transect S_1 axial surfaces and F_1 hinge lines, suggesting that F_1 is non-coaxial with F_2 (Figs. 4–6). Common wavelengths and amplitudes for F_1 folds in outcrop range from 5–15 cm. F_1 folds were not observed in the Lionhead or Hull Cove members of the Jamestown Formation, but were observed in all other stratigraphic units. In the Beavertail Point member of the Jamestown Formation and the Fort Burnside Formation, F_1 folds are open to isoclinal. In these stratigraphic units, quartzite layers form parallel folds, but in mica-rich layers the hinges of F_1 folds have thickened (Fig. 5). F_1 folds in the Dutch Island Harbor Formation are cylindrical with tight to locally open inter-limb angles (Figs. 3, 6). Few F_1 axes were measured because most were visible only on S_2 foliation surfaces. However, F_1 axes that could be measured have steep to shallow plunges and generally fall on a very broad N-S girdle (Fig. 7a). In addition, measured axial planes associated with F_1 are typically upright and strike N-S. Poles to F_1 axial planes fall on a diffuse E-W girdle (Fig. 7a) and define a SSE-trending fold axis, consistent with F_2 fold axes.

Early faults developed synchronously with F_1, as indicated by the observation on an S_2 surface of centimetre to decimetre offset along one limb of an F_1 fold (Fig. 8). Additionally, early faults complicate stratigraphic relationships by juxtaposing formations in the wrong stratigraphic order. Bedding is truncated across the early faults that disrupt the stratigraphy, confirming that they are faults, not stratigraphic contacts (Fig. 9). For example, folded bedding planes of the Short Point member are truncated by an early-stage fault and juxtaposed with the Beavertail Point member (Fig. 9). These faults are folded by F_2, but not F_1 and are interpreted as syn-F_1 faults; similar to the intra-formational faults observed on S_2 surfaces. No thrust faults are observed on S_2 cleavage planes, and all disruption of F_1 folds is attributed to syn-F_1 faults.

The S_1 fabric forms a continuous cleavage defined by the alignment of platy minerals. S_1 is axial planar to F_1 folds and is poorly developed in outcrop except within and near F_1 fold hinges of mica-rich layers (Fig. 5). It is rarely present in quartzite layers. Locally, S_1 is better developed than S_2, but only within mica-rich layers of the Beavertail Point member and Dutch Island Harbor Formation.

In thin section, compositional layering (S_0) is typically recognizable as light layers, composed of quartz and carbonate, with minor amounts of fine muscovite alternating with dark layers made up of fine muscovite and lesser quartz (Fig. 10). Both layers contain chlorite, and siliceous and/or siderite nodules. Pyrite crystals are most abundant in the Dutch Island Harbor Formation, and less abundant in other formations. Graphite is more abundant in darker mica-rich layers, but is also present in lighter layers. Features interpreted to be microstylolites are locally present sub-parallel to S_0, but could also be crenulated graphite layers.

S_1 is a penetrative metamorphic fabric in thin section, defined principally by a very well-developed alignment of fine muscovite. Some larger blades of muscovite and minor amounts of chlorite also define this fabric (Fig. 10). Where present, S_1 is generally sub-parallel to bedding except in the hinges of F_1 folds. S_1 is also preserved as mineral inclusions in siderite and siliceous nodules that overgrew S_1 (Fig. 11). In siderite nodules, S_1 is defined by aligned inclusions of pyrite, white mica, rare chlorite, and elongate quartz. In siliceous nodules, S_1 is defined by aligned inclusions of mostly elongate quartz, minor fine muscovite, and rare chlorite (Fig. 12). S_1 is everywhere evident in mica-rich layers, but S_1 is typically not well developed in quartz-rich layers where it is defined by rare muscovite grains.

F_2/S_2 structures

The dominant fold generation, F_2, deforms bedding into E-verging, overturned, and locally recumbent folds. Associated with F_2 is an axial planar cleavage (S_2), which is commonly the most pervasive fabric in outcrop (Figs. 9, 13). F_2 folds bedding, F_1, S_1, and the early faults that truncate F_1 fold limbs and disrupt the stratigraphic order. F_2 folds are typically asymmetrical with inter-limb angles ranging from open to tight. Centimetre to decimetre-scale F_2 folds are commonly parasitic to metre-scale F_2 folds and have

