

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

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Résumé de l'article

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 (F1) and axial planar metamorphic foliation (S1). F1 is folded by a more prominent, E-verging, NNE- to NNW-trending, non-coaxial fold generation (F2) and an associated pressure solution-enhanced crenulation cleavage (S2). A third map-scale fold generation is inferred from NNE-trending broad folding of F2 and S2. N-S extension resulted in boudins that deformed S2 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 S2 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 preexisting 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 (F1) et une foliation métamorphique (S1) de plan axial. Le F1 est causé par la formation d'un pli (F2) non coaxial plus dominant, à vergence est et d'orientation NNE-NNW ainsi que par une schistosité de crénulation (S2) 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 F2 et de la S2 d'orientation NNE. Une extension N-S a produit des boudins qui déforment la S2 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-NNW. Dans la zone de cisaillement verticale de Beaverhead, les roches du Cambrien sont juxtaposées aux roches de la Pennsylvanie du bassin Narragansett, et la S2 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 bassin Narragansett adjacent. On n'a trouvé aucune donnée appuyant la création d'une déformation avant l'orogénèse alléghanienne ni celle d'un chevauchement et d'une accretion orientés vers le nord ou le nordouest d'un terrane semblable à la zone de Meguma lors de l'orogénèse alléghanienne. Si la zone de cisaillement verticale de Beaverhead constituait une limite de terrane qui existait avant l'orogénèse de l'Avalonien, les sédiments cambriens et pennsylvaniens du bassin Narragansett se sont déposés après l'accrétion du terrane. [Traduit par la rédaction]

# 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.

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## 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

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

[Traduit par la rédaction]

## 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).

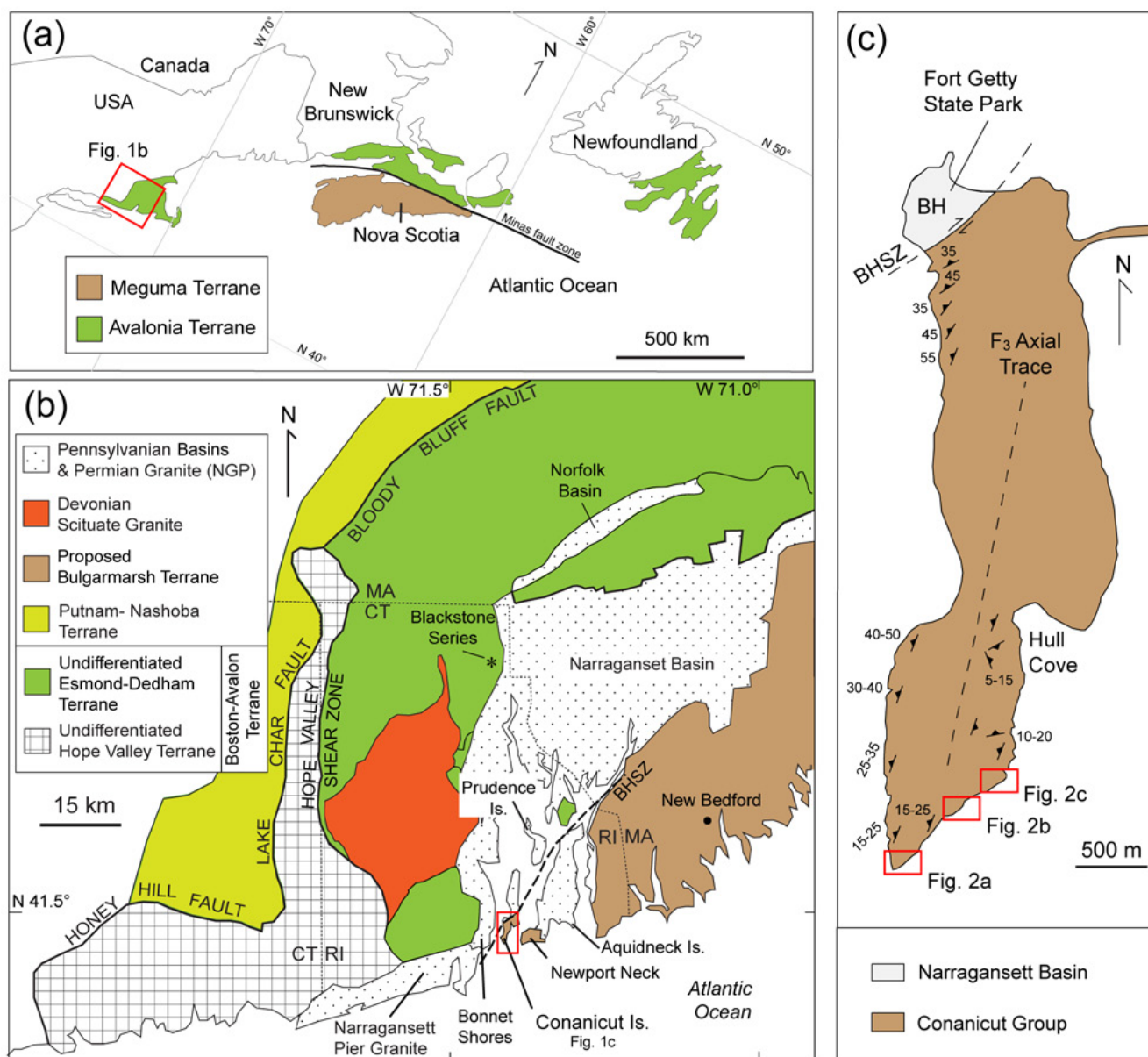
The mainly Neoproterozoic sedimentary, volcanic, and plutonic rocks and overlying Cambrian-Ordovician sedimentary rocks of Avalonia experienced a period of tectonic quiescence until a tectonothermal event in the Silurian-Devonian, evidence for which is preserved in rocks in parts of Avalonia in New Brunswick 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 Alleghanian (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 Alleghanian 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 Alleghanian 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  $599 \pm 2$  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  $595 \pm 12$  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, ductile 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  $S_{1b}$ , 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

