STRUCTURE OF THE SPRUCE BROOK THRUST STACK AT THE BASE OF THE HUMBER ARM ALLOCHTHON, WESTERN NEWFOUNDLAND APPALACHIANS

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Structure of the Spruce Brook Thrust Stack at the base of the Humber Arm Allochthon, Western Newfoundland Appalachians

by:

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Abstract

Spruce Brook drains a low-lying area east of the Lewis Hills and south of Blow-Me-Down Mountain in Western Newfoundland. The area is underlain by a dismembered succession of Cambrian-Ordovician platform carbonate and a succession of siliciclastic rocks assigned to the Taconic syn-tectonic flysch deposits of the Goose Tickle Group. Structurally juxtaposed against these strata are rocks of the Humber Arm Allochthon including altered ultramafic rocks and metamorphic rocks of the Bay of Islands Complex, as well as continental shelf and slope sedimentary rocks of the Humber Arm Supergroup.

The occurrences of platform carbonate constitute thin, planar, structural slices that are bounded by thrust faults. The thrust slices are overall moderately east-dipping and imbricated from west to east. Their internal structural architecture is characterized by west-verging asymmetrical fold forms that are attributed to a combination of buckle folding and ramp-related bending. Contact relationships at the leading edge of the carbonate thrust stack indicate that strata of the Goose Tickle Group are structurally interleaved with the carbonate thrust sheets. Furthermore, the eastern trailing edge of the carbonate thrust stack is structurally overlain by the basal strata of the Humber Arm Supergroup, suggesting that the carbonate thrust stack lies as a duplex within the deformed Taconic foreland flysch succession and carries on its roof thrust the Humber Arm Allochthon.

The thrust stack is cut by a major out-of-sequence thrust array that truncates and re-imbricates pre-existing structures related to the initial emplacement in the thrust stack. The out-of-sequence array includes a steep fault zone that carries a duplex of serpentinite and amphibolite of the Bay of Islands Complex suggesting that the emplacement and subsequent deformation of the Spruce Brook Thrust Stack is indicative of the structural interaction between the basal portion of the allochthon and the upper portion of the par-autochthonous succession during the Taconic Orogeny.

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Chapter 1

Introduction

1.1 Introduction

The island of Newfoundland was first recognized as part of the Appalachian Mountain belt by Logan (1863) who compiled some of the first regional geology maps of Canada, incorporating the pioneering work on Newfoundland geology by J.B Jukes and Alexander Murray. The first generalized geological maps of Newfoundland were published in 1918 by Alexander Murray and J.P. Howley; founding members of the Geological Survey of Newfoundland. Since that time, Newfoundland has been recognized as a type section through the Appalachian Orogenic belt and an important proving ground for modern plate tectonics theories.

Early investigations into Appalachian geology applied models of the very popular geosyncline theory of continental accretion (Kay 1951). These models, however, did not provide an adequate mechanism for the styles of deformation documented in the Appalachians, nor could they account for the juxtaposition of oceanic and continental lithosphere that characterizes the belt.

The advent of plate tectonics theories in the 1960's revolutionized the understanding of the Appalachian orogenic belt. Wilson (1966) proposed that the western and eastern portions of the Appalachian Orogen were separated in the early Paleozoic by a proto-Atlantic ocean: Iapetus, that closed in the late Paleozoic. The processes of ocean opening and closing provided the necessary deformation mechanisms to account for the formation of orogenic belts along continental plate margins and the presence of oceanic crust in these belts. The first plate tectonic models for the Appalachian Orogen were those of Dewey (1969) and Bird and Dewey (1970). The island of Newfoundland was shown to represented a transect across a complete 'Wilson Cycle' recording the development of a passive rifted margin during ocean opening and its subsequent destruction by subduction and continental collision (Stevens, 1970; Church and Stevens, 1971; Dewey and Bird, 1971; Williams, 1971).

Williams (1964 and 1979) divided the island into four northeast trending lithotectonic zones; from west to east: the Humber, Dunnage, Gander and Avalon zones (Figure 1.1). The Humber Zone represents the original continental margin of the Laurentian (North American) continent. Accreted to it are suspect terranes of the Dunnage and Gander Zones including mafic-volcanic and ophiolitic rocks representing the last vestiges of the Iapetus Ocean basin. The Avalon Zone is thought to be a part of the Gondwanan (African-European) continent that formed the eastern margin of Iapetus. The juxtaposition of these terranes is the culmination of three main phases of orogenesis: the Taconic orogeny in middle Ordovician times, the Acadian orogeny during the Silurian-Devonian (Salinic) and the Carboniferous Alleghanian orogeny.

1.2 Study Area: Location and Physiography

This is a study of the Humber Zone in western Newfoundland, which constitutes the Great Northern Peninsula and extends south to St. Georges Bay. The study focuses on an area located about 40 km southwest of the city of Corner Brook at the eastern end of Humber Arm in the Bay of Islands (NTS 12B/16, Georges Lake map sheet) (Figure 1.1 and Figure 1.2). The area is accessible by truck off Trans Canada Highway Route 1 along Loggers School road, part of a network of logging roads connecting Corner Brook to the town of Stephenville. The area is located in the Blue Hills, at the head waters of Spruce Brook. The brook runs southeast to Georges Lake incorporating numerous small tributaries throughout the study area. There are several small ponds in the area, most of

