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Taconian Obduction and Silurian Exhumation of the Betts Cove Ophiolite, Canadian Appalachians[1]

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ABSTRACT

In the Newfoundland Appalachians, the Betts Cove Complex and cover rocks of the Snooks Arm Group form a composite section of Ordovician marginal oceanic crust that is unconformably overlain by Silurian terrestrial sedimentary rocks and bimodal volcanics of the Cape St. John Group. Tectonic fabrics that characterize both the Ordovician and the Silurian rock sequences are subdivided into pre- to syn-obduction (Taconian) structures, Silurian extensional structures, and Acadian compressional structures. Pre-obduction structures consist of syn-oceanic normal faults in the Betts Cove ophiolite. Thrusting fabrics found along parts of the contact between the ophiolite and the Snooks Arm Group are attributed to the obduction of the oceanic crust over the Laurentian margin during the Taconian orogeny. Normal faults and shear zones of inferred Silurian age are preserved in the Snooks Arm Group and along the contact with the Cape St. John Group. These faults are contemporaneous with Silurian sedimentation and magmatism and are attributed to the exhumation of the oceanic crust. Southeast-verging reverse faults and folds that characterize the regional deformation in the Baie Verte peninsula postdate the exhumation and are attributed to compressive deformation related to the Devonian Acadian orogeny.

Introduction

The obduction of ophiolites over continental margin rocks is thought to occur early in the tectonic history of most orogens, and ophiolitic sequences that preserve their original stratigraphic relationships are commonly found in continental reentrants (e.g., Harris 1992), where the effects of post-accretion tectonism are minimized. Most of the ophiolites in the Paleozoic Appalachian/Caledonian belt, however, are found within the internal part of the orogen and have been severely affected by post-obduction compressional and/or extensional deformation. It is commonly difficult to separate the relative timing of these deformational events unless the deformed ophiolitic sequence is suitable for radiometric dating, or is covered by younger rock units that can be used to discriminate structures related to different deformational events.

Deformation of the northern Appalachian Orogen is considered to be the product of two principal orogenic pulses, the Middle/Late Ordovician Taconian, and the Late Silurian/Middle Devonian Acadian. The Taconian orogeny is associated with the accretion onto the Laurentian continental margin (i.e., Humber zone of Williams 1979) of a diverse suite of oceanic and arc terranes (i.e., Dunnage zone), including fragments of ophiolitic sequences (Williams 1979). The Acadian orogeny is commonly attributed to continental collision between Laurentia and Gondwana (Osberg 1978; Williams and Hatcher 1983; Tremblay and Pinet 1994). Recently, the existence of a Silurian continental collision (referred to as the Salinian orogeny; Dunning et al. 1990; Cawood et al. 1994, 1995) has been proposed to account for widespread metamorphism and plutonism of Early Silurian age in the Humber zone of Newfoundland, but there are still uncertainties about the significance of the cooling ages and structures attributed to the Silurian event (Jamieson et al. 1993; Hibbard et al. 1995).

In Newfoundland, most ophiolites are found in the vicinity of the contact between the Humber and Dunnage zones (i.e., the Baie Verte-Brompton line (BBL) of Williams and St-Julien 1982; figure 1*a*), and as Acadian thrust slices (e.g., the Bay of Island

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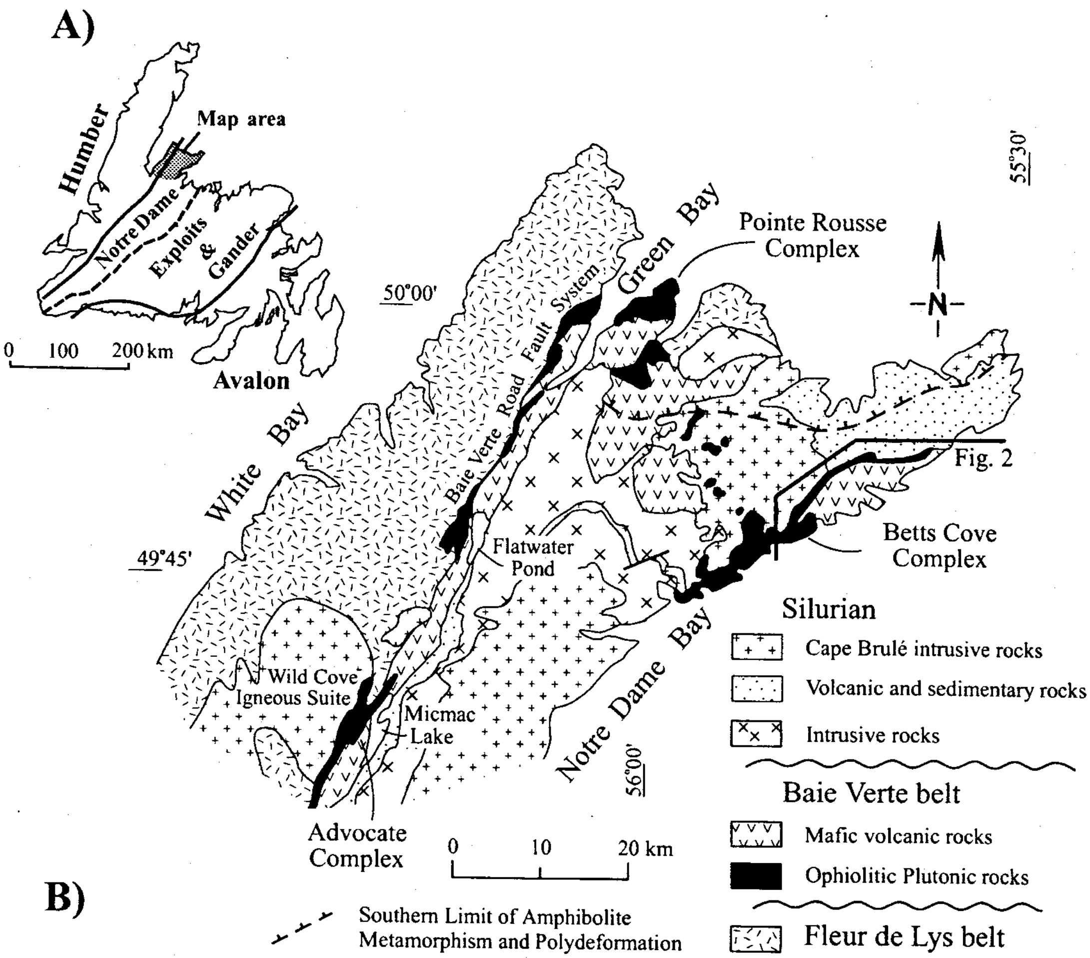


Figure 1. (*a*) Tectonostratigraphic division of the Newfoundland Appalachians. The Dunnage zone is made up of the Notre-Dame and Exploits subzones. The Exploits subzone and the Gander zone are shown as a single unit for clarity. (*b*) Geological map of the Baie Verte Peninsula. Modified from Hibbard (1983).

ophiolite: Waldron and Stockmal 1994) above allochthons of the Humber zone. The BBL is considered to represent a suture zone formed during the Taconian orogeny. However, it is a complex structural zone characterized by multiple dip-slip and strike-slip ductile and brittle/ductile shearing events that took place from Ordovician through Devonian time (see Goodwin and Williams 1996). As a result, ophiolites that occur along the BBL itself are typically strongly tectonized and dismembered, whereas those more removed from the line (e.g., the Betts Cove Complex; figure 1*b*) better preserve their early structural history. This paper presents a detailed structural analysis of the Betts Cove Complex and its Ordovician cover sequence (figure 1*b*), which were not strongly disrupted by tectonic juxtaposition and accretion to the Laurentian margin during the Taconian orogeny, allowing characterization of their post-Taconian exhumation and compressive deformation in Silurian and Devonian time.

