Devonian Extension in Northwestern Newfoundland: $^{40}Ar/^{39}Ar$ and U-Pb Data from the Ming's Bight Area, Baie Verte Peninsula

S. D. Anderson, R. A. Jamieson,[1] *P. H. Reynolds, and G. R. Dunning*[2]

Department of Earth Sciences, Dalhousie University, Halifax, Nova Scotia B3H 3J5, Canada

ABSTRACT

The Ming's Bight Group of northwestern Newfoundland, an outlier of Humber Zone continental margin rocks, is entirely surrounded by ophiolitic rocks of the Dunnage Zone. Structures in the Ming's Bight Group and adjacent units record three main phases of deformation. The earliest structures relate to Silurian sinistral transpression previously documented in the region. Two later phases of extensional deformation produced a series of dextral oblique-normal shear zones and faults that now separate the Ming's Bight Group in the footwall from ophiolitic and granitoid rocks in the hangingwall. $^{40}Ar/^{39}Ar$ and U-Pb data constrain the times of oblique-normal shear and cooling. Metagabbro in the Point Rousse Ophiolite Complex, which lies in the hangingwall, preserves disturbed Ordovician hornblende $^{40}Ar/^{39}Ar$ ages, whereas adjacent shear zones record Devonian ages. Hornblendes in Pacquet Harbour Group amphibolites within extensional shear zones mainly record $^{40}Ar/^{39}Ar$ ages of 390–380 Ma. Synkinematic titanite and rutile porphyroblasts from an extensional shear zone on the northwestern margin of the Ming's Bight Group have been dated by the U-Pb method at 388 and 380 Ma, interpreted as growth and cooling ages, respectively. The titanite and hornblende ages suggest that the main phase of ductile oblique-normal shear was underway at 405–385 Ma. Ming's Bight Group schists and pegmatites produced concordant muscovite $^{40}Ar/^{39}Ar$ ages averaging 362 Ma, interpreted as the time of footwall cooling below 350°C. We suggest that the Ming's Bight Group is a mid-Devonian symmetrical core complex formed within a local transtensional regime developed during dextral oblique transcurrent movement along the Baie Verte Line. The timing and tectonic setting of extension do not support recent models for "extensional collapse" in the northern Appalachians.

Introduction

Although the Paleozoic history of the northern Appalachians has generally been interpreted in terms of collisional tectonics (e.g., Williams 1979; van Staal et al. 1998 and references therein), there is growing recognition that extension also played an important role in the evolution of the orogen (e.g., Cawood et al. 1995; Malo and Kirkwood 1995; van Staal and de Roo 1995; O'Brien 1998). Evidence for extension includes the widespread preservation of early to mid-Paleozoic low-grade rocks in central Newfoundland, normal or oblique-normal kinematics on some faults and shear zones, locally abrupt transitions from low-grade to high-grade rocks, thermochronological data indicating rapid cooling of some metamorphic complexes, and regionally extensive late- to postorogenic basins. Some authors have proposed that the orogen experienced "extensional collapse" during mid-Paleozoic time (e.g., Cawood et al. 1995; van Staal and de Roo 1995; Lynch 1996). However, clear evidence for the postulated normal faults has so far been limited to a few widely separated localities with poor age constraints (e.g., Waldron and Milne 1991; Malo and Kirkwood 1995; Tremblay et al. 1997; O'Brien 1998). This article summarizes field and geochronological evidence for a system of Devonian ductile and brittle-ductile normal-sense shear zones on the Baie Verte Peninsula of northwestern Newfoundland. These shear zones, which separate hangingwall ophiolitic rocks from footwall metaclastic rocks of the Ming's Bight Group, are interpreted to have formed during dextral oblique transcurrent motion along the Baie Verte Line.

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[1] Author for correspondence; e-mail: beckyj@is.dal.ca.

[2] Department of Earth Sciences, Memorial University, St. John's, Newfoundland A1B 3X5, Canada.

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Regional Geological Setting

The Ming's Bight Group is a sequence of semi-pelitic to psammitic schists correlated (Hibbard 1983 and references therein) with late Proterozoic to early Paleozoic metaclastic rocks of the Fleur de Lys Supergroup (fig. 1). Collectively, these rocks are interpreted as remnants of the early Paleozoic rifted continental margin of Laurentia (Humber Zone), deformed and metamorphosed during Ordovician to Silurian accretion of volcanic arc (Dunnage Zone) and continental (Avalon Zone) terranes during the Taconian and Salinian orogenies (e.g., Williams 1979; Dunning et al. 1990; Cawood et al. 1996; Waldron et al. 1998). The Humber-Dunnage boundary in western Newfoundland is represented by the Baie Verte Line (fig. 1; Williams and St-Julien 1982), a steep fault zone marked by disrupted ophiolite complexes that records a complex history of oblique transcurrent deformation (e.g., Hibbard 1983; Goodwin and Williams 1990; Bélanger et al. 1996). The position of the Ming's Bight Group requires explanation because these Humber Zone rocks are now on the "wrong side" of the Baie Verte Line (fig. 1).

Rocks on the Baie Verte Peninsula experienced a complex Ordovican to Silurian structural and metamorphic history. West of the Baie Verte Line, Late Ordovician burial and rapid Silurian exhumation of continental margin deposits produced eclogite and amphibolite facies metamorphism

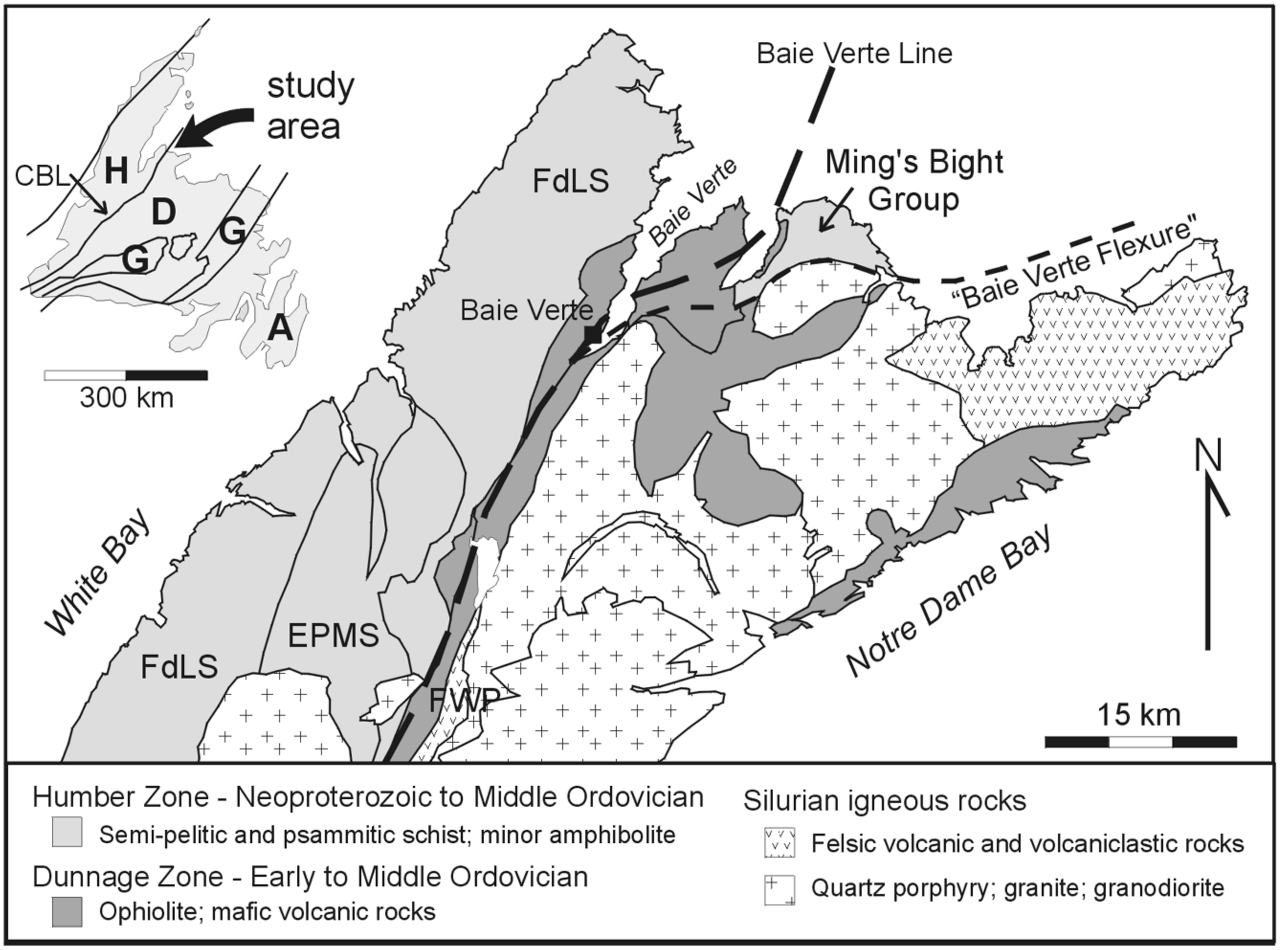


Figure 1. Generalized geological map of the Baie Verte Peninsula showing the position of the Ming's Bight Group relative to Humber Zone metaclastic rocks of the Fleur de Lys Supergroup (*FdLS*) and East Pond Metamorphic Suite (*EPMS*) west of the Baie Verte Line, and Dunnage Zone ophiolitic and silicic magmatic rocks east of the Baie Verte Line (after Hibbard 1983). Location of Baie Verte Line after Miller and Wiseman (1994); Baie Verte Flexure after Hibbard (1982); *FWP* = Flat Water Pond Group. Inset shows the lithotectonic zones defined in Newfoundland (Colman-Sadd et al. 1990): *H* = Humber, *D* = Dunnage, *G* = Gander, *A* = Avalon, *CBL* = Corner Brook Lake area.

(Jamieson 1990; Cawood et al. 1994; Waldron et al. 1998) accompanied by polyphase deformation that included southwest-directed thrusting and both sinistral and dextral ductile shear zones (Bursnall and de Wit 1975; Piasecki 1988; Goodwin and Williams 1990). East of the Baie Verte Line, Early Ordovician ophiolites and related island arc complexes (e.g., Kidd et al. 1978) formed above an east-dipping subduction zone proximal to the Laurentian margin (e.g., Williams et al. 1988; van Staal et al. 1998). Obduction of ophiolite and other allochthonous rocks accompanied arc-continent collision during the Ordovician Taconian orogeny (Stevens 1970; Williams 1979), although the timing of this event is somewhat controversial. Rocks in southwestern Newfoundland record Early Ordovician arc-continent collision (van Staal et al. 1998), but the Anticosti foreland basin does not record subsidence related to this event until Late Ordovician time (Waldron et al. 1998). It therefore seems likely that Taconian arc-continent collision was diachronous and that parts of the Laurentian margin that were originally widely separated were juxtaposed by transcurrent displacement. Ordovician arc accretion was followed by intrusion of voluminous Silurian plutons (Dunning et al. 1990; Cawood and Dunning 1993). Mid-Paleozoic oblique transcurrent deformation affected both Humber and Dunnage Zone rocks and led to protracted, polyphase deformation along the Baie Verte Line.

The role of the Ming's Bight Group within this tectonic framework has never been clear. To account for the anomalous position of these Humber Zone rocks, Hibbard (1982) suggested that the Baie Verte Line was deflected to the south of the Ming's Bight Group along the "Baie Verte Flexure" (fig. 1) and that intrusion of the Dunamagon Granite, then thought to be Ordovician, marked the end of movement on this part of the Baie Verte Line. Based on Devonian-Carboniferous $^{40}Ar/^{39}Ar$ ages from the Ming's Bight Group and adjacent units, Dallmeyer and Hibbard (1984) suggested that the northeastern Baie Verte Peninsula was affected by an episode of Acadian shortening not seen elsewhere in the region. It has since been recognized that the Dunamagon granite is Silurian (429 ± 4 Ma, U-Pb zircon; Cawood and Dunning 1993) and that its contact with the Ming's Bight Group is tectonic rather than intrusive (McDonald 1993). These observations require reassessment of the structural and stratigraphic relationships between the Ming's Bight Group, Dunamagon Granite, and adjacent arc-related and ophiolitic rocks of the Pacquet Harbour Group and Point Rousse Ophiolite Complex (figs. 1, 2).

Shear Zones Bounding the Ming's Bight Group

Shear zones that separate the Ming's Bight Group from adjacent ophiolitic and granitoid rocks (fig. 2) record a complex, three-phase deformation history (table 1) based on overprinting relationships (Anderson 1998). D_1 structures are preserved along the contact between the Ming's Bight Group and Pacquet Harbour Group (Pelee Point Shear Zone; fig. 3) and between the Pacquet Harbour Group and Point Rousse Ophiolite Complex (Scrape Thrust; fig. 2). External to these shear zones, the Ming's Bight Group and Pacquet Harbour Group contain regionally developed, bedding-parallel S_1 foliations transposed by fabrics assigned to D_2 and D_3. D_1 structures that cut the Early Silurian Dunamagon Granite and Burlington Granodiorite record shortening under greenschist to amphibolite facies conditions. The sinistral-reverse Stog'er Tight Shear Zone that cuts the Point Rousse Ophiolite Complex (fig. 2) dates to ca. 420 ± 5 Ma (U-Pb on hydrothermal zircon; Ramezani 1992), and D_1 is inferred to have taken place during a regional phase of Late Silurian sinistral transpression (Anderson 1998). Many of the early structures associated with shortening have been described elsewhere (e.g., Kirkwood and Dubé 1992; Ramezani 1992; Dubé et al. 1993); however, extensional structures assigned to D_2 and D_3 have not been documented previously. They are particularly well exposed in the Pacquet Harbour and Ming's Tickle areas on the southeast and northwest margins of the Ming's Bight Group (figs. 3, 4).

