

Taconian Obduction and Silurian Exhumation of the Betts Cove Ophiolite, Canadian Appalachians¹

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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 1a), and as Acadian thrust slices (e.g., the Bay of Island

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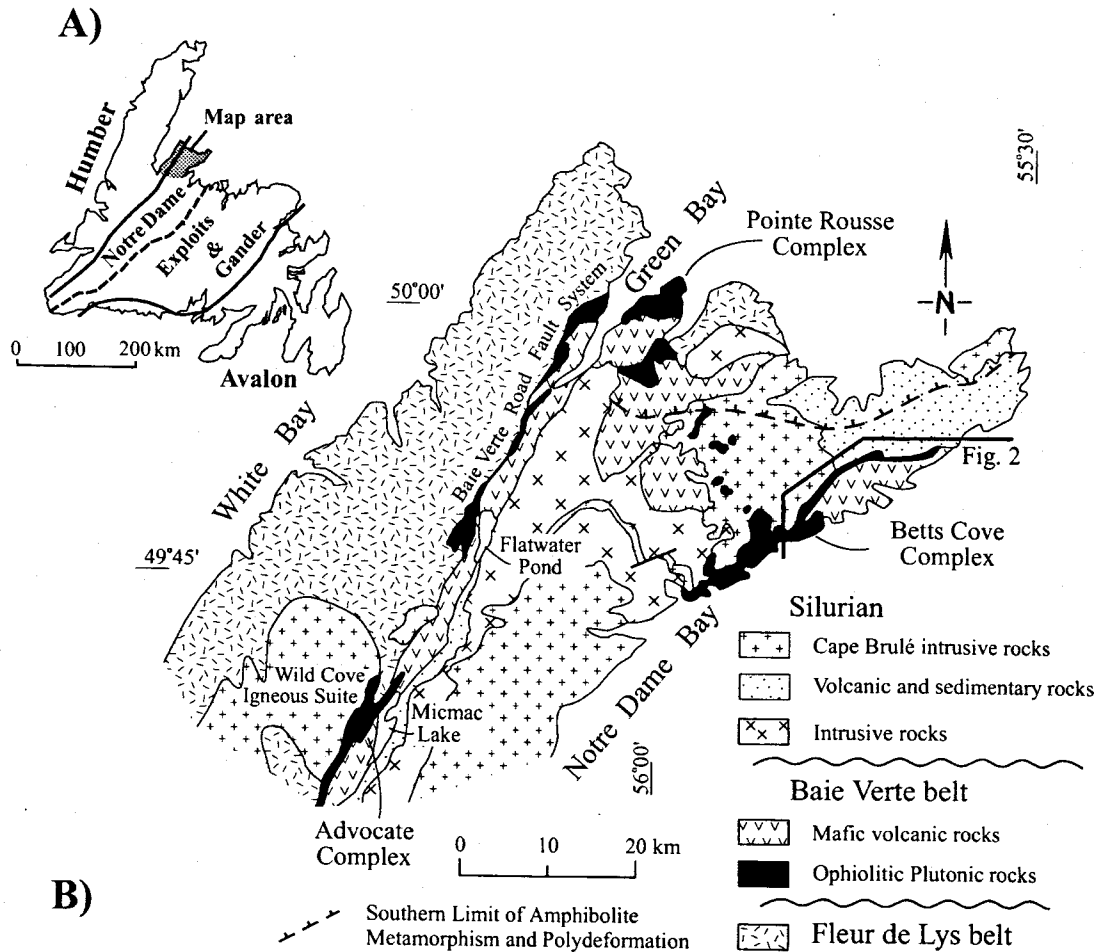


Figure 1. (a) Tectonostratigraphic division of the Newfoundland Appalachians. The Dunnage zone is made up of the Notre-Dame and Exploits subzones. The Exploits subzone and the Gander zone are shown as a single unit for clarity. (b) Geological map of the Baie Verte Peninsula. Modified from Hibbard (1983).

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 1b) better preserve their early structural history. This paper presents a detailed structural analysis of the Betts Cove Complex and its Ordovician cover sequence (figure 1b), 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 1b) 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 $^{40}\text{Ar}/^{39}\text{Ar}$ 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 1b) 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 1b), 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 Rouse, Advocate, and Betts Cove complexes; figure 1b) 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 fluvatile conglomerates and sandstones interbedded with basaltic lavas and felsic tuffs belonging to the Cape St. John and Micmac Lake Groups (figure 1b; 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 1b), 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 1b). 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 tectonite.