Geology of the Baie-Verte Peninsula

In Newfoundland, the Baie Verte Peninsula (figure 1*b*) encompasses rock units belonging to both the Humber and the Dunnage zones. Helikian(?) to lower Paleozoic rocks of the Humber Zone comprise: a lower structural level of eclogite, gneiss, and migmatites (e.g., the East Pond Metamorphic Suite); a cover sequence of metaclastic schist, marble, amphibolite and greenschist (e.g., the Fleur de Lys Supergroup); and a granitoid sequence (e.g., the Wild Cove Pond Igneous Suite; Hibbard 1983). These rocks are collectively referred to as the Fleur de Lys belt, which is characterized by polyphase deformation and metamorphism traditionally ascribed to the Taconian orogeny (Williams 1979;

Hibbard 1983). Tectonism has been recently reinterpreted as belonging to the Salinian orogeny on the basis of Silurian $^{40}Ar/^{39}Ar$ ages from metamorphic rocks of the Fleur de Lys Supergroup, and U/Pb ages from syn- to post-kinematic intrusions of the Wild Cove Pond Igneous Suite (Cawood et al. 1994, 1995).

Southeast of the BBL, the Baie Verte Peninsula comprises a window of continental metamorphic rocks, Ordovician ophiolitic, sedimentary and volcanic rocks, Silurian volcano-sedimentary rocks, and large granitoid intrusions (Hibbard 1983).

A window of metamorphic rocks belonging to the Ming's Bight Group (herein referred to as the Ming's Bight inlier) crops out east of the Baie Verte Road fault system (figure 1*b*) and is composed of rocks considered correlative with the Fleur de Lys belt (Hibbard 1982, 1983). The implication is that the Dunnage Zone rocks are allochthonous, and that much of the ophiolite terranes are underlain at depth by rocks of the Laurentian continental margin. The tectonic contact and associated structures between the Ming's Bight Group and the surrounding ophiolitic rocks and volcanics define the Baie Verte flexure, interpreted as a consequence of pre-existing promontories along the Laurentian margin (Hibbard 1982). Along the Baie Verte flexure, metamorphic grade and intensity of deformation decrease progressively toward the southeast (south of the line indicated on figure 1*b*), as polydeformed amphibolite-grade rocks grade into greenschist facies rocks that contain only one penetrative fabric (Hibbard 1983).

Although distinguishable on the basis of their geographic position and structural state, the various Ordovician ophiolitic complexes and volcanic cover rocks of the peninsula (i.e., the Point Rousse, Advocate, and Betts Cove complexes; figure 1*b*) are considered to be roughly correlative. In the Baie Verte Peninsula, the Ordovician rock units are unconformably overlain (Neale et al. 1975; Bédard et al. 1997) by a thick pile of shallowly dipping fluviatile conglomerates and sandstones interbedded with basaltic lavas and felsic tuffs belonging to the Cape St. John and Micmac Lake Groups (figure 1*b*; Hibbard 1983). These rocks are dated as Silurian (427 ± 2 Ma; Coyle 1990) and have been folded along northeast-trending axes. Well-developed unconformities between the Ordovician rocks and Silurian rocks of the Baie Verte belt (Williams 1995) have traditionally been ascribed to erosion of the Taconian orogen. There is considerable evidence that regional structures and metamorphism are the result of a later, post-Taconian thermal event, but there is some debate about whether it should be grouped with the Salinian (Silurian) or the Acadian (Devonian) orogeny (Hibbard 1983; Piasecki 1995; Williams 1995; see below).

Several large granitoid plutons intrude the ophiolitic rocks, and locally, rocks belonging to the Cape St. John Group. These granitoids include the Burlington granodiorite and the Dunamagon granite (figure 1*b*), both of which were originally considered to be Ordovician intrusions on the basis of U/Pb zircon ages (Mattinson 1975; Hibbard 1982; Dallmeyer and Hibbard 1984; Currie 1995). Recently however, Early Silurian U/Pb ages of 432 ± 2 Ma and 429 ± 4 Ma have been established for the Burlington granodiorite and the Dunamagon granite (Cawood and Dunning 1993). Several large granitic bodies, collectively known as the Cape Brulé quartz-feldspar porphyry, appear to define a roof and ring-dike facies within the Burlington granodiorite (figure 1*b*). A U/Pb age of 430 +5/−3 for the Cape Brulé (G. Dunning, pers. comm. 1996) indicate that it too is Silurian, with an age nearly identical to the Cape St. John Group lavas.

The Betts Cove Complex and Cover Rocks

The Betts Cove Complex and the Snooks Arm Group outcrop as a steeply southeasterly dipping arcuate belt along the shore of Notre Dame Bay (Upadhyay 1973; Hibbard 1983; Bédard et al. 1997). A gabbro from the Betts Cove Complex has been dated at 488 +3/−2 Ma (U/Pb on zircon; Dunning and Krogh 1985), approximately coeval with other ophiolites of the Notre Dame subzone (Williams 1995).

The plutonic part of the Betts Cove Complex is dominated by layered lherzolitic and pyroxenitic cumulates, crosscut by dikes and sills of pyroxenite, gabbro, gabbronorite, and trondhjemite. The abundance of cumulus orthopyroxene is compatible with formation in equilibrium with a boninitic magma, as are the high Cr/Al of spinels and low TiO_2 contents of clinopyroxenes (Bédard unpub. data). Talc-carbonate schists and serpentinites line most of the ophiolite's northwestern contact (figure 2; Bédard et al. 1997), and these are interpreted to represent altered and deformed equivalents of the ultramafic cumulates, and perhaps, slivers of mantle tetonite.

Locally, the ultramafics grade up directly into an extensive sheeted dike unit, although more commonly, the contact is either lined by later (although probably cogenetic) quartz gabbronorite intrusions, or is marked by shear zones with shallow paleo-

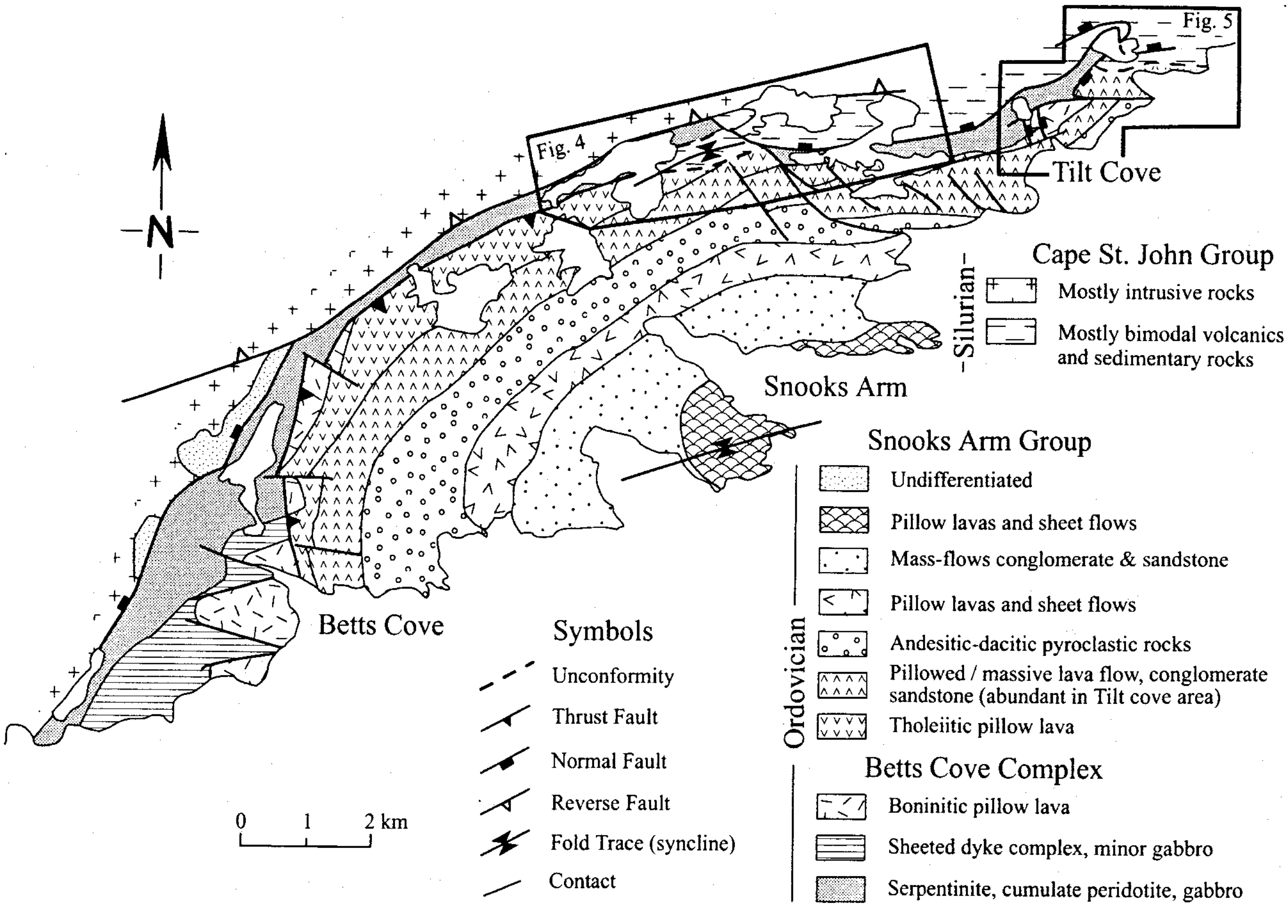


Figure 2. Geological map of the Betts Cove Complex. Modified from Bédard et al. (1997). See figure 1*b* for location.