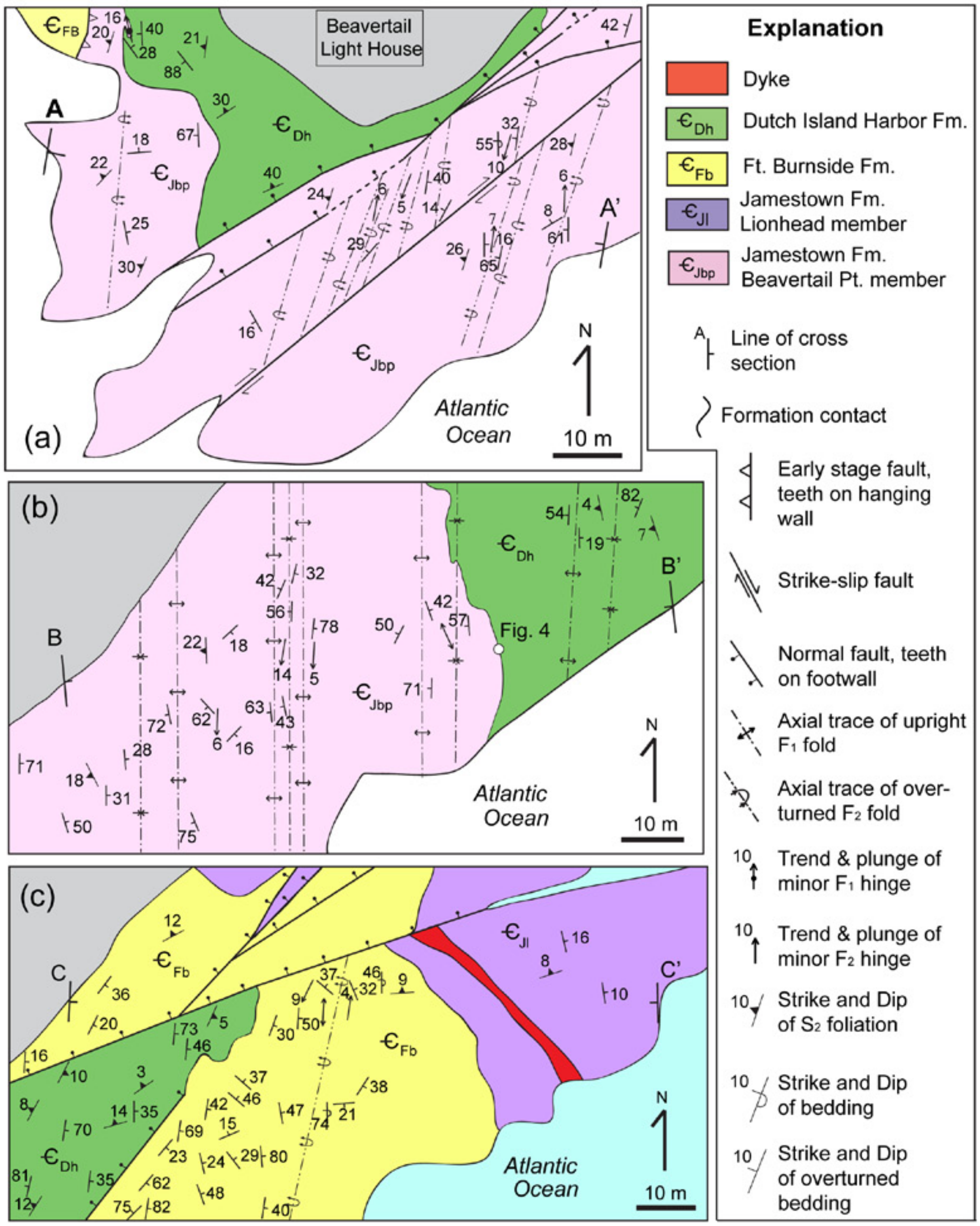

Figure 2. Selected detailed maps from Beavertail State Park (see Fig. 1 for locations; see Carter, 2008 for complete maps). Note location of Fig. 4 on Fig. 2b

wavelengths of 0.5 cm to 5 m with amplitudes ranging from 0.5 cm to 5 m. F_2 fold axes trend NNE to NNW and plunge shallowly (0–10°) north and south (Fig. 7a). Many F_2 folds have periclinal fold axes that split or die out along the hinge line and are doubly plunging, which most likely causes the variable plunge of F_2 fold axes (Fig. 7a). Bedding poles fall on a broad E-W girdle, consistent with F_2 fold axes orientations (Fig. 7a). In general, F_2 folds have a similar trend as F_1 folds, but are typically non-coaxial because of the generally steeper plunge of F_1 folds (Fig. 7a). In outcrop, interference patterns of F_1 and F_2 are rare, but where present confirm non-coaxial fold generations as a result of a difference in plunge (Fig. 4).

In two localities along the southeastern coastline of the field area, the Beavertail Point member of the Jamestown Formation is in contact with the Dutch Island Harbor Formation and folded by F_1 and F_2 (Figs. 2, 4). Skehan et al. (1981) interpreted this contact as an early fault associated with F_1 on the basis of their stratigraphic interpretation (Beavertail Point member as the oldest unit and the Dutch Island Harbor formation as the youngest unit). However, in

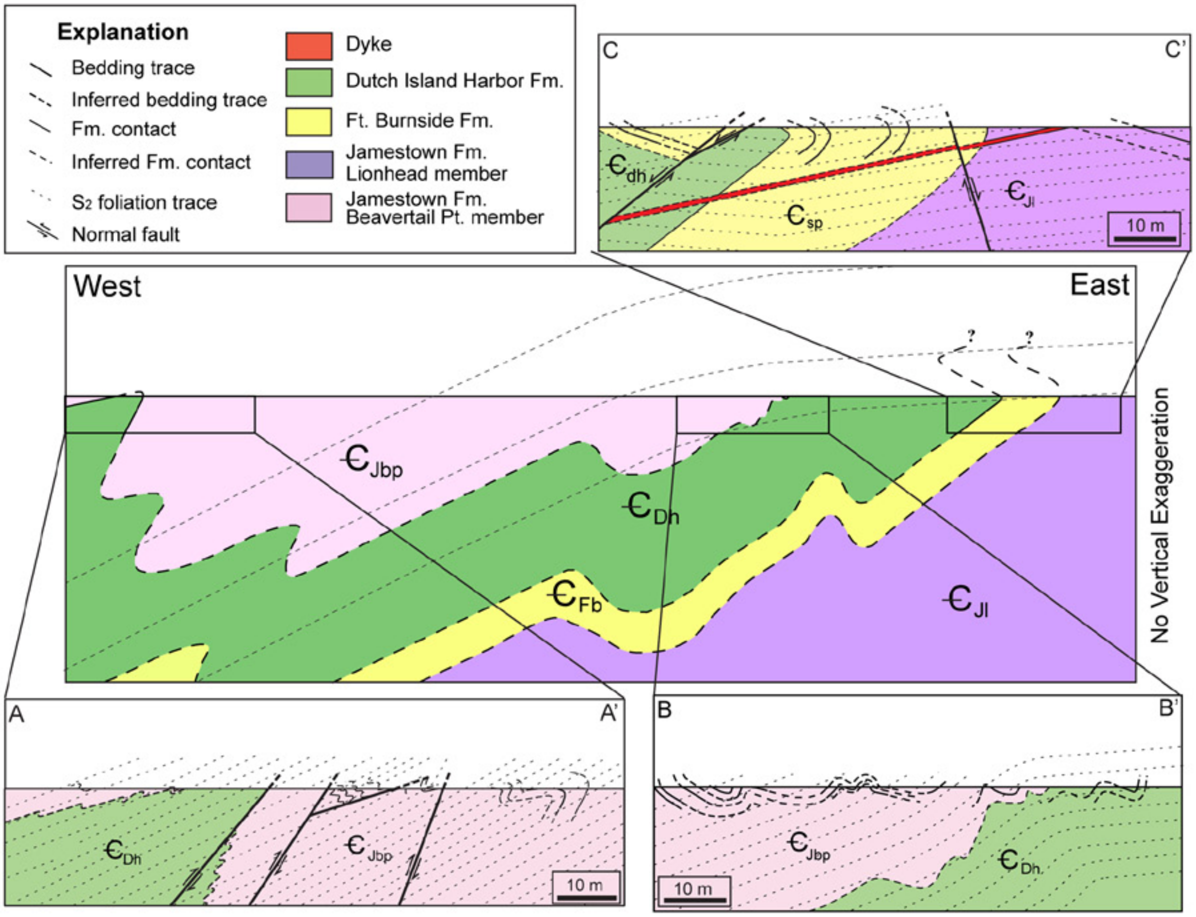

Figure 3. Generalized cross section for the southeastern coastline of Beavertail State Park showing E-verging F_2 syn-form cored by the Beavertail Point member of the Jamestown Formation which becomes W-verging toward the east due to refolding by F_3 (for complete cross section, see Carter 2008). Selected detailed cross sections from Figs. 2a, b and c to illustrate structures: Cross section A-A' shows E-verging F_2 fold cored by the Dutch Island Harbor Formation, parasitic F_2 folds and the S_2 axial planar cleavage. Cross section B-B' shows upright to W-verging F_1 folds and monoclines that are transected by the S_2 cleavage. F_3 tightens F_1 and folds S_2 on eastern half of cross section. Cross section C-C' shows a recumbent F_2 fold, parasitic F_2 folds, the S_2 axial planar cleavage, and a lamprophyric dyke (red) cross cutting all of the Cambrian formations.