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-

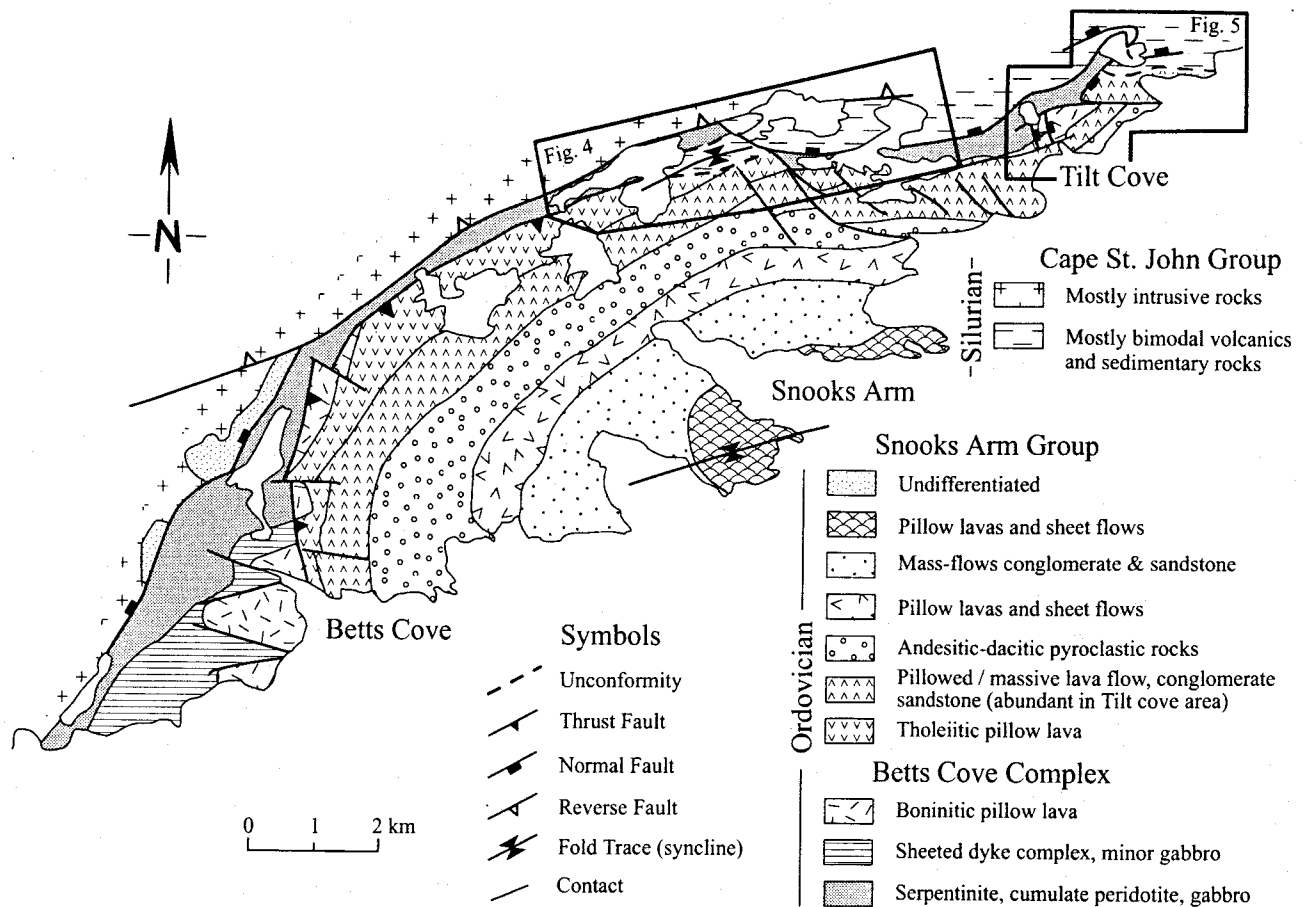


Figure 2. Geological map of the Betts Cove Complex. Modified from Bédard et al. (1997). See figure 1b for location.

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 fluvial 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-porphyrific 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