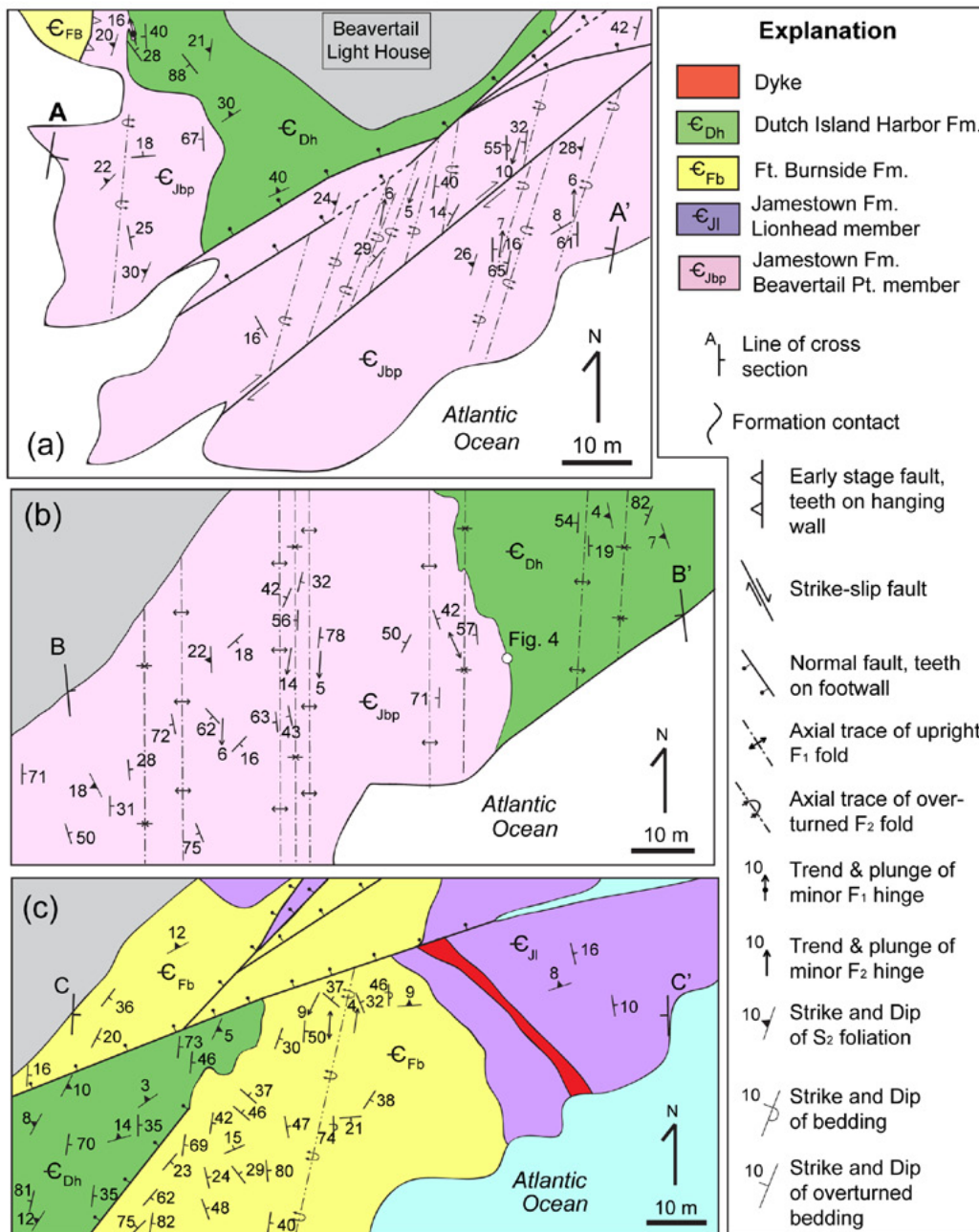


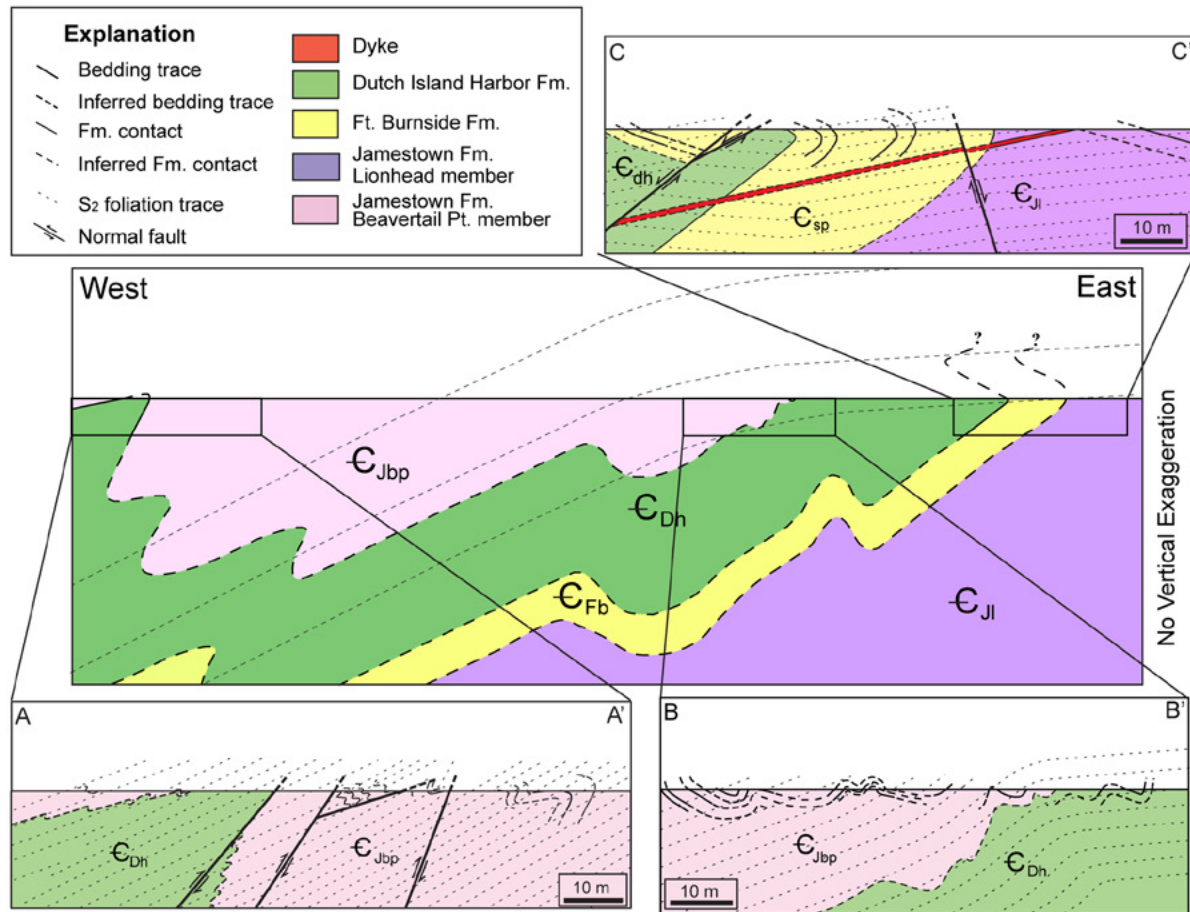
Figure 2. Selected detailed maps from Beavertail State Park (see Fig. 1 for locations; see Carter, 2008 for complete maps). Note location of Fig. 4 on Fig. 2b