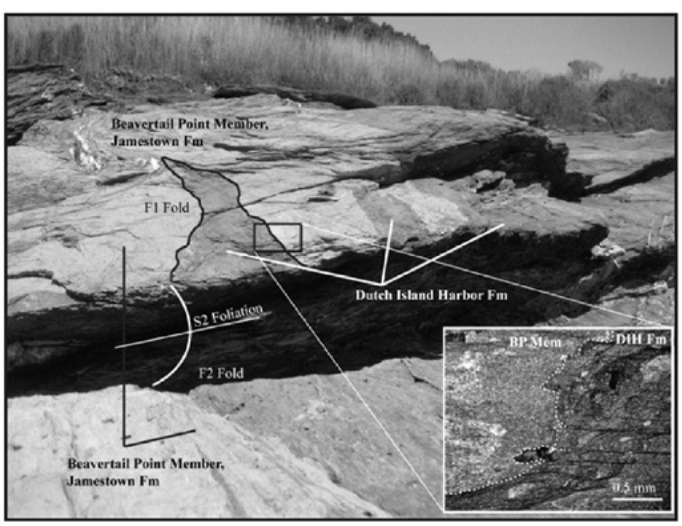

Figure 4. Photograph showing the contact between the Beavertail Point (BP) member of the Jamestown Formation (light grey) and the Dutch Island Harbor (DIH) Formation (dark grey to black) along the southeast coastline of Beavertail State Park (see Fig. 2b for location). Formation contact is folded by F_1 (solid black line) and F_2 (solid white line), and is transected by the S_2 foliation. Note F_2 fold does not show up well because of shadow. Lower right inset is photomicrograph of the folded formation contact (white dashed line, F_2) from this locality. Pressure solution crenulation cleavage (S_2) in photomicrograph does not penetrate the Beavertail Point member because of contrasting lithologies (more quartz rich). Photograph looks north.

Figure 5. Photograph showing F_1 fold and S_1 axial planar cleavage in the Fort Burnside Formation, looking down on the S_2 cleavage plane. Black nodules (mm-scale) are composed of siderite and Fe-oxide. Compass sighting arm points north.

Figure 6. Photograph showing asymmetrical F_1 folds in the Fort Burnside Formation. The pervasive cleavage cross cutting the F_1 axial planes is S_2. Long dimension of compass is oriented NNE-SSW.

our field and petrographic observations we found no evidence of brecciation along this boundary or any other evidence of faulting (Fig. 4). Thus we interpret it as a stratigraphic contact between the Dutch Island Harbor Formation and the Beavertail Point member of the Jamestown Formation. With this interpretation, we suggest that the major structure cropping out along the southeast coastline of the field area is a synformal, E-vergent F_2 fold cored by the Beavertail Point member (Fig. 3).

In addition to folds of bedding, S_2 is axial planar to folds of two different styles of quartz veins, indicating that the veins were emplaced prior to, and later folded by, F_2 folds. En échelon quartz-filled extension fractures are deformed into tight to isoclinal folds. Such veins are typically 1–3 cm in thickness, and when unfolded range in length from 0.5–2 m. Other quartz veins folded by F_2 were likely planar structures first before being folded by F_2. Such veins are typical where S_2 is shallowly dipping and are recumbently folded, with inter-limb angles that are closed to isoclinal. These folds have wavelengths varying from 1 cm up to 3 m, amplitudes ranging from 1 cm to 4 m, and vein thicknesses of 1–4 cm.

The penetrative S_2 cleavage is present across the entire field site (Fig. 1c). In outcrop, S_2 forms a smooth, continuous pressure solution cleavage (e.g., Figs. 9, 13). This cleavage is axial planar to F_2 and transects F_1 axial planes (Figs. 3–6), verifying that it formed after F_1. S_2 generally strikes NNE and is shallowly to moderately west dipping (Fig. 7b).

In thin section, the S_2 fabric is a crenulation cleavage of S_1 enhanced by pressure solution and microstylolites. Within mica-rich layers, S_2 forms tight to isoclinal crenulations of S1 that are parasitic to mm-scale folds of S_0 and S_1 (Fig. 10). Seams of hematite and graphite are parallel to and truncate limbs of the crenulations (Fig. 10). Pervasive pressure solution along the crenulation limbs has resulted in a decrease of the inter-limb angle from that observed in outcrop. On the limbs of mm-scale folds, parasitic folds of S_1 are asymmetric, whereas in the hinge they are symmetric. Wavelengths for these folds range from 0.08 mm to 0.5 mm, with amplitudes between 0.1 mm to 0.5 mm. S_2 is better developed in mica-rich layers than quartz-rich layers, where S_2 is best observed as microstylolites. In mica-rich layers, blades of white mica bend around fold hinges, but in quartz-rich layers individual white mica and muscovite grains have been recrystallized in fold hinges. The very close spacing of S_2 indicates why S_2 is commonly more pervasive than S_1 at the outcrop scale (Fig. 10).

The S_2 fabric wraps around the siderite and siliceous nodules (Figs. 11, 12), and pressure shadows composed of mostly muscovite, elongate quartz, and calcite with minor amounts of chlorite and rare clinozoisite have grown off of them parallel to S_2 (Fig. 12). Clusters of pyrite crystals that grew prior to S_2 also have pressure shadows composed primarily of mica, quartz, and iron carbonate aligned parallel to S_2.