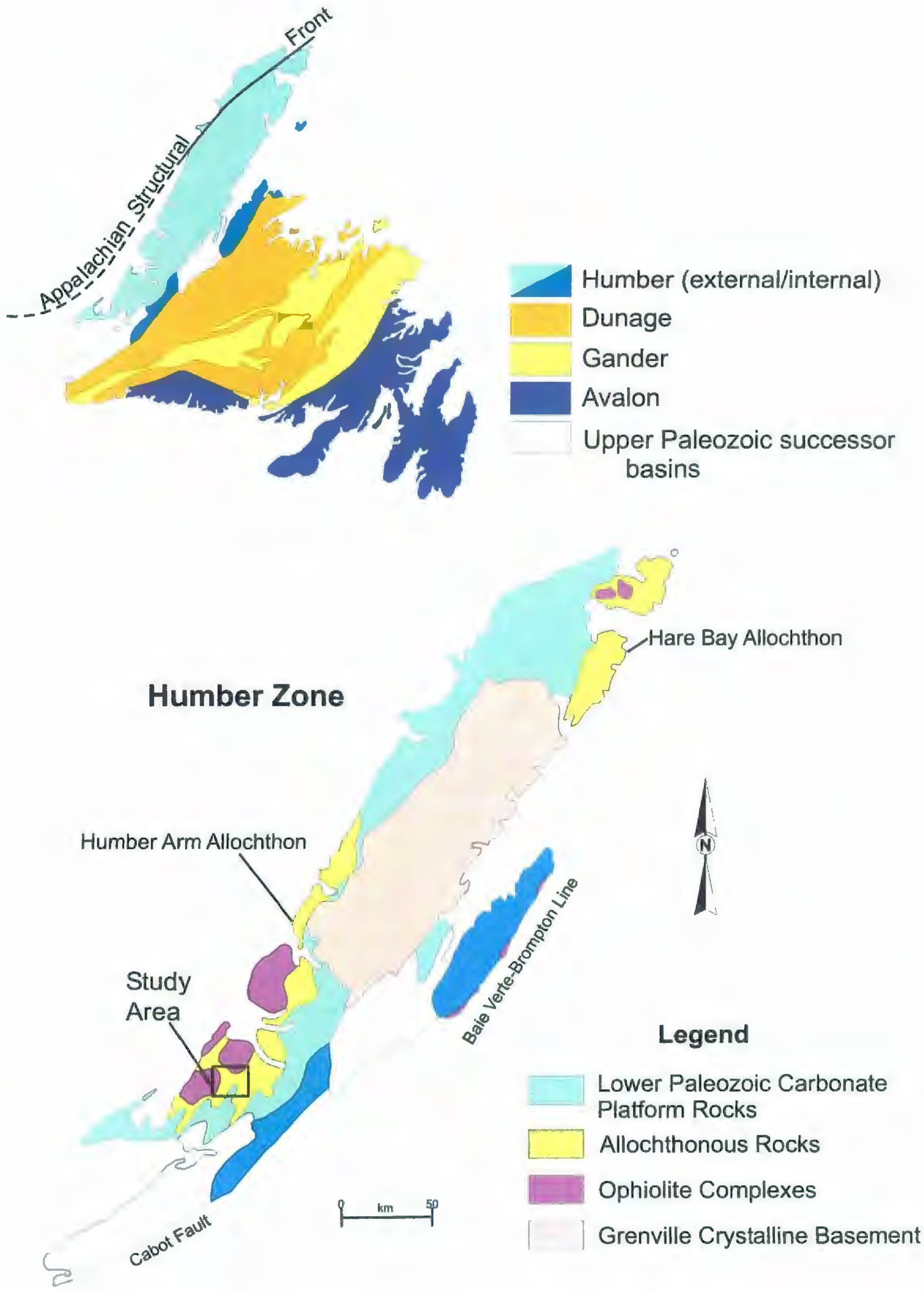


Figure 1.1: Lithotectonic Zones of the Newfoundland Appalachians (after Williams, 1973) and lithotectonic components of the Humber Zone (after Waldron et al., 1994).

which are unnamed with the exception of the Spruce Ponds, located in the southern portion of the study area. The Lewis Hills and Blow Me Down Mountain lie to the west and north of the study area, respectively (Figure 1.2).

The terrain is generally one of low rolling hills with steep valleys. The area is heavily vegetated, largely by second growth forest since the majority of the area was logged in the late 1970's to early 1980's. Many of the small subsidiary trails used for harvesting are still passable and provide excellent access to even the most remote parts of the study area. These roads also tend to expose bedrock where overburden is thin, making reconnaissance mapping very efficient. Outcrop is otherwise restricted to local scarps and the numerous small brooks that crosscut the area. Low-lying areas are commonly marshy and thick glacial till covers the flanks of some hills.

1.3 Regional Geology of the Humber Zone

The Humber Zone is bounded to the west by the Appalachian Structural Front and to the east by the Baie Verte-Brompton Line (Figure 1.1). It can be divided into external and internal portions based on deformation style and regional metamorphic grade which increase from west to east. The internal Humber Zone thus forms a narrow, discontinuous belt of highly deformed and metamorphosed rocks exposed along the Baie Verte- Brompton Line where they are juxtaposed with disrupted ophiolite complexes (Figure 1.1). To the west, the rocks of the external Humber Zone are comparatively less deformed and are generally of low metamorphic grade (Williams, 1995).

The external Humber Zone is characterized by two main allochthonous terrains: the Hare Bay Allochthon on the Northern Peninsula and the Humber Arm Allochthon in the Bay of Islands (Figure 1.1). These are large thrust stacks capped by island arc igneous complexes and ophiolite complexes. The lower structural slices of the allochthons consist of Cambrian-Ordovician deep marine sedimentary and volcanic rocks. The allochthons were assembled and thrust to the west during the Taconic orogeny in the middle Ordovician.

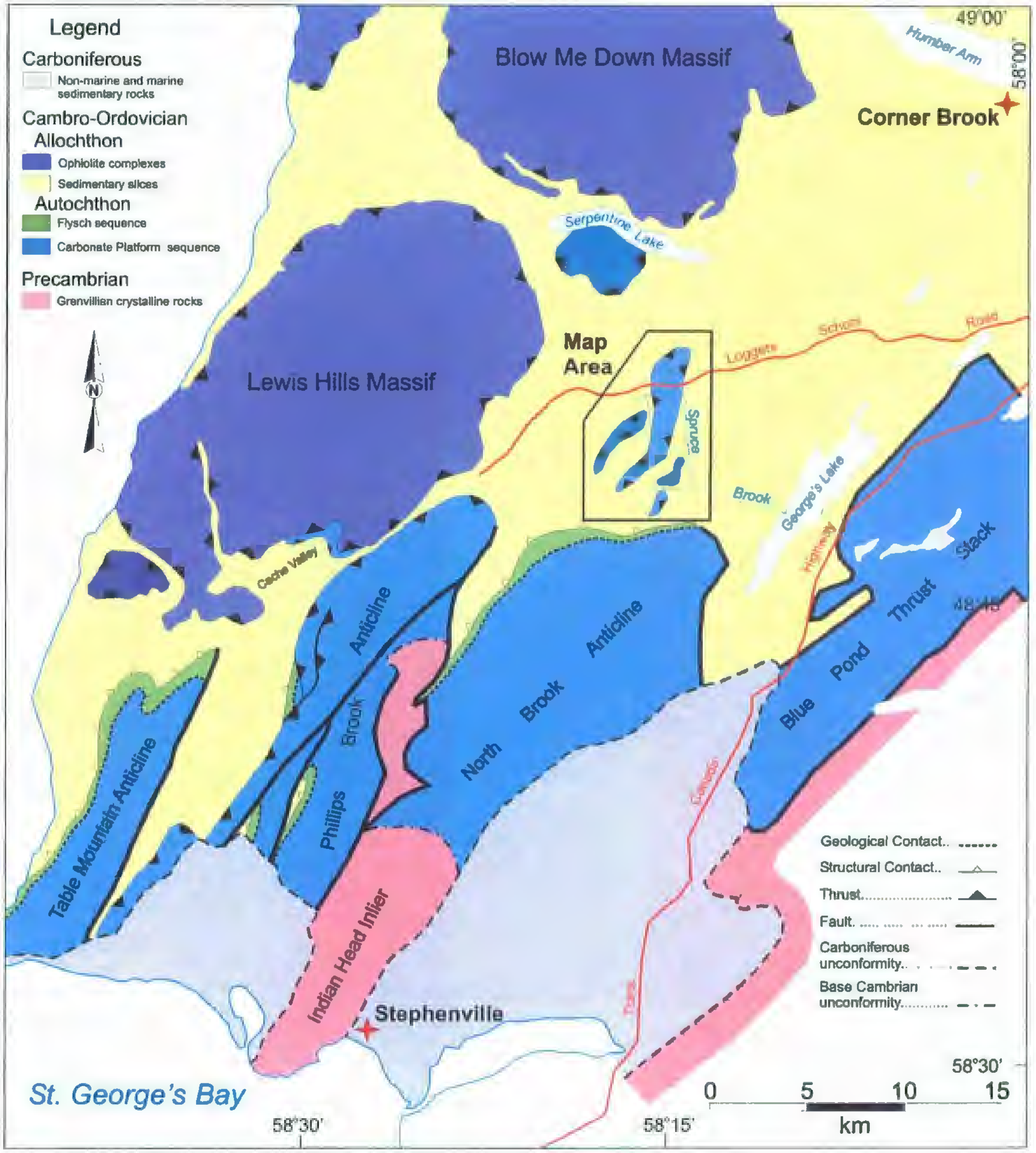


Figure 1.2: Simplified geological map of the southern portion of the external Humber Zone based on Williams and Cawood, (1989); modified from Knight and Boyce, (2002).