dips. Where the contact is not a fault, the sheeted dikes grade up through a mixed sequence of dikes and pillow septa into a sequence of boninitic pillow lavas approximately equivalent to the lower lavas of Coish et al. (1982). Both the dikes and the lower lavas belong to a boninitic lineage and are interpreted to represent the inception of seafloor spreading in a forearc environment (Bédard et al. 1997).

The boninites of the Betts Cove Complex are overlain by tholeiitic pillow lavas that were previously included in the ophiolitic sequence (the upper lavas and tholeiitic lower lavas of Coish et al. 1982; Upadhyay 1973), but which we now consider to be the lowermost formation of the Snooks Arm Group (figure 2; Bédard et al. 1997). The Snooks Arm Group consists of thick packages (~300–500 m each) of increasingly more evolved tholeiitic pillow lavas and sheet flows, alternating with equally thick packages of (1) proximal volcanogenic clastic sediments derived from basalts with chemical signatures similar to those of the interbedded lavas; (2) juvenile arc-related andesitic to rhyolitic pyroclastic rocks; or (3) turbidites and pelagites. Basaltic dikes and sills, some up to 200 m thick, intrude the pyroclastic and sedimentary rocks preferentially and appear to have fed the interbedded basaltic lavas. Black shales of the Snooks Arm Group contain early Arenig graptolites, *D. bifidus* Zone (Williams 1995), indicating that these rocks are Lower Ordovician and only slightly younger than the underlying ophiolitic sequence. Interlayered boninites and tholeiites are found near the base of the Snooks Arm Group in a few places (figure 2), suggesting that the contact between the ophiolite and the cover sequence was originally depositional. In most places where it is observed, however, the contact between the boninites and tholeiites is faulted.

The Betts Cove Complex and the Snooks Arm Group are unconformably overlain by the Cape St. John Group (Neale 1957; Neale et al. 1975). A well-exposed angular discordance between the Snooks Arm and the Cape St. John Groups occurs north of Tilt Cove (figure 2; Neale et al. 1975). The Cape St. John Group consists of fluviatile sandstones and conglomerates that alternate with felsic ignimbrites, flow-banded and brecciated rhyolites, and massive amygdaloidal basaltic lava flows. The ignimbrites are characterized by locally abundant red chert and fuchsite clasts, and one of them has been dated at 427 ± 2 Ma (U/Pb; Coyle 1990). The Cape St. John and older rock units are intruded by quartz-feldspar-mica-porphyritic dikes and sills (henceforth QFP), which also contain abundant fuchsite and serpentinite inclusions, implying an ophiolitic substrate and subsurface continuity of ophiolites in the Baie Verte Peninsula. Petrologic similarities, regional correlations, and recent age dating suggest that the Cape Brulé Porphyry, the Cape St. John felsic volcanics, and the QFP dikes cutting the ophiolite are cogenetic sequences of Silurian age (Dallmeyer and Hibbard 1984; Coyle 1990; Currie 1995; Williams and DeGrace 1995).

Deformational Episodes

Several episodes of deformation can be identified in the Betts Cove Complex and cover rocks. In the following, these episodes are subdivided into: (i) pre-obduction faults, (ii) synobduction faults, (iii) normal faults associated with exhumation of the ophiolite, and (iv) compressional structures related to regional deformation.

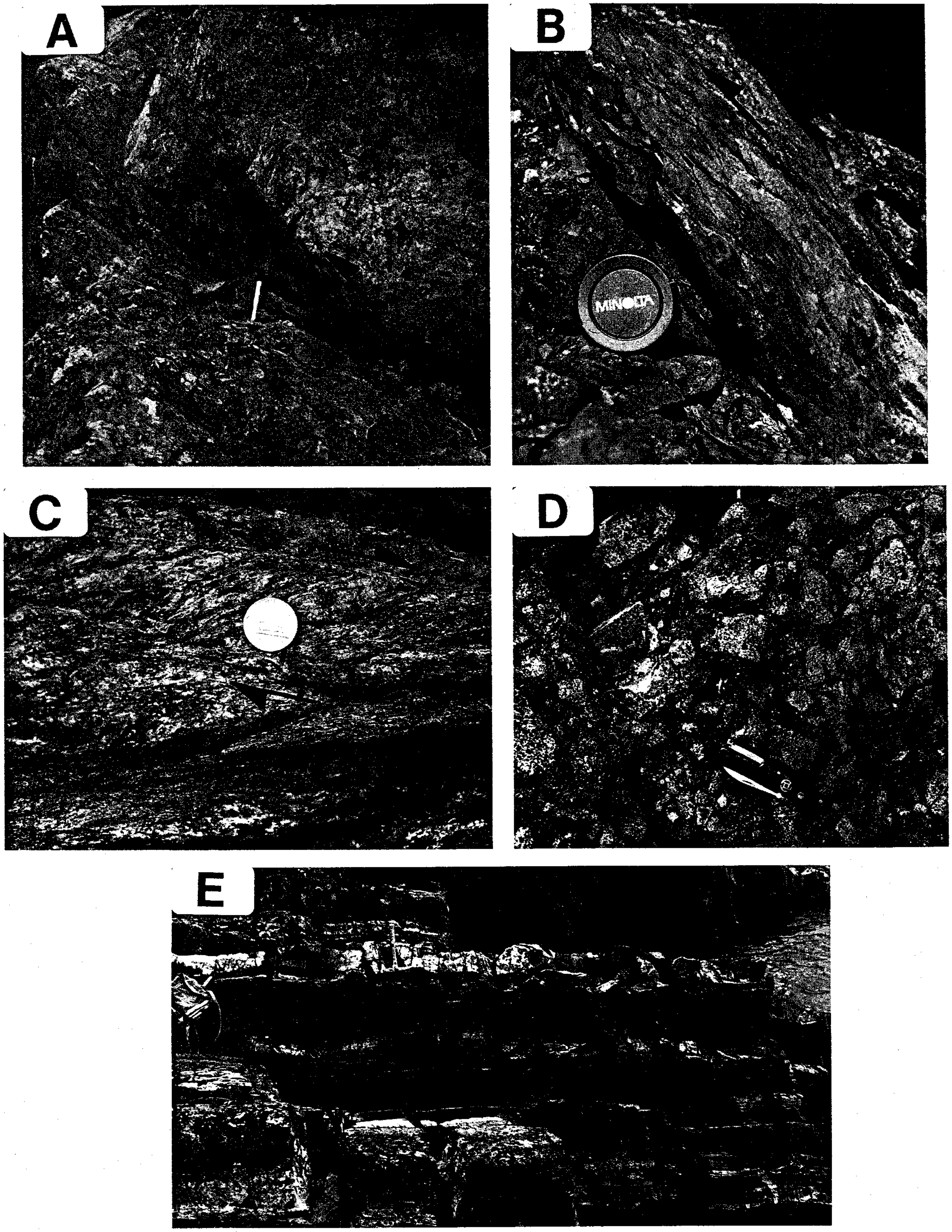
Pre-Obduction Structures. Many northwest- to southwest-trending faults with steep paleo-dips cut the stratigraphy of the Betts Cove Complex (figure 2). In the area around Betts Cove, individual faults have apparent offsets up to 1 km and show apparent normal motions inferred on the basis of lithological offsets. Many of these faults, and related breccia-filled fissures in the adjoining lavas, have axial mafic dikes of boninitic affinity or are impregnated by magmas of boninitic affinity, and so are clearly of intraoceanic origin (Bédard et al. 1997). Their geometry is consistent with an origin as high-level, brittle faults related to seafloor spreading. The map scale distribution of lithologies implies that the normal lava/sheeted dike stratigraphy of the Betts Cove Group was dissected into a series of horst and graben structures. Rare, conjugate sets of higher-grade, syn-magmatic shear zones with shallow paleo-dips found within the sheeted dikes may represent associated ductile detachments. A full analysis of the movement along these faults, and the stress-regime that gave rise to these motions, is beyond the scope of this paper. Considerable hydrothermal activity occurred along some of these structures, locally with the development of abundant chlorite and the deposition of pyrite + chalcopyrite + sphalerite mineralization. It has been proposed that the high-level brittle faults controlled the occurrence of Cyprus-type mineralization in the Betts Cove Group (Upadhyay and Strong 1973; Saunders and Strong 1986).

