PRELIMINARY INVESTIGATIONS INTO THE STRUCTURAL GEOLOGY OF THE BONAVISTA PENINSULA, NORTHEAST NEWFOUNDLAND

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ABSTRACT

The Bonavista Peninsula is divided into three Neoproterozoic siliciclastic tectonostratigraphic domains including, from west to east: the West domain comprising the 620–600 Ma arc-derived, turbiditic Connecting Point Group; the Central domain comprising mainly rocks of the terrestrial to marine, volcano-sedimentary Musgravetown Group (<600–545 Ma); and an East domain correlative to rocks of the East Avalon Basin (Conception, St. John's and Signal Hill groups; <585–545 Ma). These domains are separated by north- to north-northeast-trending faults zones: the Indian Arm Fault and the Spillars Cove–English Harbour fault zone. Each domain preserves evidence of at least two regional deformation events. These have been traditionally recognized across the Avalon Zone of Newfoundland as the Neoproterozoic Avalonian Orogeny (D_1) and the mid-Paleozoic Acadian Orogeny (D_2). The main deformational elements that characterize the more easily recognizable D_2 event include: north-northeast- and south-southwest-plunging, open to tight, upright folds with a regionally developed, axial-planar, north- to north-northeast-trending, subvertical penetrative cleavage (S_2) that is nearly ubiquitous across all three domains but best expressed in Cambrian cover sequences. D_1 is less evident, as it lacks a regionally developed penetrative cleavage. Steeply, but variably east- and west-plunging folds that are clearly overprinted by S_2 cleavage provide clear evidence of Neoproterozoic D_1 deformation. The F_1 fold axes vary from a generally east–west trend in areas where bedding dips shallowly, to more variable trends close to north- and northeast-trending faults, where Acadian transposition appears to have reoriented the steep limbs, in particular, of Avalonian folds. North-directed Avalonian thrusting, with asymmetric, thrust-style folding has been recognized in the west and central domains. Avalonian deformation is also recognized in the East domain where it is clearly overprinted by D_2 deformation. These data substantiate the evidence for Avalonian deformation documented elsewhere in the Avalonian Terrane of Newfoundland and characterize Avalonian deformation style so that its elements can be distinguished from later, Acadian deformation elements.

INTRODUCTION

Two regional deformation events are recognized in the Avalon Zone of Newfoundland: the Neoproterozoic Avalonian Orogeny and the mid-Paleozoic Acadian Orogeny (*e.g.*, Rodgers, 1967; Hughes, 1970; Dallmeyer *et al.*, 1981, 1983; O'Brien *et al.*, 1983). Previously cited evidence of Precambrian orogenesis includes Precambrian magmatism (*e.g.*, Krogh *et al.*, 1988), coarse clastic rocks derived from local volcanic rocks (Lilly, 1966), and Precambrian angular unconformities (*e.g.*, McCartney, 1967; Anderson *et al.*, 1975; Mills *et al.*, *this volume*). However, Precambrian thrust tectonics have, thus far, been documented solely in the vicinity of Flatrock on the Avalon Peninsula (King, 1990; Rice, 1996; Calon, 2001). Regional Paleozoic defor-

mation and related metamorphism across the Avalon Zone are attributed to the Devonian Acadian event at *ca.* 390–370 Ma (Dallmeyer *et al.*, 1983) or possibly at 420–400 Ma (van Staal, 2007; van Staal *et al.*, 2009). Paleozoic deformation is best expressed in the Cambrian cover successions, preserved at Keels and near Ocean Pond on the Bonavista Peninsula, where the subvertical, north-northeast-trending S_2 fabric is strongly developed, and F_2 fold axes plunge shallowly to the north-northeast or south-southwest (*see* O'Brien, 1994; Mills, 2014).

This study has led to further recognition of Avalonian deformation and the effects of Acadian overprinting. This paper documents the deformation style in select areas across the Bonavista Peninsula.

STRUCTURAL DOMAINS ON THE BONAVISTA PENINSULA

For this study, the Bonavista Peninsula is divided into three structural domains, including (from west to east): the West domain, comprising rocks of the 620–600 Ma Connecting Point Group; the Central domain comprising mainly rocks of the Musgravetown Group (<600–545 Ma); and the East domain, consisting of rocks of the Avalon Basin (Conception, St. John's and Signal Hill groups; >582–545 Ma; Figure 1). Cambrian inliers are present in the West and Central domains (Figure 1). The domains are separated by north-northeast-trending faults or fault zones, namely (from west to east): the Indian Arm Fault, and the Spillars Cove–English Harbour fault zone (SCF).

WEST DOMAIN

The Connecting Point Group (CPG) comprises the oldest rocks on the Bonavista Peninsula (*ca.* 620 to >600 Ma; *see* Mills *et al.*, *this volume*). The >3500-m-thick pile of Neoproterozoic epiclastic, marine turbiditic sandstone, siltstone, and shale, and minor conglomerate and mixtite occurs stratigraphically above the volcanic Love Cove Group, the remnant of a Neoproterozoic volcanic island-arc that supplied volcaniclastic sediment to the marine basin, now represented by the CPG (Knight and O'Brien, 1988; Dec *et al.*, 1992). Geochronological constraints include a 620 ± 2 Ma greenschist-facies volcanic rock from the top of the Love Cove Group (O'Brien *et al.*, 1989) and a 610 ± 2 Ma tuff bed from the middle of the CPG succession (Dec *et al.*, 1992; Mills *et al.*, *this volume*). The CPG is overlain conformably to unconformably by the terrestrial to marine, latest Neoproterozoic, volcanic and sedimentary Musgravetown Group.

Black Shale Unit of the Middle CPG

Deformation in the CPG rocks is most pronounced in the black shale and argillite exposed on the southeast side of the Northwest Arm of Sweet Bay, east of Winter Brook (Figure 1). A north-trending cleavage is locally developed (Plate 1A), consistent with the orientation of the S_2 cleavage that is regionally and penetratively developed across the Bonavista Peninsula, with only minor refraction across sub-Cambrian unconformities (*e.g.,* O'Brien, 1994; *see* also Riveros, 1998). At Station 15AM087, the intersection between bedding and S_2 cleavage plunges steeply to the north-northeast (Figure 2), and is steeper than, but consistent with, the intersection of the average S_2 with the π girdle for all bedding data along this stretch of shoreline. The fold axis calculated from the regional bedding data plunges gently toward the southeast (Figure 2) and does not lie in the Acadian (S_2) cleavage plane. The orientation patterns demonstrate super-

position of Acadian and pre-existing Avalonian fold structures (*e.g.*, Plate 1D) and imply folding of steeply tilted beds of the CPG, overprinted by north-northeast-striking steep Acadian cleavage.

Folds are more common in this black shale to argillite unit than in any other succession within the CPG, and are variable in style, scale and orientation. Some examples include tight, recumbent folds (Plate 1B), refolded isoclinal folds (Plate 1C) and asymmetric folds that locally show apparent northeast vergence (Plate 1D), compatible with the inferred northwest–southeast Avalonian fold trend. Although these rocks have sustained both Avalonian and Acadian deformation, it is locally difficult to distinguish tectonic structural elements from synsedimentary deformation. Some of the structures observed in the black argillite appear to be incompatible with both Avalonian and Acadian structures observed elsewhere in the West domain and may represent syndepositional structures. Moreover, the rheological contrast between the black shale and the more competent siliceous turbidites above and below this unit, may have caused strain to partition into the incompetent shale that may form zones of regional detachment during thrust tectonics.

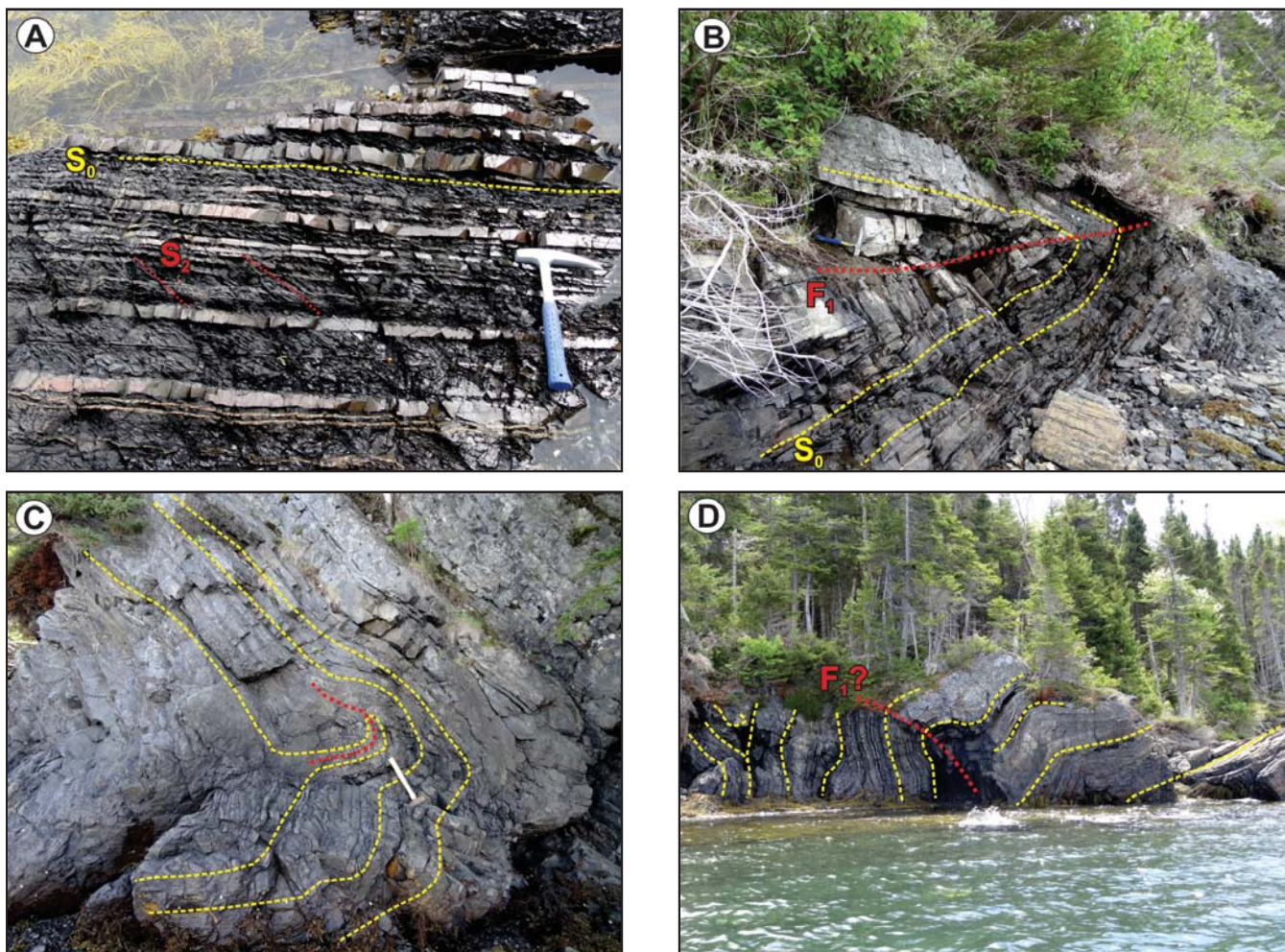### Interbedded Sandstone and Mudstone of the Upper CPG