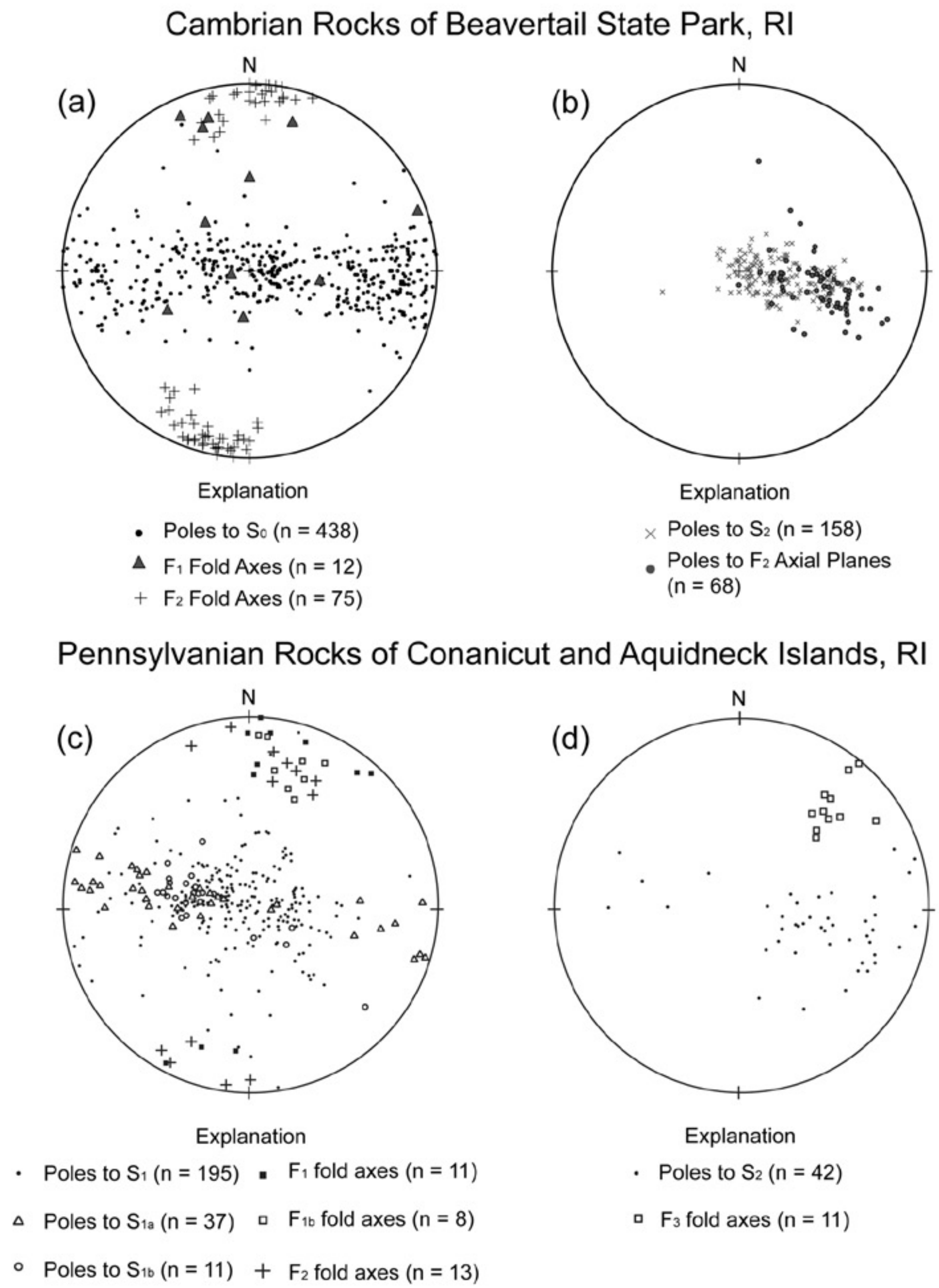

Figure 7. Equal area, lower hemisphere stereonets for the Cambrian rocks of Beavertail State Park (a, b), and for the Pennsylvanian rocks of Conanicut and Aquidneck Islands, Rhode Island (c, d); unpublished data from S. Mosher and her students). Note similarity in orientations of comparable structural elements in the Cambrian and Pennsylvanian rocks. (a) Poles to bedding (S_0), F_1 and F_2 fold axes for Cambrian rocks. Spread of poles to S_0 along an E-W girdle is consistent with F_2 fold axes. (b) Poles to S_2 and F_2 axial planes for Cambrian rocks fall on a generally on a WNW-trending girdle, consistent with folding about a NE-SW F_3 fold axis. (c) Poles to S_1, S_{1a}, and S_{1b} and F_1, F_{1b} and F_2 fold axes of Pennsylvanian rocks. Spread of poles to S_1, S_{1a}, and S_{1b} along a WSW-trending girdle is consistent with F_2 fold axes. (d) Poles to S_2 for Pennsylvanian rocks on a generally on a WNW-trending girdle, consistent with folding about NE-trending F_3 fold.

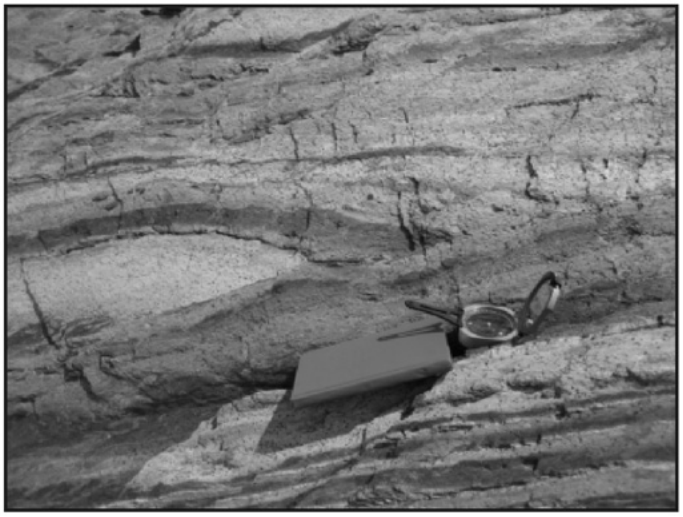

Figure 8. Photograph showing F_1 fold with lower limb truncated by fault (white line). Bedding on either side is unaffected. View is looking down at S_2 in the Fort Burnside Formation. Compass sighting arm points north.

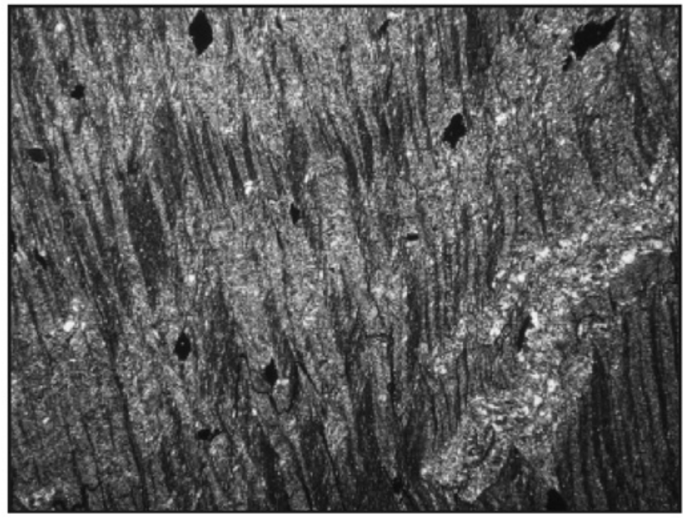

Figure 10. Photomicrograph of F_2 crenulations of S_1 with limbs truncated by pressure solution seams (sub-vertical). Quartz and fine white micas define S_1, are sub-parallel to bedding, and are bent around the hinges of F_2 crenulations. Photomicrograph from the Beavertail Point member. Field of view is 1.1 mm (long dimension) in XPL.

Figure 9. Photograph showing tectonic contact (solid white line) between the Fort Burnside Formation (left of solid white line) and Beavertail Point member (right of solid white line). Bedding (dashed line) of the Fort Burnside Formation is folded by F_2 with an axial planar cleavage S_2 (solid black line). Bedding is absent in the Beavertail Point member. Tectonic contact (solid white line) truncates bedding in the Fort Burnside Formation and is folded by F_2. Backpack at center is for scale.