Several of these steeply (paleo)-dipping faults extend up-section into the overlying Snooks Arm Group lavas and sediments. Measured throws along the faults appear to decrease up-section, suggesting that they are growth faults, and that significant, though decreasing amounts of extension continued throughout deposition of the Snooks Arm Group. The lower parts of some fault blocks appear to record significant tilting and erosional planning-off prior to deposition of overlying sediments.

Normal faults that cut the stratigraphy of the Betts Cove Complex and the lowermost units of the Snooks Arm Group are clearly syn-volcanic in origin because many of them have axial mafic dikes cogenetic with the host lavas (Bédard et al. 1997). These structures must therefore be coeval with the period of seafloor spreading that led to the formation of the Betts Cove ophiolite at ca. 488 Ma (Dunning and Krogh 1985). Paleontological data from the overlying Snooks Arm Group are consistent with this age.

Obduction-Related Structures. Structures that can be strictly assigned to obduction processes are poorly preserved in the Betts Cove Complex. Although there are strongly sheared metaperidotites all along the northwestern margin of the ophiolite, there is no direct evidence for westward thrusting of the ophiolite massif over great distances. Either later faulting events have obliterated any evidence of earlier low-angle thrusting, or else the exposed section of the ophiolite does not reach the structural level of the metamorphic sole.

A better candidate for an obduction-related structure is a northwest-verging thrust fault that marks the contact between rocks of the Betts Cove Complex and the Snooks Arm Group (figure 2). There are no major folds associated with this thrust, and deformation is confined to the contact between the two units. The fault is marked by shear fabrics bearing consistent shear-sense indicators (C/S, shear bands, marker displacement), which occur both in the footwall and in the hangingwall (figure 3*a* and 3*b*). In localities where the hangingwall rocks are well exposed, immediately to the north of Betts Cove, the thrust is marked by the structural stacking of slices of mafic lava 10 m in width, each of which is separated by narrow (<30 cm-wide) zones of brittle/ductile shearing (figure 3*b*). The thrust fault truncates the normal stratigraphic succession characterizing the Betts Cove Complex, juxtaposing Snooks Arm Group tholeiites against the sheeted dikes and cumulates. Far-


A
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ther north, this fault runs along the contact between mafic rocks of the Snooks Arm Group and Betts Cove Complex serpentinites and talc-carbonate schists. Here, the deformation is commonly more ductile in the footwall, due to the marked rheological contrast between incompetent footwall serpentinites and competent hangingwall basalts. In the Red Cliff Pond area (figure 4), the thrust fault disappears under the unconformably overlying sediments of the Cape St. John Group, providing a Silurian (~430 Ma) upper age limit for movement. We believe that this thrust fault formed when a relatively coherent slab of Snooks Arm Group rocks slid over the underlying Betts Cove Complex during obduction of the oceanic crust over Laurentia during the Taconian orogeny (see below).

Some of the steeply paleo-dipping pre-obduction faults and chloritic shear zones now have steeply dipping lineations inconsistent with the sense of motion inferred from lithological offsets. We suspect that these steeply dipping lineations are due to reactivation of weak chlorite schists during obduction.

Extensional Structures: Exhumation of the Obducted Oceanic Crust (?). Following their structural docking with Laurentia, the Betts Cove Complex and the Snooks Arm Group were affected by normal faults. Evidence for this normal faulting event is best preserved in the Long Pond (figure 4), and the Tilt Cove-Beaver Cove Pond (figure 5) areas. Elsewhere, later reverse faults obliterate these extension-related structures. Fault rocks attributed to these normal faults vary from cataclasite to protomylonite and mylonite. Normal fault structures and fabrics are found both in the Betts Cove/Snooks Arm series and in the Silurian rock units. In the latter, fault fabrics indicative of normal-sense shearing are most commonly found in QFP intrusions of the Cape Brulé series.

In the Long Pond area (figure 4), normal-sense shearing is associated with a brittle/ductile deformation zone situated at the contact between the serpentinite/talc-carbonate schist of the Betts Cove Complex, and a QFP intrusion that crosscuts the Cape St. John volcanics. The deformation zone is marked by a mylonitic fabric that dips moderately (~60°) toward the north-northwest, with down-dip stretching lineations (figure 4*a*). In the field, shear-sense indicators are best developed in the porphyry and consist mostly of displaced markers (e.g., quartz veins, xenoliths). Within the shear zone, the porphyry is transformed into porphyroclastic quartz + sericite + calcite mylonites and protomylonites. The microstructure of fault rocks is dominated by 1-to-5 mm quartz porphyroclasts in a fine-grained (<50 μm) matrix composed of quartz + sericite ± calcite with, locally, nascent quartz ribbons (figure 4*c*). Quartz porphyroclasts show undulose extinction and are characterized by abundant intragranular fractures filled by strain-free, fine-grained recrystallized quartz, minor sericite, and calcite. Shear-sense indicators such as C/S fabrics, σ-type porphyroclasts and quarter structures (see Hanmer and Passchier 1991) are consistent with a normal sense of movement, with the upper plate descending toward the north-northwest (figure 4*c*).

In the Tilt Cove–Beaver Cove Pond area (figure 5), normal-sense faults are found at several localities in the vicinity of contacts of the Betts Cove Complex with the Cape St. John and/or the Snooks Arm groups and again, are commonly associated with QFP intrusions. West of Windsor Lake (figure 5), well-developed C/S fabrics indicative of normal-sense shearing occur both in serpentinites and in Cape St. John basalts (figure 3*c*). Fault breccias composed of fragments of Cape St. John sandstones (figure 3*d*) are also found locally in the vicinity of sheared serpentinites and basalts. At Beaver Cove Pond, normal-sense shear fabrics are mostly developed within a hypabyssal, xenolith-rich QFP intrusion crosscutting the Cape St. John basalt and sandstone. Detailed mapping of this area allows two important relationships to be constrained. First, the normal-sense deformation zone crosscuts the basal unconformity of the Cape St. John Group (figure 5), and secondly, the fabric in the normal fault has been folded (figures 5*b* and 6*a*), and defines

Figure 3. (*a*) Thrust fault along the contact between the Betts Cove Complex and the Snooks Arm Group. Hammer for scale. (*b*) Close-up of sheared rocks that mark the thrust faults shown in figure 3*a*. The anastomosing shearing foliation and incipient C/S fabrics indicate a left-handed shear sense (toward the NW). The lens cap is 5 cm in diameter. (*c*) Shear bands indicating right-handed movement (e.g., hangingwall down toward the NW) along a low-angle normal fault in the Windsor Lake area (see figure 5). The fault rock is a serpentinite mylonite of the Betts Cove Group. Coin diameter is 2 cm. (*d*) Cataclasite developed in sandstones of the Cape St. John Group in the Windsor Lake area. These fault rocks are found in the hangingwall of NW-dipping normal faults of the area. (*e*) Fracture/slaty cleavage axial-planar to the syncline in the Snooks Arm Group. Field photograph from the hinge zone of the regional fold. Hammer for scale.