Southeast Margin of the Ming's Bight Group. D_2 structures are regionally developed in the southeastern Ming's Bight Group, Dunamagon Granite, and Pacquet Harbour Group and dominate within the ca. 400-m-thick southeast-dipping Woodstock Shear Zone (fig. 3), which trends parallel to the northwest contact of the Cape Brule Porphyry. In Ming's Bight Group schist in the footwall of this shear zone, the S_2 foliation is typically a differentiated crenulation cleavage formed by transposition of S_1. In general, the S_2 foliation intensifies toward the southeast, forming a penetrative mylonitic foliation in the Pacquet Harbour Group and the southern part of the Dunamagon Granite. Immediately west of the Cape Brule Porphyry, mylonitic amphibolites derived from Pacquet Harbour Group volcanic rocks contain a penetrative S_2 fabric defined by biotite and hornblende porphyroblasts, recrystallized quartz-rich bands, and a pronounced compositional banding. In thin section, well-equilibrated textures and sigmoidal inclusion trails in garnet, staurolite, and hornblende porphyroblasts

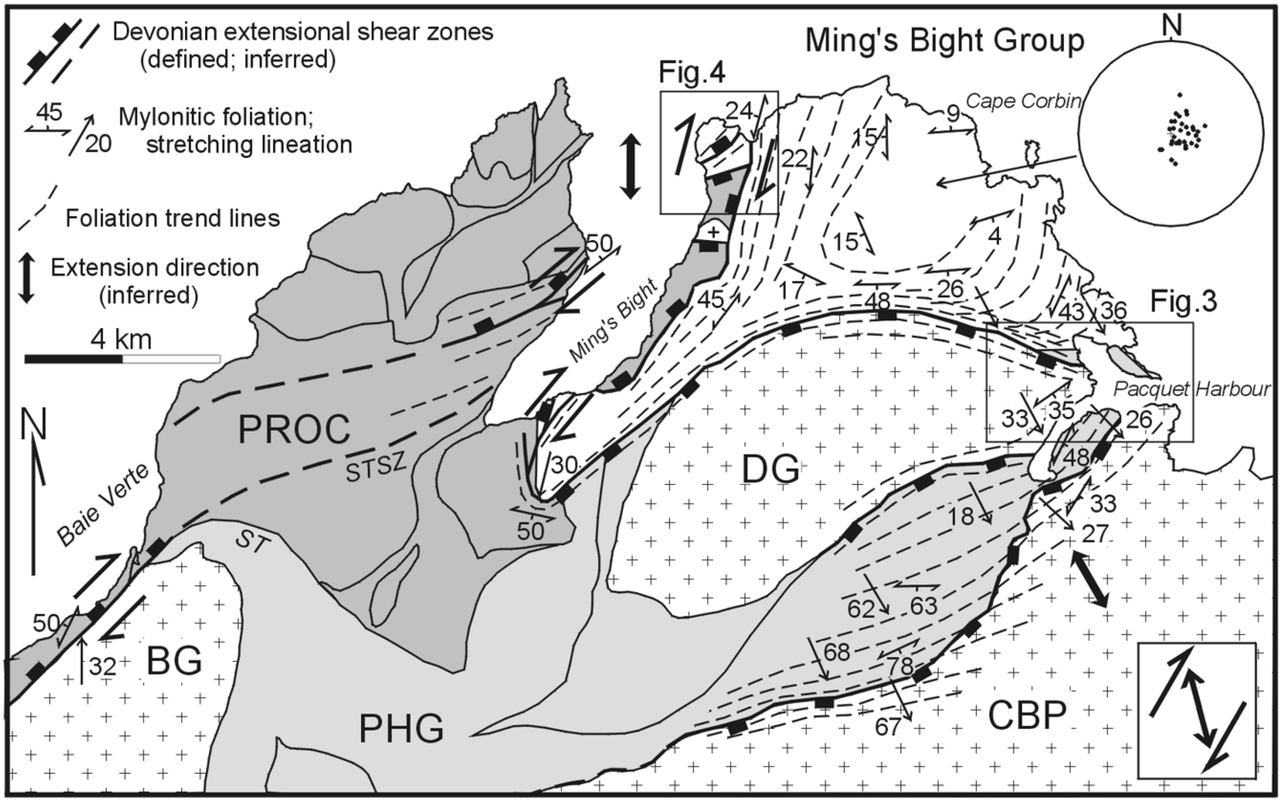


Figure 2. Map of the Ming's Bight Group and surrounding rocks showing D$_2$-D$_3$ foliation and lineation trends and kinematic shear sense of the main shear zones and faults. *PROC* = Point Rousse Ophiolite Complex; *BG* = Burlington Granodiorite; *PHG* = Pacquet Harbour Group; *DG* = Dunamagon Granite; *CBP* = Cape Brule Porphyry; *ST* = Scrape Thrust; *STSZ* = Stog'er Tight Shear Zone. Lower-hemisphere, equal-area projection shows poles to low-angle S$_2$ foliations that dominate the region south of Cape Corbin. The heavy, double-ended arrows denote the inferred bulk extension direction in the Ming's Bight and Pacquet Harbour areas. Inset in lower right illustrates the inferred regional D$_2$-D$_3$ kinematic framework of dextral transtension.

indicate syntectonic D$_2$ mineral growth and recrystallization under amphibolite facies conditions.

A locally developed, southeast-plunging, L$_2$ mineral lineation is defined by the preferred orientation of hornblende porphyroblasts, broadly parallel to an L$_2$ stretching lineation defined by clasts in volcanic breccia and conglomerate in the Pacquet Harbour Group and by K-feldspar augen and mafic xenoliths in the Dunamagon Granite. The S$_2$ fabric is axial planar to open to isoclinal, reclined, southeast-plunging F$_2$ folds with wavelengths ranging from <1 cm to ca. 500 m. In the higher structural levels of the Woodstock Shear Zone, rootless, intrafolial F$_2$ folds verge southwest. Their axes are generally subparallel to L$_2$ and in many locations define sheath and tubular folds with bisectors subparallel to L$_2$. D$_2$ shear-sense indicators, including σ-porphyroclast systems, S-C fabrics, shear bands, and en-echelon sigmoidal tension gashes, consistently indicate normal-sense noncoaxial shear with top-side down to the southeast.

D$_3$ structures are associated with the ca. 200-m-thick Big Brook Shear Zone developed in the Ming's Bight Group and Pacquet Harbour Group along the northern contact of the Dunamagon Granite (fig. 3). The south-dipping S$_3$ foliation is defined by a preferred orientation of biotite and chlorite and contains a rare, southeast-plunging biotite mineral lineation. Mineral assemblages and textures associated with the S$_3$-L$_3$ fabrics indicate greenschist facies conditions during D$_3$. In places, S$_3$ is associated with 1–5-m-thick zones of mylonite; in other places it is a discrete, widely spaced, extensional crenulation cleavage formed by transposition of S$_1$ and S$_2$ (fig. 5*a*). Shear bands consistently indicate normal-sense noncoaxial shear.

In the footwall of the Big Brook Shear Zone, the

Table 1. Summary and Correlation of Deformation in the Ming's Bight and Pacquet Harbour Areas

	Ming's Bight area	Pacquet Harbour area
High-angle dextral transtensional shear (ca. 385–370 Ma):		
D_3	Ductile to brittle-ductile, dextral-normal oblique-slip shear zones; includes Northern Ming's Tickle Shear Zone (post-405 Ma, syn-388–380 Ma, pre-360 Ma)	Ductile, normal shear; includes Big Brook Shear Zone (post-380 Ma, pre-360 Ma)
Low-angle dextral transtensional shear (ca. 405–385 Ma):		
D_2	Ductile, dextral strike-slip shear; includes Grand Toss Cove Shear Zone (post-420 Ma, pre-388 Ma)	Ductile, dextral-normal oblique-slip shear; includes Woodstock Shear Zone (post-430 Ma, syn-385 Ma, pre-360 Ma)
Regional sinistral transpressional shear (ca. 425–405 Ma):		
D_1	Ductile, sinistral-reverse oblique-slip shear; includes Scrape Thrust and Stog'er Tight Shear Zone (post-430 Ma, syn-420 Ma, pre-405 Ma)	Ductile, sinistral-reverse oblique-slip shear; includes Pelee Point Shear Zone (post-430 Ma, pre-385 Ma)

Ming's Bight Group is intruded by a suite of granitic pegmatite dikes, 1–15 m thick, that dip steeply to the northwest and southeast and can be traced for up to 500 m along strike. They are typically oriented nearly orthogonal to L_2, although they consistently cut D_2 structures. Pegmatite dikes near the Big Brook Shear Zone locally contain a spaced fabric defined by fine- to coarse-grained muscovite folia that anastomose around K-feldspar phenocrysts. This fabric is continuous with S_3 in the country rock and is therefore ascribed to D_3. These relationships indicate pegmatite intrusion after D_2 but before the end of D_3, and dike orientations are consistent with intrusion into an extensional stress regime (i.e., subvertical σ_1, subhorizontal σ_3).

Northwest Margin of the Ming's Bight Group. Along the east side of Ming's Bight, D_2 structures are associated with the Grand Toss Cove Shear Zone (fig. 4) that generally separates Point Rousse Ophiolite Complex in the hangingwall from Ming's Bight Group in the footwall (although the hangingwall structure is more complex in detail). In Grand Toss Cove, the shear zone is 200–300 m thick and is characterized by 5–10-m-thick mylonite zones, preferentially developed in semipelitic schist, that anastomose around disrupted pods of massive psammite. The mylonitic S_2 foliation dips shallowly west and is defined by foliated muscovite, biotite, and quartz ribbons that wrap around subhedral plagioclase porphyroblasts. S-C fabrics (fig. 5*b*), shear bands, and mica fish consistently indicate dextral shear. The intersection lineation between the S-planes, C-planes, and shear bands plunges shallowly to the west, indicating a component of strike-slip shear.

The S_2 foliation is axial planar to open to isoclinal, reclined, west-plunging F_2 folds that mainly verge north. Typically, the S-planes of the S-C fabrics are parallel to the F_2 axial planes, and the F_2 hinge lines are subparallel to the S-C intersection lineation, consistent with folding during shear within the Grand Toss Cove Shear Zone. Outside the shear zone, S_2 typically forms a spaced crenulation cleavage that is axial planar to open to isoclinal, reclined F_2 folds that plunge shallowly to the west. These folds are common in the Ming's Bight Group and are locally present in the Point Rousse Ophiolite Complex.

D_3 shear zones are well exposed along the coast of Ming's Bight between Caplin Cove and Ming's Tickle (fig. 4) but sparsely developed farther south. They are generally 5–20 m wide and dip moderately to shallowly southwest and northwest. Along shear-zone margins, D_3 fabrics transpose D_1-D_2 structures in rocks of the Ming's Bight Group and Point Rousse Ophiolite Complex. D_3 shear zones typically contain a semipenetrative mylonitic S_3 foliation transitional into a 5–10-m-thick central zone of penetrative S-C mylonite. S_3 is defined by biotite and chlorite, with muscovite in Ming's Bight Group schist and hornblende in mafic rocks of the Point Rousse Ophiolite Complex. Quartz-rich domains in these mylonites contain well-developed polycrystalline ribbon textures and a strong crystallographic preferred orientation.

S_3 locally contains a mineral lineation defined by chlorite and hornblende, roughly parallel to a stretching lineation defined by quartz-filled strain shadows. In many places, hornblende porphyroblasts are randomly oriented within and across the S-C fabric, suggesting hornblende growth after D_3 shear. Shear-sense indicators, including S-C fabrics, shear bands (fig. 5*c*), mica fish, σ-porphyroclasts, and quartz-filled tension gashes, indicate dextral-normal oblique shear. In the Northern Ming's

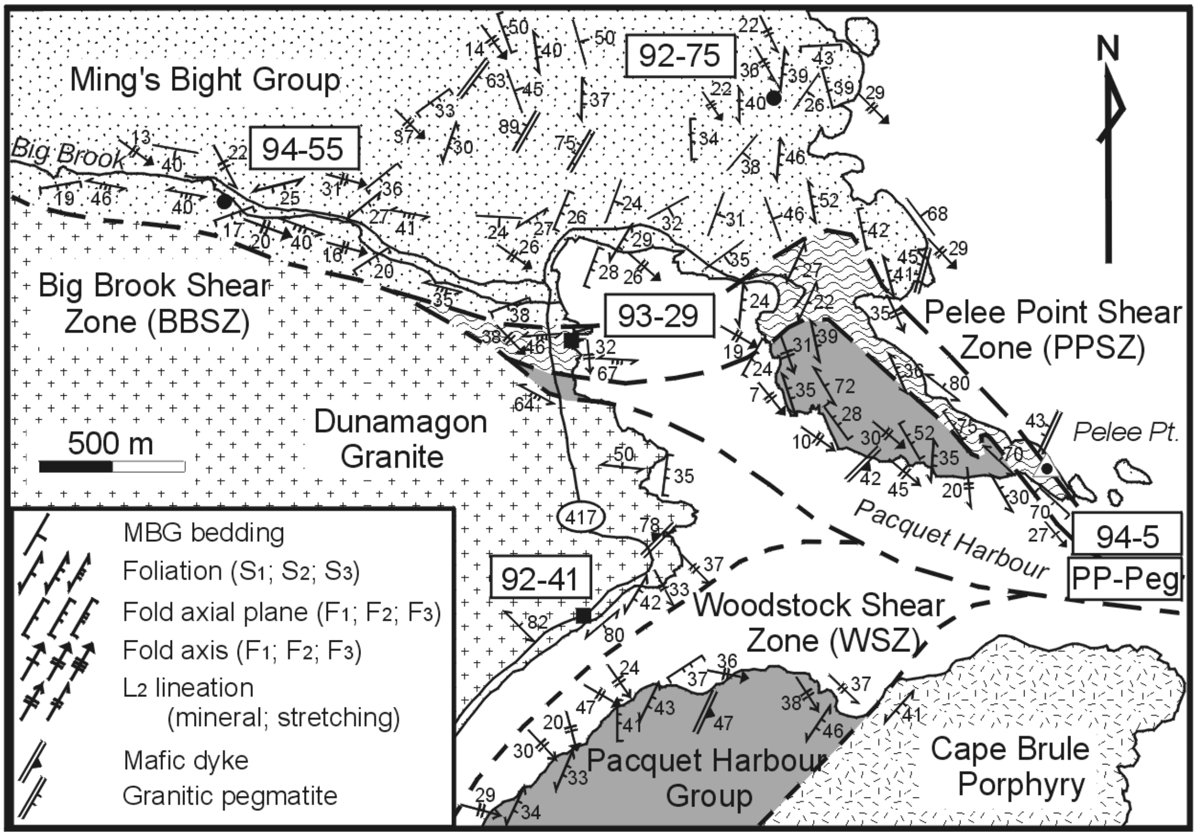


Figure 3. Geology and structures of the Pacquet Harbour area (see fig. 2 for map location). Numbered solid black circles and squares indicate locations of muscovite and hornblende geochronology samples. Open triangle indicates location of Pelee Point Pegmatite (*PP-Peg*) U-Pb sample (see also fig. 6). Long dashes = trace of Pelee Point Shear Zone; short dashes = trace of Woodstock Shear Zone; short-and-long dashes = trace of Big Brook Shear Zone.