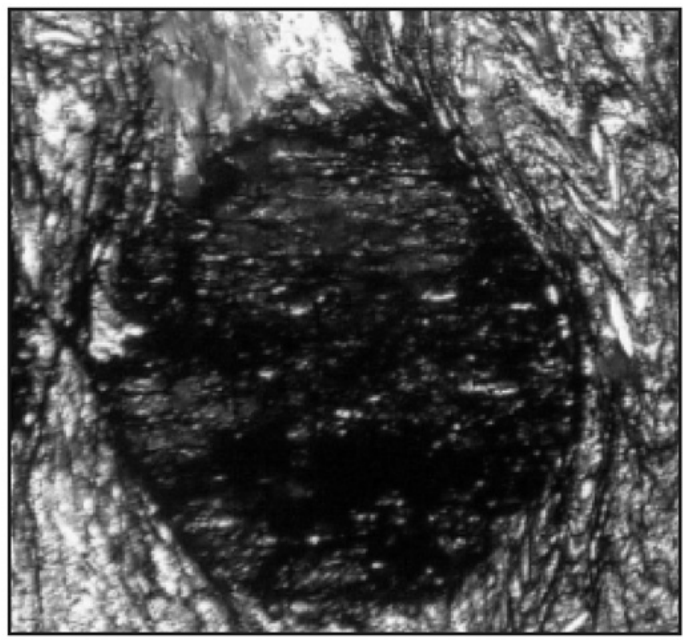

Figure 11. Photomicrograph of siderite nodule preserving the S_1 foliation as white mica mineral inclusions and bands of Fe-oxide. Tails of white mica, quartz and minor chlorite have grown parallel to S_2 off of the nodule. S_1 in matrix is defined by an alignment of white mica, and S_2 is a crenulation of S_1 enhanced by pressure solution seams (sub-vertical). Note folding of metamorphic muscovite blades defining S_1 in crenulation hinges (upper right), and S_2 wraps the siderite nodule and is not observed within the inclusion pattern. Photomicrograph from the Fort Burnside Formation. Field of view is 1.0 mm (long dimension) and in PPL.

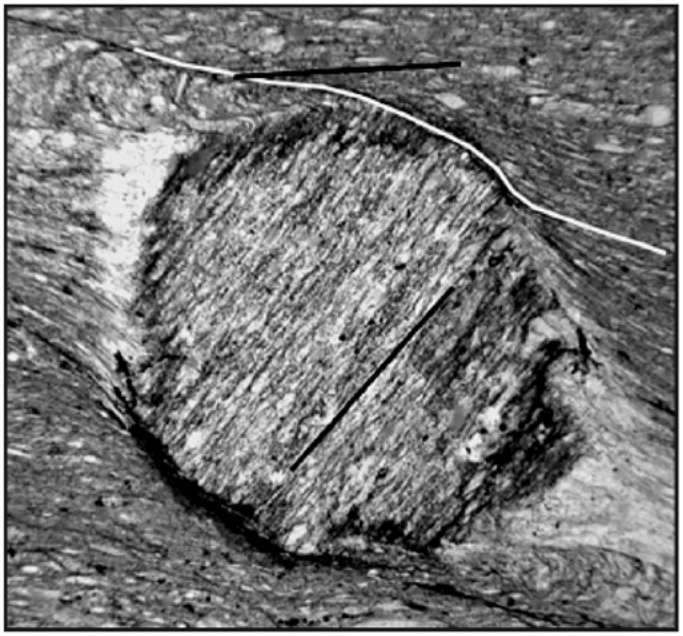

Figure 12. Photomicrograph of a siliceous nodule from the Beavertail Point member. S_1 is preserved as elongate quartz composing most of the siliceous nodule (black line). S_2 wraps the nodule and tails of muscovite, quartz and minor chlorite have grown parallel to S_2 off of the nodule (white line). Field of view is 1.0 mm (long dimension) and in PPL.

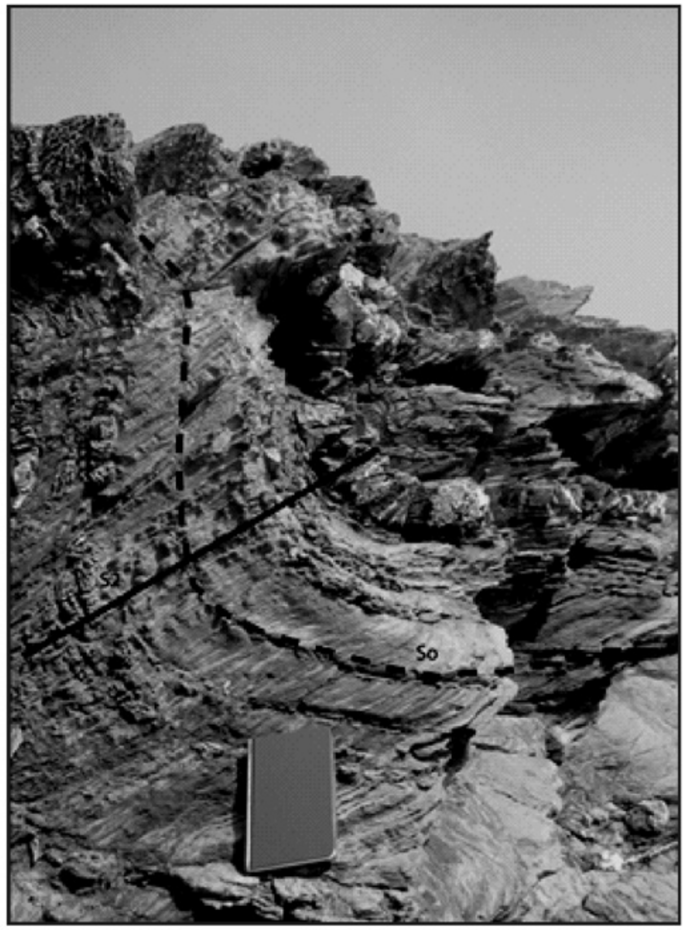

Figure 13. Photograph showing F_2 fold of bedding (dashed line) with pervasive axial planar S_2 (solid line). View north of Beavertail Point member composed of greenish-grey to brown phyllite with tan quartzite beds. Note quartz veins in the quartzite beds accommodate folding, and the pervasive cleavage is S_2 (solid line), axial planar to an F_2 fold of bedding (dashed line). Field notebook at center bottom is for scale.

F_3 and S_c Structures

The youngest fold generation, F_3, is recorded by map-scale gentle to open folding of S_2. This fold generation is inferred from changes in S_2 orientation along continuous exposure on the coastline of Beavertail State Park (Fig. 1c). On the western coastline of the park, the S_2 fabric dips moderately to the west, whereas it is shallowly dipping on the eastern coastline (Figs. 1–3). Poles to S_2 and F_2 axial planes spread along a WNW to ESE-striking girdle defining a NNE-trending fold axis (Fig. 7b), consistent with a shallowly plunging NNE-trending F_3 fold axis. Although defined by the change in S_2 orientation, F_2 and F_1 folds, S_1 and early faults are also observed to be folded by this generation. For example, F_2 folds change from overturned to recumbent across the F_3 folds (Figs. 2, 3).

In thin section, mica-rich layers of the Short Point member contain post-S_2 crenulations. These crenulations formed only on highly pressure-solved limbs of S_2 crenulations along very mica-rich bands. The crenulations are at moderate to high angles to S_2 (Fig. 14) with wavelengths of <0.075 mm and up to 0.15 mm in amplitude. Multiple sets of differently oriented, and locally cross-cutting, crenulations are observed within the same thin section. Locally, crenulations curve from low to high angles relative to S_2, and some are localized between siderite nodules, indicating that shearing may have accompanied their development. No spatial relationship to F_3 is observed; hence we term these S_C, because their relationship to post-F_2 deformation is unknown.