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 ( $0-10^\circ$ ) 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

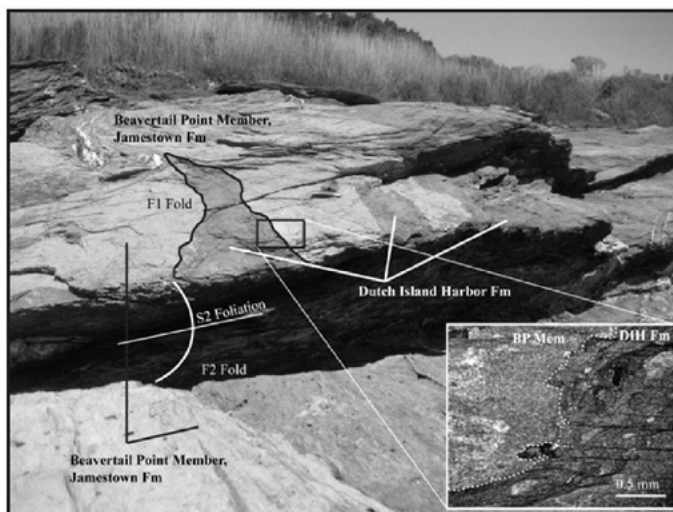
of  $F_1$  and  $F_2$  are rare, but where present confirm non-coaxial fold generations as a result of a difference in plunge (Fig. 4).

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-formed 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

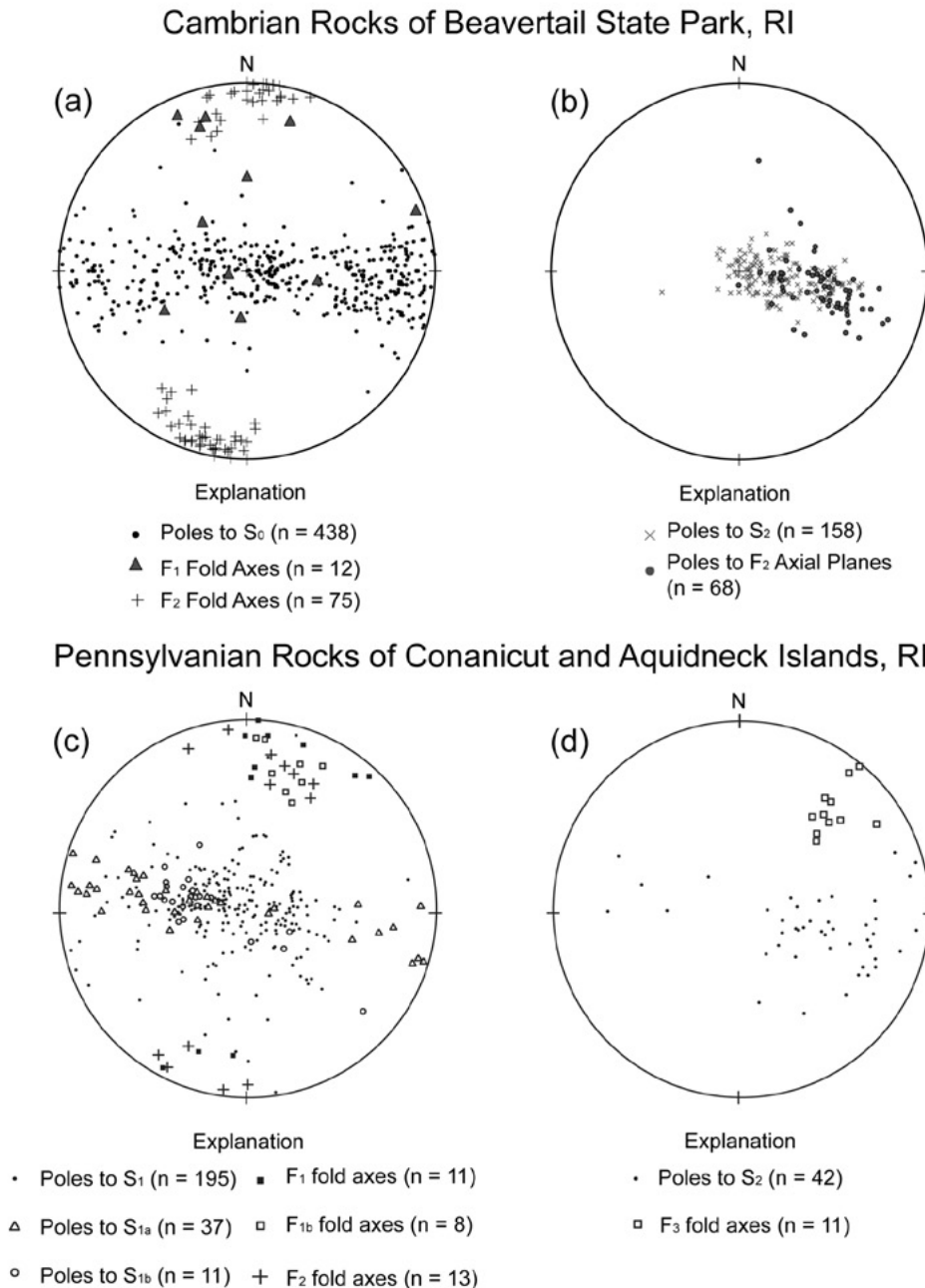
member (Fig. 3).