Tickle Shear Zone (NMTSZ; fig. 4), overprinting relationships indicate an increment of early D_3 dextral-reverse oblique shear. Tight to isoclinal F_3 folds locally developed within D_3 shear zones have axes typically subparallel to the S-C intersection lineation, although orientations can be quite variable. Curvilinear and sheath folds are common, particularly adjacent to the footwall of D_3 shear zones cutting the Ming's Bight Group. South of Ming's Bight, open, recumbent, symmetrical D_3 folds that plunge shallowly to the south and north are interpreted to have accommodated subvertical shortening in domains with steep D_1 fabrics.

Several D_3 shear zones contain discrete, generally 2–5-m-thick zones of chlorite schist that overprint earlier, mylonitic S_3 fabrics. They contain penetrative S-C fabrics and abundant fault-fill and breccia-type quartz veins in their central portions (fig. 5*d*). A gradational contact is locally preserved between chlorite schist and adjacent mylonite, and S-C fabrics in both schist and mylonite record the same sense of movement. The chlorite schist is interpreted to have formed by hydrothermal alteration and recrystallization of mylonite during a later increment of D_3 shear. In the Northern Ming's Tickle Shear Zone, the gradational contact between schist and mylonite locally contains coarse-grained rutile and titanite porphyroblasts that overgrow an earlier mylonitic fabric but are wrapped around by the S_3 chlorite foliation.

The final increment of D_3 deformation produced narrow (<2 m), brittle-ductile, high-angle dextral-normal faults with local zones of cataclasite and fault breccia. Thick cataclasite zones in parts of the Grand Toss Cove Shear Zone probably formed during this late D_3 faulting.

$^{40}Ar/^{39}Ar$ Results

Samples of hornblende and muscovite from the Point Rousse Ophiolite Complex, Pacquet Harbour Group, Dunamagon Granite, and Ming's Bight

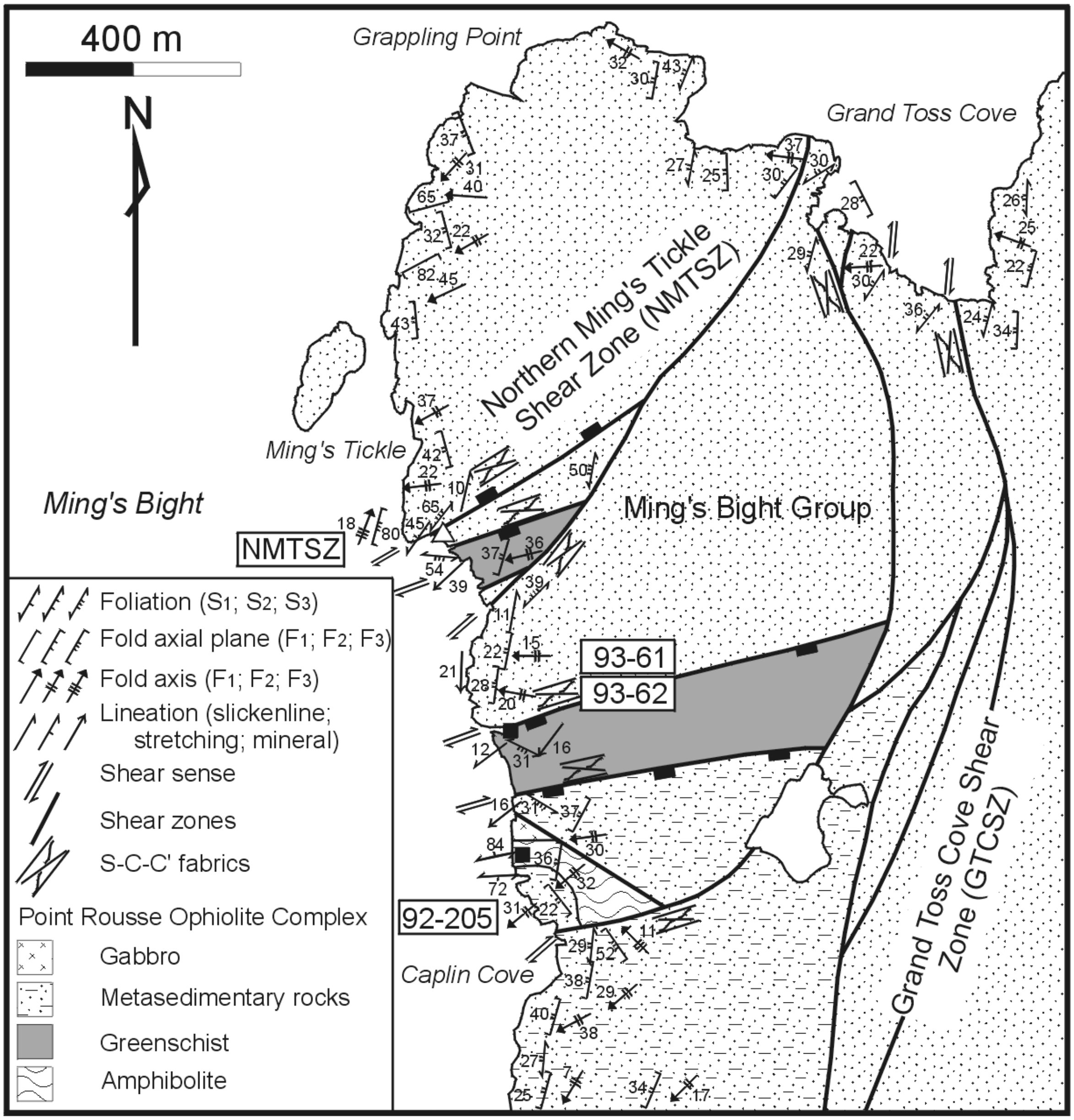


Figure 4. Geology and structures of the Ming's Tickle area (see fig. 2 for map location). Numbered solid black squares indicate hornblende geochronology sample localities. Open triangle indicates location of NMTSZ U-Pb sample (see also fig. 6).

Group were dated by the conventional $^{40}Ar/^{39}Ar$ method. Analytical methods are described in Hicks et al. (1999); the flux monitor was hornblende standard MMhb-1 (assumed age 520 ± 2 Ma; Samson and Alexander 1987). Sample locations and results are summarized in figure 6, and the $^{40}Ar/^{39}Ar$ age spectrum plots are shown in figures 7 and 8 (complete data are available from coauthor P. H. Reynolds upon request). Unless stated otherwise, the mainly mid- to Late Devonian (Tucker et al. 1998) ages reported below are given with their 2σ uncertainties.

Point Rousse Ophiolite Complex. Three samples from fault-bounded slivers of the Point Rousse Ophiolite Complex along the east side of Ming's Bight (figs. 4, 6) yielded variably discordant $^{40}Ar/^{39}Ar$ hornblende spectra (fig. 7*a*). Samples 93-61H and 93-62H are from a late (D_3) extensional shear zone that dissects ophiolitic rocks near Caplin Cove (fig. 4). Field and petrographic relationships

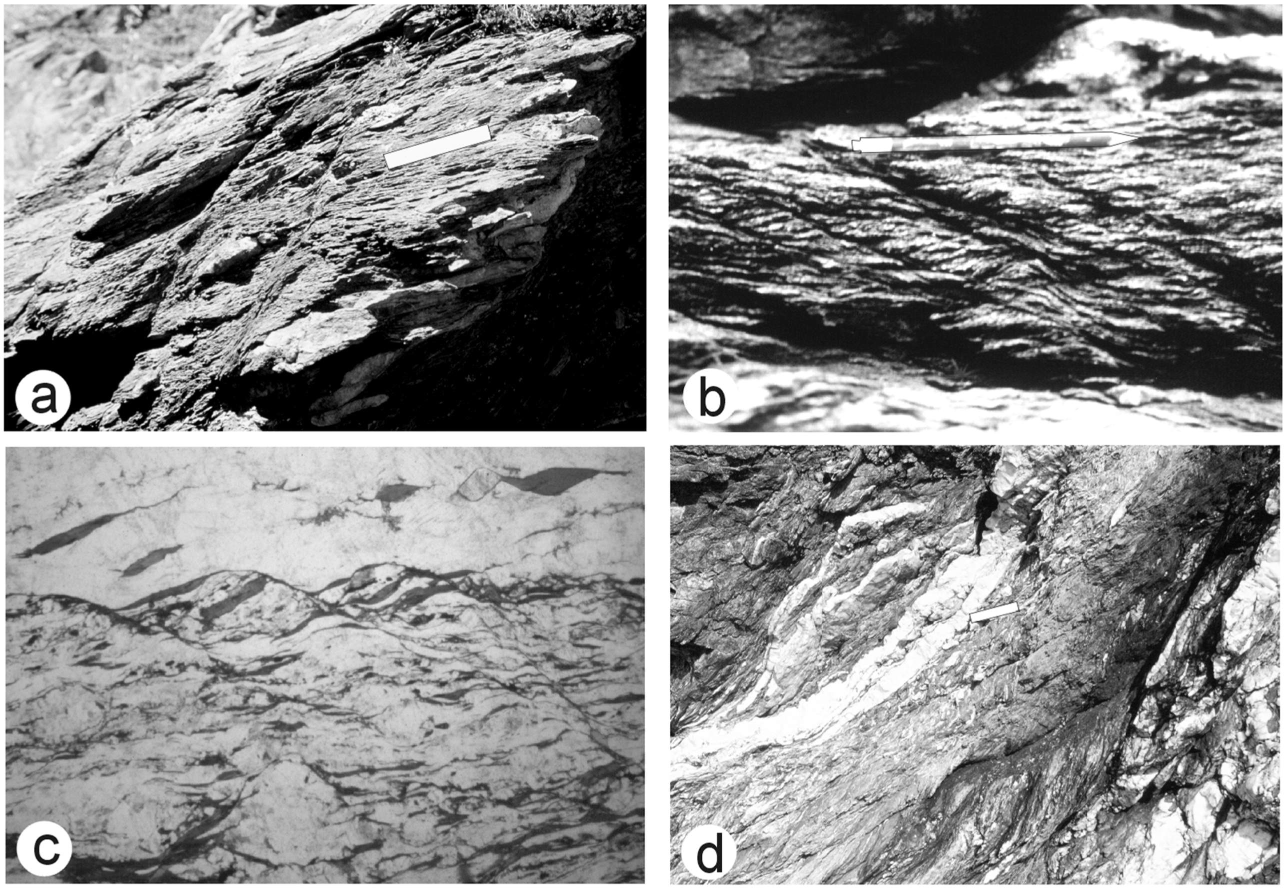


Figure 5. Characteristic structures associated with normal-sense faults and shear zones in the study area. *a*, S_2, axial planar to F_2 folds transposed by discrete, spaced, normal-sense D_3 crenulation cleavage planes, BBSZ, Pacquet Harbour, looking west. Ruler is 15 cm long. *b*, Shear bands developed in D_2 S-C mylonite (X-Z section, looking west) GTCSZ, Grand Toss Cove. Pencil is 20 cm long. *c*, Photomicrograph (X-Z section, looking southeast) of D_3 shear bands and mica fish in mylonitic Ming's Bight Group, Ming's Tickle area. Field of view 0.5 mm. *d*, Narrow zone of D_3 chlorite schist, NMTSZ, east side of Ming's Bight (looking northeast), showing dextral asymmetric shear bands and fault-fill and breccia veins. Ruler is 15 cm long.

(Anderson 1998) suggest that amphibolite mylonite (93-62H) developed from metagabbro (93-61H). Hornblende in the mylonite is medium-grained, locally poikiloblastic, and defines a strong foliation and weak lineation. Hornblende in the metagabbro, inferred to have replaced original pyroxene, is coarse-grained, randomly oriented, and highly poikiloblastic. The third sample (92-205H) is from polydeformed amphibolite, locally gradational into metagabbro, that contains a penetrative D_1 mylonitic fabric overprinted by D_2-D_3 structures. It contains weakly strained, fine- to coarse-grained, acicular hornblende that overgrows S_1 but is commonly parallel to the axial planes of F_2-F_3 crenulations.