Brittle deformation and associated structures

Boudinage commonly warps bedding and the S_2 fabric. Boudins are generally 1–3 m in length, but locally are up to 15 m. Most boudins are rounded with flat edges at their necks. Quartzite layers acted competently, whereas phyllitic layers

Figure 14. Photomicrograph of S_2 cleavage (sub-horizontal in image) defined by crenulation of S_1 (solid white line) and accompanying pressure solution forming the alternating quartz-rich and mica-rich layers. S_2 is affected by multiple S_C crenulations (dashed white lines in different orientations located at the upper right, bottom and middle center) at high angles to S_2. Photomicrograph from the Fort Burnside Formation. Field of view is 2.36 mm (long dimension) and in XPL.

were more ductile. Within completely mica-rich areas, the layers display foliation boudinage and blocky quartz veins are common in neck regions. The trend of several boudins displays predominantly N-S extension.

After the formation of F_2 and S_2 and before brittle faulting, another generation of quartz and/or siderite veins formed. The veins vary from blocky to fibrous and some contain chlorite as well. Styles of veining include quartz and/or siderite filled en échelon extension fractures, planar quartz and siderite veins, and large blocks of vein quartz with minor chlorite. The latter blocks range in size from 1–3 m^2 and are typically separated by 5–15 m. Because vein quartz is commonly present at the necks of several small-scale boudins, this observation suggests that these blocks are necks of large-scale boudins. In addition, sigmoidal and planar en échelon quartz veins cross cut S_2. Arrays of these veins typically range from 0.5–1 m but are up to 10 m in length with widths of 15–30 cm to 5 m. Spacing between en échelon fractures is typically 1–3 cm, but can be up to a metre. Within an array, thicknesses of individual veins range from 1–15 cm. Planar veins that commonly cut S_2 vary from 0.1 cm to 10 cm in thickness. Planar veins display a variety of orientations, but generally strike NW and dip moderately SW suggesting NE-SW extension (Fig. 15a). The wide variety of quartz veins that were emplaced prior to, during, and after F_2 indicates that silica was mobile throughout deformation.

A 1–2 m thick lamprophyre dyke in Beavertail State Park cross-cuts S_2 and all fold generations (Fig. 1c). The dyke is composed of quartz, carbonate (replacement of quartz), feldspar, and muscovite with minor pyrite. It strikes roughly NW-SE and dips rather shallowly (~30°) to the SW and is not reoriented along with S_2 by the map-scale F_3 fold, indicating its emplacement post-dated F_3. Its orientation is similar to that of most planar quartz veins and suggests that it may be associated with the NE-SW extension related to the veins. Locally, the dyke displays pinch and swell type boudinage over 3–4 m. Also, it is cut by brittle faults and pervasively by several quartz and calcite veins.

Brittle faults and related fractures with no demonstrable offset cut all fold generations (F_1, F_2, and F_3), their associated fabrics (S_1 and S_2), the dyke and all other structures. Faults and related fractures strike N to NE and ENE to ESE (Figs. 2, 15b). Sense of motion on faults was determined from quartz and chlorite slickenlines, deflection of S_2 offset beds and/or displacement on spatially associated kink bands (see below). Minor sinistral and dextral motions were observed, but normal motion is predominant (Fig. 15c). T-axes generally trend NW-SE and P-axes have a variety of orientations, but are mostly steeply plunging. These data indicate normal motion with extension in the NW-SE direction. Although previous maps (e.g., Skehan *et al.* 1981) and those from this study (also see Carter 2008) show a large number of steeply dipping “faults” in these same orientations; most do not show demonstrable offset of structures, unit contacts or layers, and commonly structures continue across the “fault” with no offset. These features are visually prominent because of the intense wave erosion along this coastline, but without evidence of offset (or with evidence of no measurable offset) should best be termed fractures. The largest offset measured on any of the faults is on the Beavertail fault of Skehan *et al.* (1981), which has no more than 5 m of normal throw based on offset of the prominent NW-trending lamprophyre dyke.

Kink bands of S_2 are spatially associated with the brittle faults (Fig. 15b) and vary from a few to multiple arrays covering areas up to a metre wide. Kink bands range from 5 mm to 10 cm across, though on average are 1–3 cm wide. They typically strike sub-parallel to faults, trending NNE to ENE. In some localities, kink bands adjacent to faults are oriented oblique to the fault by ~10–30° and form en échelon arrays indicating oblique motion; some indicate faults with sinistral and others with dextral components of motion. Almost all kink bands record a NW side up motion of no more than 1–2 cm, consistent with the NE-strike of normal faults, predicted from the T and P axes.

The vertical Beaverhead shear zone (BHSZ), located in the northwestern part of the field area, juxtaposes the Cambrian formations with Pennsylvanian formations of the Narragansett Basin and affects the S_2 fabric (Fig. 1c). Near the BHSZ, the strike of S_2 in the Cambrian rocks shows progressive clockwise rotation (Fig. 1c). The deflection of S_2