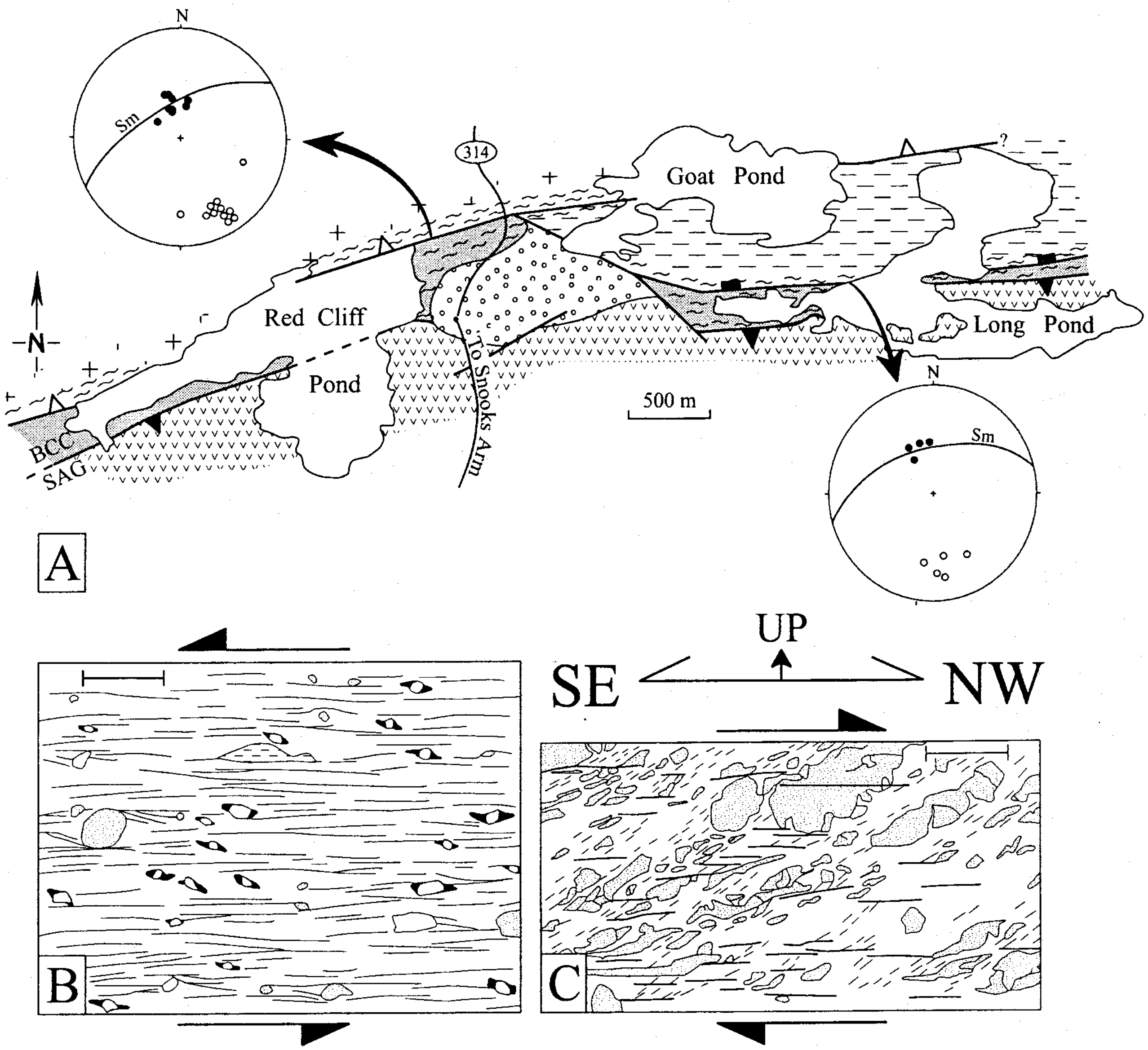


Figure 4. (*a*) Geology of the Red Cliff Pond area. See figure 2 for location. Rock unit patterns are the same as figure 2. Note the northwest-verging thrust fault at the contact between the Betts Cove Complex (BCC) and the Snooks Arm Group (SAG). Lower hemisphere, equal area stereographic plots for mylonitic foliations (Sm, open dots) and stretching and/or mineral lineations (black dots) along the Red Cliff Pond shear zone and the normal fault of the Long Pond area are shown in the upper left and the lower right, respectively. (*b*) and (*c*) show sketches of thin sections oriented parallel to the XZ plane of finite deformation (i.e., perpendicular to the mylonitic foliation, XY, and parallel to the lineation, X). (*b*) Mylonite of the Red Cliff Pond shear zone indicating reverse shearing toward the SE. Note asymmetrical pressure shadows on σ-type feldspar porphyroclasts (white minerals). Dotted minerals are quartz porphyroclasts, stippled mineral is chlorite. Continuous lines show the trace of the mylonitic foliation. Shear sense is sinistral. Scale bar is 2 mm. (*c*) Protomylonite from the normal fault of the Long Pond area; a quartz-rich tectonite characterized by asymmetrical quartz porphyroclasts (dotted minerals) and nascent C/S fabric. Shear sense is dextral. Scale bar is 2 mm.

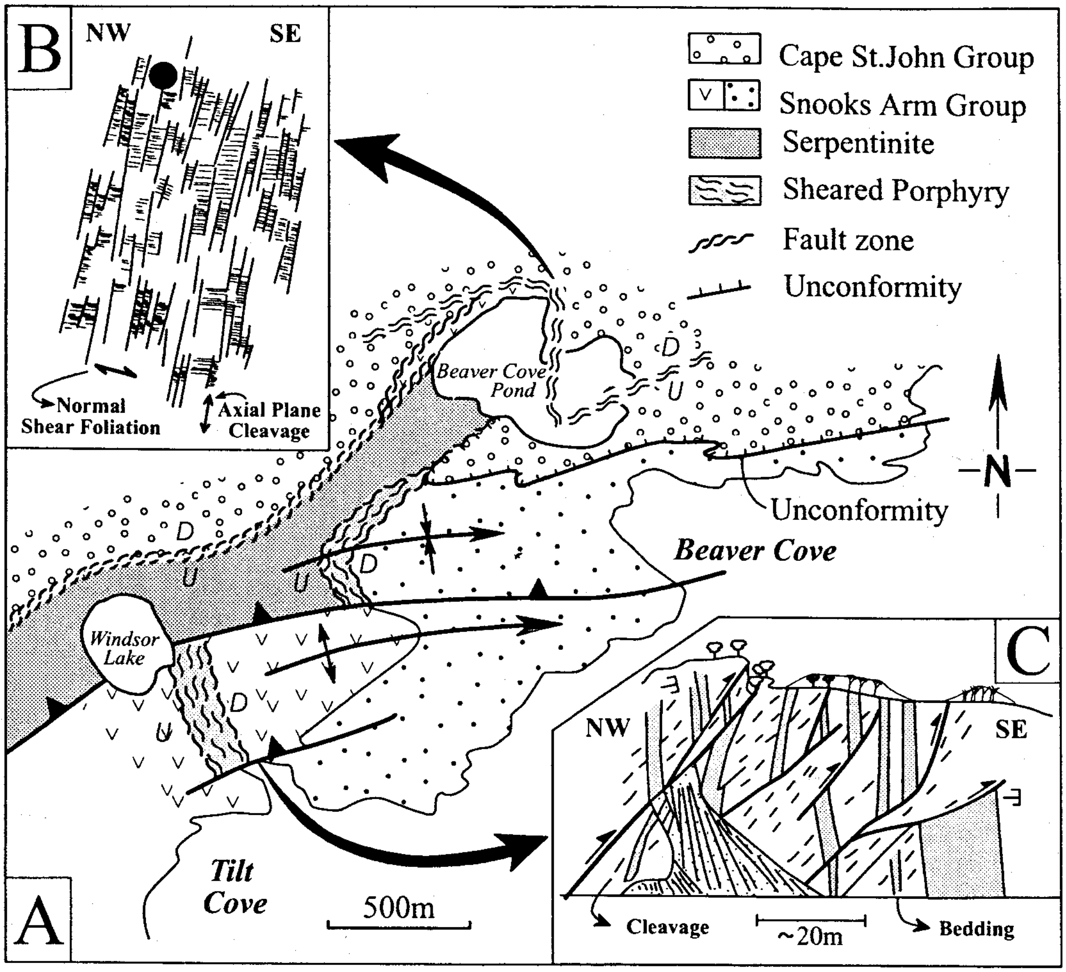


Figure 5. (*a*) Geological map of the Tilt Cove/Beaver Cove Pond area. See figure 2 for location. (*b*) Sketch of a field photograph illustrating the relationship between the penetrative northwest-southeast trending foliation attributed to normal faulting and the regional cleavage in the Beaver Cove Pond area. The lens cap (black dot) is 5 cm in diameter. (*c*) Sketch of structural relationships between reverse faults, regional folds and the related axial-planar cleavage exposed in cliffs at Tilt Cove.

a northeast-plunging anticline with an axial-planar crenulation cleavage subparallel to the regional foliation in surrounding rocks.