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.

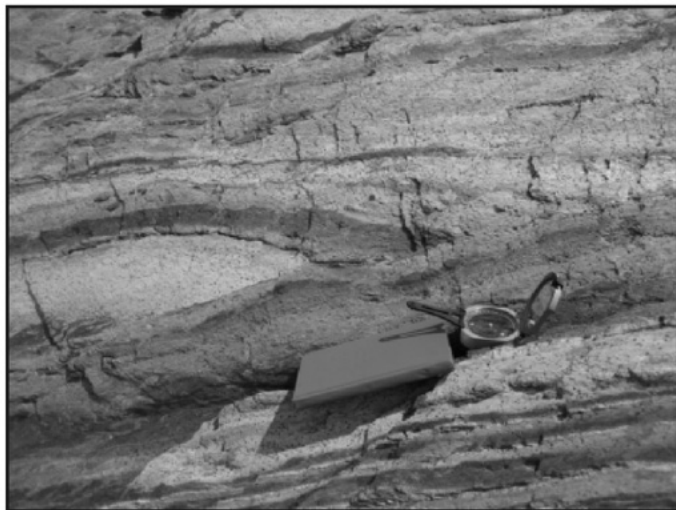
The penetrative  $S_2$  cleavage is present across the entire field site (Fig. 1c). In outcrop,  $S_2$  forms a smooth, continuous pressure solution cleavage (e.g., Figs. 9, 13). This cleavage is axial planar to  $F_2$  and transects  $F_1$  axial planes (Figs. 3–6), verifying that it formed after  $F_1$ .  $S_2$  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  $S_1$  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).

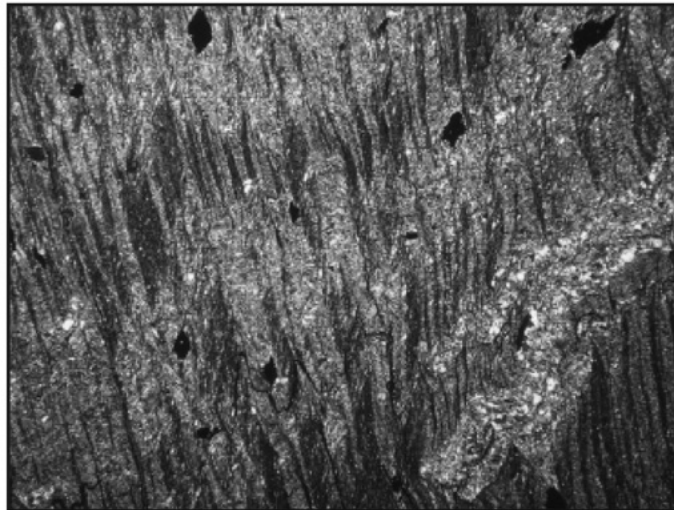
The  $S_2$  fabric wraps around the siderite and siliceous nodules (Figs. 11, 12), and pressure shadows composed of mostly muscovite, elongate quartz, and calcite with minor amounts of chlorite and rare clinozoisite have grown off of them parallel to  $S_2$  (Fig. 12). Clusters of pyrite crystals that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