The allochthons structurally overlie an autochthonous succession that includes Precambrian crystalline basement overlain by Precambrian to lower Cambrian rift-related clastic sedimentary and volcanic rocks. The rift succession is overlain by an important sequence of Cambrian-Ordovician platform carbonate and middle Ordovician clastic sedimentary rocks. These rocks are age equivalent to marine sedimentary rocks carried in the lower slices of the allochthons and are interpreted as proximal facies equivalents.

The autochthonous succession is defined mainly on the Northern Peninsula and Port au Port Peninsula, but there are also several important exposures in the area north of Stephenville (Figure 1.2). In this area the autochthonous succession, including basement, is deformed by thick-skinned fold and thrust structures. These structures are termed par-autochthonous because they were not subjected to significant tectonic transport. The par-autochthonous structures are locally emplaced over rocks of the Taconic Humber Arm Allochthon. The structures are therefore attributed to a post-Taconic phase of deformation, possibly the Salinic Acadian Orogeny.

The par-autochthonous structures are locally unconformably overlain by Carboniferous sediments (Figure 1.1 and 1.2). These are the youngest rocks in the Humber Zone. They constitute syn-tectonic basin-fill successions in Carboniferous-age transtensional basins formed on major strike slip faults. These faults are attributed to the Alleghanian Orogeny, the third phase of deformation to affect the Humber Zone.

1.3.1 Autochthonous and Par-autochthonous rocks of the external Humber Zone

The basement rocks of the autochthonous succession are Precambrian in age and are correlated to the granitoid and gnessic rocks of the nearby Grenville Structural Province. Basement is unconformably overlain by upper Precambrian to lower Cambrian clastic sedimentary and volcanic rocks of the Labrador Group (Figure 1.3) (Williams and Stevens, 1974). These rocks record the development of the Laurentian rifted margin. Mafic dykes and flows are thought to represent the first rift-related volcanic activity and are dated at 550 Ma (Bostock et al., 1983). Sedimentation of the Bradore and Forteau

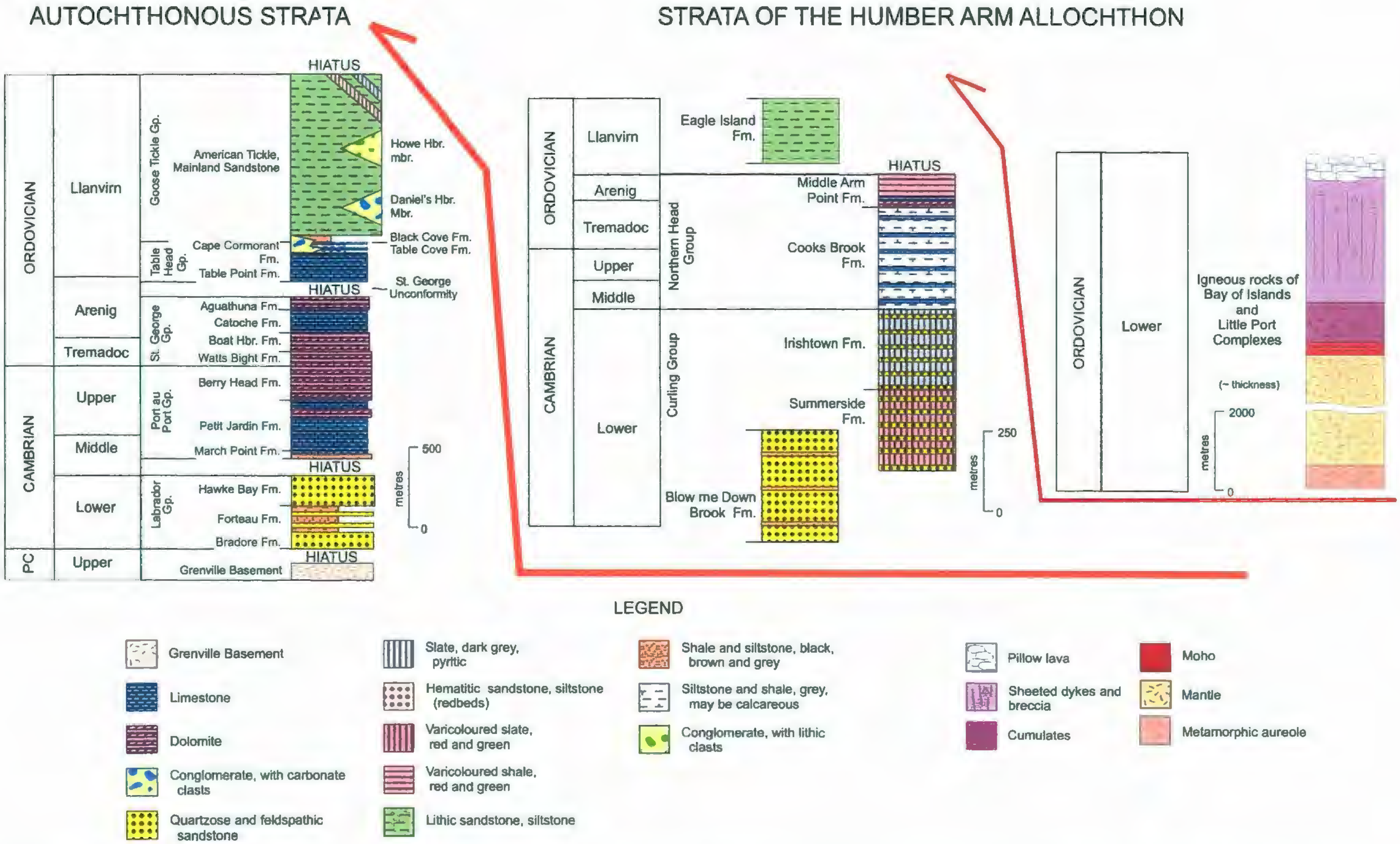


Figure 1.3: Stratigraphic columns for the autochthonous and allochthonous successions of the external Humber Zone, Western Newfoundland. Modified after Burden et al. (2001)

formations during this time shows a marked change in depositional environment defined by the termination of coarse clastic deposition. This is interpreted as the transition from continental rifting to sea-floor spreading (Williams and Hiscott, 1987).

After rifting in the Late Precambrian, the Laurentian margin developed as a broad continental shelf upon which formed a large carbonate platform during the Cambrian to middle Ordovician. The carbonate platform stratigraphy in Newfoundland is divided into the middle to upper Cambrian Port au Port Group, upper Cambrian to lower Ordovician St. George Group, and the middle Ordovician Table Head Group (Figure 1.3). The St. George and Table Head groups are separated by a widespread unconformity known as the St. George Unconformity. Detailed stratigraphic and paleontological studies of the carbonate platform in Newfoundland (e.g. James et al., 1987) suggest that the platform had a long development history, evolving from a high-energy narrow platform in the middle-late Cambrian to a low-energy wide (c.500 km), rimmed platform in the lower Ordovician to middle Ordovician.

The carbonate platform rocks are overlain by middle Ordovician clastic sedimentary rocks of the Goose Tickle Group including black graptolitic shales, lithic arenites, and limestone conglomerates (Figure 1.3) (Hiscott, 1984). The sandstones of the Goose Tickle Group contain a variety of sedimentary rock fragments, mafic to felsic volcanic rock fragments, serpentinite grains, and heavy minerals including hypersthene and chromite. These rocks are interpreted as flysch deposits (Williams, 1995) produced from subaerial erosion of rocks east of the Humber Zone.