Thin- to medium-bedded, siliceous sandstone and mudstone of the CPG were examined, in detail, at a roadside outcrop along Highway 230 (Figures 1 and 3A). At Station 15AM131, poles to bedding planes define a π girdle with an F_1 fold axis that plunges very gently to the southwest (Figure 3B). Cleavage dips steeply to the east-southeast, again consistent with S_2 cleavage elsewhere on the peninsula. All measured bedding–cleavage (S_0–S_2) intersection lineations (L_2) plunge gently to the south-southwest, indicating gentle south-southwest-plunging F_2 folds (Figure 3B). The fold axis calculated from the bedding data is offset (to the west) from L_2. The offset is inferred to result from superposed deformation, *i.e.,* the rocks may have been part of an F_1 (Avalonian) fold train that was overprinted and modified by D_2 (Acadian) deformation.

Lower Connecting Point Group–The Kate Harbour North Section

North of Kate Harbour, in the Sweet Bay area, several faults are preserved in rhythmic bedded, fine-grained, siliceous sandstone and shale (distal turbidites; Figure 4). These rocks are variably reddened near the Kate Harbour fault (O'Brien, 1994; Figure 4), and comprise an imbricate thrust stack (Figure 5) that structurally overlies medium- to thick-bedded, locally rippled, grey sandstone of the Kate Harbour formation (upper Connecting Point Group; *see*

Figure 1. *Regional geological map of the Bonavista Peninsula showing the West (mainly Connecting Point Group), Central (mainly Musgravetown Group), and East (Conception, St. John's and Signal Hill groups) structural domains. Abbreviations: Plate Cove volcanic belt (PCvb), Indian Arm fault (IAF), Trinity East fault (TEF), Robinhood Bay fault (RBF), and Spillars Cove–English Harbour fault (SCF).*

Plate 1. *Black shale unit of the Connecting Point Group showing: A) bedding–cleavage relations; top to the northeast; B) tight, recumbent fold having undetermined facing direction; C) refolded isoclinal fold, likely the product of synsedimentary slumping, overprinted by tectonic folding (F_1?); and D) asymmetric fold having shallow-dipping, upright limb to the south and subvertical limb to the north, possibly an example of Avalonian mesoscopic folding. View to southeast in B, C and D.*

Mills, 2014). The faults exposed along the northeast–southwest-trending coastal section are mainly bedding parallel, and have short ramp sections that show slight obliquity between footwalls and hanging walls (Figure 5A, B). The south-dipping thrust stack is dominated by hinterland (back limb)-dipping imbricates, and have small ramp anticlines located at both hanging wall and footwall ramp segments (Figure 5C, F). Southernmost faults are steeper and more complex and both faults and bedding become shallower to the north, consistent with northward thrust propagation. The bedding pole distribution (Figure 5G) is clearly overprinted by the regional S_2 cleavage (Figure 5H). The S_2 cleavage and associated, shallowly north-northeast–south-southwest-plunging F_2 fold axes (Figure 5H) are notably oblique to the trend of other measured (Figure 5I) and calculated fold axes (Figure 5G) in the thrust stack. Similar to that at Station 15AM131, this obliquity (offset) is the result of weak Acadian overprinting.

Further evidence for two deformation events comes from the regional map pattern: east-trending fold axes defined by bedding reversals (F_1 folds) west of the Paleozoic cover rocks at Ocean Pond (Figure 1) contrast with the S_2 cleavage and associated north-northeast–south-southwest fold axes within the Paleozoic cover (Mills, 2014). Onlap of Cambrian strata over previously deformed Precambrian rocks at Ocean Pond provides the only unequivocal evidence that D_1 must be Precambrian.

CENTRAL DOMAIN

Musgravetown Group

The Central structural domain is mostly underlain by volcanic and sedimentary rocks of the Musgravetown Group (Figure 1). Much of the northern part has been previously mapped as various lithofacies of the shallow-marine Rocky
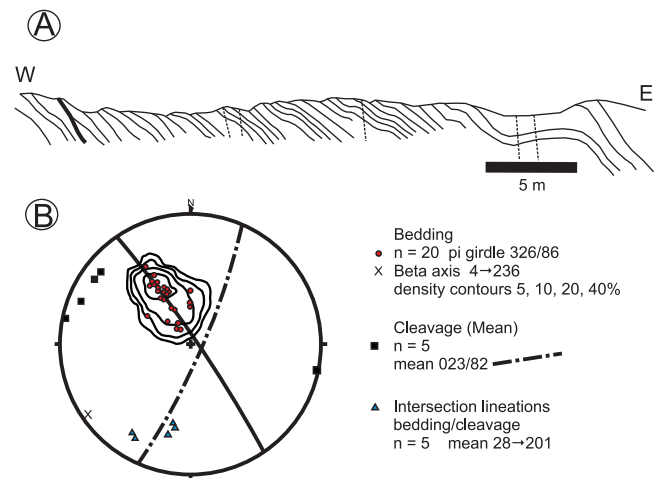
bedding n = 43
density contours 3, 6, 12%
pi girdle: 239/62
calculated beta axis: 28°→149°
cleavage n = 6
mean cleavage orientation 008/76

Station 15AM087:
Bedding: 313/70
Cleavage: 348/76
FA: 70°→030°
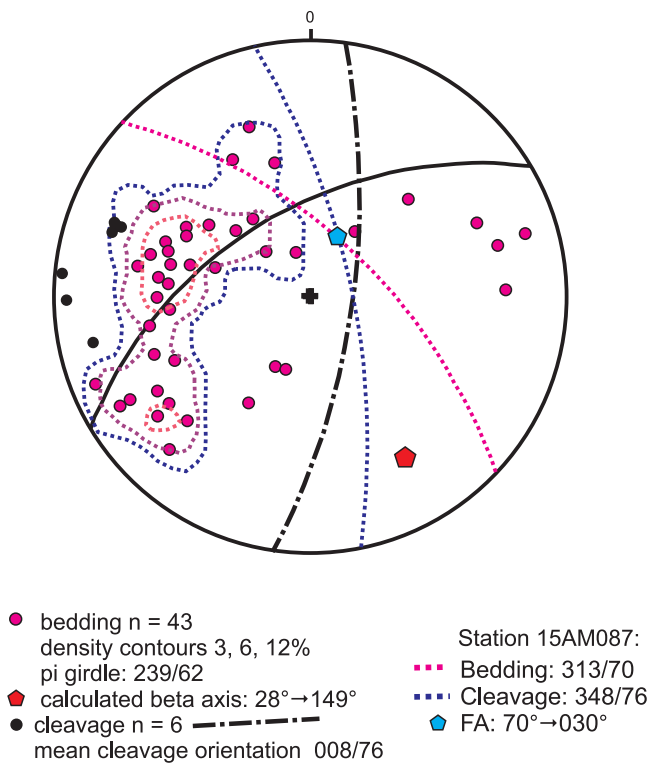
Figure 2. *Composite, lower hemisphere, equal area plot of poles to bedding planes, cleavage, and calculated fold axis determined for the coastal stretch northeast of Winter Brook (see Figure 1). Bedding, cleavage and their intersection lineation is also given for Station 15AM087 (UTM coordinates: 299522 m W, 5367482 m N; NAD 27, Zone 22; Plate 1A). FA = fold axis.*

Harbour Formation (O'Brien and King, 2004, 2005; Normore, 2010). Bedding steepens significantly with proximity to north- and north-northeast-trending faults, such as near the Trinity East fault (TEF), Robinhood Bay fault (RBF) and Spillars Cove–English Harbour fault zone (SCF; Figure 1).

Rocks Proximal to the Indian Arm Fault: The Plate Cove Volcanic Belt

The north-trending Plate Cove volcanic belt comprises basalt, andesite, felsic flows and breccias, and subordinate interflow sedimentary rocks that generally face eastward. The mafic volcanic rocks have a chemical signature consistent with formation from an enriched mantle source, likely in a rift-related tectonic regime (Mills and Sandeman, 2015) and early, concomitant extension may have accompanied volcanism.