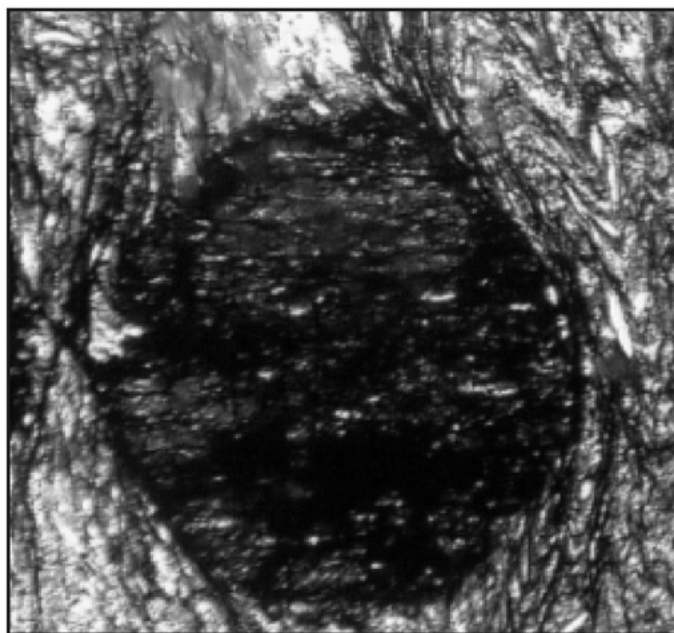
**Figure 8.** Photograph showing  $F_1$  fold with lower limb truncated by fault (white line). Bedding on either side is unaffected. View is looking down at  $S_2$  in the Fort Burnside Formation. Compass sighting arm points north.



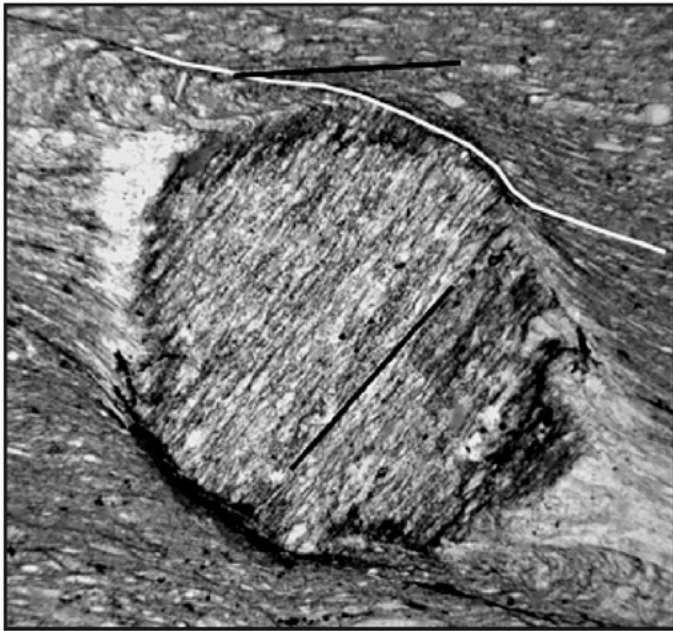
**Figure 10.** Photomicrograph of  $F_2$  crenulations of  $S_1$  with limbs truncated by pressure solution seams (sub-vertical). Quartz and fine white micas define  $S_1$ , are sub-parallel to bedding, and are bent around the hinges of  $F_2$  crenulations. Photomicrograph from the Beavertail Point 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.