1.3.2 Taconic allochthons: the Humber Arm Allochthon

The carbonate platform and the overlying siliciclastic flysch are structurally overlain by the Humber Arm Allochthon; a westerly transported imbricate thrust stack measuring 200 km long, 50 km across, and having a structural thickness on the order of a few kilometers. The lower and intermediate slices of the allochthon are mostly Cambrian to middle Ordovician siliciclastic sedimentary rocks of the Humber Arm Supergroup that are interpreted as continental shelf and slope deposits. These rocks are time-equivalent with the autochthonous carbonate platform succession and are thus thought to be deep-water facies equivalents (Williams, 1995). The upper slices of the allochthon are preserved as klippe consisting of island arc igneous rocks of the Little Port Complex (Williams, 1973; Malpas and Stevens, 1979) and the ophiolite suite of the Bay of Islands Complex (Church and Stevens, 1971).

The Humber Arm Super Group is divided into the Late Precambrian to Early Cambrian Blow Me Down Brook Formation, lower to middle Cambrian Curling Group, middle Cambrian to Tremadoc Northern Head Group and the Arenig-Llanvirn Eagle Island Formation (Figure 1.3). The Curling and Northern Head groups are distal margin sedimentary rocks that make up the lower slices of the Allochthon, while the rift-related sandstones of the Blow Me Down Brook Formation are structurally isolated within the intermediate slice of the allochthon. The Eagle Island Formation is interpreted as a syntectonic, transported, flysch unit and it occurs at several structural levels within the Allochthon.

Structural boundaries between the thrust slices of the Humber Arm Allochthon are generally defined as wide fault zones characterized by highly deformed rocks interpreted as tectonic mélange because of their chaotic appearance (Stevens, 1970; Williams and Godfrey, 1980; Waldron, 1985; Williams and Cawood, 1989, Waldron et al., 1998)

The Humber Arm Allochthon was assembled and emplaced during the Taconic Orogeny in lower-middle Ordovician time. This orogenic event marks the beginning of the destruction of the Iapetus Ocean by collision of the Laurentian and Gondwanian plates. The allochthon formed as a slab of oceanic lithosphere (Bay of Islands Complex) was detached from the easterly subducting Laurentian plate and thrust to the west. Structural slices of continental slope sediments (Humber Arm Supergroup) were subsequently incorporated into an accrectionary wedge at its leading edge. During emplacement of the allochthon in the Early-Middle Ordovician, a peripheral bulge formed in response to loading of the crust. The peripheral bulge migrated across the carbonate platform as the

Allochthon moved west, causing the exhumation and collapse of the platform. This event is marked by a period of block faulting and karstification of the platform, represented by the St. George Unconformity. The basin formed by subsidence of the immediate foreland of the thrust stack was an important depocenter for flysch deposits of the Goose Tickle Group. Carbonate deposition continued during this time along the foreland edge of the flysch basin (Table Head Group) until the entire platform was buried by siliciclastic flysch. The Humber Arm Allochthon would ultimately come to structurally overly the carbonate platform and the foreland flysch basin.

1.4 Purpose and Scope

This study examines the basal portion of the Humber Arm Allochthon, particularly the wide fault zone that constitutes the basal thrust of the allochthon. The study documents fine-scale structural relationships between allochthonous and autochthonous rock units occurring in this fault zone. Interpretations of these relationships will be directly related to the kinematics of the fault zone. They will have implications for the emplacement history of the allochthon itself, and will give insight into the morphology of the upper portion of the autochthon and its response to emplacement of the allochthon.

The Spruce Brook area was chosen for this study based on previous work (next section) which depicts several small occurrences of platform limestone and Ordovician flyschoid rocks outcropping in close proximity to occurrences of Bay of Islands Complex and Humber Arm Supergroup. The juxtaposition of rocks from various structural levels of both the autochthonous and allochthonous successions indicates that the Spruce Brook area has a complex structural history. Although the area has been mapped by previous workers, this structural history has not been adequately defined and the significance of the structural relationships in the area has been largely overlooked. The purpose of this study is therefore to document the structural relationships at Spruce Brook and interpret them in the context of the regional geology of the Humber Zone.

The study will draw comparisons between the geology of the Spruce Brook area and other exposures of the basal portion of the Humber Arm Allochthon, particularly where allochthonous rocks lie adjacent to occurrences of platform carbonate and flysch. These localities include Cache Valley and Serpentine Lake. It will also examine the upper portions of carbonate-cored Acadian par-autochthonous structures which expose the basal detachment of the allochthon.

1.5 Previous Work

The first detailed geological investigation into the Spruce Brook area was by Walthier (1949). He described the large carbonate occurrence as a horst block that he called the Spruce Brook Horst. Walthier (1949) also produced a detailed map of serpentinized ultramafic rocks immediately south of the Spruce Brook Horst. This is the site of the Bond Asbestos Mine that was explored by the Johns Asbestos Company of New York in the 1890's. The locations of the mine pits and slag piles are shown on a detailed sketch map in the Walthier (1949) study.

The Spruce Brook carbonate occurrences are shown on the reconnaissance scale map of Williams (1985) as a single outlier of the North Brook Anticline (see later, this section) and its stratigraphy was assigned largely to the Table Head Group. The carbonate occurrences were re-mapped by Williams and Cawood (1989) as four separate klippe carrying Cambrian-Ordovician stratigraphy and overlying an undifferentiated Ordovician mélange unit (Figure 1.4). This map also shows a thin sliver of amphibolite in the footwall of the klippe exposed on its eastern edge. These rocks are correlated to the metamorphic aureole at the sole of the Bay of Islands ophiolite complex. The locations of other small occurrences of ultramafic rock in the Spruce Brook area are noted on the Williams and Cawood (1989) map, but the structural controls on these occurrences are not illustrated.