A roadcut along Highway 235, near Summerville (*see* Figure 1, Plate 2), provides an accessible exposure within the volcanic belt. Bedding along the roadcut varies in strike from north-northwest to northeast and the dip is moderate to

Bedding
n = 20 pi girdle 326/86
Beta axis 4→236
density contours 5, 10, 20, 40%

Cleavage (Mean)
n = 5
mean 023/82

Intersection lineations
bedding/cleavage
n = 5   mean 28→201

Figure 3. *A) Schematic cross-section through eastern Connecting Point Group outcrop on Highway 230 (15AM131; UTM coordinates: 309754 m W, 5363180 m N; NAD 27, Zone 22) showing low-amplitude, long wavelength, open-fold geometry. Solid lines represent bedding, dashed lines represent cleavage; B) Stereoplot showing poles to bedding planes, calculated π girdle and fold axis as well as cleavage and bedding–cleavage intersection lineations. Note that the calculated fold axis (X) is offset to the west relative to measured bedding–cleavage intersection lineations. This is interpreted to reflect modification of an original Avalonian fold train that was overprinted by Acadian deformation.*

steep. Deformation elements observed there include: a well-developed, north-northeast-striking, subvertical S_2 cleavage (Plate 2A); a steeply S-plunging syncline cored by basalt (Plate 2B); variable orientation of bedding – S_2 cleavage intersection lineations (L_2; Plate 2C); and locally developed, small-scale kink bands (Plate 2D, E). Evidence for early D_1 deformation includes the variable orientation of the lineation, which indicates that bedding had been folded into variably shallow to steep dips prior to S_2 cleavage development (Plate 2C).

Small-scale kinks are locally developed on the S_2 cleavage surface, indicating that S_2 had developed prior to the small-scale kinks. The kinks are developed in chlorite schist that occurs between maroon, aphanitic volcanic flows, and likely formed due to gravity-loading, causing the steep, S_2 cleavage to kink along subhorizontal axial planes. Subhorizontal, quartz-filled tension gashes occur locally, indicative of vertical extension likely due to late unroofing or erosion of the thickened volcanic pile.

Rocks West of the Plate Cove Volcanic Belt

Immediately east of, and stratigraphically above the Plate Cove volcanic belt, is the volcanoclastic pebble conglomerate, the Plate Cove facies (O'Brien and King, 2005).
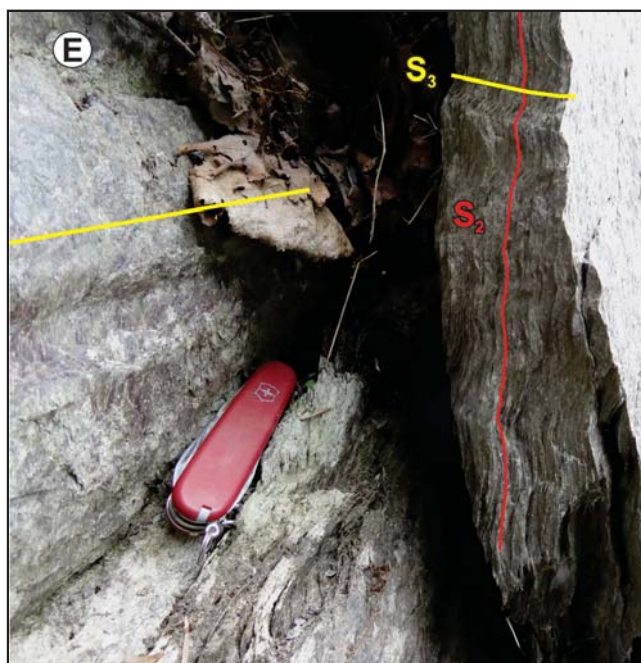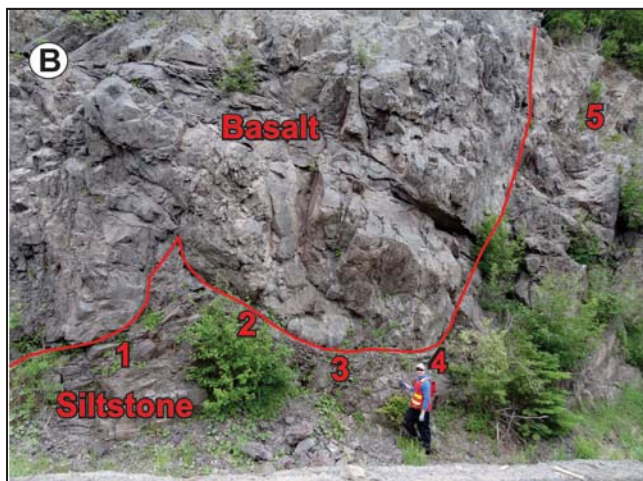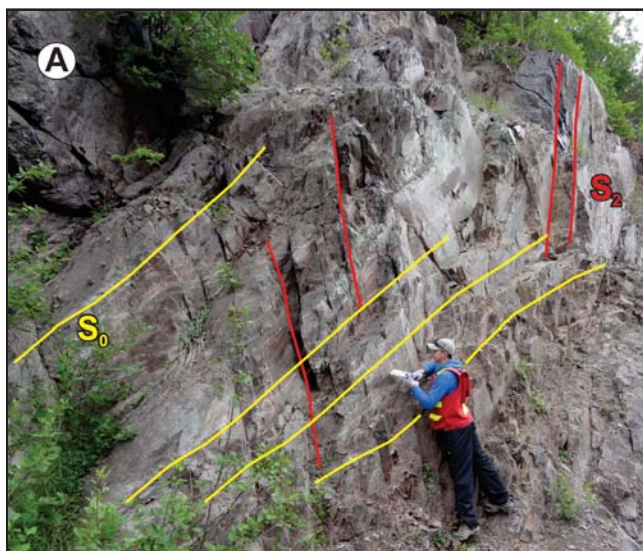
Plate 2. *Structural elements from the Plate Cove volcanic belt at the Summerville roadcut along Highway 235 (see Figure 1 for location): A) Bedding–cleavage relations. Bedding = 025/64; Acadian cleavage = 175/88. B) Asymmetric syncline at Summerville roadcut. Basalt at core of syncline is wrapped by laminated siltstone. View to the southeast. C) Bedding–cleavage intersection lineation (yellow) on Acadian cleavage surface in maroon siltstone. The pitch of the lineation is variable from subhorizontal (upper right) to 47° north (near student). D) Well-developed small-scale kinks of S_2 cleavage in chlorite schist: interpreted to have developed as a result of gravity-loading causing the Acadian cleavage to kink. E) Detail of micro-kinks (yellow = S_3 axial surface through kinked S_2 cleavage) in chlorite schist formed by gravity-loading causing the subvertical Acadian cleavage (red) to kink. UTM coordinates: 312026 m W, 5369278 m N; NAD27, Zone 22.*
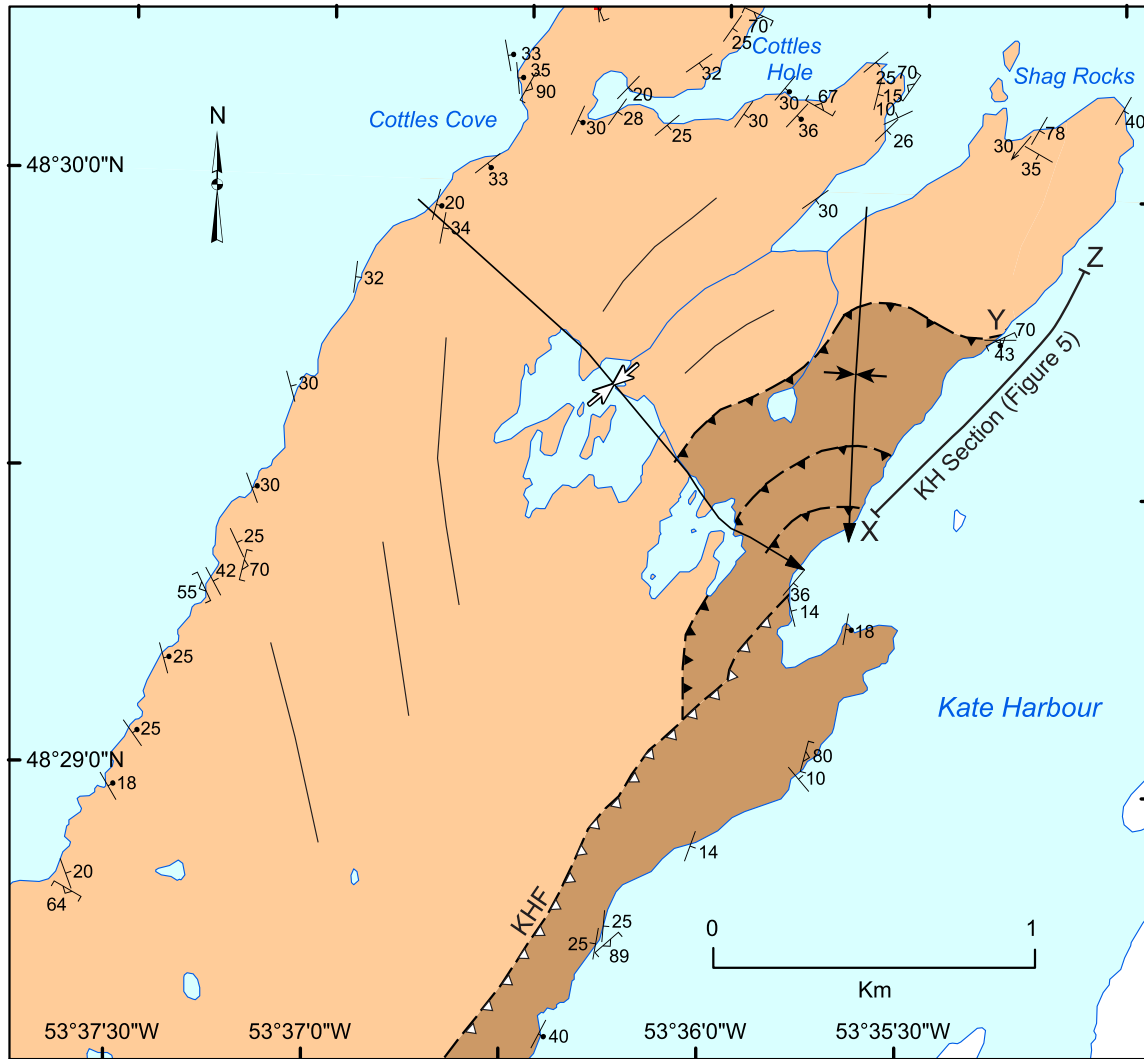
Figure 4. *Preliminary geological map of the northern Sweet Bay area, north of Kate Harbour and south of Cutler Head (*see *Figure 1). The regional bedding measurements shown are used to generate the bedding stereoplot (Figure 5H). KHF = Kate Harbour fault. Coordinates for points x, y and z are given in caption for Figure 5.*
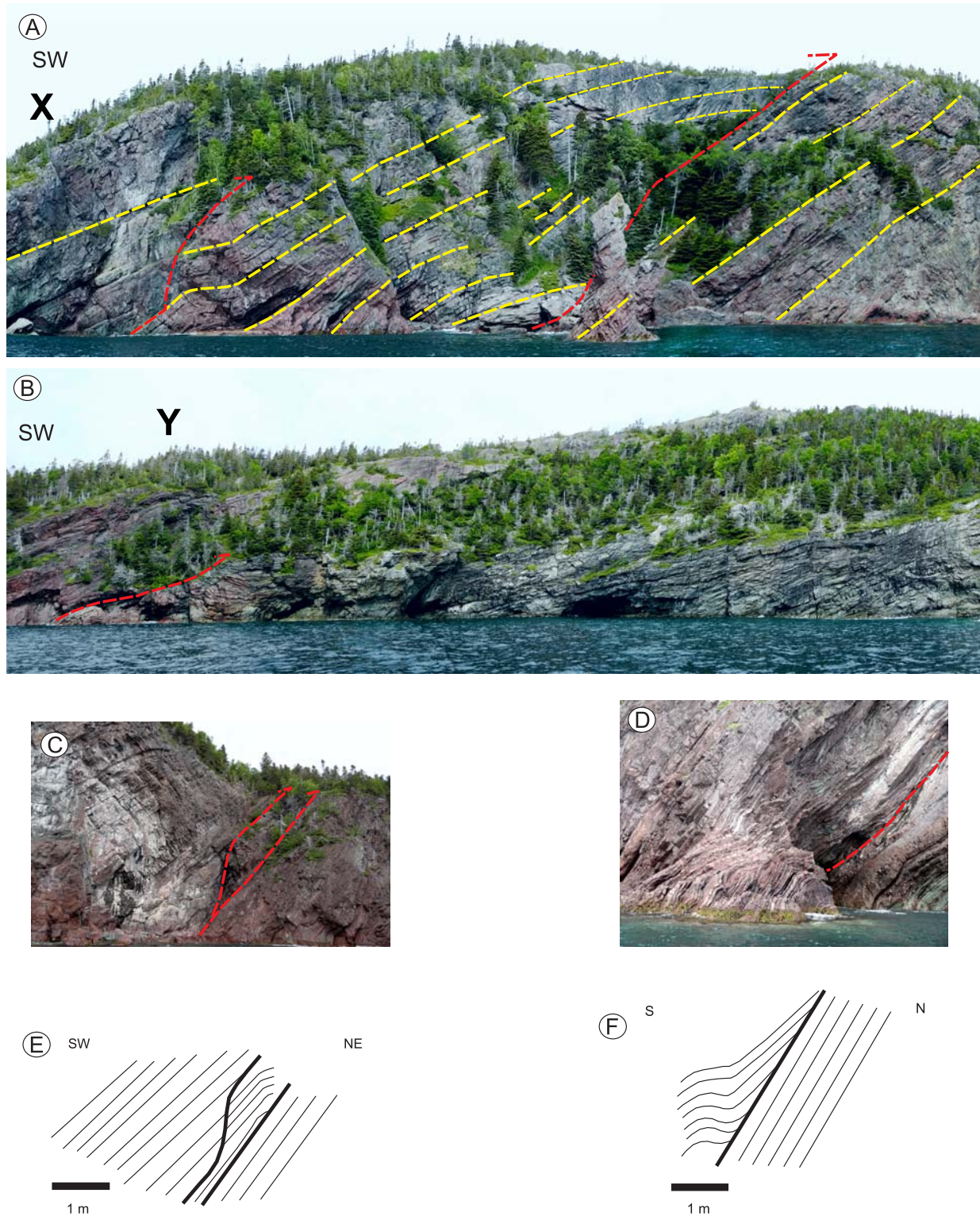
Figure 5. *Panoramic photomosaic of the coastal section south of Kate Head, Sweet Bay area, showing part of a northwest-verging fold/thrust system (A and B view to the northwest). The faults are mainly bedding-parallel, and have short ramp sections that show very slight obliquity between the footwalls and hanging walls. Southernmost faults are steep and both faults and bedding become progressively more shallowly southeast-dipping toward the north, consistent with northwest-directed thrusting. (UTM coordinates for points X: 30846 m E, 5373924 m N; Y: 308822 m E, 5374294 m N; Z: 309146 m E, 5374618 m N; NAD27, Zone 22). Close-up photographs, C and D, and accompanying sketch maps, E and F, respectively, detail the*
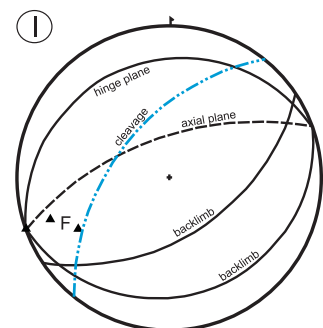
NE