Metagabbro (93-61H) and mylonite (93-62H) spectra are both highly discordant (fig. 7*a*), with lower temperature steps yielding Devonian apparent ages (≤400 Ma), higher temperature steps yielding Ordovician apparent ages (≥470 Ma), and an irregular pattern of intermediate ages at intermediate temperatures. The final 70% of gas released from metagabbro (93-61H) has an average age of 474 ± 6 Ma, which is older than most of the ages from the mylonite. The sample produced a relatively narrow range of $^{37}Ar/^{39}Ar$ ratios over the final ~90% of gas release, consistent with the range of Ca/K ratios determined from microprobe data (fig. 7*a*). Isotopic data from the metagabbro appear uncorrelated and provide no useful age estimate. In contrast, mylonite sample 93-62H yielded more variable $^{37}Ar/^{39}Ar$ ratios, generally lower than those inferred from measured Ca/K (fig. 7*a*), suggesting

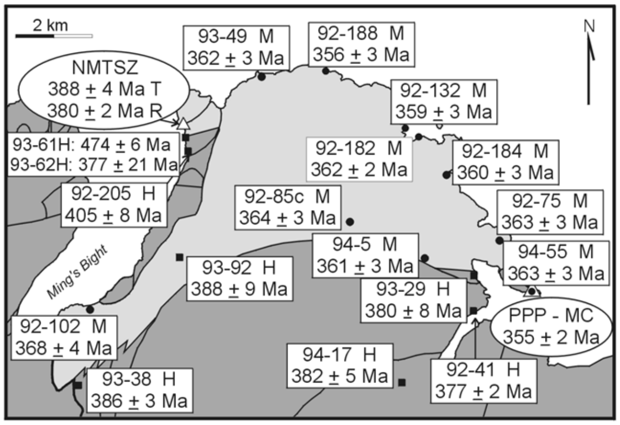


Figure 6. Locations and ages of geochronology samples discussed in text. Squares = hornblende samples (*H*); circles = muscovite samples (*M*); triangles = U-Pb samples (*T* = titanite; *R* = rutile). Preferred $^{40}Ar/^{39}Ar$ ages are shown within rectangles, U-Pb ages within ovals; see figures 7, 8, and 10 for data. See figure 2 for geological unit names.

K-rich incipient alteration during or after mylonitic recrystallization. Isotope correlation analysis of the final ~70% of data from this sample, the portion most closely identified with hornblende, yields an age of 377 ± 21 Ma with a statistically acceptable fit of points to the isochron.

The spectrum for sample 92-205H is dominated by several concordant steps (fig. 7*a*) corresponding to release temperatures of 950°–1025°C and 1150°–1200°C. Apart from a small initial first step, this sample has a relatively narrow range in $^{37}Ar/^{39}Ar$ ratios consistent with the values inferred from measured Ca/K. A weighted average age of 405 ± 8 Ma was calculated from steps that incorporate 88% of the ^{39}Ar released.

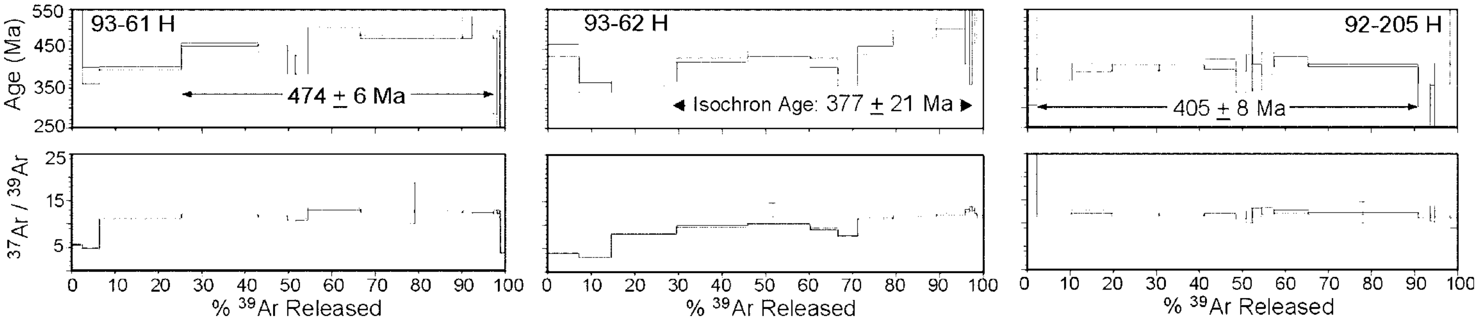
Pacquet Harbour Group. Sample 93-38H was collected from mylonitic amphibolite within a sequence of pillow basalts and gabbro cut by a D_1 transpressional shear zone that separates the Point Rousse Ophiolite Complex from the Pacquet Harbour Group south of Ming's Bight (figs. 2, 6). Sample 94-17H is from mylonitic amphibolite within pillowed metabasalts and mafic volcaniclastic rocks on the southeastern side of the Dunamagon Granite (fig. 4). Hornblende in both samples forms fine- to medium-grained, idioblastic to xenoblastic, relatively strain-free grains locally intergrown with actinolite. Sample 93-92H, from a fault-bounded amphibolite sliver surrounded by Ming's Bight Group schist, is interpreted as a tectonic enclave of Pacquet Harbour Group emplaced along a D_1 transpressional shear zone (Anderson 1998). In this sample, an early generation of twinned, variably poikiloblastic, equant hornblende grains is surrounded by finer-grained recrystallized hornblende; the coarser-grained population was selected for analysis. Hornblende in samples 93-92H and 93-38H defines a strong foliation (S_1) and a prominent lineation (L_1); hornblende in sample 94-17H is parallel to S_2.

The spectra obtained from samples 93-38H and 93-92H are very similar (fig. 7*b*), with mean ages of 386 ± 3 Ma, corresponding to release temperatures of 900°–1200°C, and 388 ± 9 Ma, corresponding to release temperatures of 950°–1250°C, respectively. Apparent ages increase in a fairly regular fashion from ~375 Ma to ~400 Ma over the bulk of the gas release. We interpret the observed gradients to have resulted from phase changes and argon isotope redistribution during vacuum heating (e.g., Lee et al. 1991) rather than reflecting the thermal history of the rocks. The corresponding isotope correlation ages are within the range 375–400 Ma, but in neither case is the statistical fit of points to line satisfactory. Sample 94-17H yielded relatively low amounts of ^{39}Ar, resulting in a poorly defined spectrum (fig. 7*b*). A plateau comprising the final ~70% of gas release, but dominated by large steps at 1025°–1050°C and 1250°C, has an age of 374 ± 18 Ma. Isotope correlation analysis yielded an acceptable isochron with an age of 382 ± 5 Ma. $^{37}Ar/^{39}Ar$ ratios for all three samples are variable but generally consistent with measured Ca/K ratios.

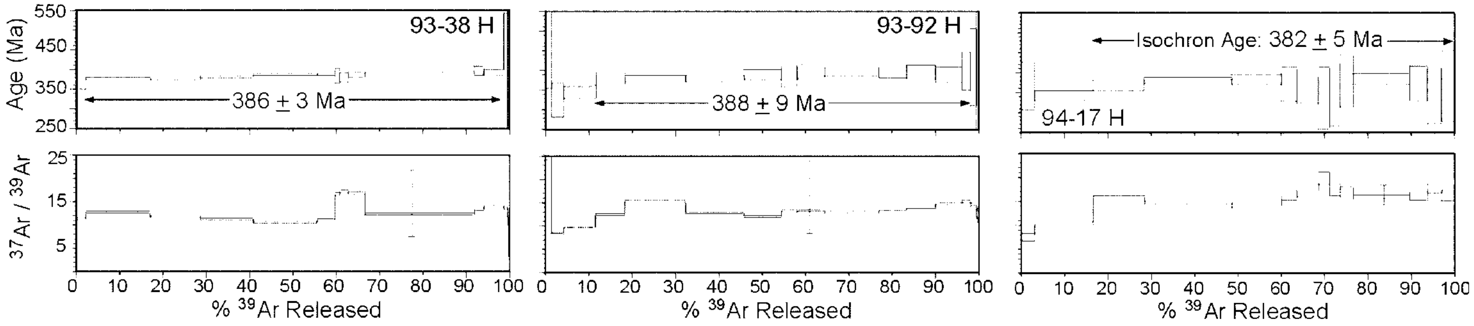
Mafic Dikes. Sample 93-29H was collected from a strongly deformed mafic amphibolite dike within the Big Brook Shear Zone on the western shore of Pacquet Harbour (figs. 3, 6). Hornblende forms fine- to coarse-grained, locally inclusion-rich, porphyroblasts that range from strongly aligned with S_2 and L_2 to randomly oriented. The age spectrum is dominated by one large and several smaller steps with ages in the range 376–380 Ma (fig. 7*c*). Hornblende-derived gas, defined on the basis of $^{37}Ar/^{39}Ar$ ratio, has an average age of 380 ± 8 Ma. The corresponding isotope correlation age is 381 ± 4 Ma, but as expected from the number of small discordant steps, the fit of points to a line is not satisfactory.

Sample 92-41H was collected from an amphibolite-grade mafic dike cutting the Dunamagon Granite (figs. 3, 6). Hornblende in this sample is fine- to coarse-grained, variably recrystallized, moderately poikiloblastic, and intergrown with biotite along grain boundaries. The hornblende yielded a spectrum with an age gradient ranging

a) Point Rousse Ophiolite Complex



b) Pacquet Harbour Group



c) Mafic Dykes

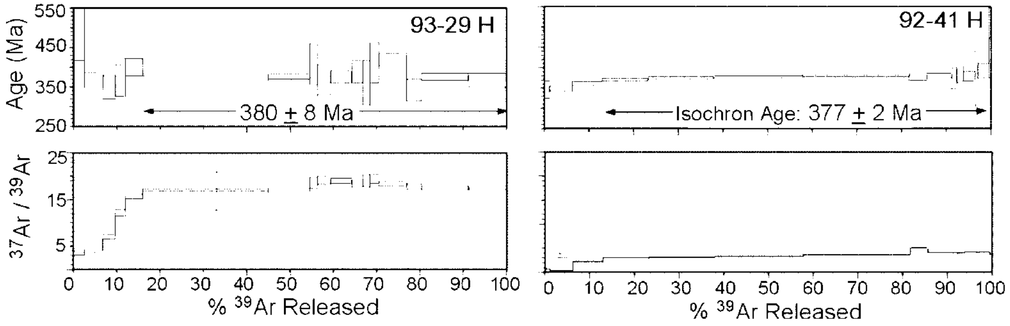
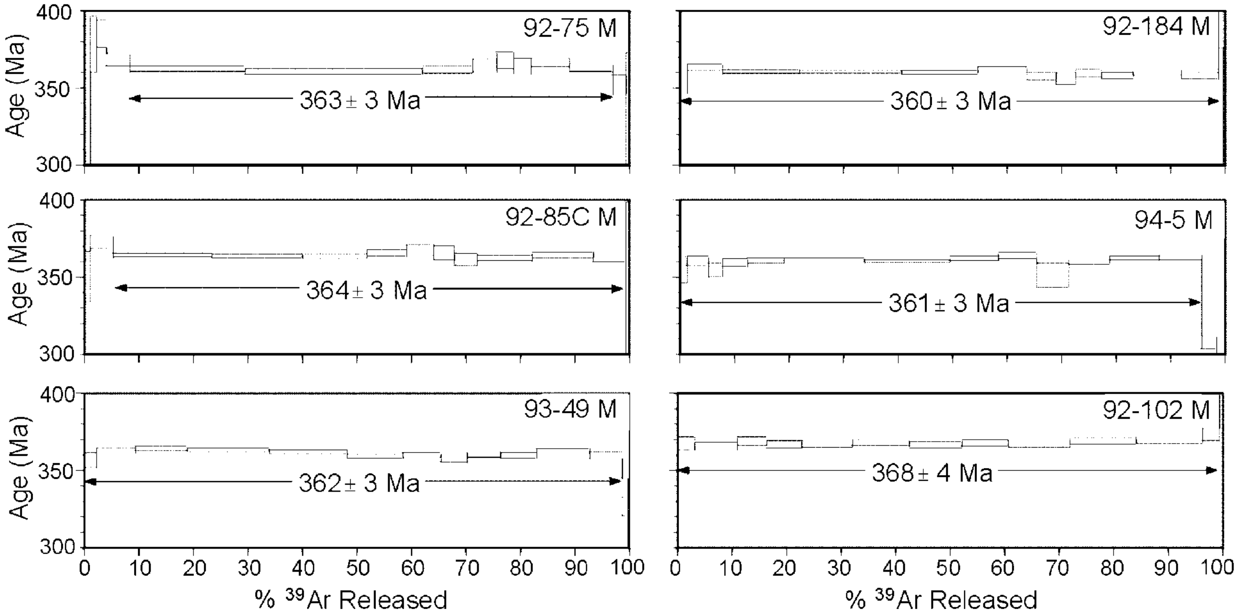


Figure 7. Apparent age (upper) and ^{37}Ar/^{39}Ar (lower) spectra from hornblende samples. Half-heights of open rectangles indicate the 1σ relative (between-step) uncertainties; preferred ages (with 2σ uncertainties) are indicated. The ranges in ^{37}Ar/^{39}Ar ratios derived from measured Ca/K abundances are indicated by the vertical lines in the lower plots. See figure 6 for sample locations.

a) Ming's Bight Group Schists



b) Pegmatites and Host Rocks

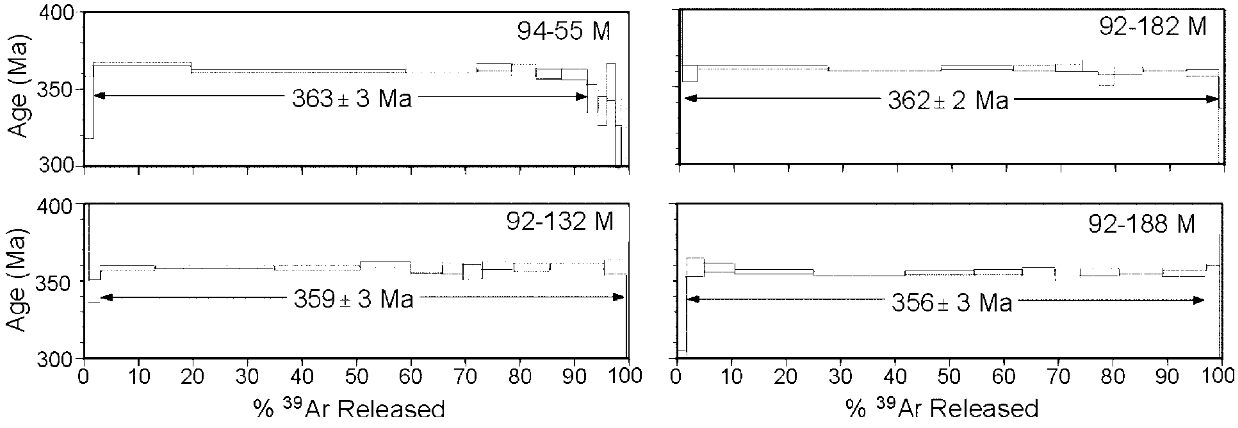


Figure 8. Apparent age spectra from muscovite samples. Preferred ages and uncertainties are as in figure 7. See figure 6 for sample locations.

from ca. 370 to ca. 390 Ma with a mean age of 377 ± 3 Ma. An isotope correlation plot of these data produced an acceptable fit with an age of 377 ± 2 Ma. The narrow range in observed ^{37}Ar/^{39}Ar ratios is consistent with measured Ca/K values (fig. 7*c*).