Between Beaver Cove Pond and Tilt Cove, QFP intrusions are particularly large and abundant and trend between east-northeast and north-northwest. Commonly, the occurrence of a major, sheared QFP intrusion corresponds to a significant change in the nature of the host lithologies to either side of the QFP. We infer that the QFPs were injected synkinematically into normal faults. In the Tilt Cove mine area, there are two orebodies, one on each side of Winsor Lake. It has been proposed that these were originally one orebody, subsequently dissected by an east-dipping normal fault, the Valley Fault (e.g., Squires 1981; Sangster pers. comm. 1995). This is consistent with our interpretation. Many of the QFPs in the Tilt Cove/Beaver Cove Pond area are strongly sheared and commonly have been affected by intense hydrothermal alteration. Many are characterized by a moderately to strongly developed foliation that varies in orientation from northwest- to northeast-trending (figure 6*a*), which is attributed to later folding and reverse faulting (figure 5; see next section).

In the Betts Cove area (figure 2), the fault that marks the base of the ophiolite has previously been interpreted as a high-angle, dip-slip fault, with upthrow of the south side (DeGrace et al. 1976). We did not find consistent kinematic indicators for that particular contact, but we believe that it belongs to the normal fault system described above. There is no evidence for out-of-sequence thrusting or major structural repetition of lithological units

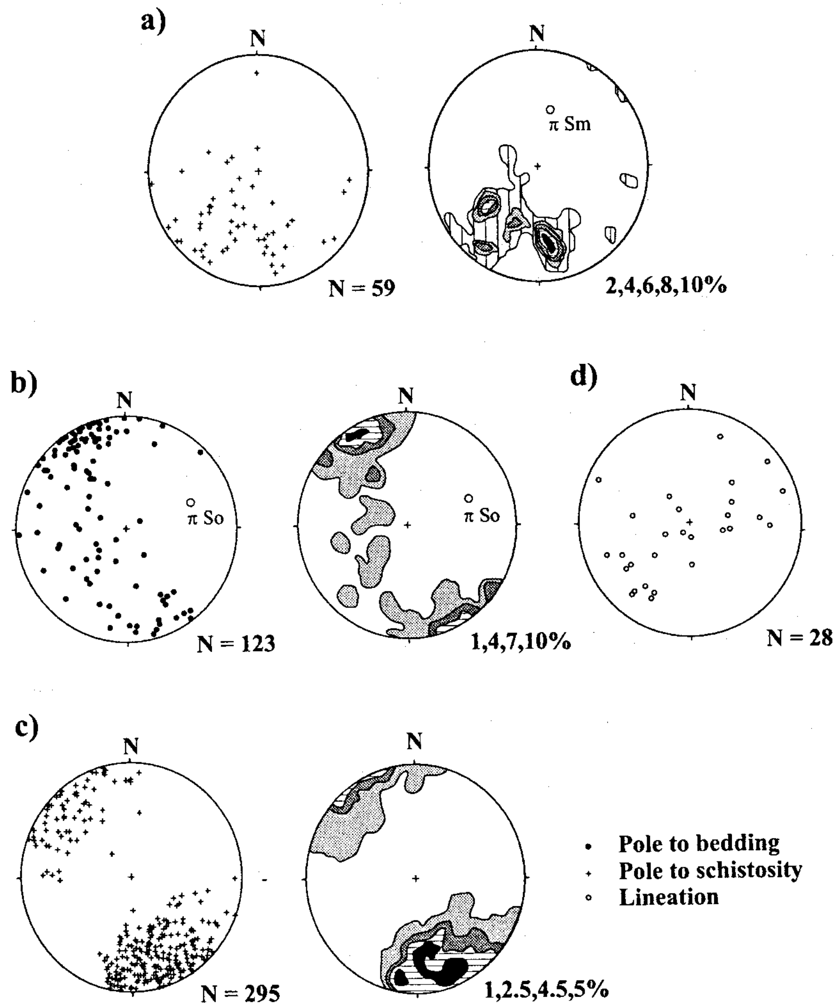


Figure 6. (*a*) Lower hemisphere, equal area stereographic, and density plots for the shear foliation measured in QFPs of the Tilt Cove/Beaver Cove Pond area (see figure 5). Variations in the trend of the foliation are attributed to superposed regional folding. Open dot indicates the position of the pole to the best fit great circle. (*b*) to (*d*): Lower hemisphere, equal area stereographic and density plots for bedding (*b*), regional cleavage (*c*), and bedding-cleavage intersection lineations and fold axes (*d*) in the Snooks Arm Group (see figure 2). ΠSo indicates the location of pole to the best fit great circle.

in the Betts Cove-Snooks Arm series. The existence of a major normal fault at the southwestern edge of the ophiolite would better explain the presence of Snooks Arm Group rocks northwest of the Betts Cove Complex, i.e., these would represent downthrown blocks in the hangingwall of a normal fault.

There are no precise constraints regarding the age of extensional normal faults in the Betts Cove Complex and Cape St. John Group. We know that these faults are younger than the Cape St. John basal unconformity, and older than the regional folding and faulting that affect the entire sequence of Ordovician and Silurian rocks of the Baie Verte Peninsula. In the Tilt Cove/Beaver Cove Pond area (figure 5), structural relationships among hypabyssal QFP intrusions and normal faults suggest that the emplacement of magma was fault-controlled, and that the QFP intrusions and normal faults are roughly coeval. If the cogenetic relationship between the QFP intrusions and the Cape Brulé Porphyry holds true, this implies that extensional faulting was active at least during the Early Silurian (i.e., at ca. 435–425 Ma), though we lack a precise upper age boundary for this event.

Compressional Structures: Regional Folding and Faulting. The most obvious deformation recorded in the Betts Cove Complex and the Snooks Arm Group is a large-scale synclinal structure (figure 2). In the Snooks Arm Group, beds vary in orientation from north-south to east-northeast and face south to south-southeast (figure 6*b*). An axial-planar slaty or spaced cleavage oriented southwest to east-west and dipping moderately northwest to north (figures 3*e* and 6*c*) is present. The fold plunges slightly to moderately toward the northeast or the southwest (figure 6*d*). The intensity of deformation increases toward the hinge zone of the syncline, and also toward the contact with Silurian rocks to the northwest, producing mesoscopic folds and transposition structures. In the Tilt Cove/Beaver Cove Pond area, these folds are commonly associated with northeast-dipping high-angle reverse faults (figure 5*c*), commonly localized by the presence of weak lithologies such as serpentinite or talc, sediments embedded within massive lavas, or pre-existing faults lined by QFPs.

The northwestern limb of the regional syncline is truncated by a major southeast-verging high-angle reverse fault, best exposed in the Red Cliff Pond area (figure 4*a*) where it corresponds to a major ductile shear zone, which we propose be called the Red Cliff Pond shear zone. The Red Cliff Pond shear zone extends up to 10 km along the contact between the Betts Cove Complex and Silurian rocks (figure 2). Southwest of the Betts Cove area, it can be traced along-strike for another 20 km, and thus represents a major, regional-scale reverse fault. We infer that it is related to the southeast-verging compressive deformation responsible for regional folding. It is best developed in rhyolitic rocks of the Cape St. John Group and the intrusive rocks of the Cape Brulé Porphyry. It is approximately 200 m thick and is marked by a penetrative northeast-southwest trending mylonitic foliation that dips approximately 70° toward the northwest, and is associated with down-dip stretching lineations (figure 4*a*). Mesoscopic shear bands and C/S fabrics imply southeast-directed shearing along the foliation. The fault rocks consist of porphyroclastic, quartz- to sericite-rich mylonites. Porphyroclasts are abundant and consist of approximately 5-to-10% of 500 μm-sized feldspars (pseudomorphed by calcite), quartz grains, and opaque Fe-rich minerals (figure 4*b*). Foliation-parallel chlorite and/or fuchsite ribbons are locally abundant and are interpreted to be pseudomorphs after mafic minerals and ultramafic xenoliths, respectively. The diameter of recrystallized quartz and sericite grains in the matrix averages 25 μm or less. Shear-sense indicators such as σ- and δ-type asymmetrical porphyroclasts (figure 4*b*), C/S fabrics, shear bands, and grain-shape fabrics in quartz ribbons clearly indicate reverse movement along northwest-dipping shear planes.