Y

1   **2**

NE

Z

(G)
F
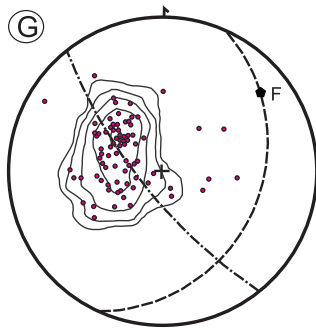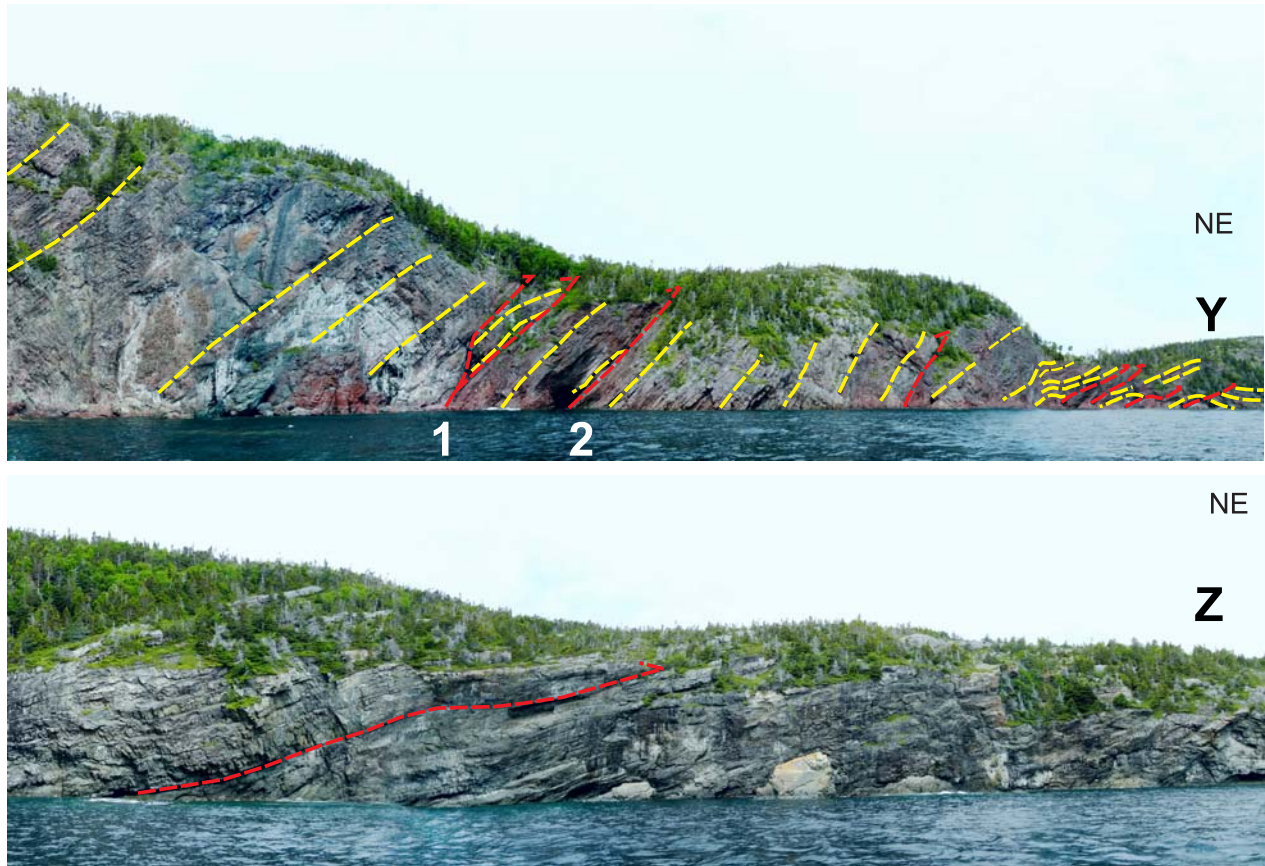
● N = 78 poles to bedding
mean bedding 023/25 RH
density contours 2, 4, 8, 16, 32%
fold axis: 12-051
pi-girdle 141/78 RH

(H)
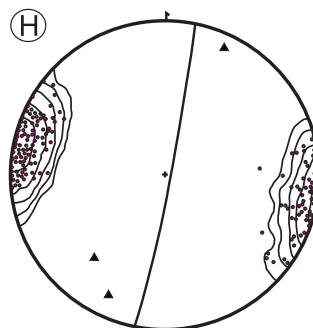
● N = 186 poles to cleavage
mean cleavage 011/87 RH
density contours 4, 8, 16, 32%
▲ fold axis N=3

(I)
hinge plane
cleavage
axial plane
backlimb
backlimb
F

bedding–fault plane geometry at locations 1 and 2 on photomosaic A. Lower hemisphere, equal area plots for structures in the Kate Head area: (G) bedding; (H) S₂ cleavage and measured fold axes; (I) fold geometry in Avalonian thrust stack (location indicated in Figures 1 and 4). The Acadian cleavage clearly transects the fold geometry outlined by the bedding pole distribution; the associated north-northeast–south-southwest Acadian fold axis trend is notably oblique to the trend of measured and calculated fold axes (east-northeast–west-southwest) in the Avalonian thrust stack.