Ming's Bight Group. Ten samples of muscovite from Ming's Bight Group schist and associated pegmatites were dated (fig. 6). Eight of the 10 samples yielded ages that overlap within error, from 359 ± 3 Ma to 364 ± 3 Ma (fig. 8), with an average age of 362 Ma.

Five of the six samples from the schist contained up to 25% fine- to coarse-grained muscovite that defines a strong foliation and is typically intergrown with biotite. Mica-rich domains define the local S_2, which transects an earlier S_1 fabric defined by fine-grained muscovite and biotite. Porphyroblasts include garnet (92-184M, 94-5M, 93-49M), staurolite (93-49M), and albite (92-102M). The sixth sample (94-5M) was collected from the hinge of an F_2 fold in the Big Brook Shear Zone. Muscovite in this sample forms porphyroblasts with numerous inclusions of quartz and plagioclase. Age variations from schist samples are small (~1%–2%) over most of the gas release; preferred ages range from 360 to

368 Ma (fig. 8*a*). The oldest age (368 ± 4 Ma; 92-102M) is from albite schist located in the southwestern part of the Ming's Bight Group near its contact with the Point Rousse Ophiolite Complex. The youngest age (360 ± 3 Ma; 92-184M) is from garnet schist at a deeper structural level on the northeast coastal section. Intervening samples show no consistent correlation of age with location or mineral assemblage (fig. 6).

Muscovite from three widely separated pegmatite dikes and from a pegmatite exocontact yielded spectra with ages ranging from 356 to 363 Ma (fig. 8*b*). Samples 94-55M and 92-182M are from weakly deformed pegmatite dikes that cut tight to isoclinal F_2 folds. Muscovite forms very coarse-grained, randomly oriented, euhedral to subhedral crystals that yielded ages of 363 ± 3 and 362 ± 3 Ma, respectively. Sample 92-188M was collected from a penetratively deformed pegmatite at Cape Hat near the northern limit of the Ming's Bight Group (fig. 6). Strongly foliated, fine- to medium-grained, subhedral muscovite flakes and mica fish yielded an age of 356 ± 3 Ma, the youngest ^{40}Ar/^{39}Ar age in this study. Sample 92-132M is from muscovite-rich schist immediately adjacent to pegmatite at Red Point. The sample comprised nearly 100% coarse-grained, randomly oriented muscovite books that yielded an age of 359 ± 3 Ma (fig. 8*b*).

U-Pb Results

Two samples from shear zones on the northwestern and southeastern boundaries of the Ming's Bight Group were dated by U-Pb thermal ionization mass spectrometry on hand-picked mineral separates. Sample locations are shown in figures 6 and 9, and the data are presented in figure 10 and table 2. Analytical methods are described in Dubé et al. (1996).

Northern Ming's Tickle Shear Zone. Chlorite schist from the Northern Ming's Tickle Shear Zone (D_3) on the northeastern shore of Ming's Bight (fig. 4) contains large, euhedral rutile and titanite porphyroblasts (fig. 9*a*) interpreted to have grown during hydrothermal alteration of Ming's Bight Group schist. The randomly oriented porphyroblasts overgrow an early mylonitic fabric (S_2 or early S_3) but are wrapped around by S_3; they are interpreted to have grown after D_2 and before or during the early stages of D_3 oblique-normal ductile shear.

The separated titanite is colorless to pale purple brown, clear to turbid, and consists of angular fragments, probably reflecting the large original grain size of the porphyroblasts. The two titanite fractions, T1 and T2 (fig. 10*a*), which contained 46 and 51 ppm U, respectively, yielded ^{206}Pb/^{238}U ages of 387–391 Ma and ^{207}Pb/^{235}U ages of 376–406 Ma (table 2). The large analytical error associated with T1 resulted from loss of the sample during the analysis. The large range in ^{207}Pb/^{235}U age is due to the uncertainty associated with the common Pb correction. The ^{206}Pb/^{238}U age of 388 ± 4 Ma, which is less affected by this correction, is taken to be the best estimate of the age of the titanite. The rutile is orange brown to deep red brown, clear to slightly turbid, and forms angular fragments or acicular striated crystals. Results from rutile fractions R1 and R2 overlap within error, with analysis R2 plotting on concordia (fig. 10*a*). The ^{206}Pb/^{238}U and ^{207}Pb/^{235}U

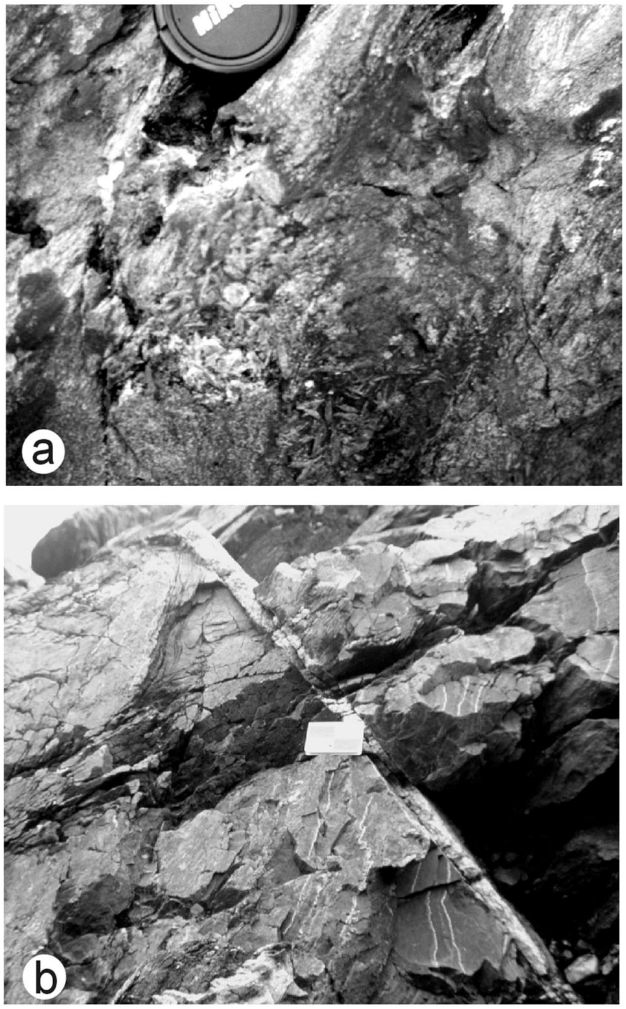


Figure 9. Outcrop photographs of U-Pb sample locations. *a*, Aggregate of coarse titanite and rutile porphyroblasts overgrowing early D_3 fabric in chlorite schist, NMTSZ, east side of Ming's Bight, looking northeast. *b*, Pegmatite vein cutting D_2 fold in Ming's Bight Group schist at Pelee Point, looking southeast. Field notebook is 20 cm long.

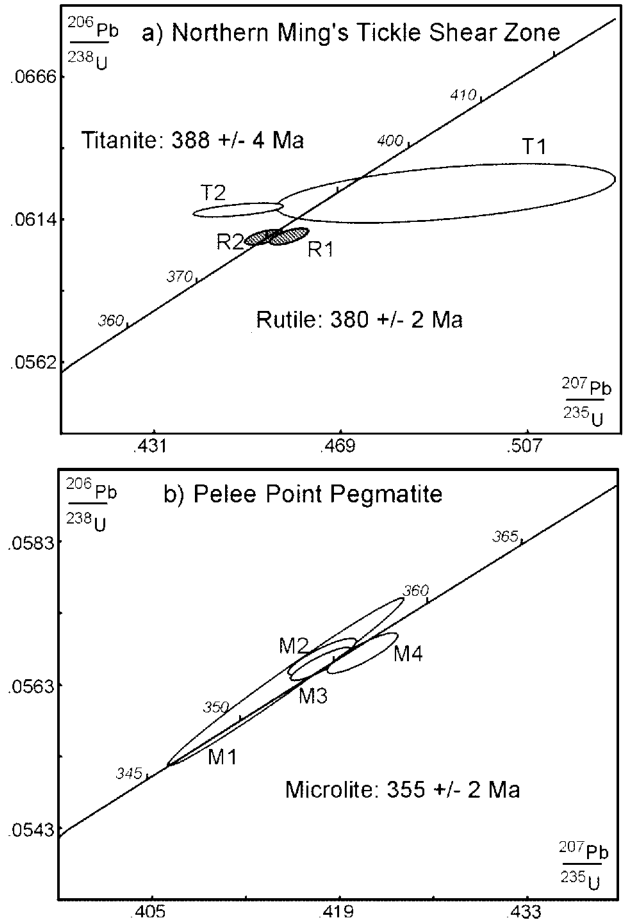


Figure 10. U-Pb discordia plots. *a*, Titanite and rutile data from the Northern Ming's Tickle Shear Zone. *b*, Microlite data from the Pelee Point Pegmatite. See figure 6 for sample locations.

ages range from 380 to 384 Ma, consistent with an age of 380 ± 2 Ma.

Pelee Point Pegmatite. The contact between the Ming's Bight and Pacquet Harbour Groups at Pelee Point is a complex ductile shear zone that is cut by variably deformed quartz veins and pegmatite dikes. The U-Pb sample was taken from a pegmatite cutting an F_2 fold of Ming's Bight Group schist on the northeastern side of Pelee Point (figs. 6, 9*b*), adjacent to the site of muscovite sample 94-55M. Although the pegmatite is postkinematic with respect to F_2 structures in the adjacent schist, feldspar phenocrysts with fractures, undulose extinction, subgrains, and bent twin planes indicate incipient recrystallization, probably at upper greenschist facies conditions. The only datable mineral recovered from the pegmatite was microlite, a Nb-Ta pyrochlore group mineral. Rounded inclusions of columbite-tantalite in the microlite are consistent with typical parageneses in rare-element class pegmatites where microlite forms as a replacement product of primary Nb-Ta minerals by reaction with deuteric fluid during cooling (e.g., Cerný and Ercit 1989). Numerous small (<1 mm) yellow crystals with good clarity and octahedral form, and lacking cracks, visible inclusions, or other inhomogeneities, were selected for analysis. All four analyses overlap concordia and each other (fig. 10*b*). The range of $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages is 354–357 Ma (table 2), consistent with an age of 355 ± 2 Ma.

Times of Deformation and Cooling

Grand Toss Cove Shear Zone. The Grand Toss Cove Shear Zone (fig. 4) separates the Point Rousse Ophiolite Complex (hangingwall) from the Ming's Bight Group (footwall). Contrasts in thermal histories of rocks above and below this structure are consistent with the field evidence that this was a long-lived extensional shear zone.

$^{40}Ar/^{39}Ar$ spectra for hornblende from two Point Rousse Ophiolite Complex samples suggest Devonian overprinting of Ordovician age rocks. The residual Ordovician signature at ca. 475 Ma dominates in coarse-grained metagabbro, whereas medium-grained mylonite yielded an imprecise Devonian age of ca. 380 Ma. The Ordovician ages are similar to the igneous age of gabbro sills within the Point Rousse Ophiolite Complex cover sequence west of Ming's Bight (483 +3/−2 Ma, U-Pb zircon; Ramezani 1992). We interpret the $^{40}Ar/^{39}Ar$ data to reflect overprinting of Ordovician crystallization ages during recrystallization in Devonian shear zones.

Amphibolite containing a penetrative D_1 fabric (92-205H) was juxtaposed with greenschist facies rocks before or during D_3 deformation and now lies in a small fault block in the hangingwall of the Grand Toss Cove Shear Zone (fig. 4). The hornblende microstructure in this sample suggests post-D_1 growth. The $^{40}Ar/^{39}Ar$ age of 405 ± 8 Ma therefore places a lower limit on the age of D_1 sinistral-reverse deformation and may record either hornblende growth during, or cooling after, D_2-D_3 dextral oblique-normal deformation.