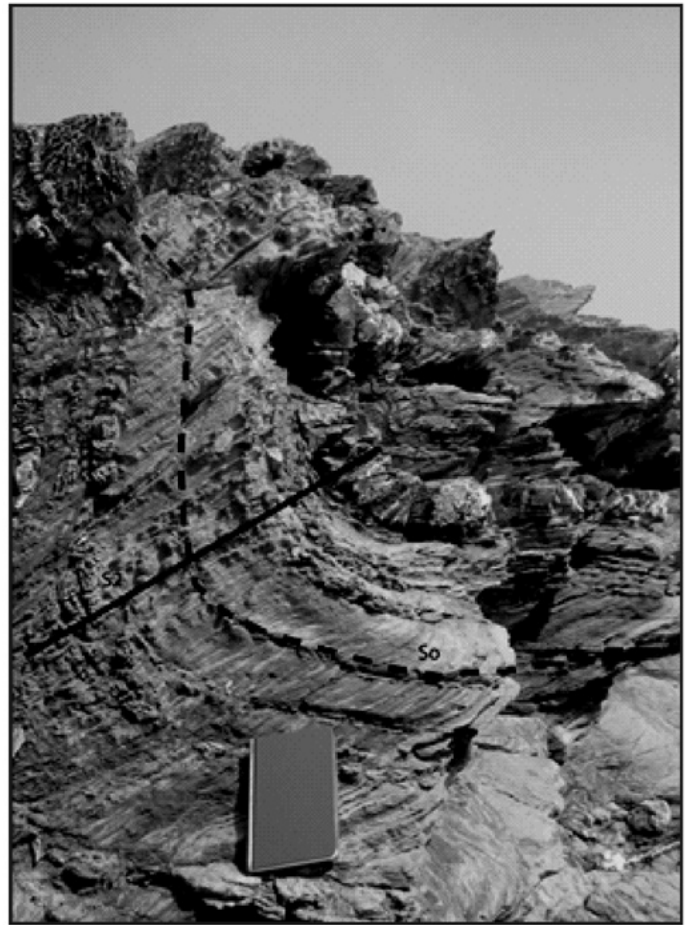


**Figure 12.** Photomicrograph of a siliceous nodule from the Beavertail Point member.  $S_1$  is preserved as elongate quartz composing most of the siliceous nodule (black line).  $S_2$  wraps the nodule and tails of muscovite, quartz and minor chlorite have grown parallel to  $S_2$  off of the nodule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

### $F_3$ 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



**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.

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.

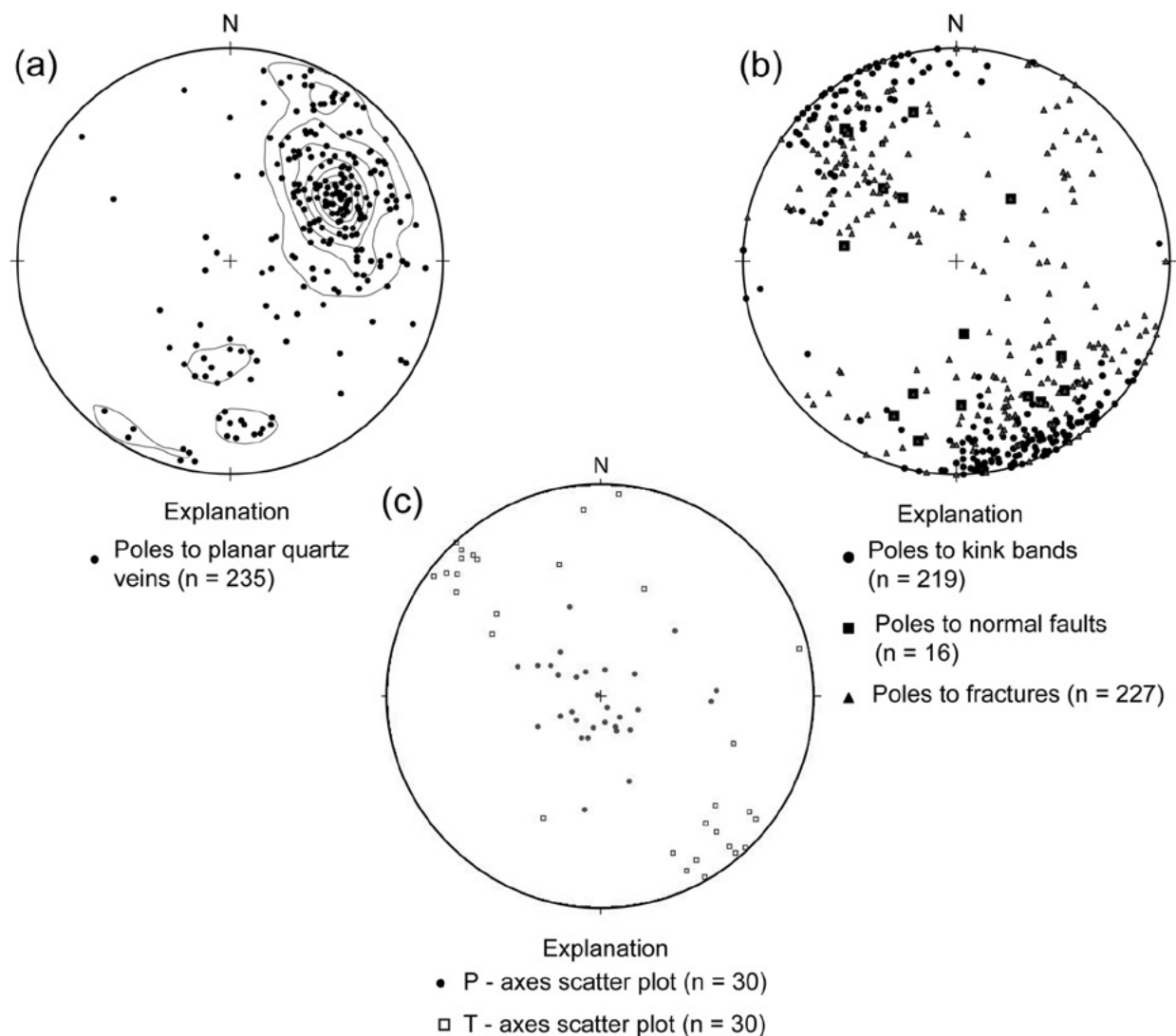
After the formation of  $F_2$  and  $S_2$  and before brittle faulting, another generation of quartz and/or siderite veins formed. The veins vary from blocky to fibrous and some contain chlorite as well. Styles of veining include quartz and/or siderite filled en échelon extension fractures, planar quartz and siderite veins, and large blocks of vein quartz with minor chlorite. The latter blocks range in size from 1–3 m<sup>2</sup> 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 ( $\sim 30^\circ$ ) 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  $\sim 10$ – $30^\circ$  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 stereonet 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  $^{40}\text{Ar}/^{39}\text{Ar}$  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 Snoko 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,  $^{40}\text{Ar}/^{39}\text{Ar}$  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  $^{40}\text{Ar}/^{39}\text{Ar}$  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.