This lithofacies comprises a steeply east-dipping coarse clastic wedge that likely accumulated during Avalonian orogenesis. Folding in the Plate Cove area is complex, but appears to broadly define a syncline–anticline pair having steep, north-dipping, west-southwest-trending axial surfaces (Figure 6). The axial traces of F_1 folds are defined by the folded bedding traces, and are clearly overprinted by a consistent subvertical, north- to north-northeast-striking S_2 cleavage (Figure 6). The dispersal of variably plunging bedding–S_2 cleavage intersection lineations along the girdle of the mean Acadian steeply east-dipping cleavage, clearly demonstrates the superposition of east–west Acadian shortening on pre-existing Avalonian fold structures that have variably dipping bedding orientations (Figure 6C). This steeply dipping succession likely represents the moderate to steep limb of an early (F_1) asymmetric fold, steepened further and overprinted during Acadian deformation. As at the Summerville roadcut discussed above, this area also locally preserves subhorizontal, quartz-filled tension gashes, consistent with an abrupt decrease in lithostatic pressure, likely due to uplift and unloading.
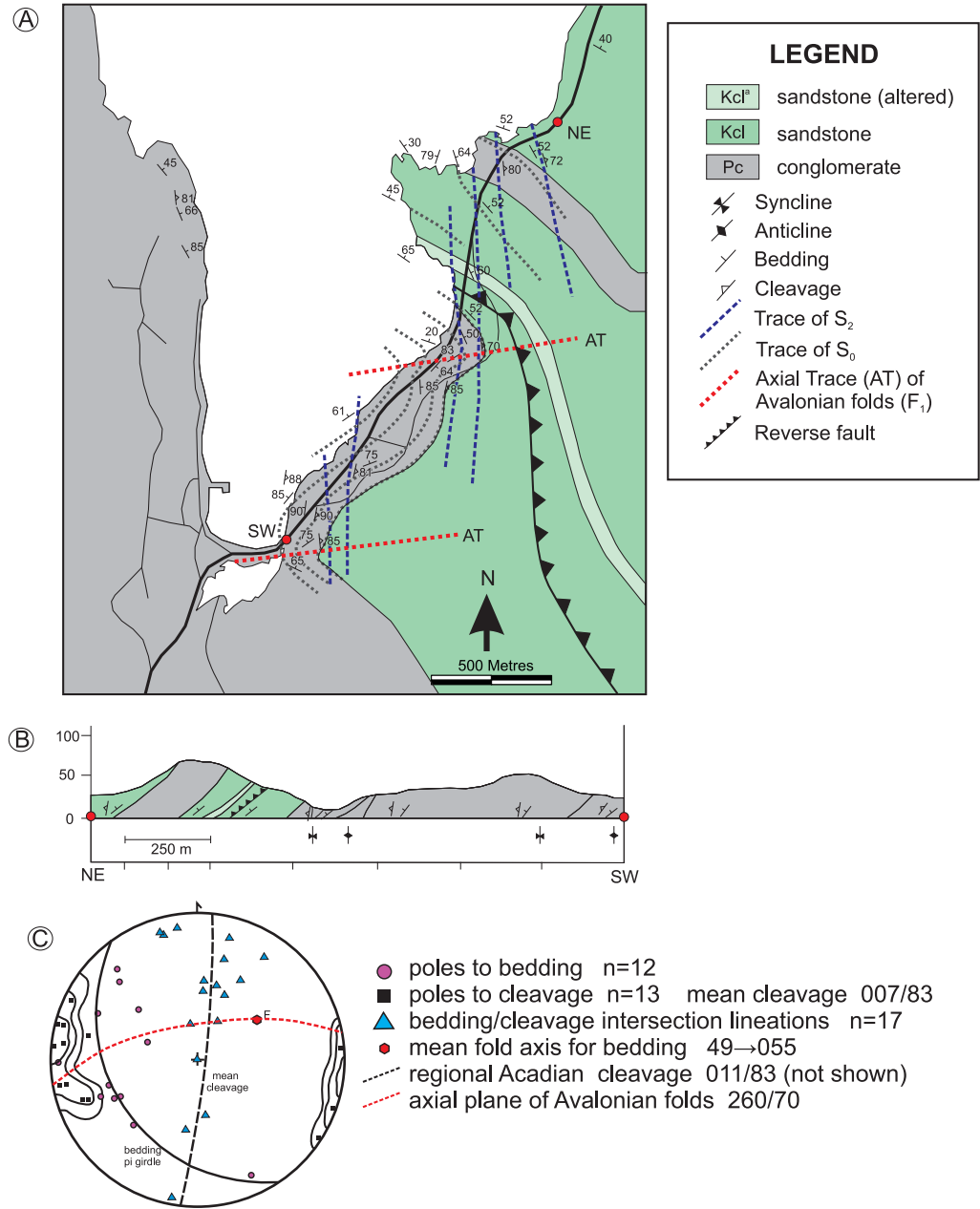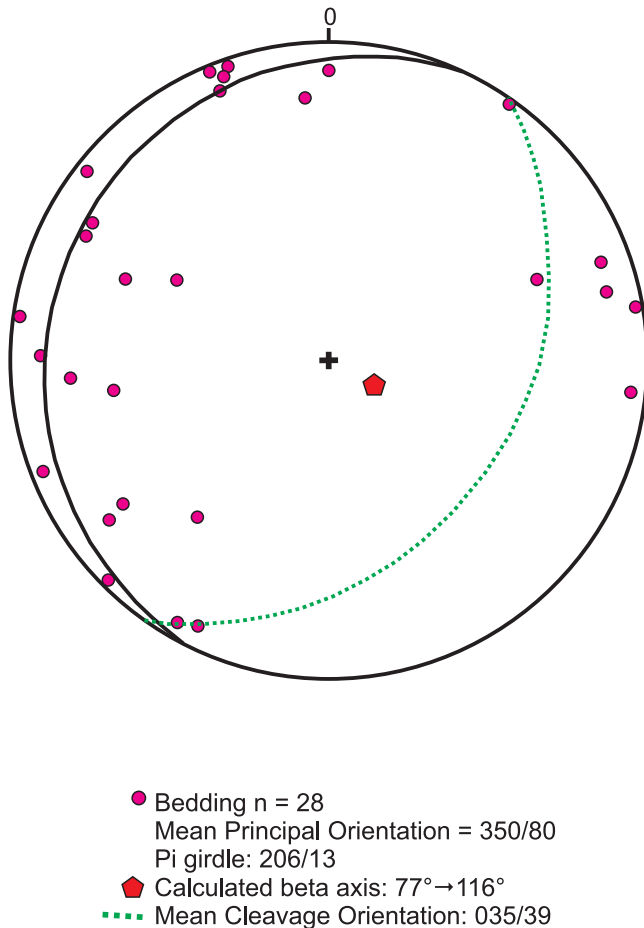

Figure 6. *A) Map of the Plate Cove area showing the trace of bedding folded by Avalonian deformation and clearly overprinted by a north-striking Acadian cleavage resulting in highly variable orientations of bedding–cleavage intersection lineations. B) Schematic cross-section along Highway 235 at Plate Cove East. C) Lower hemisphere, equal area plot for structural elements in the Plate Cove area, including: bedding, Acadian cleavage, bedding–cleavage intersection lineation, and calculated Avalonian fold axis.*

Rocks Proximal to the Robinhood Bay Fault – The Skerwink Peninsula

The Robinhood Bay fault (Normore, 2011) is a fault zone characterized by subvertical, north-striking rocks and inferred north-trending faults that extend northward from Port Rexton but apparently shallow or terminate before reaching Blackhead Bay to the north (Figure 1; *see* Normore, 2011). From east to west, shallowly south-dipping strata, north of Fox Island, curves abruptly to southeast-dipping and then steeply east-dipping on the west side of Robinhood Bay, where the west limb of the southeast-plung-

Bedding n = 28
Mean Principal Orientation = 350/80
Pi girdle: 206/13
Calculated beta axis: 77°→116°
Mean Cleavage Orientation: 035/39

Figure 7. *Lower hemisphere, equal area plot of poles to bedding for rocks on the Skerwink Peninsula, defining a pi girdle with calculated fold axis plunging 77°→116° and average (S₁?) cleavage of 035/39 (n=2).*