Regional-scale folds and faults in the study area and in the Baie Verte belt are younger than the Silurian and Devonian(?) rocks affected by these structures, and older than flat-lying Carboniferous rocks that are found in the Baie Verte Peninsula (not shown in figure 1*b*; Hibbard 1983) and which unconformably overly Silurian-Devonian granitoids immediately to the south of the peninsula (Dean and Strong 1975).

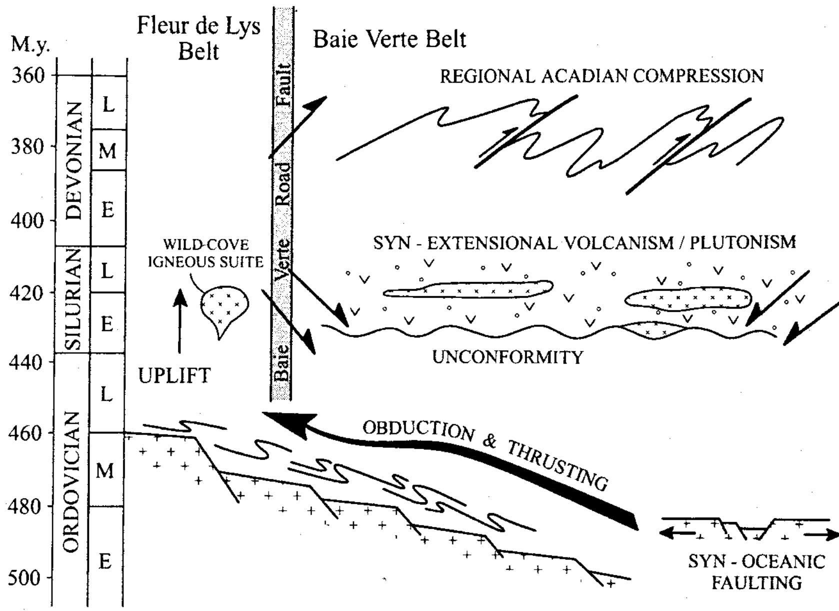
Discussion

Structural Evolution of the Betts Cove Complex. Geochronological data that can constrain the age of deformation and metamorphism in the Baie Verte Peninsula are sparse. However, clear and unambiguous stratigraphical relationships among the principal lithotectonic units of the peninsula can be used to define the age range of the deformational events described below (figure 7).

The structural development of the Betts Cove Complex and cover rocks is schematically represented on figure 8. Following obduction onto the Laurentian margin in Early to early Middle Ordovician time, the Betts Cove Complex and Snooks Arm Group formed a titled composite segment of oceanic crust and cover rocks (figure 8*a*), structurally overlying continental rock units which would be correlatives of the Fleur de Lys belt. In the Baie Verte Peninsula, the continental rocks over which the various units of the Dunnage zone have been thrust (not shown in figure 8*a*) are locally represented by the metamorphosed rocks of the Ming's Bight inlier (figure 1*b*). Deep seismic data (Quinlan et al. 1992), imply that the basement occurs at depth below the exposed Dunnage zone rocks and consists of Grenvillian crystalline rocks and overlying Lower Paleozoic cover rocks of the Laurentian. There are no direct age data on obduction-related structures in the Betts Cove Complex. However, a pre-Late Ordovician time for the docking of the Betts Cove Complex (figure 7) is consistent with the timing inferred from other ophiolitic complexes for the Taconian orogeny in the Newfoundland Appalachians (e.g., Stevens 1970; Williams 1979; Hibbard 1983).

In the Early Silurian, an erosional unconformity was formed on the tilted Betts Cove Complex and Snooks Arm Group. Fluviatile sandstones/conglomerates and subaerial bimodal volcanics of the Cape St. John Group and correlatives were deposited above obducted oceanic terranes of the Baie Verte Peninsula (figure 8*b* and 8*c*), whereas coeval hypabyssal intrusive rocks of the Cape Brulé Porphyry were intruded into both the Ordovician and the Silurian sequences. This period of coeval sedimentation, volcanism, and plutonism was synchronous with extensive normal faulting (Hibbard 1983; Jamieson et al. 1993; and this study). These normal faults, locally preserved as northwest-directed dip-slip faults at the margins of the Betts Cove Complex, dissected the obducted oceanic terranes and the overlying sequence of subaerial sediments and volcanics of the Cape St. John Group. Although the relationships as we have represented them in figure 8*b* and 8*c* might suggest that the normal faults postdate the Cape St. John unconformity, we believe that the faults and the unconformity are penecontemporaneous, and it is the continued normal faulting and associated erosion that led to the exhumation of the Ordovician oce-

Figure 7. Geochronological constraints for volcanism, plutonism, metamorphism and tectonism in the Baie Verte Peninsula. See text for discussion.



anic crust and to the formation of unconformable relationships with the Silurian cover sequence.

During the Acadian orogeny, compressive deformation led to the development of folds and southeast-directed reverse faults (such as the Red Cliff Pond shear zone) in the composite oceanic crust and overlying sequences (figure 8*d*). In both the Baie Verte and Fleur de Lys belts, the vergence of Acadian deformation has been east-directed, as shown by this study and other structural analyses of the Baie Verte Peninsula (Bursnall and DeWit 1975; Hibbard 1983, 1994; Piasecki 1995). The $^{40}Ar/^{39}Ar$ ages from metamorphosed Ordovician mafic volcanics of the Baie Verte Peninsula vary between 356 and 350 Ma for hornblende, and between 347 and 340 Ma for biotite, while hornblendes from several metamorphic samples of the Ming's Bight inlier also yielded similar well-defined plateau or total-gas ages of 356 and 357 ± 5 Ma (Dallmeyer and Hibbard 1984). These data led Dallmeyer and Hibbard (1984) to propose an upper age limit of ca. 345–355 Ma for regional metamorphism and associated deformation within rocks of both the Ming's Bight inlier and the Baie Verte belt, which they correlated with a Middle to Late Paleozoic (Alleghanian?) tectonothermal event. However, Carboniferous rocks of the Baie Verte Peninsula were not involved in the deformational phase recorded by the Silurian-Devonian sequence (Hibbard 1983), suggesting that this thermal event and associated deformations are due to the Acadian rather than to the Alleghanian orogeny (figure 7).

Tectonic Implications for the Baie Verte Peninsula. The Cape St. John Group, the Cape Brulé Porphyry, and similar age correlative rocks of the Sprindale Peninsula have been interpreted as the result of post-Ordovician cauldron subsidence (Coyle 1990). The margins of subsiding cauldrons are commonly subject to intense shear deformation, and fossil examples would probably be interpreted as syn-magmatic normal faults. The country rocks surrounding such cauldrons are commonly injected by ring-dikes and subjected to intense faulting and hydrothermal alteration. It seems reasonable to infer that the Cape Brulé porphyry represents a shallowly emplaced roof facies of a batholithic granitoid complex. The presence of a granitic ring-dike embedded within the Burlington granodiorite (figure 1*b*) also suggests cauldron subsidence. The similar ages and petrographic character of the Cape St. John rhyolitic volcanics and their intrusive correlatives suggest they could be volcanic ejecta from this granitoid batholith. The large volume of these rhyolitic ejecta is consistent with their formation in association with a major caldera complex.