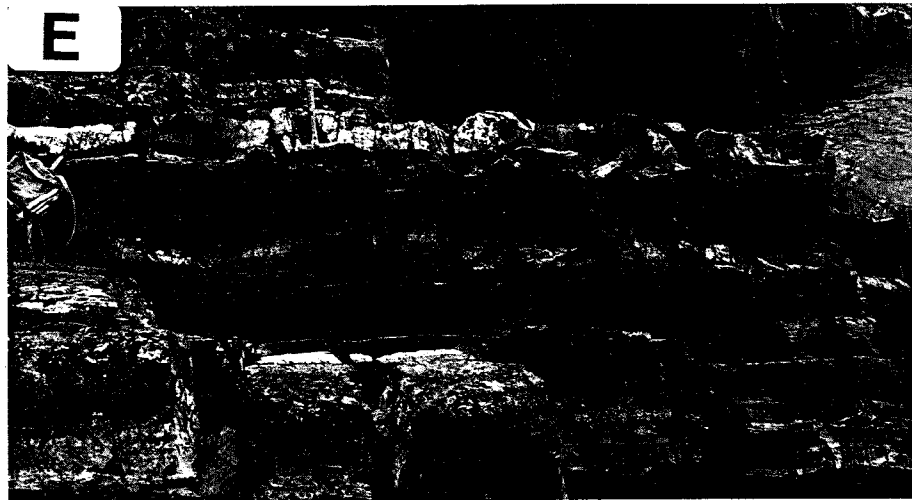
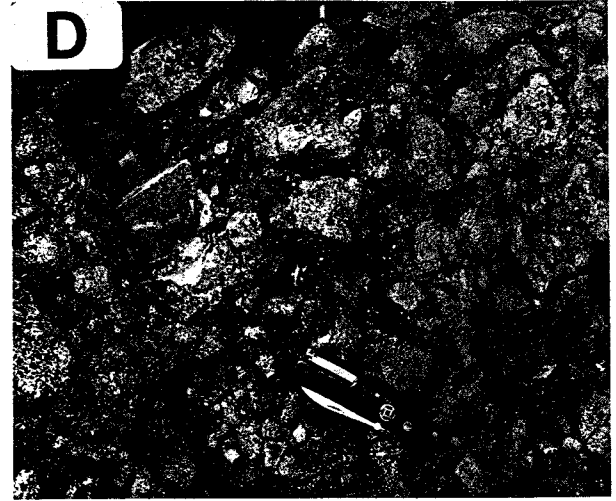
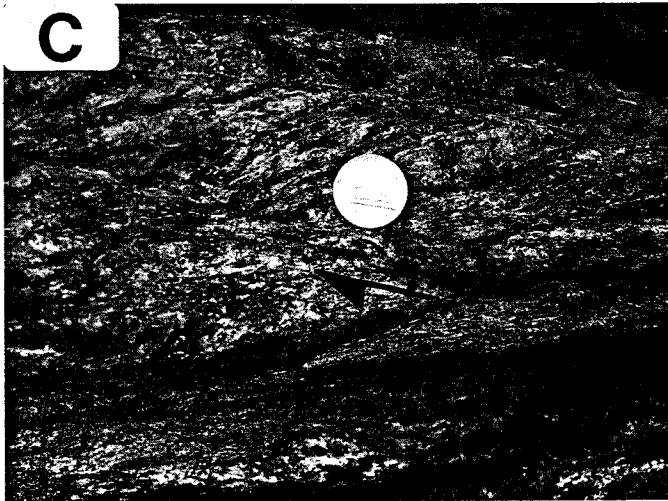
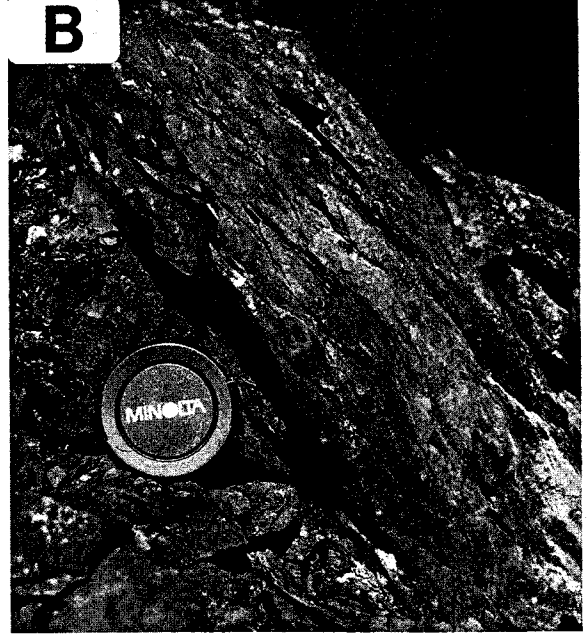
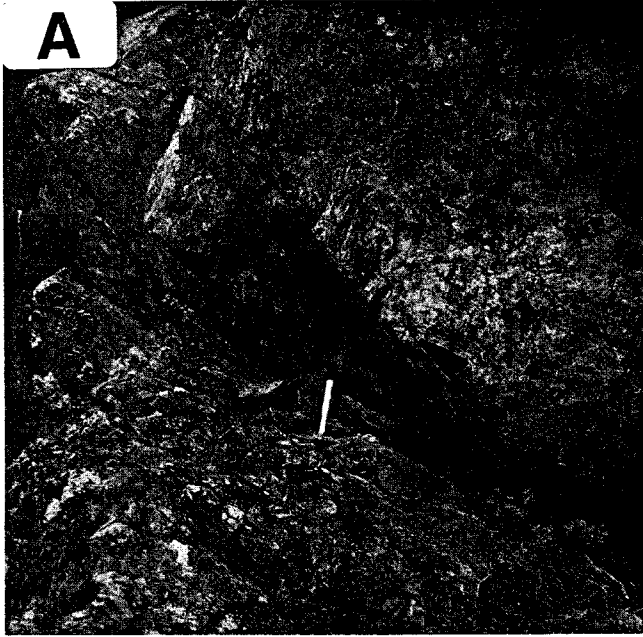
the Betts Cove Group (Upadhyay and Strong 1973; Saunders and Strong 1986).