Location	CAMBRIAN		PENNSYLVANIAN	
	Beavertail State Park	North Conanicut Island	Aquidneck Island	
<b>D<sub>1</sub></b>	Open to isoclinal F <sub>1</sub> folds with variable orientations and plunges. Early faults. S <sub>1</sub> defined by aligned muscovite and chlorite	F <sub>1A</sub> folds and NNE-trending, WNW-verging, tight to isoclinal and shallowly plunging F <sub>1B</sub> folds. S <sub>1a</sub> and S <sub>1b</sub> are defined by aligned chlorite, muscovite, and pressure solution	NNE-trending, WNW-verging, tight to isoclinal and shallowly plunging F <sub>1</sub> folds. S <sub>1</sub> is defined by aligned chlorite, muscovite, and pressure solution	
<b>D<sub>2</sub></b>	NNW to NNE-trending, open to tight, E-verging to recumbent, shallowly plunging F <sub>2</sub> folds. S <sub>2</sub> is a pressure solution cleavage with microstylolites	NNE-trending, ESE-verging, open to tight, shallowly plunging F <sub>2</sub> folds. S <sub>2</sub> is a pressure solution cleavage	NNE-trending, ESE-verging, open to tight, shallowly plunging F <sub>2</sub> folds. S <sub>2</sub> is a pressure solution cleavage	
<b>D<sub>3</sub></b>	NNE-trending, gentle, shallowly plunging F <sub>3</sub> fold. Multiply oriented crenulation cleavages (S <sub>c</sub> )	NE-trending, upright to recumbent, shallowly plunging F <sub>3</sub> folds. NNE-trending sinistral oblique-slip faults	E-trending kink bands.	
<b>D<sub>4</sub></b>	N-S trending boudinage	N-S trending, dm-scale boudinage	Minor N-S trending boudinage	
<b>Late-Stage</b>	NNE-ENE trending kink bands and normal faults	N-trending, steeply dipping brittle normal faults	N-trending, steeply 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<sub>1</sub> folds are tectonic structures and S<sub>1</sub> a metamorphic fabric, not soft-sediment slump features. During our mapping at a scale of 1:1000, we observed no thrust faults on S<sub>2</sub> cleavage planes. Also, thrusting along S<sub>2</sub> could not have caused folding of quartz veins as S<sub>2</sub> is axial planar to the folded quartz veins. The early faults we observed are folded by F<sub>2</sub> and are associated with the formation of F<sub>1</sub>, truncating one limb of F<sub>1</sub> folds.

We also found no evidence that the Cambrian rocks were thrust northwestward over the Pennsylvanian rocks along the BHSZ during D<sub>1</sub> as proposed by Skehan and Rast (1990). Thrusting and fold vergence in the Narragansett Basin during D<sub>1</sub> 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<sub>3</sub> and D<sub>4</sub>.

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<sub>1</sub>) followed by back-folding with eastward vergence (D<sub>2</sub>) (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<sub>3</sub>), 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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