ing regional syncline steepens to vertical within the north-trending Robinhood Bay fault zone (Normore, 2011; Figure 1). In width, the steeply dipping belt extends about 3.5 km from Robinhood Bay in the Port Rexton area westward to Freshwater Bay at Lockston. Bedding reversals within the belt indicate tight folding and Figure 7 shows that the succession along the coast of the Skerwink Peninsula is dominated by subvertically plunging fold structures. Locally, shearing may occur along subvertical limbs where strain is likely partitioned into incompetent beds. The more competent sandstone layers form impressive lobes of cuspate-lobate folds (Plate 3A) that lie as parasitic fold structures on the subvertical regional folds. Shallow, southeast-dipping cleavages appear to be associated with these folds, and may be Avalonian in age. Upright, wedge-shaped stacks and local truncation of beds (Plate 3B) indicate the occurrence of thrust activity along the Skerwink Peninsula, but the lack of unequivocal younging indicators prevents robust structural analysis.
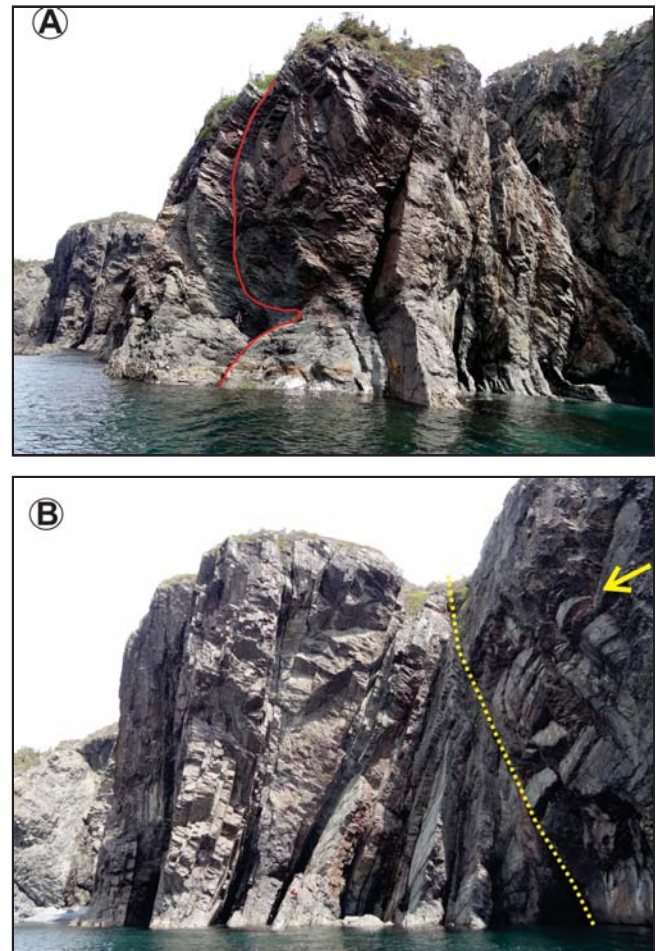
Plate 3. *Subvertical high-strain belt on the Skerwink Peninsula. A) Cuspate-lobate folds with subhorizontal axial planes in grey-green laminated siltstone and fine-grained sandstone. During buckling, the more competent, sandier beds form lobes; less competent siltstone forms the cusps. B) Possible subvertical thrust sheets; sense undetermined. Lobate folds occur along cliff to the east (yellow arrow). To the immediate southeast (not shown), flute marks show younging to the east, indicating an apparent overturned thrust (dashed yellow line). View north for A and B . UTM coordinates: 326872 m W, 5359307 m N; NAD27, Zone 22.*

Rocks East of the Robinhood Bay Fault – Fox Island

Several faults occur along the west shoreline of Fox Island, east of the Robinhood Bay Fault (Figure 8). North of Fox Island, fine-grained sandstone and siltstone of the Big Head Formation (Normore, 2011) is overlain by coarse-grained, cross-stratified sandstone and pebble conglomerate of the Rocky Harbour Formation. The uppermost coarse clastic unit of the Rocky Harbour Formation (the Monk Bay–Hodderville facies *of* O'Brien and King, 2004) is capped by green-grey laminated siltstone (Herring Cove
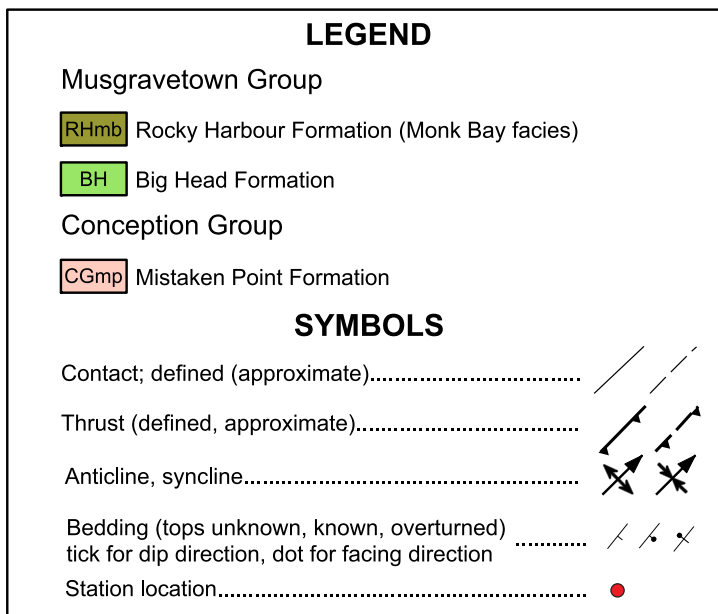
Figure 8. *Inset map of the Fox Island area, south of Port Rexton, showing stations referred to in the text and in plate captions.*

facies *of* Normore, 2011; King's Cove North facies *of* O'Brien and King, 2002), which, in turn, is overlain by the Crown Hill Formation on the northern Bonavista Peninsula and by rocks assigned to the Mistaken Point Formation of the Conception Group on the southern part of the peninsula (Fox Island area south of Port Rexton, Figure 1; *see* Normore, 2011). Analyses of the faults may shed light on the apparent stratigraphic discrepancy between northern and southern parts of the peninsula.

Immediately south of the bridge across Herring Cove to Fox Island, thin- to medium-bedded siltstones referred to as the Herring Cove facies by Normore (2011) outcrop along an east–west-trending exposure (~100 m east of Station 15AM147, Figure 8). Several asymmetric, west-verging folds ranging from open to tight and over-turned (Figure 9), occur at this locality and these have shallowly south-southwest- and northeast-plunging axes. Bedding-parallel shearing and small inner-arc thrusts are present, consistent with intraformation-al folding and thrusting in an overall west-directed, contractional regime.

Farther west, the first of several faults is exposed along the west shore of Fox Island (Figure 8). Here, south-dipping mudstone with local convolute beds is folded and thrust-faulted to the north (Station 15AM147, Plate 4, Figure
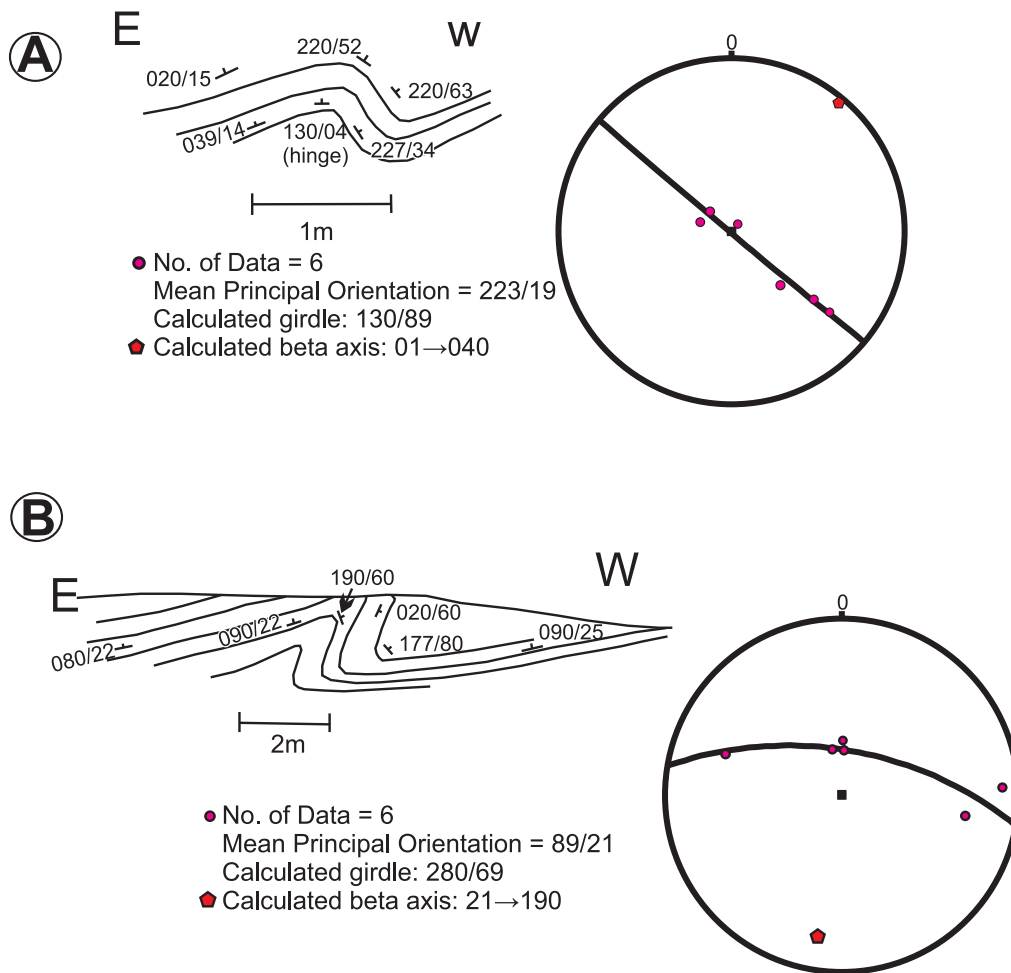
Figure 9. *Sketches and lower hemisphere, equal area plots illustrating fold geometry along roadside, northern Fox Island: A) asymmetric open fold with calculated fold axis of 1° toward 040°; B) asymmetric, overturned, tight fold with calculated fold axis plunging 21° toward 190°. The sketches are viewed to the south and show measured bedding geometry along the folds.*

apparent thrust geometry but lack of unequivocal tops indicators impedes structural interpretations. About 300 m southeast, subvertical siltstone in the apparent footwall is fault-juxtaposed against similar wavy-bedded siltstone and fine sandstone (Station 15AM143, Figure 8; Plate 8), but, again, younging direction was not observed. These last two fault exposures (Stations 15AM143 and 15AM144) occur along strike and may represent different expressions of the same fault. If the hanging wall in these successions is right-way-up, the fault can either be a listric normal fault or an overturned folded thrust fault. If the hanging wall is overturned, then it may lie in the overturned limb of a thrust-related ramp anticline (*i.e.,* a break-thrust). Overall, the geometry of the thrust-related structures along the west coast of Fox Island is consistent with north-directed thrusting.