U-Pb data from the Northern Ming's Tickle Shear Zone, one of a number of dextral-normal shear zones lying in the hangingwall of the Grand Toss Cove Shear Zone (fig. 4), provide the best constraint on the age of D_2-D_3 extensional deformation in the study area. Titanite and rutile porphyroblasts in chlorite schist postdate D_2 but pre-

Table 2. U-Pb Analytical Data

		Concentration		Measured		Corrected atomic ratios				Age (Ma)		
Sample fraction	Weight (mg)	U (ppm)	Pb rad. (ppm)	Total common Pb (pg)	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{206}Pb}$	$\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{235}U}$	$\frac{^{207}Pb}{^{206}Pb}$	$\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{235}U}$	$\frac{^{207}Pb}{^{206}Pb}$
Northern Ming's Tickle Shear Zone (rutile, titanite):												
R1[a]	.872	16	.9	224	257	.0165	.06088 ± 26	.4592 ± 32	.05470 ± 30	381	384	400
R2[a]	.890	15	.8	192	285	.0078	.06085 ± 24	.4541 ± 32	.05412 ± 32	381	380	376
T1[b]	.500	46	2.8	1729	70	.0656	.06245 ± 88	.4910 ± 284	.05702 ± 298	391	406	492
T2[b]	.581	51	3.0	2159	71	.0512	.06185 ± 20	.4488 ± 74	.05263 ± 80	387	376	313
Pelee Point Pegmatite (microlite):												
M1[c]	.242	29,560	1524.5	68,912	388	.0020	.05687 ± 96	.4189 ± 72	.05342 ± 14	357	355	347
M2[c] three	.005	38,637	1997.8	1944	404	.0079	.05669 ± 20	.4177 ± 20	.05344 ± 14	355	354	348
M3[c] single	.004	46,992	2417.9	1442	525	.0045	.05659 ± 18	.4176 ± 18	.05352 ± 12	355	354	351
M4[c] single	.004	32,848	1696.6	847	512	.0054	.05674 ± 24	.4207 ± 22	.05378 ± 14	356	357	362

[a] Clear, orange, abraded.
[b] Clear, slightly turbid, abraded.
[c] Clear, yellow, abraded.

date or are synchronous with early D_3 dextral oblique-normal slip. The greenschist facies mineral assemblage in the shear zone suggests that titanite probably formed below its nominal closure temperature (600°–650°C; e.g., Heaman and Parrish 1991), and hornblende (92-205H) from amphibolite at a similar structural level records a date of 405 Ma. The titanite date of 388 ± 4 Ma is therefore interpreted as a growth age, and the rutile date of 380 ± 2 Ma is most likely a cooling age. D_2 ductile shear on the Northern Ming's Tickle Shear Zone must therefore have begun before 388 Ma, and the latest D_3 brittle-ductile movement must have postdated 388 Ma.

Hornblendes from the footwall of the Grand Toss Cove Shear Zone (samples 93-38H, 93-92H) yielded mean ages of 386 ± 3 and 388 ± 9 Ma. Both samples have penetrative D_1 fabrics, and sample 93-92H is associated with a D_1 shear zone. The hornblende ages must therefore be related to recrystallization during, or cooling after, D_1. Data from the hangingwall of the Grand Toss Cove Shear Zone show that D_1 predated 405 Ma and that D_2 predated 388 Ma. We therefore interpret the hornblende ages of ca. 390–385 Ma to reflect cooling during the early stages of unroofing of the Ming's Bight Group by D_2 normal-sense ductile shear.

Two muscovite samples from Ming's Bight Group schist in the footwall of the Grand Toss Cove Shear Zone record ages of 368 ± 4 and 362 ± 3 Ma (fig. 6). The older age is from a sample (92-102M) close to the fault and the other is from a sample (93-49M) at a deeper structural level. The youngest age obtained in this study, 356 ± 3 Ma, is from a deformed pegmatite (92-188M) that lies at an even deeper structural level beyond the immediate influence of the shear zone (fig. 6). This trend of decreasing age with increasing structural depth is compatible with cooling following progressive unroofing of the western side of the Ming's Bight Group during D_2-D_3 extension along the Grand Toss Cove Shear Zone.

In summary, D_1 sinistral-reverse deformation in the hangingwall of the Grand Toss Cove Shear Zone predated 405 Ma, oblique-normal D_2 ductile shear began before 388 Ma, and the latest increments of D_3 brittle-ductile movement postdated 388 Ma. Hornblende (388 Ma) and muscovite (368 Ma) from the footwall of the shear zone (fig. 6) define a cooling curve segment with a cooling rate of about 9°C/m.yr. (fig. 11).

Big Brook Shear Zone. Field and microstructural observations indicate that the final stages of D_3 dextral oblique-normal deformation on the Big Brook Shear Zone postdated amphibolite facies metamorphism and high-temperature ductile shear at higher structural levels along the D_2 Woodstock Shear Zone (fig. 3; table 1; Anderson 1998). All three hornblende ages from the region between the two shear zones overlap at about 380 Ma (fig. 6). Hornblende in samples 93-29H and 94-17H grew syn- to post-S_2, and the onset of D_2 extension on the Woodstock Shear Zone must therefore have predated 380 Ma.

Amphibolite facies metamorphism accompanied the formation of D_2 extensional fabrics in both the Dunamagon Granite and a mafic dike cutting this pluton (Anderson 1998). A U-Pb titanite age of 386 ± 2 Ma from the pluton has been interpreted as the age of peak metamorphism (G. R. Dunning, unpub. data) and therefore also represents the age of D_2 deformation. We interpret the ca. 380-Ma

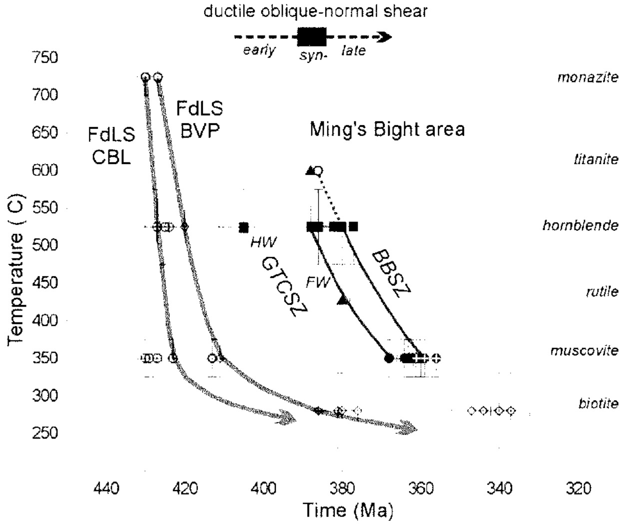


Figure 11. Temperature-time plot for Ming's Bight Group and adjacent rocks. Age data from this study are shown by solid symbols: squares = hornblende; circles = muscovite; circles with crosses = pegmatite samples; triangles = U-Pb ages. Other data from Dallmeyer (1977) and Dallmeyer and Hibbard (1984) (open diamonds), Cawood and Dunning (1993), and Cawood et al. (1994) (open circles). Nominal closure temperature ranges from Heaman and Parrish (1991) and Hanes (1991). Cooling curves for the Fleur de Lys Supergroup (*FdLS*) from the western Baie Verte Peninsula (*BVP*) and Corner Brook Lake (*CBL*) area are shown for comparison. Broad arrow shows probable cooling path for Ming's Bight Group and adjacent units; heavy lines bounding this arrow join samples from similar structural levels in the Big Brook (*BBSZ*) and Grand Toss Cove (*GTCSZ*; *HW* = hangingwall; *FW* = footwall) shear zones; dotted line joins titanite and hornblende data from the Dunamagon Granite. See text for discussion.

hornblende age from the dike as the time of cooling from the 386-Ma metamorphic peak (ca. 600°–650°C; McDonald 1993) recorded by the titanite. Data from these samples define the high-temperature part of a cooling curve for this area (dashed line, fig. 11).

Four samples from Ming's Bight Group schist in the footwall of the Big Brook Shear Zone (fig. 6) record analytically indistinguishable muscovite ages of 361–364 Ma, regardless of textural or mineralogical association. This suggests that these ages date the time of cooling through ca. 350°C (e.g., Hanes 1991). Hornblende (93-29H, 380 Ma) and muscovite (94-5M, 361 Ma) from within the Big Brook Shear Zone define a cooling path segment with an average cooling rate of ca. 9°C/m.yr. When combined with data from the Dunamagon Granite, the overall cooling rate for the vicinity of the Big Brook Shear Zone is ca. 11°C/m.yr.

Pegmatites. Muscovite dates from pegmatites range from 363 to 356 Ma, and microlite from pegmatite at Pelee Point yielded a U-Pb age of 355 Ma. The pegmatite dikes truncate D_2 folds (e.g., fig. 9*b*), and their orientations and microtextural evidence for localized high-temperature recrystallization suggest that they were intruded before D_3, that is, before ca. 380 Ma. If so, the dates must be cooling ages, and the muscovite data provide no constraint on the time of pegmatite intrusion except that it must have predated 363 Ma, the oldest age obtained from these rocks.

Cooling History. A temperature-time curve for the Ming's Bight area has been constructed from hornblende and muscovite ages and nominal closure temperature ranges (fig. 11). Although the oldest of these ages come from the Grand Toss Cove Shear Zone and the youngest come from the Big Brook Shear Zone, there is considerable overlap in data from the two areas, which are therefore considered together. Footwall cooling rates of 9°–11°C/m.yr. are inferred for the temperature range 600°–350°C, with slower cooling below 350°C indicated by biotite ages from Dallmeyer and Hibbard (1984). Tectonic exhumation by thrusting or extension leads to rapid cooling that normally postdates most of the deformation responsible for the unroofing (e.g., Jamieson et al. 1998; Ring et al. 1999). We attribute the relatively rapid cooling of the Ming's Bight Group and adjacent rocks after ca. 390 Ma to the effects of Devonian tectonic exhumation along D_2-D_3 extensional shear zones that were active at 405–385 Ma. Flat-lying Late Devonian to Early Carboniferous sedimentary deposits unconformably overlying Ordovician-Silurian rocks to the north and south of the study area (Haworth et al. 1976; Hibbard 1983) indicate that the present surface was largely exposed by the end of the Devonian. Slower cooling between 360 and 340 Ma (fig. 11) presumably reflects relaxation of perturbed near-surface isotherms following extension.

The thermal history inferred for the Ming's Bight Group east of the Baie Verte Line differs dramatically from that recorded in Fleur de Lys Supergroup rocks west of the Baie Verte Line (fig. 11) even though the two units are generally considered correlative. Data from both the Corner Brook Lake area to the south (Cawood et al. 1994; fig. 1) and the Baie Verte Peninsula west of the present study area (Dallmeyer 1977; Cawood and Dunning 1993) indicate that the Fleur de Lys Supergroup cooled at rates of 20°–30°C/m.yr. following peak metamorphism at 430–425 Ma (fig. 11). Rapid Silurian cooling west of the Baie Verte Line cannot be related to the episode of Devonian extension recorded in the Ming's Bight area, and it is equally unlikely that it reflects postorogenic erosion; cooling must have resulted from tectonic exhumation along structures that were active at or shortly before ca. 430 Ma.

Cooling of the Fleur de Lys Supergroup has been attributed to extensional unroofing immediately following Silurian peak metamorphism (e.g., Cawood et al. 1995; Tremblay et al. 1997). Normal faults associated with Silurian volcanic-plutonic complexes on the eastern Baie Verte Peninsula (Tremblay et al. 1997; fig. 1) have been attributed to Silurian regional extension; however, direct evidence for early Silurian extensional shear zones associated with the Fleur de Lys Supergroup is lacking. Alternatively, rapid cooling could have resulted from thrusting accompanied by synorogenic erosion. Syn- to postmetamorphic thrusts (ca. 434 Ma) are well documented in the Corner Brook Lake area (Cawood et al. 1994, 1996). On the Baie Verte Peninsula, Silurian sinistral-reverse shear zones cut the Point Rousse Ophiolite Complex (Ramezani 1992), and evidence for Silurian shortening has been documented in the Flat Water Pond Group (Bélanger et al. 1996; Anderson 1998; fig. 1). In the absence of clear evidence for Silurian extensional unroofing west of the Baie Verte Line, it seems more likely that rapid cooling of the Fleur de Lys Supergroup was related to thrusting and synorogenic erosion.

Regional Tectonic Implications

Mid-Paleozoic Tectonic Evolution of the Baie Verte Peninsula. Silurian sinistral transpression in the northern Appalachians was followed in many places by dextral transcurrent shear, with a transition from dextral transpression in Early to Middle Devonian time to dextral transtension in Middle Devonian time (e.g., Malo et al. 1992; O'Brien et al. 1993; Hibbard 1994; Lin 1995; Malo and Kirkwood 1995; van Staal and de Roo 1995; Dubé et al. 1996). A similar transition from Silurian sinistral transpression to Devonian dextral transtension affected the Baie Verte Peninsula. Structures compatible with Silurian sinistral oblique-reverse shear have been documented along the Baie Verte Line (e.g., Hibbard 1983, 1994; Piasecki 1988; Goodwin and Williams 1990), within the Point Rousse Ophiolite Complex (e.g., Kirkwood and Dubé 1992; Ramezani 1992; Dubé et al. 1993), and in the Flat Water Pond Group (Bélanger et al. 1996). Evidence for dextral transcurrent to transpressional deformation of probable Devonian age has been reported from the Baie Verte Line (e.g., Piasecki 1988, 1995; Goodwin and Williams 1990; Piasecki et al. 1990), Marble Cove Slide (fig. 12; Goodwin and Williams 1996), and the east side of Ming's Bight (Anderson 1998). The structural and ^{40}Ar/^{39}Ar data presented here indicate that dextral oblique-normal shear zones were active east of the Baie Verte Line at 405–385 Ma.