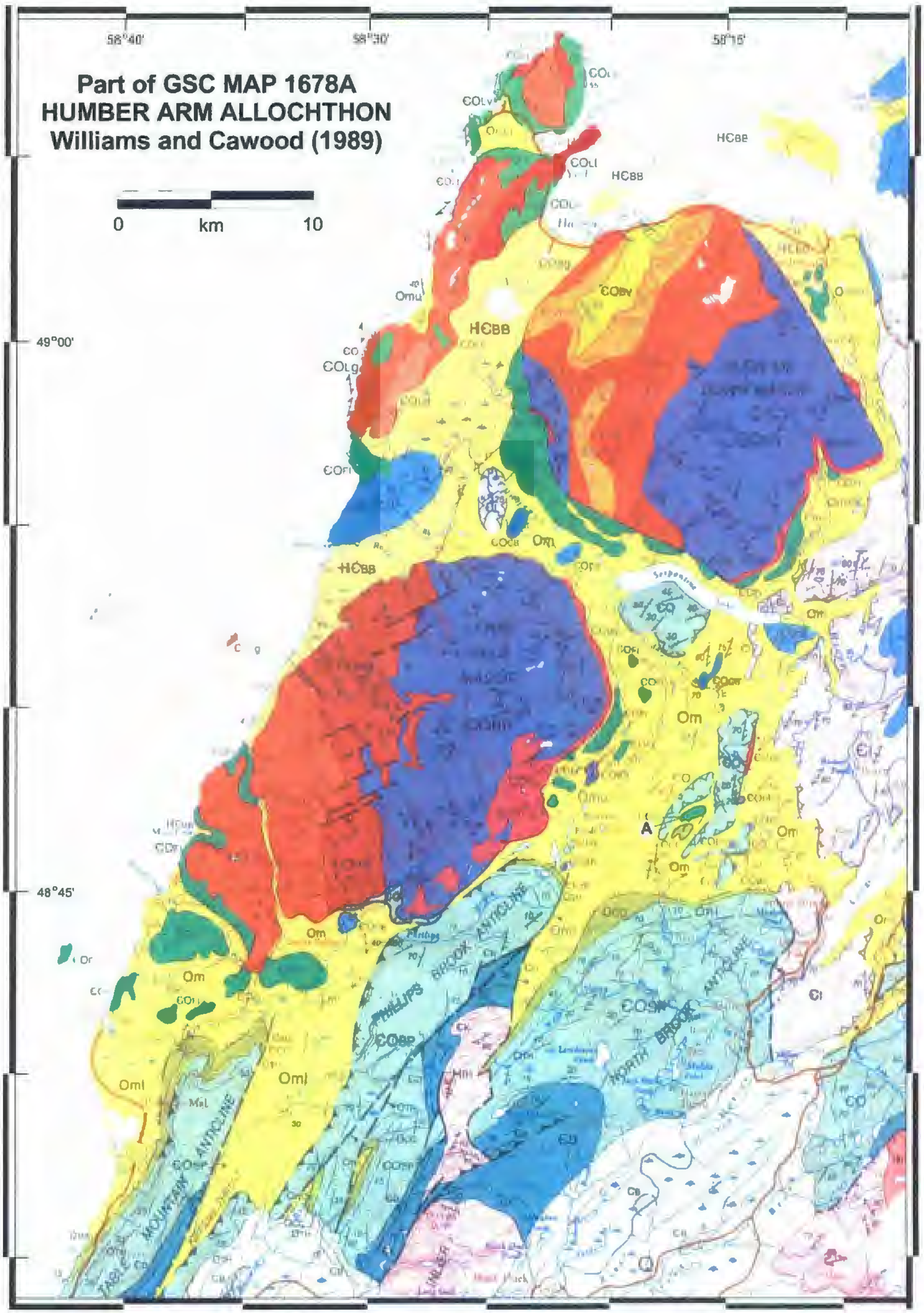


Figure 1.4: Geology of the Humber Arm Allochthon including the North Brook, Philip's Brook and Table Mountain anticlines, the Serpentine Lake, Cache Valley, and Spruce Brook carbonate occurrences, Lewis Hills and Blow Me Down ophiolite Massifs (Williams and Cawood, 1989). See text for description of location 'A'.

Humber Arm Allochthon

Group	Unit	Description
Bay of Islands Complex	COBd	Altered mafic dykes
	COBg	Layered to massive gabbro, diorite, minor trondhjemite
	COBh	Serpentinized harzburgite, dunite, pyroxenite and lherzolite
	COBs	Greenschist, amphibolite, minor quartz-mica schist of metamorphic sole
	COFI	**Fox Island Group:** black, green, purple, and red pillow lava, with minor red siltstone, sandstone and limestone
Humber Arm Supergroup	HCBB	**Blow Me Down Brook Formation:** grey to pink arkosic sandstone and conglomerate; red and grey argillite
	COCB	**Cooks Brook Formation:** thin bedded black shale and light grey limestone with thick limestone breccia units
	CI	**Irishtown Formation:** black shale with thick white quartzite and conglomerate units
	Om	Undivided melange

Autochthon and Par-autochthon

Unit	Description
Occ	**Goose Tickle Group:** grey shale with turbiditic and crossbedded sandstone; limestone breccia
CO	**St. George and Table Head Groups** (OTH)**:** limestone, dolostone and shale
HIH	**Indian Head Complex:** pink and grey feldspar gneiss; massive and foliated granite and anorthosite

The structure was termed the Spruce Ponds Klippe by Knight and Boyce (2002) who produced a 1: 65 000 scale map of the Spruce Brook area (Figure 1.5). These workers determined the internal stratigraphy of the carbonate occurrences and assigned the stata to formations (and locally members) of the Port au Port, St. George and Table Head Groups. Their unit assignments were based on macrofossil assemblages and rock descriptions correlable to type sections for the carbonate platform stratigraphy in the autochthonous portion of the external Humber Zone.

Knight and Boyce (2002) maintain the original structural interpretation (Williams and Cawood 1989) of the carbonate occurrences as klippe. They identify seven klippe thought to represent the erosional remnants of a single thrust slice that emplaced platform carbonate rocks over mélange and Goose Tickle Group rocks (Figure 1.5). This interpretation is supported by their mapping which shows recessively weathering shales in lowland areas between blocks of carbonate. Their mapping shows little or no offset on stratigraphic horizons across the margins of the blocks suggesting that the blocks where all part of a single thrust sheet. Knight and Boyce (2002) further interpret that after its emplacement, the thrust slice was folded about north to northeast trending and plunging fold axes. These folds are thought to re-fold an earlier generation of folds in the carbonate and they produce a regional axial planer cleavage in the fine-grained siliciclastic rocks of the footwall terrane.

The siliciclastic rocks in the footwall of the carbonate occurrences were divided by Knight and Boyce (2002) into Goose Tickle Group, Humber Arm Supergroup and undivided mélange (Figure 1.5). Their mélange unit consists largely of black shale and slate; however, they identify a number of lithologically different terranes. Several of the terranes are thought to be derived from Goose Tickle Group rocks and may thus be classified as broken formation. Another unit within the mélange is described as black shales with melanocratic blocks that include the ultramafic rocks at the Bond Asbestos Mine. One occurrence of pebble conglomerate containing mafic volcanic clasts is recognized within the mélange terrane. This occurrence appears on the Williams and Cawood (1989) map as Fox Island River Group, but was tentatively assigned to the Blow