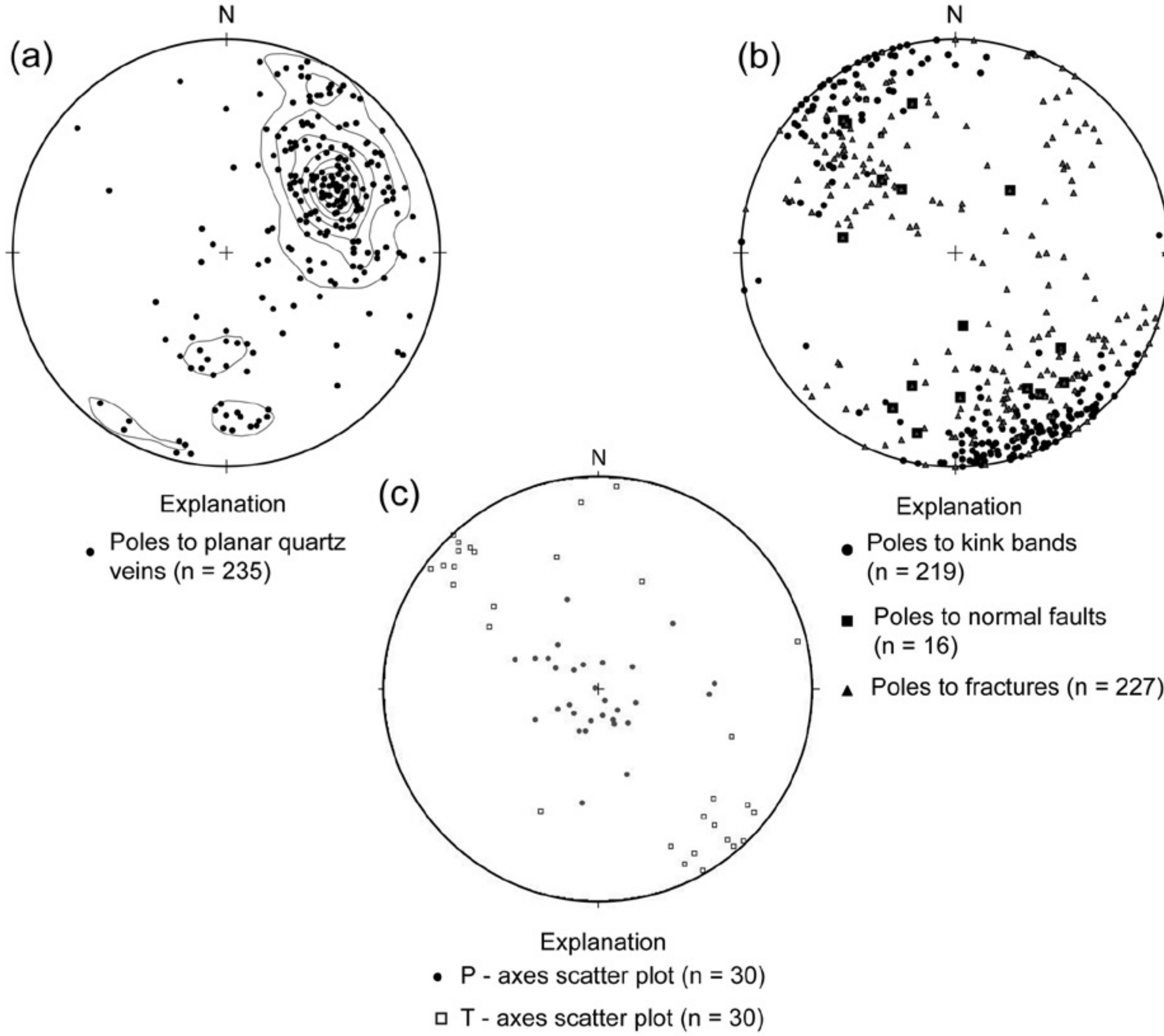

Figure 15. Equal area, lower hemisphere stereonets for late-stage structures from Cambrian rocks at Beavertail State Park, Rhode Island. (a) poles to planar quartz veins. Contours are 1% area contours. General orientation for planar quartz veins strike NW and dip moderately SW. (b) Poles to kink bands, normal faults and fractures show they are spatially related and generally trend NE to ENE. 90–95% of the kink bands have NW side up. (c) P-axes (circles) and T-axes (squares) determined using fault plane kinematic indicators predominantly show normal motion with NW extension.

as it approaches the BHSZ is consistent with dextral motion and indicates that S_2 developed prior to the last recorded dextral motion on the zone (Mosher 1983; Mosher and Berryhill 1991; Burks and Mosher 1996).

Metamorphism

The dominant metamorphic mineral is muscovite which is aligned parallel to S_1. The only metamorphic index mineral present is chlorite, and it is either sub-parallel or at high angles to S_1. In addition, rare tails of chlorite and clinozoisite have grown parallel to S_2 off pyrite, siderite, and siliceous nodules. Round grains that resemble isolated sand grains are composed of chlorite. The freshness and distinct grain shape of the chlorite suggest that it replaced a preexisting detrital mineral of a different composition during metamorphism. Given the absence of biotite, the metamorphic grade of this area could not have been higher than lower greenschist facies, and peak temperatures occurred during the formation of S_1, and continued during the development of S_2. Whole rock $^{40}Ar/^{39}Ar$ cooling ages for muscovite which defines the S_1 fabric in the Cambrian rocks ranges from 240 to 260 Ma (Dallmeyer 1982).

DISCUSSION

Comparison with Pennsylvanian rocks of the Narragansett Basin

Because the Pennsylvanian metasedimentary rocks are intensely deformed by D_3 and D_4 within the Beaverhead shear zone and to a lesser extent along other faults and shear zones, it is appropriate to compare Pennsylvanian rocks on Conanicut and Aquidneck islands (Fig. 1b) that lie outside the BHSZ with the Cambrian rocks south of the shear zone. Garnet- to staurolite-grade metasedimentary rocks on Conanicut Island to the north are geographically closest, but rocks on Aquidneck Island to the east are at the same metamorphic grade as the Cambrian rocks and hence more directly comparable. The summary below is based on extensive research by S. Mosher and her students (also see Farrens 1982; Henderson and Mosher 1983, and summary in Snoke and Mosher 1989).

In Pennsylvanian rocks on Conanicut Island, the first deformation produced F_{1a} and F_{1b} folds and associated S_{1a} and S_{1b} axial planar foliations, whereas on Aquidneck Island only one generation (F_1 and S_1) was produced. F_{1b} and F_1 are generally tight to isoclinal, NNE-trending, WNW-verging, shallowly plunging folds (Fig. 7c, Table 1). $S_{1a,b}$ and S_1 are defined by very well-developed parallel arrangement of muscovite and chlorite in phyllite and schist and pressure solution cleavage in more quartz-rich rocks. Open to tight, NNE-trending, shallowly plunging, ESE-verging F_2 folds deform $S_{1a,b}$ and S_1 and are nearly coaxial to F_{1b} and F_1, respectively (Fig. 7c, Table 1). F_2 folds have an associated axial planar crenulation cleavage, S_2, enhanced by pressure solution. F_2 folds are more numerous on Aquidneck Island. In the higher metamorphic grade Pennsylvanian rocks on Conanicut Island, garnet, staurolite, and biotite grew between D_1 and D_2.

Evidence of D_3 and D_4 are expressed on both islands, but to different extents. On Conanicut Island, numerous NNE-trending sinistral oblique-slip faults are observed. Adjacent to the faults, NE-trending, shallowly plunging, upright to recumbent F_3 folds (Fig. 7d, Table 1) with an axial planar crenulation cleavage is present, along with sinistral tension gashes and sheath folds. On Aquidneck Island, S_1 and S_2 are affected only by E-trending kink bands, although the spread of S_2 along an ESE-trending girdle suggests later open refolding (Fig. 7d, Table 1). On both islands, late-stage boudins with N-S extension affected the metasedimentary rocks. Boudinage is more prevalent on Aquidneck Island where decametre-scale foliation boudinage is observed. In some localities on Aquidneck Island, clockwise younging superposed crenulation cleavages are present. Lastly, on both islands, earlier structures are cut by N-trending, steeply dipping brittle normal faults.

Structures and associated foliations and cleavages affecting the Cambrian rocks are very similar in style, orientation, relative timing, and deformation fabrics to those affecting the adjacent Pennsylvanian rocks on Conanicut and Aquidneck islands. Previous workers have suggested correlation of all but the first generation structures, and by implication that F_1 in the Pennsylvanian rocks equates to F_2 in the Cambrian rocks. However, F_1 folds affecting the Pennsylvanian rocks verge westward, whereas F_2 folds in the Cambrian rocks verge eastward. It is highly unlikely that correlative fold generations in adjacent localities would have different vergences. Additionally, F_2 in both Pennsylvanian and Cambrian rocks verges eastward and has similar deformation fabrics. Hence, correlation of F_2 between localities is more plausible. F_1 folds in both areas are tectonic in origin and have the same orientations, styles, and minerals defining the fabrics. Given the proximity of these rocks, it is unlikely that the Cambrian rocks escaped the more penetrative first deformation to affect the Pennsylvanian rocks. Thus we correlate F_1 folds in the Cambrian and Pennsylvanian rocks.