A Silurian timing for extensional deformation in the Betts Cove area would overlap the range of $^{40}Ar/^{39}Ar$ metamorphic ages (429–421 Ma; hornblende and mica ages respectively, Dallmeyer 1977) and U/Pb ages found in syn- to postkinematic felsic intrusions (427–423 Ma; monazite, zircon, and titanite, Cawood and Dunning 1993) from the Fleur de Lys belt west of the BBL. Cawood et al. (1994, 1995) argued that such ages correspond to peak metamorphic conditions and syn-orogenic plutonism related to continental collision and crustal thickening during the Salinian orogeny. However, the lithologies and chemistry of the Cape St. John

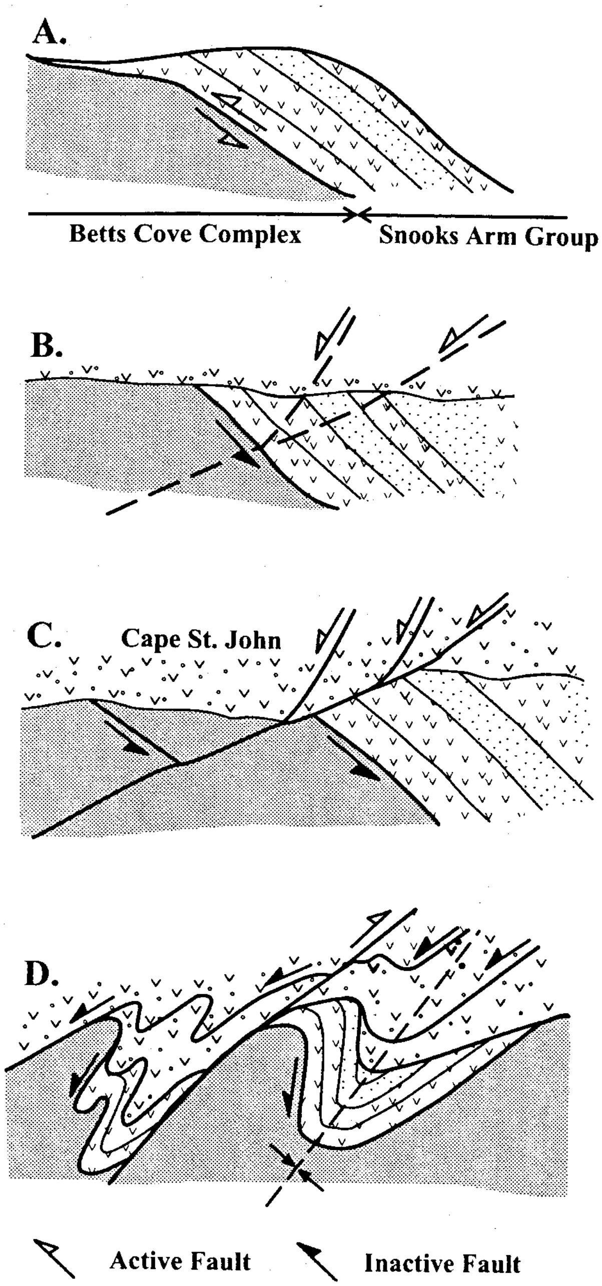


Figure 8. Structural evolution of the Betts Cove Complex and of the Snooks Arm and Cape St. John groups. (*a*) Structural juxtaposition of the Snooks Arm Group and the Betts Cove Complex during the obduction of the Newfoundland ophiolites. (*b*) and (*c*) Normal faulting and coeval sedimentation/volcanism of the Cape St. John Group in Early Silurian time. (*d*) SE-verging folding and faulting during the Acadian orogeny in Devonian time. See text for discussion.

volcanics and associated intrusions are not fully consistent with collision- or subduction-related models (Strong 1980; Strong and Coyle 1987), and alternative interpretations involving a Silurian period of crustal extension have been suggested (Hibbard et al. 1995; Jamieson et al. 1993; see below).

It has been proposed that Silurian normal faulting along the Baie Verte Road fault system (equivalent to the Baie Verte-Brompton line) can account for the strong contrast in metamorphic grade between the Fleur de Lys and Baie Verte belts (Cawood et al. 1995; Piasecki 1995). The inferred movement sense for normal faulting along the Baie Verte–Brompton line is east-directed (i.e., relative uplift of the Fleur de Lys belt), consistent with the structural vergence of associated deformation and fault fabrics (Bursnall and DeWit 1975; Hibbard 1983; Piasecki 1995). This normal faulting event is currently attributed to a rapid exhumation of the Fleur de Lys metamorphic sequence, immediately following a period of major continental collision and associated crustal and lithospheric thickening in Early Silurian time (i.e., the Salinian orogeny; Dunning et al. 1990; Cawood et al. 1995).

In the Newfoundland Humber zone, the Salinian orogeny seems to correspond with Early Silurian peak metamorphism and widely distributed suites of granitoid intrusions (see Cawood et al. 1995). $^{40}Ar/^{39}Ar$ studies on correlative metamorphic rocks of the southern Québec Humber zone yield similar Early Silurian ages (Castonguay et al. 1995; 1997), suggesting that this Salinian event may be widespread. However, associated structures in southern Québec cannot be attributed to a major collisional event. Rather, they are clearly related to Silurian backthrusting and/or extensional deformation (Pinet et al. 1996; Castonguay et al. 1997). As a result, it is tempting, as suggested by Jamieson et al. (1993), to interpret $^{40}Ar/^{39}Ar$ metamorphic ages from the Newfoundland Humber zone as cooling ages recording a phase of regional extension that followed Taconian thrust loading of the Laurentian margin. In terms of such a model, the Baie Verte belt and Silurian cover sequence might belong to the upper plate of a detachment fault that dissected the thickened Laurentian margin in Early Silurian time. The Cape St. John Group and associated intrusive rocks would then have been emplaced in either pull-apart basins opened by the reactivation of major pre-existing faults (such as the Baie Verte Road fault system) or in successor basins resulting from post-orogenic extensional faulting.

Cawood et al. (1995) concluded that the Salinian event must be related to continental collision, because the syn- to post-kinematic Early Silurian plutonism of the Humber zone has an overall calc-alkaline evolution trend. However, felsic melts produced during extension may have a wide variety of geochemical signatures. Anatexis of continentally-derived detritus, or coupled intra-crustal assimilation-fractionation processes, could generate a pseudo-calc-alkaline trend (Bédard 1986; Harris et al. 1990; Inger 1994; Innocent et al. 1994). Preliminary geochemical data from the mafic lavas of the Cape St. John Group suggest anorogenic signatures (Bédard unpub. data). As an alternative to the petrogenetic interpretation of Cawood et al. (1995), Early Silurian granitoid intrusions crosscutting the Fleur de Lys belt (Wild Cove igneous suite and correlatives) could be attributed to crustal melting induced either by internal heating and subsequent isothermal decompression of a tectonically thickened crust (Jamieson and O'Beirne-Ryan 1991), or as a response to enhanced basal heat flow through the lithosphere-asthenosphere boundary (Inger 1994).

Conclusion

The Betts Cove Complex of the Baie Verte belt constitutes a well preserved composite section of Ordovician marginal basin oceanic crust, which contains abundant evidence of syn-volcanic extension. Obduction-related structures associated with thrusting of this oceanic crust over the continental margin of Laurentia are represented by a major NW-verging thrust fault at the base of the Snooks Arm Group. There is no evidence for significant folding during that deformational event. This allows a better characterization of post-accretion exhumation and compressive deformation in Silurian and Devonian time. Following its docking with Laurentia, the Betts Cove Complex was exhumed in Early Silurian time, during a deformational episode dominated by normal faulting and associated with terrestrial sedimentation, bimodal anorogenic volcanism, and felsic plutonism. Early Silurian sedimentation and magmatism in the Baie Verte belt is probably coeval with the exhumation of the internal Humber zone and with felsic plutonism in the Fleur de Lys belt. The structural analysis and interpretation of the Betts Cove Complex and cover rocks bear on the debate concerning the nature of tectonism in the northern Appalachians during the Silurian. It can be argued that following its emplacement onto the continental margin, the obducted oceanic crust experienced significant extensional deformation during the Silurian, and that this extension was coeval with bimodal volcanism and batholithic felsic plutonism. During the Acadian orogeny, both the Betts Cove Complex and the Silurian sediments and lavas were folded and faulted in response to southeast-directed compressional deformation centered along major faults genetically related to the Baie Verte–Brompton Line.

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