8) above green siltstone and coarse sandstone to pebble conglomerate of the Monk Bay facies (upper Rocky Harbour Formation *of* O'Brien and King, 2002). This thrust breaks through the upper, overturned limb in the very tight footwall syncline. Approximately 500 m south, an open, ramp bend anticline occurs in the hanging wall of a north-directed thrust fault (Station 15AM146, Figure 8; Plate 5). The thrust shows hanging wall and footwall ramp geometry. Dark-grey siltstone and laminated to lenticular sandstone occur in both the hanging wall and footwall of the thrust, indicating only minor stratigraphic separation. One kilometre farther south, a well-preserved ramp anticline plunges moderately to the south-southwest (Station 15AM145, Figure 8; Plate 6). Although this configuration is consistent with east-directed thrusting, the thrust stacks and thrust faults are apparently folded (Figure 8). Two hundred metres farther still to the south (Station 15AM144, Figure 8; Plate 7), steeply south-dipping, thin-bedded fine sandstone and siltstone show

Spillars Cove–English Harbour Fault Zone

A preliminary assessment of the subvertical beds was undertaken at Lance Cove, one kilometre west of Spillars Cove (Figure 1) and the regional fault zone. Slump folding is common in the grey, thinly laminated siltstone and mudstone of the St. John's Group (Plate 9A). Tops indicators give younging to the east in most beds, although west-younging beds are also present in the cove, indicating tight to isoclinal folding. One subvertical, north-northeast-trending fault cuts obliquely through subvertical beds (Plate 9B), but no slip-direction indicators were found. The lack of younging indicators also obstructed the overall structural interpretation at the Lance Cove area.

Minor kinks of the fault-zone structures have subhorizontal axial-planar surfaces (202/14; 022/10; Plate 9C). The north–south-trending, shallowly dipping kink bands are

Plate 4. *North-directed thrust fault at northwest tip of Fox Island. Bedding in hanging wall and footwall flats is 088/18; thrust orientation is bedding-parallel along footwall and hanging wall flats, but ramps up steeper on the south side of tight, overturned syncline in the footwall. Bedding on the overturned (south) limb of the syncline is 100/70. The convolute beds occur in thick, competent mudstone layer at base of hanging wall. View to the east. Station 15AM147 on Figure 8. UTM coordinates: 328565 m W, 5361728 m N; NAD27, Zone 22.*

Plate 5. *Open, ramp bend anticline in hanging wall of thrust with thrust ramping through the footwall. Bedding labelled for forelimb and backlimb in hanging wall as well as proximal and distal to fault in FW. View to east. Station 15AM146 on Figure 8. UTM coordinates: 328660 m W, 5361249 m N; NAD27, Zone 22.*

inferred to have formed after the beds were tilted to their subvertical position, likely due to layer-parallel compression under lithostatic load. The steeply dipping belt must also have had considerable relief (>1 km) during the Acadian Orogeny to overcome the load stress to produce the gravity-induced kink bands.

EAST DOMAIN

East Avalon Basin (Conception–St. John's–Signal Hill Groups)

The dome at Catalina is recognized as part of a series of north-northeast–south-southwest-trending, doubly plunging

structural culminations and depressions on the eastern Bonavista Peninsula (*e.g.,* O'Brien and King, 2002; Normore, 2010, 2011). Clear, outcrop-scale evidence of the two interfering deformation events are described and illustrated below.

At Goodland Point, Catalina (Figure 1), a subvertical, north-northeast-trending S_2 cleavage is well developed in gently dipping, thin-bedded turbiditic mudstone of the Mistaken Point Formation (Plate 10) near the crest of the culmination. Open and upright, very low amplitude buckle folds have axial surfaces parallel to the main regional S_2 cleavage orientation. Approximately 200 m north, fold interference is evident at outcrop-scale where an open and
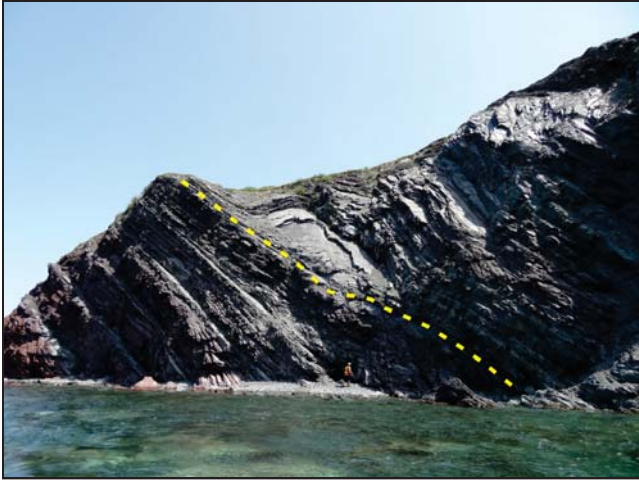
Plate 6. *Ramp anticline plunging ~25° to the west-south-west, and a small leading syncline consistent with thrusting to the east-northeast. View to east. Station 15AM145 on Figure 8. UTM coordinates: 329253 m W, 5360261 m N; NAD27, Zone 22.*
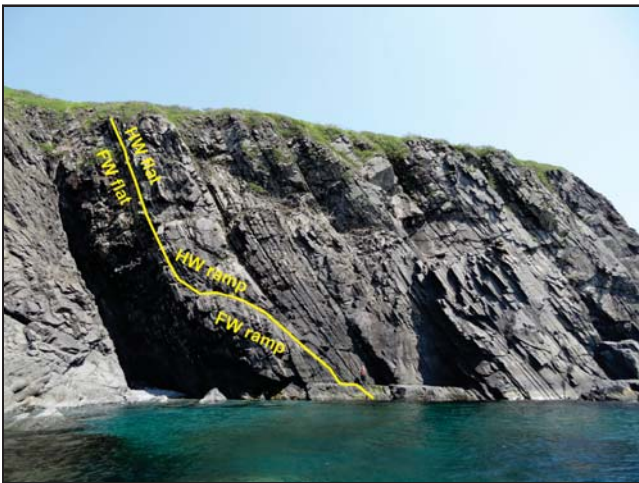
Plate 7. *Possible thrust fault at southern Fox Island. Bedding in the hanging wall is 109/55; bedding in the footwall is 109/61; the fault plane is oriented at 144/50 close to sea level. Hanging wall strata show mild wedge-shaped geometry and thickening to the top of the cliff that may be indicative of growth strata. View to the east. Station 15AM144 on Figure 8. UTM coordinates: 329232 m W, 5360045 m N; NAD27, Zone 22.*

upright, doubly plunging syncline having shallow west-southwest–east-northeast axes is refolded by an open and upright, gently south-southwest-plunging F_2 syncline–anticline pair (Plate 11). Further evidence of the style of the early folds is evident on the north side of Shepherd Cove where a steeply inclined, asymmetric, shallowly southwest-plunging anticline occurs (Plate 12; Figure 10). The forelimb dips moderately to steeply to the northwest, whereas

Plate 8. *Possible thrust fault at southern Fox Island. Steeply southwest-dipping fault (yellow) separates steeply south-west-dipping beds (120/56; red) in hanging wall flat geometry from subvertical beds in the footwall ramp geometry (110/80; orange); a well-developed cleavage or fracture pattern is evident in footwall (subhorizontal; purple). View to the northwest. Station 15AM143 on Figure 8. UTM coordinates: 329490 m W, 5359893 m N; NAD27, Zone 22.*

the backlimb dips gently to the southeast and is associated with gentle, open, mesoscopic folds. Minor parasitic folds also occur locally on the forelimb of the F_1 fold. At the hinge of the Avalonian anticline, a weakly developed cleavage obliquely overprints the core of the fold (Plate 12). Since the orientation of the cleavage there is broadly consistent with the orientation of the regional S_2 cleavage, it is interpreted as Acadian S_2 cleavage overprinting a pre-existing F_1 anticline, rather than as an early, transecting S_1 cleavage.

SUMMARY

AVALONIAN DEFORMATION (D_1)

There is no regionally developed penetrative cleavage associated with D_1. Evidence of D_1 deformation comes primarily from folded, variably dipping successions that are clearly overprinted by the consistent (almost ubiquitous) north-northeast-trending, subvertical S_2 cleavage, as documented at Plate Cove, Kate Harbour, and Catalina. North-directed thrusting and associated thrust-related, asymmetric folds are recognized in the Connecting Point Group (Kate Harbour section, east of Winter Brook) as well as in possible Conception Group rocks at Fox Island. Although north-directed thrusting is evident in both the *ca.* 610 Ma CPG and in the *ca.* 565 Ma Conception Group rocks at Fox Island, it remains unclear whether the timing was the same in both areas, or whether compressional stages of Avalonian orogenesis were episodic. Angular unconformities between Con-
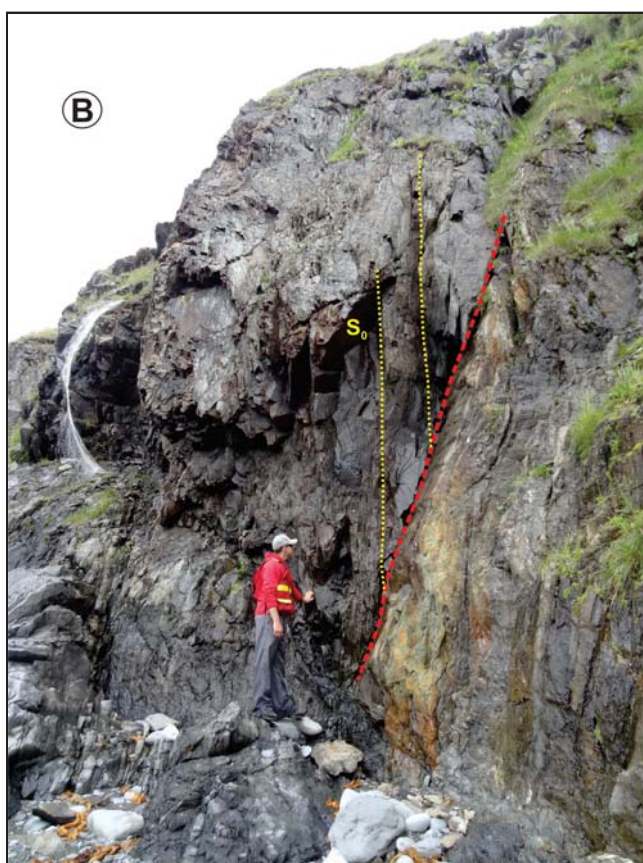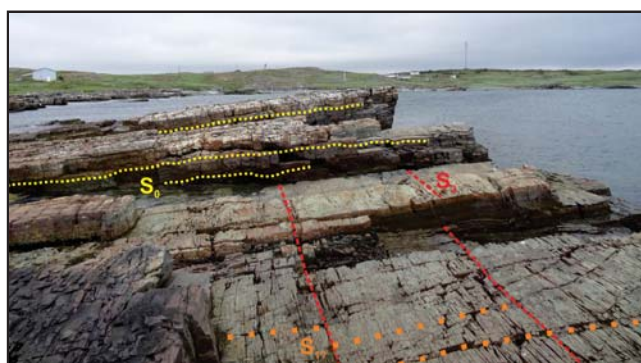
Plate 9. *Structural observations at Lance Cove: A) Folded, laminated siltstone of St. John's Group. Bedding is 014/89; cleavage is 199/89 and axial planar to folds. Vergence is to the east. View to south. B) Steeply east-dipping fault truncating bedding in thinly laminated siltstone of St. John's Group. View to south. C) Subvertical Acadian cleavage in St. John's siltstone and mudstone is steeper than bedding, indicating possible presence of an antiform to the west. View to north-northeast. UTM coordinates: 346515 m W, 5392048 m N; NAD27, Zone 22.*