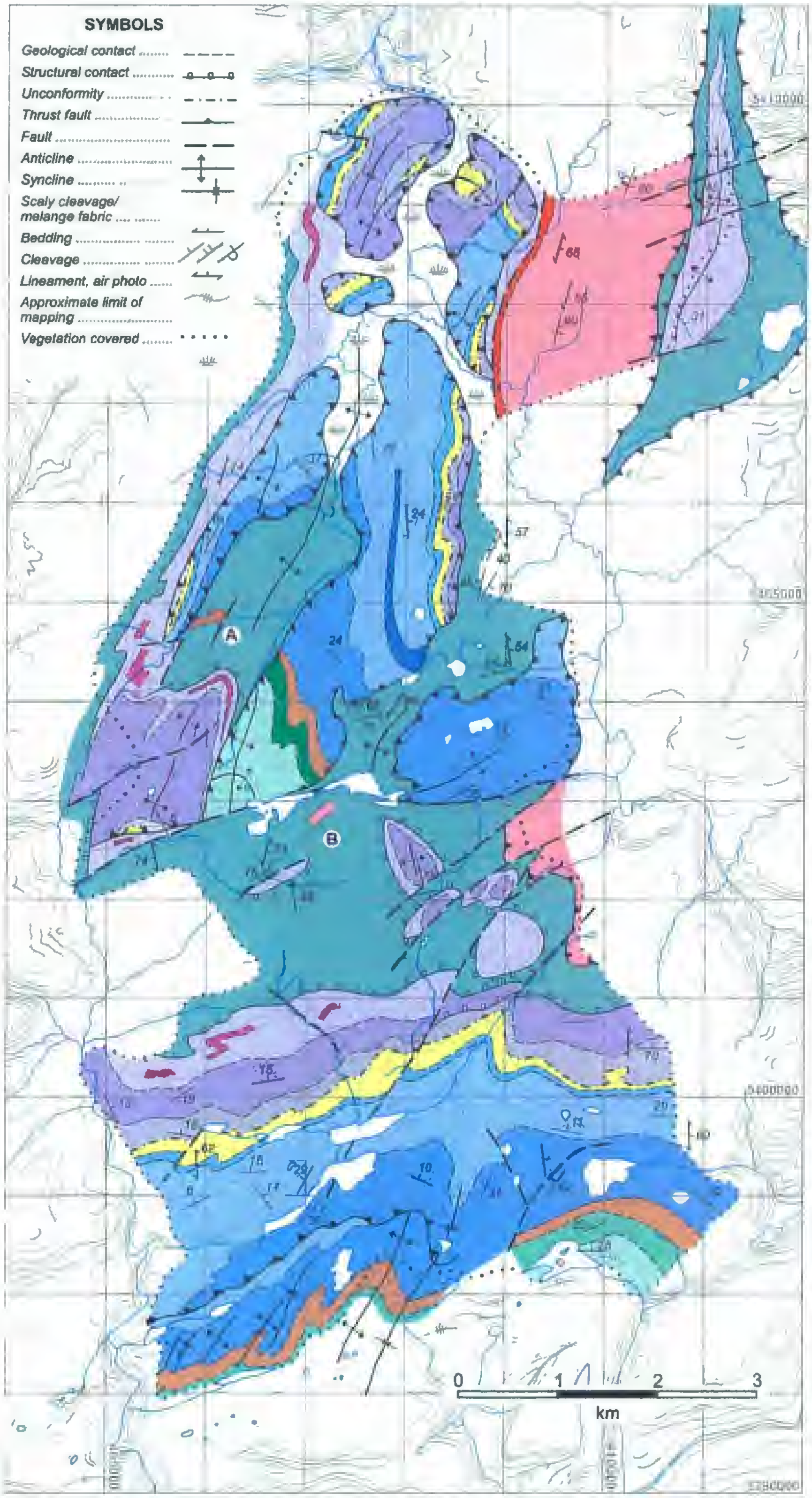


Figure 1.5: Geological map of the Spruce Brook area, including the northern closure of the North Brook Anticline (Knight and Boyce, 2002). See text for descriptions of locations A and B.

LEGEND

HUMBER ARM ALLOCHTHON

- Ultramafic rocks (metamorphic sole): foliated to massive to brecciated
- Blow Me Down Brook Formation: conglomerate, sandstone, minor volcanic
- Irishtown Formation: quartz arenite, slate

PARAUTOCHTHON

Goose Tickle Group

- American Tickle Formation: slate, minor sandstone and siltstone
  - Daniels Harbour Member: limestone conglomerate
- Undivided: includes broken formation and thin melange; dominantly grey slate

Table Head Group

- Table Point Formation: limestone, minor dolostone
  - Spring Inlet Member: fenestral limestone, grainstone and minor dolostone

St. George Group

- Aguathuna Formation: dolostone and limestone
- Catoche Formation: limestone
  - Costa Bay Member: white limestone
  - Thrombolite Moundstone
- Boat Harbour Formation: limestone and dolostone
- Watts Bight Formation: black limestone, minor dolostone, chert

Port au Port Group

- Berry Head Formation: dolostone and minor limestone
- Undivided Berry Head and Petit Jardin formations: dolostone

Figure 1.5: Geological map of the Spruce Brook area, including the northern closure of the North Brook Anticline (Knight and Boyce, 2002).

Me Down Brook Formation of the Humber Arm Supergroup by Knight and Boyce (2002) (locality A Figure 1.4 and 1.5) (see Chapter 2 for more detailed discussion).

The area east of Spruce Brook is shown by Knight and Boyce (2002) as underlain by Irishtown Formation of the Humber Arm Supergroup. This is the western-most extent of this unit with the exception of one small occurrence immediately south of Spruce Ponds (Knight and Boyce, 2002) (locality B, Figure 1.5). The occurrence of Irishtown Formation in the Spruce Brook area marks the western-most extent of a large north-south trending belt of Humber Arm Supergroup that extends south from the north shore of Humber Arm to George's Lake (Williams and Cawood, 1989). The belt includes the Cooks Brook syncline, a large fold structure that sits immediately east of the Blow Me Down ophiolite massif. To the west, Williams and Cawood (1989) define a belt of Blow Me Down Brook Formation sandstone and shale along the south shore of the Bay of Islands where it is interpreted to underlie the Blow Me Down and Lewis Hills ophiolite massifs (Figure 1.4). The area between the Cooks Brook Syncline and exposures of Blow Me Down Brook Formation is defined by Willliams and Cawood (1989) as a belt of Ordovician black shale mélange which constitutes the basal portion of the allochthon. The belt is characterized by isolated occurrences of Cooks Brook Formation limestones, Fox Island River Group volcanic rocks, ultramafic rocks, and several large occurrences of platform carbonate including the Spruce Brook carbonate occurrences (Figure 1.4).

Other important occurrences of platform carbonate in the mélange belt at the base of the Humber Arm Allochthon are exposed at Cache Valley and Serpentine Lake. These occurrences are shown on the Williams and Cawood (1989) map and were studied in detail by Schillereff (1980) and Godfrey (1982) respectively. Schillereff (1980) correlated the carbonate stratigraphy at Cache Valley to the St. George and Table Head Groups and suggested that the slice represents either a post-emplacement thrust sheet or a structural slice within the basal portion of the Humber Arm Allochthon. Alternative models for the emplacement of the Cache Valley sliver have been proposed by Cawood (1988) and by Palmer et al. (2002). Cawood (1988) suggests that the carbonate sliver was emplaced by gravity sliding of the Lewis Hills ophiolite massif during the Acadian orogeny. Conversely, Palmer et al. (2002) correlates the basal thrust of the Cache Valley sliver to a large west-verging thrust fault called the Phillip's Brook fault exposed to the west where it cuts the par-autochthonous carbonate succession. These workers suggest that the Cache Valley sliver represents an erosional outlier of the (Taconic ?) Phillip's Brook fault hangingwall, which is now folded by the Acadian Phillip's Brook Anticline.

At Serpentine Lake, carbonate units of the St. George and Table Head Groups are interpreted to structurally overlie black shale mélange (Godfrey, 1982) and are in turn, structurally overlain by rocks of the Humber Arm Supergroup and the Bay of Islands Complex. The carbonate slice is thus interpreted as an integral part of the assembled Humber Arm Allochthon. The proposed mechanism for emplacement of the slice involves uplift of the carbonate platform by flexure during early allochthon emplacement followed by short-cut faulting into the platform, detaching the Serpentine Lake slice and incorporating it into the imbricated accretionary prism below the Bay of Islands ophiolite massif (Godfrey, 1982).

Structural relationships between the base of the Humber Arm Allochthon and the top of the autochthonous succession are documented in studies of the major par-autochthonous structures in the area north of Stephenville. The structures are depicted in the Williams and Cawood (1989) and Williams (1985) maps as three northeast plunging structures named (from west to east) the Table Mountain, Phillip's Brook and North Brook anticlines (Figure 1.4). The anticlines expose the autochthonous succession including basement and the platform carbonate succession.

The Phillip's Brook Anticline has been studied in detailed by Palmer et al. (2002) and Knight and Boyce (2000). Palmer et al. (2002) notes that the anticline breaches through the allochthon in the southwest but the basal detachment of the allochthon is preserved at several localities along the western margin and northern closure of the anticline. At these localities the carbonate and flysch dip beneath the allochthon and the detachment is folded about the axis of the anticline. In the north the base of the allochthon is delineated by a sheared zone of scaly black shale and locally mylonitized carbonate. Knight and

Boyce (2000) note that the northern end of the anticline is missing approximately 200m of the upper platform stratigraphy and the truncated succession is in direct structural contact with rocks of the Humber Arm Allochthon and Lewis Hills ophiolite. The workers suggest that the truncation may be attributed to deep erosion into the platform in the middle Ordovician or that the succession was decapitated by thrust faulting occurring in the early stages of allochthon emplacement.