Subsequent structures (including faults, kink bands, multiple cross-cutting crenulations, and boudins) are also similar and readily correlated. The gentle to open F_3 folds affecting the Cambrian rocks may be correlative with the F_3 folds associated with D_3 sinistral shear along faults in the basin, but more likely are similar to the later N-trending F_4 folds observed further west at Bonnet Shores in the basin (Fig.1b) associated with D_4 (Reck and Mosher 1988). On the rest of Conanicut and Aquidneck islands, exposure is primarily restricted to N-trending outcrops which are not optimal for viewing gentle to open folds in this orientation, although as noted above, S_2 on Aquidneck Island appears folded on a regional scale. On Bonnet Shores, gentle to open N-trending F_4 folds were observed to reorient the S_2 crenulation cleavage. Normal, sinistral, and dextral faults in the same orientations affect both Cambrian and Pennsylvanian rocks. On the basis of the remarkable similarity of structures in all respects, we propose that all deformation recorded in the Cambrian rocks occurred during the Alleghanian orogeny, or possibly later in the case of normal faults.

The relative timing of metamorphism and deformation is the same in both the Pennsylvanian and Cambrian rocks. Additionally, $^{40}Ar/^{39}Ar$ muscovite dates of about 250 Ma from Aquidneck Island (Pennsylvanian rocks) and from whole-rock phyllite samples from Beavertail State Park (Cambrian rocks), which are at the same metamorphic grade, are the same within error and show similar age spectra (Dallmeyer 1982). All the $^{40}Ar/^{39}Ar$ muscovite cooling ages are 240 to 260 Ma across the range of metamorphic grades in the Narragansett Basin (Dallmeyer 1982).

Table 1. Summary table of deformational events in Pennsylvanian rocks of the Narragansett Basin proximal to Cambrian Conanicut Group rocks in Beavertail State Park.

	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

Comparison with previous interpretations

Our results are more compatible with the preliminary work by Murray and Skehan (1979) and Burks (1981) than later work by Skehan *et al.* (1981) and Skehan and Rast (1990). Detailed petrographic work described above demonstrates unequivocally that F_1 folds are tectonic structures and S_1 a metamorphic fabric, not soft-sediment slump features. During our mapping at a scale of 1:1000, we observed no thrust faults on S_2 cleavage planes. Also, thrusting along S_2 could not have caused folding of quartz veins as S_2 is axial planar to the folded quartz veins. The early faults we observed are folded by F_2 and are associated with the formation of F_1, truncating one limb of F_1 folds.

We also found no evidence that the Cambrian rocks were thrust northwestward over the Pennsylvanian rocks along the BHSZ during D_1 as proposed by Skehan and Rast (1990). Thrusting and fold vergence in the Narragansett Basin during D_1 was to the west (e.g., Mosher 1983, 1987), not northwest. In addition, detailed mapping of the Cambrian rocks adjacent to the BHSZ and Pennsylvanian rocks on the eastern shore of Conanicut Island adjacent to the trace of the BHSZ by Henderson and Mosher (1983) did not find any evidence for thrusts. On the western shore, no exposures were found near the contact, and no thrusts are observed. Pennsylvanian rocks in Fort Getty State Park lie within the vertical BHSZ and are intensely deformed by both D_3 and D_4.

Deformation in the Narragansett Basin is interpreted to have resulted from closure of the basin as a result of final collision of Africa with North America, with first west-directed deformation (D_1) followed by back-folding with eastward vergence (D_2) (Mahler-Cogswell and Mosher 1994). Subsequent interaction between the two continents is interpreted to have caused sinistral shear along NNE-trending zones in the western passage of Narragansett Bay and the western basin margin (D_3), followed by dextral shear along a NE-trending zone, including the BHSZ and southwestern part of the basin (Mahler-Cogswell and Mosher 1994). The deformation of the Cambrian rocks matches that of the basin outside of the intense shear zones, and thus is compatible with this tectonic model.

The proposal by Skehan and Rast (1990) and Rast and Skehan (1990) that the BHSZ is a terrane boundary between the Esmond-Dedham and Bulgarmarsh terranes is not substantiated by our work or other work in the basin. Our work also does not support the suggestion of Skehan and Rast (1990) that the Cambrian rocks are part of the Meguma terrane which was thrust over the Pennsylvanian rocks along the BHSZ from some distance to the southeast as a result of a north- to northwest-directed collision during D_1 and followed by a north-directed D_2. No structures in the southern Narragansett Basin or adjacent Cambrian rocks show evidence of NW- or N-directed transport. As discussed above, transport during D_1 in the southern part of the basin was westward and during D_2 was eastward. The northern part of the basin located far from the BHSZ shows ENE-trending fold axes, but they follow the basin margins and were likely caused by closure of the basin and not likely to be related to D_1 or D_2 in the south (Mosher 1983). Additionally, the low-grade, open to tight, NNE-trending, E-verging F_2 folds with associated crenulation cleavage enhanced by pressure solution observed in both Cambrian and Pennsylvanian rocks could not have formed as a result of N-directed thrusting.

Moreover, Pennsylvanian rocks of the Narragansett Basin lie on both sides of most of the BHSZ (Fig. 1b), and the grade of metamorphism is similar across the zone. The chlorite-grade Cambrian rocks (this study) are adjacent to biotite-grade Pennsylvanian rocks on Beaverhead at Fort Getty State Park (Burks 1981) and eastern Conanicut Island (Henderson and Mosher 1983); chlorite-grade rocks on Aquidneck Island (Farrens 1982) are adjacent to biotite-grade rocks on Prudence Island (Thomas 1981) (see Fig. 1b for locations). Also, the Pennsylvanian fossils have the same age range (Stephanian) on both sides of the shear zone (Skehan *et al.* 1986). Thus, no evidence exists that the BHSZ is a major thrust fault. If a major terrane boundary exists underneath the Narragansett Basin, terrane accretion occurred prior to the formation of the basin; otherwise pre-Alleghanian structures would likely be preserved in the Cambrian rocks.

We propose that the Cambrian sediments were deposited on older Neoproterozoic Avalonian basement and remained undeformed until the Alleghanian orogeny. We suggest that deformation related to the accretion of this part of Avalonia to composite Laurentia was accommodated in the western margin of the SENE Avalon terrane (i.e., the Hope Valley terrane) and that the Cambrian rocks escaped deformation until the Alleghanian orogeny. The Pennsylvanian sediments of the Narragansett Basin were deposited on both Neoproterozoic Avalonian basement and on Cambrian sedimentary rocks, at least in the southernmost part of the basin.

CONCLUSIONS

Deformation recorded by Cambrian rocks at Beavertail State Park is correlative with that in Pennsylvanian rocks of the Narragansett Basin. Field mapping and petrographic analysis allow comparison of structures within the two areas. Results indicate that the sequence of deformation and metamorphism, as well as the styles, orientations and geometries of structures are nearly identical, as are deformational fabrics. No evidence exists for structures associated with deformation earlier than the Alleghanian orogeny exists. Hence, all deformation and metamorphism of the Cambrian rocks is interpreted to have occurred during the Alleghanian orogeny.

Our study further shows that the proposed northwestward thrusting of a Meguma-like terrane onto the Pennsylvanian rocks followed by north-directed transport during the Alleghanian orogeny is incompatible with the deformation history of the area. No evidence supporting such thrusting is observed. If the Beaverhead shear zone is a reactivated terrane boundary between the Esmond-Dedham and another Avalonian terrane, accretion must have occurred before the deposition of the Cambrian and Pennsylvanian sediments.

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