Plate 10. *Shallowly west-southwest-dipping beds (S_0; 158/09) with subvertical Acadian cleavage (S_2; 007/90) and gentle, open and upright, axial-planar folds in laminated mudstone of the Ediacaran Mistaken Point Formation at Catalina dome. The variably developed spaced cleavage or joint set ($S_{1?}$; 110/55) may be Avalonian. View to north. UTM coordinates: 347515 m W, 5375111 m N; NAD27, Zone 22.*

necting Point Group and younger late Precambrian successions (*see* Mills *et al.*, *this volume*) indicate that the Avalonian Orogeny was protracted, and episodic. The geometry of the early Avalonian folds differs across the peninsula, because of Acadian overprinting and refolding of bedding sequences.

ACADIAN (?) DEFORMATION (D_2)

Minor, low amplitude and large wavelength, shallowly north-northeast- and south-southwest-plunging folds in

lower Paleozoic rocks and a well-developed, generally north-northeast-striking, subvertical S_2 cleavage are characteristic of Acadian deformation and interpreted by other

Plate 11. *Interference fold pattern at Catalina dome. Open and upright Avalonian F_1 syncline (plunging 4° toward 240°; yellow) is refolded by open, upright Acadian syncline–anticline pair (plunging 7° toward 198°; orange). View to the south. UTM coordinates: 347515 m W, 5375111 m N; NAD27, Zone 22.*
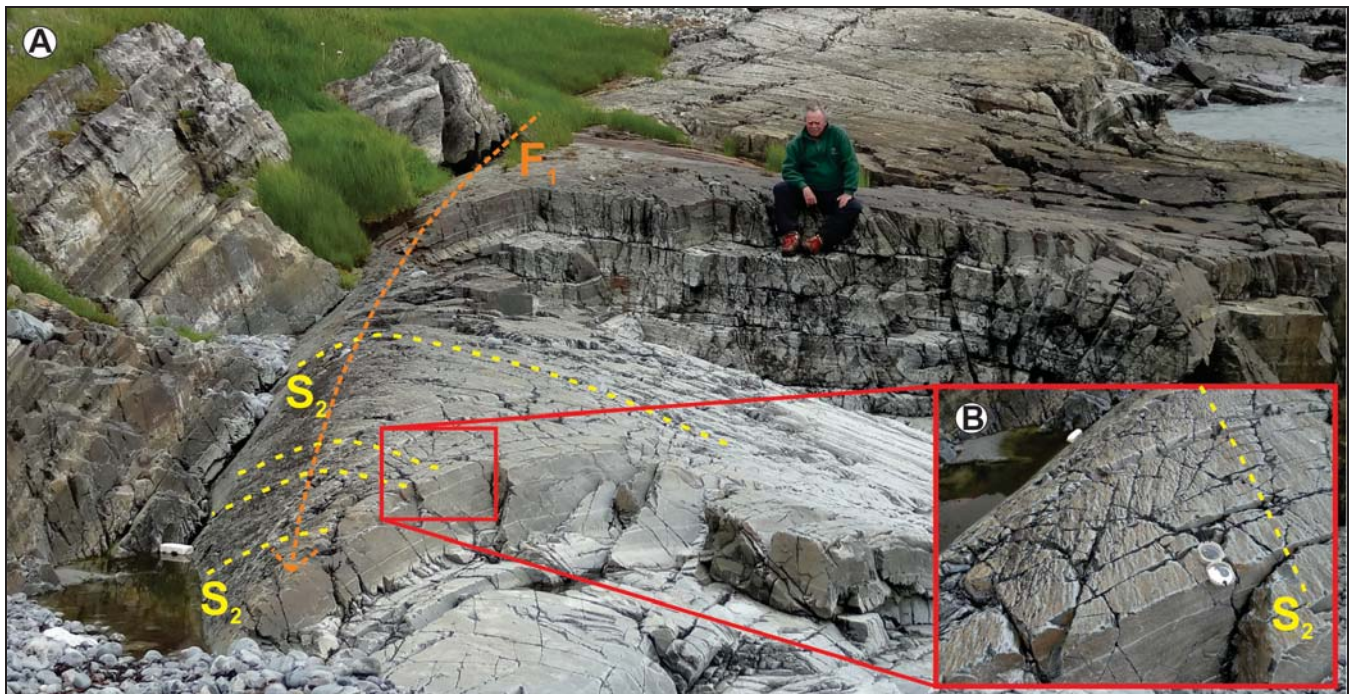
Plate 12. *A) Gently southwest-plunging, asymmetric Avalonian anticline (F_1) overprinted by steep Acadian cleavage (S_2; 035/56). Note steep northwest forelimb, shallow southeast backlimb. View to the east-northeast. B) Close-up of weakly developed Acadian S_2 cleavage (seen mainly as bedding – S_2 cleavage intersection lineations) overprinting the gently southwest-plunging, Avalonian anticline. View to northeast. UTM coordinates: 347700 m W, 5375410 m N; NAD27, Zone 22.*

workers as having formed in a transpressional setting (*e.g.,* Holdsworth and O'Brien, 1993). North-northeast-trending fault zones and associated subvertical panels at the Indian Arm Fault, the Robinhood Bay Fault and Spillars Cove–English Harbour fault zone may be products of Acadian transpression. Earlier fabrics would have been trans-
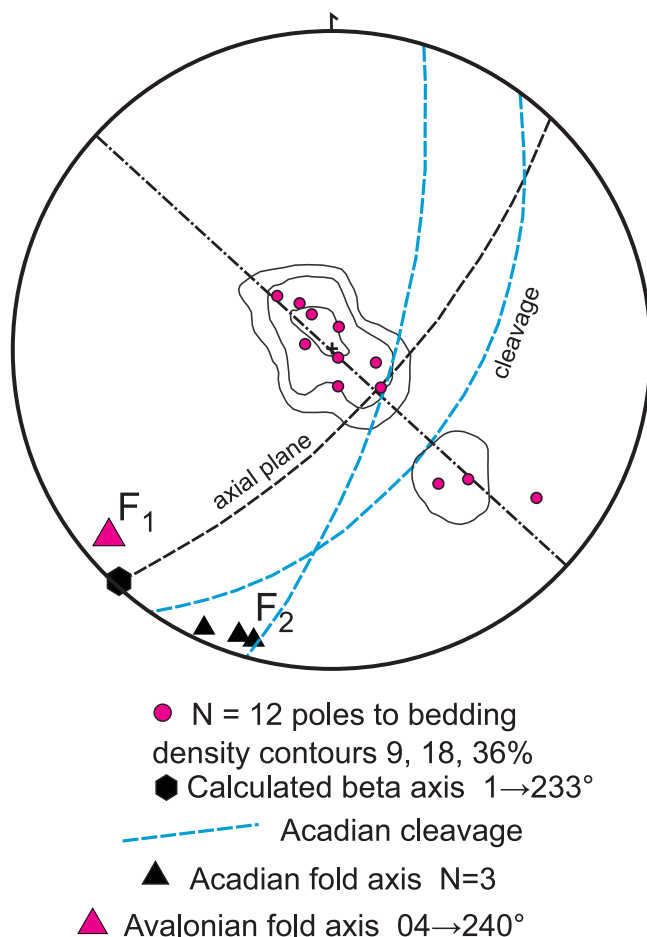
Figure 10. *Lower hemisphere, equal area plot of poles to bedding measured along the Avalonian anticline shown in Plate 12. Both the measured and calculated fold axes do not lie within the Acadian cleavage plane, consistent with overprinting of a pre-existing Avalonian fold by Acadian deformation.*

posed in each of these fault zones. The effects of the Acadian overprinting on the pre-existing Avalonian structures are variable, but Avalonian fold and thrust structures can be recognized and differentiated from Acadian effects by their distinct styles and orientation patterns.

LATE EXTENSIONAL EVENTS

Evidence of late (post-D_2), extensional tectonism is present in the Plate Cove volcanic belt and overlying conglomerate, and includes quartz-filled tension gashes, horizontal ladder veins (pinnate veins) and local subhorizontal kink bands of the S_2 fabric. Minor normal faults were also observed locally (*e.g.,* Monk Bay area). These structural elements are likely late Acadian, as they overprint early Acadian deformation, and likely formed due to the collapse of the uplifted Acadian belt.

GEOCHRONOLOGICAL CONSTRAINTS

Avalonian D_1 deformation may have initiated as early as *ca.* 600 Ma, the age constraint for the angular unconformity at Southward Head (Mills *et al., this volume*). North-directed thrusting must be older than the Cambrian since the shallow-marine Cambrian cover sequence at Ocean Pond overlies the Connecting Point Group with angular unconformity. The D_2 deformation is presumed to be Acadian in age and related to the accretion of Avalonia to the Laurentian margin (van Staal *et al.*, 2009) and is younger than all rocks exposed on the Bonavista Peninsula. The timing of deformation remains to be corroborated by geochronological studies.

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