Although the complex orogen-scale kinematic history presumably resulted from orogen-scale plate boundary processes (e.g., van Staal et al. 1998), some local structural complexity may reflect deformation partitioning around the Burlington Granodiorite (figs. 2, 12; Anderson 1998). During

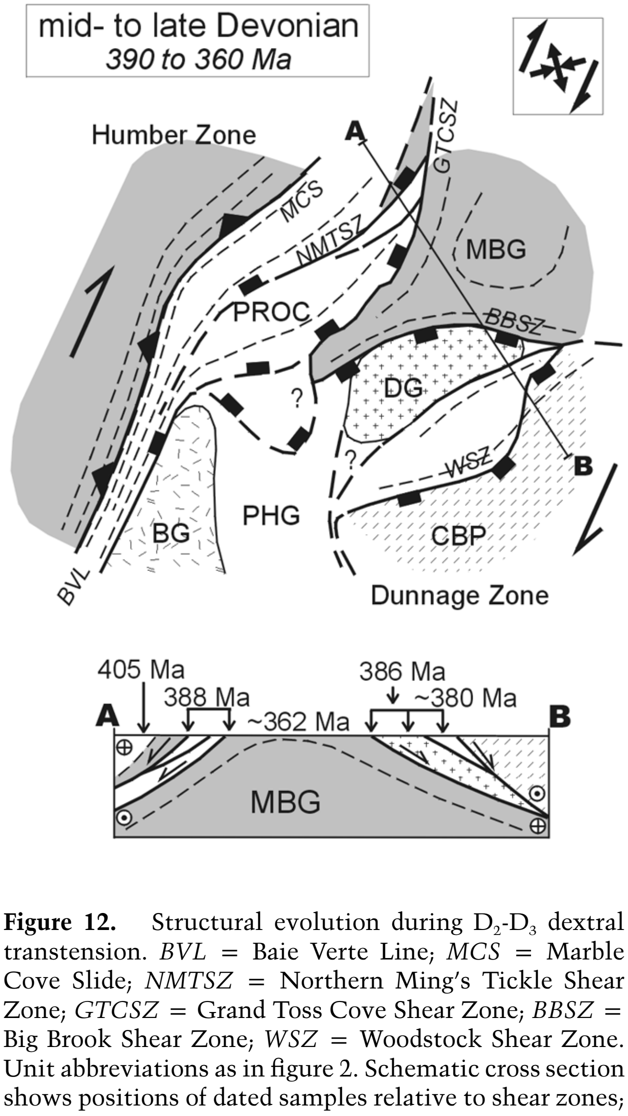


Figure 12. Structural evolution during D_2-D_3 dextral transtension. *BVL* = Baie Verte Line; *MCS* = Marble Cove Slide; *NMTSZ* = Northern Ming's Tickle Shear Zone; *GTCSZ* = Grand Toss Cove Shear Zone; *BBSZ* = Big Brook Shear Zone; *WSZ* = Woodstock Shear Zone. Unit abbreviations as in figure 2. Schematic cross section shows positions of dated samples relative to shear zones; inset in upper right shows the inferred regional kinematic framework. See text for discussion.

regional northwest-southeast shortening (e.g., Bélanger et al. 1996), perturbation of regional sinistral transcurrent flow around the batholith should have formed a transpressional restraining bend (e.g., Vilotte et al. 1984), leading to sinistral oblique-reverse slip within the Point Rousse Ophiolite Complex. This could also account for northeastward displacement of ophiolitic rocks marking the Baie Verte Line, consistent with potential field data suggesting that the Baie Verte Line passes through the Point Rousse Ophiolite Complex (Miller and Wiseman 1994) rather than through Pacquet Harbour as proposed by Hibbard (1982; "Baie Verte Flexure"; fig. 1). We speculate that east-vergent thrusting associated with Silurian transpression contributed to both exhumation of the Fleur de Lys Supergroup and burial of the Ming's Bight Group (Anderson 1998).

In mid-Devonian time, dextral transcurrent shear along the Baie Verte Line is interpreted to have reactivated the Silurian transpressional restraining bend as a releasing bend (Anderson 1998), resulting in localized extensional strain in the immediate footwall of the releasing bend north and east of the Burlington Granodiorite (fig. 12). The Ming's Bight Group, Dunamagon Granite, and Pacquet Harbour Group, buried during Silurian transpression, were exhumed along mid-Devonian normal faults. According to this hypothesis, the position of the Ming's Bight Group east of the Baie Verte Line is due to its fortuitous exposure during Devonian extension. Other Laurentian margin rocks are presumably present beneath Dunnage Zone allochthons elsewhere in west-central Newfoundland (e.g., Quinlan et al. 1992; Waldron et al. 1998).

Although Devonian-Carboniferous $^{40}Ar/^{39}Ar$ ages from the Ming's Bight area have been attributed to a distinct episode of Acadian shortening (Hibbard 1983; Dallmeyer and Hibbard 1984; Tremblay et al. 1997), this study shows that they record cooling following Devonian extension. Older ages to the south (e.g., Dallmeyer and Hibbard 1984) are from rocks that lie structurally above the normal faults responsible for the unroofing and therefore escaped mid-Devonian ductile recrystallization and associated thermal effects. We have found no regionally developed contractional structures that could account for the cooling ages obtained in this study.

Is the Ming's Bight Group a Core Complex? The Ming's Bight Group is a dome-shaped area of intensely deformed, amphibolite facies metamorphic rocks separated from relatively less deformed, lower-grade rocks along two broadly contemporaneous normal-sense shear zones that coincide with gradients in extensional strain and metamorphic grade (figs. 2, 12). To the northwest, the Grand Toss Cove (D_2) and Northern Ming's Tickle (D_3) shear zones are kinematically compatible with north-south subhorizontal extension. To the southeast, the geometries and kinematics of the Woodstock (D_2) and Big Brook (D_3) shear zones are compatible with northwest-southeast subhorizontal extension. These relationships suggest that extensional strain was accommodated along symmetrically opposed shear zones (figs. 2, 12) that were coeval with exhumation and cooling of the Ming's Bight Group. Between the southeast-dipping structures north of Pacquet Harbour and northwest-dipping structures east of Ming's Bight is a region dominated by shallow S_2 foliations (fig. 2). This fabric is axial planar to tight to isoclinal, recumbent folds that are cut by northeast- and southwest-striking, steep pegmatite dikes. Pegmatites at Cape Corbin, and Ming's Bight Group schist at one inland location, exhibit chocolate-tablet boudinage in the plane of the subhorizontal fabric. These structures are consistent with coaxial subvertical shortening and suggest that Cape Corbin and the area to the southwest (fig. 2) lie along the axis of extension in the Ming's Bight Group. Based on these observations, we interpret the Ming's Bight Group as a symmetrical core complex (e.g., Hetzel et al. 1995).

Extensional Collapse in the Northern Appalachians? A number of authors have suggested that "extensional collapse" affected the northern Appalachians in mid-Paleozoic time (e.g., Cawood et al. 1995; van Staal and de Roo 1995; Lynch 1996; O'Brien 1998). This term has been used to describe a variety of orogenic and postorogenic processes (e.g., Dewey 1988) but now generally implies a relatively short-lived episode of crustal extension temporally and spatially associated with, and by inference genetically related to, orogenic convergence and crustal thickening (e.g., Rey et al. 2000). Although synorogenic extension does not require the existence of thick crust and crustal thickening does not inevitably lead to extension (e.g., Marotta et al. 1999; Willett 1999), extensional collapse is often equated with the existence of thick and/or weak orogenic crust (Rey et al. 2000).

The most compelling evidence for significant extension in the northern Appalachians is the map pattern of central Newfoundland (Colman-Sadd et al. 1990), where low-grade early Paleozoic volcanic and sedimentary rocks of the Dunnage Zone are widely preserved and commonly juxtaposed against underlying higher-grade metamorphic rocks over short distances. The relatively thin crust under the Newfoundland Appalachians (e.g., Stockmal et al.

1990; Quinlan et al. 1992) is also consistent with extension, but it is not clear whether this was related to late Paleozoic Appalachian tectonism or to Mesozoic opening of the Atlantic Ocean. In addition, normal faults of inferred Silurian age have been reported from the Humber Zone (Waldron and Milne 1991) and both the Notre Dame (Lafrance and Williams 1992; Tremblay et al. 1997) and Exploits (O'Brien 1998) subzones of the Dunnage Zone. Silurian magmatism in central Newfoundland (e.g., Dunning et al. 1990), rapid cooling of metamorphic rocks in the Humber Zone of Newfoundland (e.g., Cawood et al. 1994, 1995) and Québec (Castonguay et al. 1997), and exhumation of Silurian blueschist in north-central New Brunswick (e.g., de Roo and van Staal 1994) have also been attributed to Silurian extension. In the Mount Cormack area of central Newfoundland, normal faults of unknown age separate ophiolites from underlying Ordovician metamorphic rocks (Colman-Sadd et al. 1992; Anderson 1998). Devonian normal faults have been documented from the Gaspé Peninsula (Malo and Kirkwood 1995) and western Cape Breton Island (Lynch 1996), and regional extension related to the formation of the Maritimes Basin was underway by mid- to Late Devonian time (e.g., Dunning et al. 1997; Calder 1998).

Proposed mechanisms for mid-Paleozoic extension include delamination and/or convective removal of suborogenic lithosphere following Silurian (Cawood et al. 1995) or Devonian (Lynch 1996) crustal thickening, subduction retreat and/or slab breakoff associated with multiple short-lived arc accretion events (van Staal and de Roo 1995), or variations in the local kinematic framework associated with oblique convergence at an irregular margin (Anderson 1998; Calder 1998). The documented normal faults range from Early Silurian to Carboniferous. Exhumed footwall metamorphic rocks range from Ordovician to Devonian, and this study has demonstrated that cooling histories for correlative units can vary dramatically over short distances (fig. 11). The existence of thick orogenic crust in the northern Appalachians at any one time has also been questioned on stratigraphic and structural grounds (e.g., Lin and van Staal 1997; Waldron et al. 1998). Synorogenic normal faults in the northern Appalachians therefore do not record a short-lived episode of extension related to thick orogenic crust. It seems more likely that the extension resulted from variations in boundary forces resulting from multiple short-lived arc accretion events (e.g., van Staal and de Roo 1995; van Staal et al. 1998) or diachronous oblique convergence along an irregular plate boundary (e.g., Stockmal et al. 1987; Lin et al. 1994; van Staal et al. 1998). Either mechanism, or a combination of both, could account for the multiple, local, short-lived, transtensional and transpressional kinematic regimes that are characteristic of mid-Paleozoic deformation in this region. However, neither process is consistent with what is normally termed "extensional collapse." We recommend that this term be avoided with reference to the mid-Paleozoic tectonics of the northern Appalachians.

Conclusions

1. The Ming's Bight Group is separated from overlying ophiolitic and granitoid rocks by ductile and brittle-ductile shear zones. Evidence for early sinistral-reverse movement is locally preserved, but the dominant structures record two stages of dextral oblique-normal displacement.
2. ^{40}Ar/^{39}Ar data from hornblende and muscovite, and U-Pb data from titanite and rutile, record mid-Devonian to Early Carboniferous growth and cooling ages. Combined with field and microstructural evidence, these data indicate that early dextral oblique-normal ductile shear at 405–385 Ma was followed by protracted brittle-ductile normal faulting.
3. Extension in the Ming's Bight area was linked to dextral oblique transcurrent movement along the Baie Verte Line. The anomalous position of the Ming's Bight Group east of the Baie Verte Line is attributed to exhumation within a local transtensional regime.
4. We conclude that the Ming's Bight Group is a mid-Devonian symmetrical core complex. However, the timing and tectonic setting of extension do not support recent models for "extensional collapse" in the northern Appalachians.

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REFERENCES CITED

Anderson, S. D. 1998. Structure, metamorphism, and U-Pb and ^{40}Ar/^{39}Ar geochronology of the Ming's Bight Group, and the Paleozoic tectonic evolution of the Baie Verte Peninsula, Newfoundland. Unpub. Ph.D. thesis, Dalhousie University, Halifax, Nova Scotia.

Bélanger, M.; Dubé, B.; and Malo, M. 1996. The Dorset showings: mesothermal vein-type gold occurrences associated with post-Ordovician deformation along the Baie Verte–Brompton Line, Baie Verte Peninsula, Newfoundland. *In* Current research, Geol. Surv. Can. Pap. 1996-E:269–279.

Bursnall, J. T., and de Wit, M. J. 1975. Timing and development of the orthotectonic zone in the Appalachian Orogen of northwest Newfoundland. Can. J. Earth Sci. 12:1712–1722.

Calder, J. H. 1998. The Carboniferous evolution of Nova Scotia. *In* Blundell, D. J., and Scott, A. C., eds. Lyell: the past is the key to the present. Geol. Soc. Spec. Publ. 143:261–302.

Castonguay, S.; Tremblay, A.; Ruffet, G.; Feraud, G.; Pinet, N.; and Sosson, M. 1997. Ordovician and Silurian metamorphic cooling ages along the Laurentian margin of the Quebec Appalachians: bridging the gap between New England and Newfoundland. Geology 25: 583–586.

Cawood, P. A., and Dunning, G. R. 1993. Silurian age for movement on the Baie Verte Line: implications for accretionary tectonics in the northern Appalachians. Geol. Soc. Am. Abstr. Program 25:422.

Cawood, P. A.; Dunning, G. R.; Lux, D.; and van Gool, J. A. M. 1994. Timing of peak metamorphism and deformation along the Appalachian margin of Laurentia in Newfoundland: Silurian, not Ordovician. Geology 22:399–402.

Cawood, P. A.; van Gool, J. A. M.; and Dunning, G. R. 1995. Collisional tectonics along the Laurentian margin of the Newfoundland Appalachians. *In* Hibbard, J. P.; van Staal, C. R.; and Cawood, P. A., eds. Current perspectives in the Appalachian-Caledonian Orogen. Geol. Assoc. Can. Spec. Pap. 41:283–301.

———. 1996. Geological development of eastern Humber and western Dunnage zones: Corner Brook–Glover Island region, Newfoundland. Can. J. Earth Sci. 33: 182–198.

Cerný, P., and Ercit, T. S. 1989. Mineralogy of niobium and tantalum: crystal chemical relationships, paragenetic aspects and their economic implications. *In* Moller, P.; Cerný, P.; and Saupe, F., eds. Lanthanides, tantalum and niobium. Berlin, Springer, p. 27–79.

Colman-Sadd, S. P.; Dunning, G. R.; and Dec, T. 1992. Dunnage-Gander relationships and Ordovician orogeny in central Newfoundland: a sediment provenance and U/Pb age study. Am. J. Sci. 292:317–355.

Colman-Sadd, S. P.; Hayes, J. P.; and Knight, I. 1990. Geology of the island of Newfoundland. Newfoundland and Labrador Dep. Mines Energy, Geol. Surv. Branch, Map 90-01, scale, 1 : 1,000,000.