East of the Phillip's Brook Anticline is the North Brook Anticline, of which only the northern closure has been mapped in detail. This portion of the structure is described by Knight and Boyce (2002) as a simple succession of gently north-dipping carbonate strata from Port au Port Group through Table Head Group (Figure 1.5). The strata are folded into small northeast plunging fold trains associated with an east-dipping cleavage fabric. The succession is locally disrupted by early faults, including one roughly bedding parallel fault that repeats over 100 m of St. George Group strata. The anticline is separated from the overlying Spruce Brook carbonate occurrences to the north, by a belt of shale mapped by Knight and Boyce (2002) as mélange. Within this belt they map a number of domal structures cored by Table Head Group limestone surrounded by American Tickle Formation (Goose Tickle Group) shale. These structures are described by Knight and Boyce (2002) as outliers of the North Brook structure that are exposed as windows through the overlying mélange belt.

1.8 Methods

This study has its basis in detailed field mapping characterized by comprehensive ground coverage and the compilation of a large set of structural data. Geological reconnaissance was conducted utilizing easily accessed outcrop exposures along roads and in the numerous small brooks cutting the map area. These initial traverses helped to generally define stratigraphic and structural relationships which were later refined with more targeted form-surface-trace mapping. Working from a 1:50 000 scale topographic map sheet and 1:12 500 scale colour air photos; traverses where designed to investigate geomorphic lineaments and general structural grain.

Outcrop station locations where recorded using a Global Positioning System (GPS) with an accuracy of 5-15m. Orientations of planar and linear fabrics were measured at each station using a Freiburg fabric compass and recorded in field note books with accompanying detailed sketches. Location and orientation data were compiled into a Microsoft Access database linked to a MapInfo 7.5 geographical information system that accurately plots station locations onto a digital topographic map sheet obtained through the Newfoundland Geological Survey. Orientation data was plotted on the MapInfo file using a program called Geo Map Symbol made available by Rod Holcombe at the University of Queensland. The final map compilation was drafted using MapInfo 7.5.

Lithological unit assignment was based chiefly on field observation; however where unit assignment was ambiguous, petrographic analysis was used to help differentiate between units. Paleontological data, including macro and micro fossils, were used to date carbonate rocks and to help correlate carbonate units to those of previous workers.

Structural interpretations for this project are developed using form-surface-trace maps to define the geometry of structural elements in plane view in combination with detailed balanced cross sections used to project structures into the subsurface and above the level of erosion. The procedures for these constructions are described in detail in Basic Methods of Structural Geology by Marshak and Mitra (1988). Angular relationships between dipping planar and linear features were calculated using GEOcalculater 4.5. Lower hemisphere, equal area plots were prepared and contoured using GEOorient 9 with a contour level of 1% unit area. Both programs are made available by Rod Holcombe at the University of Queensland. All orientation data presented in this study are given in dip/dip-direction and plunge-trend formats for planes and lines respectively.

Chapter 2

Stratigraphy

2.1 Introduction

This chapter presents descriptions of rock units defined in the Spruce Brook area. These include lower Paleozoic carbonate and siliciclastic rock units, mafic-ultramafic igneous rock units and metamorphic rock units. Unit descriptions are based on field observation and thin section analysis. Thickness estimates are based on map patterns, detailed structural cross sections, and field observations.

2.2 Lower Paleozoic Platform Carbonate

Cambrian-Ordovician platform carbonate strata in the Spruce Brook area are exposed in a generally north-south trending belt that is approximately 8 km in length and about 5.5 km wide (Insert 1). Topographic relief is fairly low in the area and the outcrop exposure is somewhat discontinuous, isolating carbonate occurrences into six main areas expressed morphologically as a series of low rolling hills. The northern termination of the belt is defined by two round hills that lie just north of Loggers School road. The main outcrop area of the belt constitutes a long ridge extending from just south of Loggers School Road to the Spruce Ponds (Insert 1). A southern branch of Loggers School Road and Spruce Brook run parallel to this ridge on its east and west sides respectively. The area west of the ridge is heavily vegetated and fairly flat lying, but mapping has delineated two large occurrences of platform carbonate (Insert 1). East of the ridge is another large occurrence of carbonate. The eastern and southern edges of this occurrence form prominent north-south and east-west trending scarps along the Spruce Brook drainage valley. The belt is terminated in the south by a prominent east-west trending lineament, but several small occurrences of carbonate are noted on hill tops in the area between this lineament and the northern closure of the North Brook Anticline, south of the map area (Insert 1).

2.3 Port au Port Group

Within the autochthonous succession of the external Humber Zone the middle/Upper Cambrian limestones of the Port au Port Group conformably overlie siliciclastic and carbonate rocks of the Labrador Group. These rocks record the development of a narrow, high-energy carbonate platform (Knight et al., 1995). At Spruce Brook, the upper portion of this succession is preserved, namely, the peritidal carbonates of the Petit Jardin and Berry Head formations.

2.3.1 Berry Head/Petit Jardin formations

The oldest carbonate strata in the Spruce Brook area are well exposed along the southeastern and southwestern branches of Loggers School Road. They consist of a unit of buff weathering, thick-bedded dolostone with rare limestone overlain by an upper unit of dolostone and dololaminite intercalated with stylo-nodular, burrowed, stromatolitic and laminated limestone (Figure 2.1 A). Knight and Boyce (2002) correlated these strata to the Berry Head and Petit Jardin formations.

2.4 St. George Group

The Lower Ordovician carbonate succession of the St. George Group was deposited conformably over the Port Au Port Group as the carbonate platform evolved into a wide, low energy platform (James et al., 1989; Knight et al., 1995). The St. George Group succession is divided into four formations, from bottom to top: Watts Bight, Boat Harbour, Catoche, and Aguathuna formations. All four units occur in the Spruce Brook area (Figure 1.3 and Insert 1).

2.4.1 Watts Bight Formation

The Watts Bight Formation is characterized by dark grey burrowed and thrombolitic dolomitic and cherty limestone (Figure 2.1 B). The formation contains some light grey weathering beds of dololaminite and the limestone is locally replaced by finely sucrosic dolostone. The contact between the Watts Bight Formation and the underlying Berry Head Formation is not directly observed; nor is the transition into the overlying Boat Harbour Formation. The upper and lower boundaries of the Watts Bight Formation are nevertheless tightly constrained by scattered outcrops along the southwestern branch of Loggers School Road. The formation is estimated to have a thickness of about 45 m in the Spruce Brook area.

2.4.2 Boat Harbour Formation

The overlying Boat Harbour Formation is composed of meter-scale parasequences of light grey to buff weathering, burrowed dolomitic limestone capped by laminated limestone or dololaminite (Knight and Boyce, 2002) (Figure 2.2 A). This unit occurs in the carbonate successions exposed in the eastern, central and western portions of the Spruce Brook map area. Of the three occurrences, only the central region contains a complete stratigraphic succession from Watts Bight Formation through Catoche Formation. Unfortunately, outcrop exposure is poor in the vicinity of the inferred Watts Bight-Boat Harbour and Catoche- Boat Harbour transitions. The thickness of the formation can therefore only be estimated from structural cross sections (See Chapter 3), which depict the unit as having an apparent thickness in excess of 150m. The thickness of the Boat Harbour Formation shown in these sections is greater than that exposed in the nearby Phillip's Brook structure (Knight

A) Upper Berry Head Formation: buff weathering dololaminite with chert, intercalated with stylonodular, burrowed and stromatolitic grey limestone.

B) Watts Bight Formation: dark grey coarsely burrrowed limestone

Figure 2.1: Berry Head Formation (Port au Port Group) and Watts Bight Formation (St. George Group) from southern branch of Loggers School Road

and Boyce 2000) where it is estimated to be approximately 100m thick. The increased thickness of the Boat Harbour Formation in the Spruce Brook area is attributed to structural thickening caused by internal deformation of the unit (See Chapter 3).