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 3a and 3b). 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 3b). 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-



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 4a). 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 4c). 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 4c).

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 3c). Fault breccias composed of fragments of Cape St. John sandstones (figure 3d) 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 5b and 6a), 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 3a. 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.

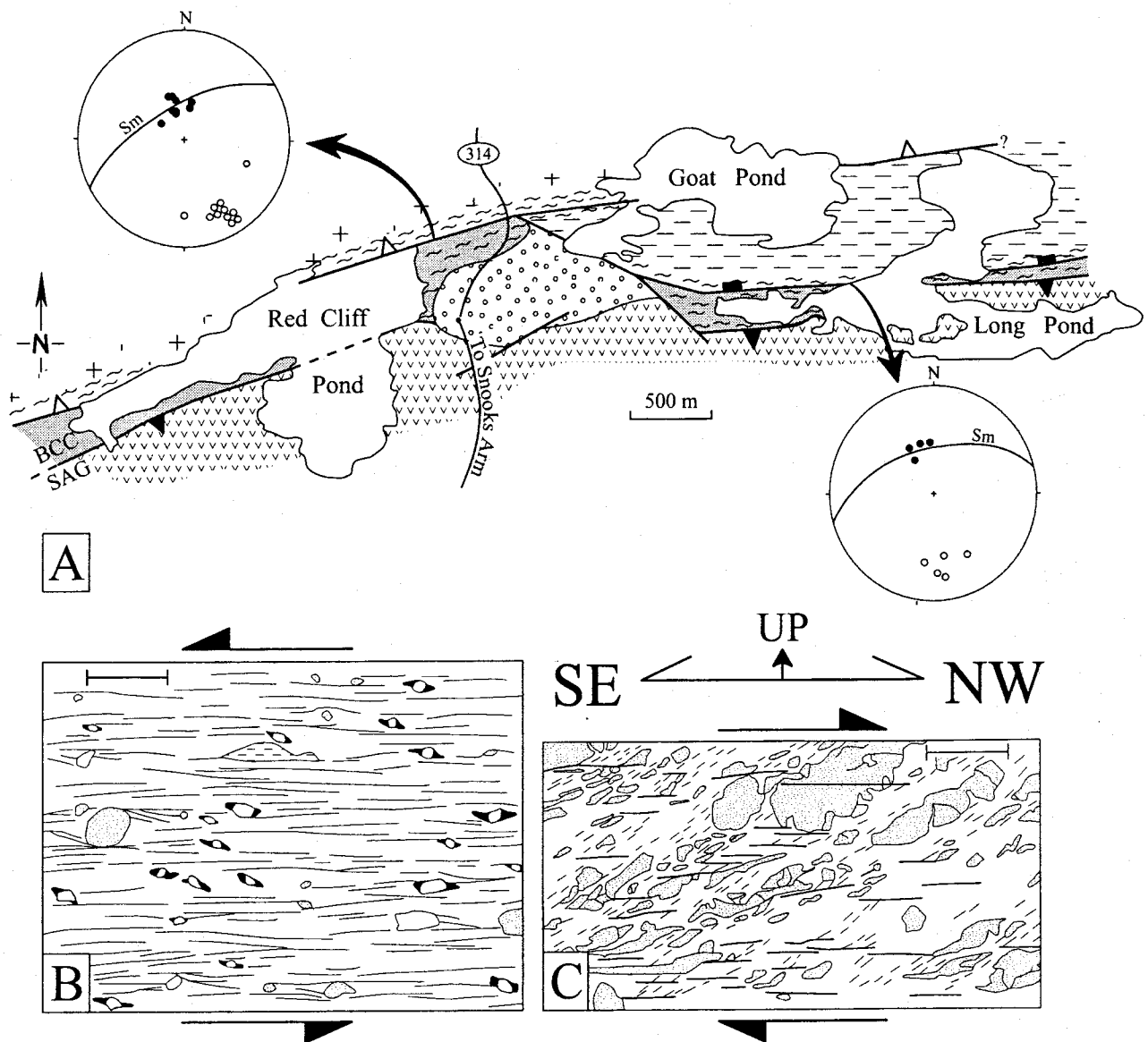


Figure 4. (a) Geology of the Red Cliff Pond area. See figure 2 for location. Rock unit patterns are the same as figure 2. Note the northwest-verging thrust fault at the contact between the Betts Cove Complex (BCC) and the Snooks Arm Group (SAG). Lower hemisphere, equal area stereographic plots for mylonitic 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.