Dallmeyer, R. D. 1977. ^{40}Ar/^{39}Ar age spectra of minerals from the Fleur de Lys terrane in northwest Newfoundland: their bearing on chronology of metamorphism within the Appalachian orthotectonic zone. J. Geol. 85:89–103.

Dallmeyer, R. D., and Hibbard, J. 1984. Geochronology of the Baie Verte Peninsula, Newfoundland: implications for the tectonic evolution of the Humber and Dunnage Zones of the Appalachian Orogen. J. Geol. 92:489–512.

de Roo, J. A., and van Staal, C. R. 1994. Transpression and extensional collapse: steep belts and flat belts in the Appalachians Central Mobile Belt, northern New Brunswick, Canada. Geol. Soc. Am. Bull. 106: 541–552.

Dewey, J. F. 1988. Extensional collapse of orogens. Tectonics 7:1123–1139.

Dubé, B.; Dunning, G. R.; Lauzière, K.; and Roddick, J. C. 1996. New insights into the Appalachian Orogen from geology and geochronology along the Cape Ray fault zone, southwest Newfoundland. Geol. Soc. Am. Bull. 108:101–116.

Dubé, B.; Lauzière, K.; and Poulsen, H. K. 1993. The Deer Cove deposit: an example of "thrust"-related breccia-vein type gold mineralization in the Baie Verte Peninsula, Newfoundland. *In* Current research, pt. D, Geol. Surv. Can. Pap. 93-1D:1–10.

Dunning, G. R.; O'Brien, S. J.; Colman-Sadd, S. P.; Blackwood, R. F.; Dickson, W. L.; O'Neill, P. P.; and Krogh, T. E. 1990. Silurian orogeny in the Newfoundland Appalachians. J. Geol. 98:895–913.

Dunning, G. R.; Piper, D. J. W.; Giles, P. S.; Pe-Piper, G.; and Barr, S. M. 1997. Chronology of early phases of rifting of the Devonian-Carboniferous Magdalen Basin in Nova Scotia from U/Pb dating of rhyolites. Geol. Assoc. Can. Abstr. 22:A-42.

Goodwin, L. B., and Williams, P. F. 1990. Strike-slip movement along the Baie Verte Line. *In* Lithoprobe East transect report 13. Vancouver, Lithoprobe, p. 75–84.

———. 1996. Deformation path partitioning within a transpressive shear zone, Marble Cove, Newfoundland. J. Struct. Geol. 18:975–990.

Hanes, J. A. 1991. K-Ar and ^{40}Ar/^{39}Ar geochronology: methods and applications. *In* Heaman, L., and Ludden, J. N., eds. Applications of radiogenic isotope systems to problems in geology. Short course handbook 19. Mineral. Assoc. Can., p. 27–57.

Haworth, R. T.; Poole, W. H.; Grant, A. C.; and Sanford,

B. V. 1976. Marine geoscience survey northeast of Newfoundland. Geol. Surv. Can. Pap. 76-1A:7–15.

Heaman, L., and Parrish, R. 1991. U-Pb geochronology of accessory minerals. *In* Heaman, L., and Ludden, J. N., eds. Applications of radiogenic isotope systems to problems in geology. Short course handbook 19. Mineral. Assoc. Can., p. 59–102.

Hetzel, R.; Passchier, C. W.; Ring, U.; and Dora, O. O. 1995. Bivergent extension in orogenic belts: the Menderes massif (southwestern Turkey). Geology 23: 455–458.

Hibbard, J. 1982. Significance of the Baie Verte Flexure, Newfoundland. Geol. Soc. Am. Bull. 93:790–797.

———. 1983. Geology of the Baie Verte Peninsula, Newfoundland. Newfoundland Dep. Mines Energy, Miner. Dev. Div. Mem. 2, 279 p.

———. 1994. Kinematics of Acadian deformation in the northern and Newfoundland Appalachians. J. Geol. 102:215–228.

Hicks, R. J.; Jamieson, R. A.; and Reynolds, P. H. 1999. Detrital and metamorphic ^{40}Ar/^{39}Ar ages from muscovite and whole-rock samples, Meguma Supergroup, southern Nova Scotia. Can. J. Earth Sci. 36:23–32.

Jamieson, R. A. 1990. Metamorphism of an Early Palaeozoic continental margin, western Baie Verte Peninsula, Newfoundland. J. Metamorph. Geol. 8: 269–288.

Jamieson, R. A.; Beaumont, C.; Fullsack, P.; and Lee, B. 1998. Barrovian regional metamorphism: where's the heat? *In* Treloar, P. J., and O'Brien, P. J., eds. What drives metamorphism and metamorphic reactions? Geol. Soc. Spec. Publ. 138:23–51.

Kidd, W. S. F.; Dewey, J. F.; and Bird, J. M. 1978. The Ming's Bight Ophiolite Complex, Newfoundland: Appalachian oceanic crust and mantle. Can. J. Earth Sci. 15:781–804.

Kirkwood, D., and Dubé, B. 1992. Structural control of sill-hosted gold mineralization: the Stog'er Tight gold deposit, Baie Verte Peninsula, northwestern Newfoundland. *In* Current research, pt. D, Geol. Surv. Can. Pap. 92-1D:211–221.

Lafrance, B., and Williams, P. F. 1992. Silurian deformation in eastern Notre Dame Bay, Newfoundland. Can. J. Earth Sci. 29:1899–1914.

Lee, J. K. W.; Onstott, T. C.; Cashman, K. V.; Cumbest, R. J.; and Johnson, D. 1991. Incremental heating of hornblende *in vacuo*: implications for ^{40}Ar/^{39}Ar geochronology and the interpretation of thermal histories. Geology 19:872–876.

Lin, S. 1995. Structural evolution and tectonic significance of the Eastern Highlands shear zone in Cape Breton Island, the Canadian Appalachians. Can. J. Earth Sci. 32:545–554.

Lin, S., and van Staal, C. R. 1997. Comment on "Tectonic burial, thrust emplacement, and extensional exhumation of the Cabot nappe in the Appalachian hinterland of Cape Breton Island, Canada." Tectonics 16: 702–706.

Lin, S.; van Staal, C. R.; and Dubé, B. 1994. Promontory-promontory collision in the Canadian Appalachians. Geology 22:897–900.

Lynch, G. 1996. Tectonic burial, thrust emplacement, and extensional exhumation of the Cabot nappe in the Appalachian hinterland of Cape Breton Island, Canada. Tectonics 15:94–105.

Malo, M., and Kirkwood, D. 1995. Faulting and progressive strain history of the Gaspe Peninsula in post-Taconian time: a review. *In* Hibbard, J. P.; van Staal, C. R.; and Cawood, P. A., eds. Current perspectives in the Appalachian-Caledonian Orogen. Geol. Assoc. Can. Spec. Pap. 41:267–282.

Malo, M.; Kirkwood, D.; DeBroucker, G.; and St-Julien, P. 1992. A re-evaluation of the position of the Baie Verte–Brompton Line in the Quebec Appalachians: the influence of Middle Devonian strike-slip faulting in the Gaspé Peninsula. Can. J. Earth Sci. 29: 1265–1273.

Marotta, A. M.; Fernandez, M.; and Sabadini, R. 1999. The onset of extension during lithospheric shortening: a two-dimensional thermomechanical model for lithospheric unrooting. Geophys. J. Int. 139:98–114.

McDonald, L. 1993. Structure of the Dunamagon Granite, Baie Verte Peninsula, Newfoundland. Unpub. B.S. thesis, Dalhousie University, Halifax.

Miller, H. G., and Wiseman, R. 1994. Potential field interpretation of the Baie Verte Peninsula, Newfoundland, utilizing constraints from Lithoprobe East seismic line 89-13. Atl. Geol. 30:25–36.

O'Brien, B. H. 1998. Origin and evolution of Silurian terrestrial basins on the obliquely-convergent composite margin of a peri-Gondwanan microplate, central Newfoundland. Geol. Assoc. Can. Abstr. 23:A-137.

O'Brien, B. H.; O'Brien, S. J.; Dunning, G. R.; and Tucker, R. D. 1993. Episodic reactivation of a late Precambrian mylonite zone on the Gondwanan margin of the Appalachians, southern Newfoundland. Tectonics 12: 1043–1055.

Piasecki, M. A. J. 1988. Strain-induced mineral growth in ductile shear zones and a preliminary study of ductile shearing in western Newfoundland. Can. J. Earth Sci. 25:2118–2129.

———. 1995. Dunnage Zone boundaries and some aspects of terrane development in Newfoundland. *In* Hibbard, J. P.; van Staal, C. R.; and Cawood, P. A., eds. Current perspectives in the Appalachian-Caledonian Orogen. Geol. Assoc. Can. Spec. Pap. 41:323–347.

Piasecki, M. A. J.; Williams, H.; and Colman-Sadd, S. P. 1990. Tectonic relationships along the Meelpaeg, Burgeo and Burlington Lithoprobe transects in Newfoundland. *In* Current research. Newfoundland Dep. Mines Energy, Geol. Surv. Branch, Rep. 90-1:327–339.

Quinlan, G. M.; Hall, J.; Williams, H.; Wright, J. A.; Colman-Sadd, S. P.; O'Brien, S. J.; Stockmal, G. S.; and Marillier, F. 1992. Lithoprobe onshore seismic reflection transects across the Newfoundland Appalachians. Can. J. Earth Sci. 29:1865–1877.

Ramezani, J. 1992. The geology, geochemistry and U-Pb geochronology of the Stog'er Tight gold prospect, Baie Verte Peninsula, Newfoundland. Unpub. M.S. thesis, Memorial University of Newfoundland, St. John's, Newfoundland.

Rey, P.; Vanderhaeghe, O.; and Teyssier, C. 2000. Gravitational collapse of continental lithosphere: definition, regimes and modes. Tectonophysics, in press.

Ring, U.; Brandon, M. T.; Willett, S. D.; and Lister, G. S. 1999. Exhumation processes. *In* Ring, U.; Brandon, M. T.; Lister, G. S.; and Willett, S. D., eds. Exhumation processes: normal faulting, ductile flow, and erosion. Geol. Soc. Spec. Publ. 154:1–27.

Samson, S. D., and Alexander, E. C. 1987. Calibration of the interlaboratory Ar/Ar dating standard, MMhb-1. Chem. Geol. 66:27–34.

Stevens, R. K. 1970. Cambro-Ordovician flysch sedimentation and tectonics in west Newfoundland and their possible bearing on a proto-Atlantic Ocean. Geol. Assoc. Can. Spec. Pap. 7:165–177.

Stockmal, G. S.; Colman-Sadd, S. P.; Keen, C. E.; Marillier, F.; O'Brien, S. J.; and Quinlan, G. M. 1990. Deep seismic structure and plate tectonic evolution of the Canadian Appalachians. Tectonics 9:45–62.

Stockmal, G. S.; Colman-Sadd, S. P.; Keen, C. E.; O'Brien, S. J.; and Quinlan, G. 1987. Collision along an irregular margin: a regional plate tectonic interpretation of the Canadian Appalachians. Can. J. Earth Sci. 24: 1098–1107.

Tremblay, A.; Bédard, J. H.; and Lauzière, K. 1997. Taconian obduction and Silurian exhumation of the Betts Cove ophiolite, Canadian Appalachians. J. Geol. 105:701–716.

Tucker, R. D.; Bradley, D. C.; Ver Straeten, C. A.; Harris, A. G.; Ebert, J. R.; and McCutcheon, S. R. 1998. New U-Pb zircon ages and the duration and division of Devonian time. Earth Planet. Sci. Lett. 158:175–186.

van Staal, C. R., and de Roo, J. A. 1995. Mid-Paleozoic tectonic evolution of the Appalachian central mobile belt in northern New Brunswick, Canada: collision, extensional collapse and dextral transpression. *In* Hibbard, J. P.; van Staal, C. R.; and Cawood, P. A., eds. Current perspectives in the Appalachian-Caledonian Orogen. Geol. Assoc. Can. Spec. Pap. 41:367–389.

van Staal, C. R.; Dewey, J. F.; MacNiocaill, C.; and McKerrow, W. S. 1998. The Cambrian-Silurian tectonic evolution of the northern Appalachians and British Caledonides: history of a complex, west and southwest Pacific-type segment of Iapetus. *In* Blundell, D. J., and Scott, A. C., eds. Lyell: the past is the key to the present. Geol. Soc. Spec. Publ. 143:199–242.

Vilotte, J.-P.; Mandariaga, R.; Daignieres, M.; and Zienkiewicz, O. 1984. The role of a heterogeneous inclusion during continental collision. Phys. Earth Planet. Int. 36:236–259.

Waldron, J. W. F.; Anderson, S. D.; Cawood, P. A.; Goodwin, L. B.; Hall, J.; Jamieson, R. A.; Palmer, S. E.; Stockmal, G. S.; and Williams, P. F. 1998. Evolution of the Appalachian Laurentian margin: Lithoprobe results in western Newfoundland. Can. J. Earth Sci. 35: 1271–1287.

Waldron, J. W. F., and Milne, J. V. 1991. Tectonic history of the central Humber Zone, western Newfoundland Appalachians: post-Taconian deformation in the Old Man's Pond area. Can. J. Earth Sci. 28:398–410.

Willett, S. D. 1999. Rheological dependence of extension in wedge models of convergent orogens. Tectonophysics 305:419–435.

Williams, H. 1979. Appalachian orogen in Canada. Can. J. Earth Sci. 16:792–807.

Williams, H.; Colman-Sadd, S. P.; and Swinden, H. S. 1988. Tectonic-stratigraphic subdivisions of central Newfoundland. *In* Current research, pt. B, Geol. Surv. Can. Pap. 88-1B:91–98.

Williams, H., and St-Julien, P. 1982. The Baie Verte–Brompton Line: Early Paleozoic continent-ocean interface in the Canadian Appalachians. *In* St-Julien, P., and Beland, J., eds. Major structural zones and faults in the northern Appalachians. Geol. Assoc. Can. Spec. Pap. 24:177–207.