2.4.3 Catoche Formation

The Catoche Formation consists of medium- to thick-bedded grey limestone that is typically burrowed and dolomite mottled (Figure 2.2 B). These limestones are locally interbedded with stylo-nodular or ribbon-bedded dolomitic lime mudstone. Scour-based lenses of grainstone occur throughout the formation and chert is common. Fossils occurring in the Catoche Formation include: macluritid and murchisonid gastropods, silicified opercula, straight cephalopods, crinoid and trilobite fragments (Knight and Boyce, 2002).

Thickness estimates for the Catoche Formation are hampered by poor outcrop exposure, intense deformation and the monotonous character of the unit. The maximum thickness of the unit is inferred from a continuous succession of Catoche Formation strata found in the central portion of the map area. Here the succession has a stratigraphic thickness of approximately 200m. The top of the unit is, however, not exposed in this locality, so the true maximum thickness of the unit may be more than 200m. The thickness of the Catoche Formation is thought to be variable in the western part of the map area where the unit has a calculated thickness of approximately 170m.

Thickness estimates for the Catoche Formation exposed in the nearby Phillip's Brook Anticline are on the order of 100m; considerably thinner than the exposures of the unit in the Spruce Brook map area (Knight and Boyce 2000). The unusual thickness of the unit at this locality must be attributed to structural thickening by internal deformation (see Chapter 3).

A) Boat Harbour Formation: meter-scale sequences of finely laminated dolomitic limestone and massive burrowed limestone.

B) Catoche Formation: dark grey medium- to thick-bedded, dolomite-motled and burrowed lime-

Figure 2.2: Boat Harbour and Catoche Formations (St. George Group) from southern branch of Loggers School Road and Spruce Brook, respectively.

The Catoche Formation is capped by the *Costa Bay Member*, an intraclastic lime-grainstone and skeletal mudstone (Knight and Boyce, 2002). The unit is distinctly light grey to white weathering and is typically finely laminated (Figure 2.3 A). The member is well exposed in the northern part of the Spruce Brook map area. Here it consists of meter-thick parasequences of finely laminated and massive limestone. At this locality the thickness of the member is estimated to be between 10 and 15m, however this is not typical of exposures of the unit in the central portion of the Spruce Brook map area. There the unit occurs variably and rarely exceeds thicknesses of a few meters.

2.4.4 Aguathuna Formation

The uppermost strata of the St. George Group belong to the Aguathuna Formation. This unit consists of meter-scale parasequences of interbedded, burrowed and stromatolitic limestone, lime grainstone, lime mudstone or bioturbated dolostone. These lithologies are interbedded with dololaminite, argillaceous dololaminite and laminated limestone (Knight and Boyce, 2002) (Figure 2.3 B).

The thin-bedded, muddy character of the Aguathuna Formation makes its host to intense internal deformation including small-scale folding and internal imbrication caused by layer parallel detachments. This often makes thickness estimates difficult to establish, particularly in light of the fact that the undeformed unit typically shows variable thickness due to erosion on the overlying St. George Unconformity. In the northern portion of the Spruce Brook map area, the unit is estimated to have a stratigraphic thickness on the order of about 10m, based on outcrops along Loggers School Road. The thickness of the Aguathuna Formation must be considerably thicker in the central portion of the map area where it is exposed in a small synclinorium. This structure is interpreted, based on down-plunge projections, to carry a package of Aguathuna Formation strata approximately 125m thick. This however may not represent a true thickness for the unit, rather an enveloping surface

A)Costa Bay Member: clean white to light grey laminated limestone

B) Aguathuna Formation: burrowed and stromatolitic grey limestone interbedded with dololaminite and argillaceous dololaminite

Figure 2.3: Coasta Bay Member (Catoche Formation) and Aguathuna Formation (St. George Group) from Loggers School Road and Spruce Brook, respectively.

for an intensely small-scale folded succession. Furthermore, it is possible that the unit is internally structurally thickened by small scale faulting occurring within the synclinorium.

2.5 The St. George Unconformity

The Lower Ordovician St. George Group is separated from the overlying Middle Ordovician Table Head Group by the St. George Unconformity. This is a wide-spread unconformity surface that is associated with a period of uplift and erosion of the carbonate platform. It is believed to be the result of the migration of a peripheral bulge formed in response to Taconic over thrust loading of the Laurentian Continental shelf (Knight et al., 1991).

The St. George Unconformity is exposed in two localities on Loggers School Road in the northern and southwestern portions of the Spruce Brook map area. At both localities the unconformity surface is sculpted by karren, suggesting significant erosion into the Aguathuna Formation. This may account for some of the observed variation in the thickness of the Aguathuna Formation in the map area.

The unconformity exposed in the northern portion of the Spruce Brook map area is overlain by a thin unit of conglomerate containing dolostone pebbles intercalated with a sequence of laminated limestones. In the south, the irregular surface of the unconformity is filled and overlain by a white stylolitic limestone that locally has a thickness of about 75 cm (Figure 2.4 A). These lithologies are assigned to the basal Spring Inlet Member of the Table Point Formation, Table Head Group.

2.6 Table Head Group

The Table Head Group represents carbonate deposition on the edge of the middle Ordovician Taconic foreland basin. These limestones are deposited unconformably over eroded and block faulted St. George Group rocks. The succession consists of well-bedded limestone of the Table Point Formation, including its basal Spring Inlet Member. The Table Point Formation is overlain by the Table Cove Formation which is increasingly argillaceous and typically shows evidence of soft sediment deformation. At type localities for the Table Head Group on the Port au Port Peninsula and at Hare Bay, the limestones grade upward into the siliciclastic Goose Tickle Group recording the burial of the carbonate platform by flysch shed from the advancing Taconic Allochthons.

2.6.1 Table Point Formation

The Table Point Formation consists of the basal *Spring Inlet Member* and an upper, unnamed limestone unit. The succession is best preserved in the southwestern corner of the Spruce Brook map area along a southern branch of Loggers School Road. Here, the St. George Unconformity outcrops near the road bed and the overlying Table Point succession is exposed in scattered outcrops in the hill to the north (Insert 1).

The Spring Inlet Member, is a thin-bedded succession of stylonodular dolomitic lime mudstone interbedded with dolomitic laminated and cross-laminated limestone or dololaminite (Figure 2.4 B). Lenses of thin-bedded grey grainstone occur throughout the unit and are locally up to a meter thick. Based on exposures along Loggers School Road, the member is estimated to be about 35-40m thick.

The overlying limestones of the upper Table Point Formation are typically well bedded stylo-nodular to lumpy, locally burrowed, dolomitic lime mudstones (Figure 2.5 A). Thin, scour based lenses of skeletal grainstone occur throughout the unit, particularly in its lower portion immediately above the transition from the Spring Inlet Member. The stylonodular to lumpy portion of the unit locally has a brecciated to conglomeratic appearance with ribbon-bedding preserved in some larger pseudoclasts. This lithology is attributed to minor gravity sliding prior to lithification of the lime mud.

A) St. George Unconformity surface showing Aguathuna Formation dolostone sculpted by karren filled by white stylolitic limestone of the overlying Spring Inlet Member

B) Spring Inlet Member: thin bedded laminated and massive fine-grained grey limestone with grainstone lens

Figure 2.4: St. George Unconformity and overlying Spring Inlet Member from a southern branch of Loggers School Road.

The top of Table Point Formation is generally not preserved in the Spruce Brook area, and most exposures of the unit are highly deformed, making thickness estimates highly inaccurate. The upper Table Point Formation is interpreted to have a minimum thickness of approximately 75 m based on structural sections, but locally has a structural thickness of more than double that amount.

2.6.2 Table Cove Formation

The Table Cove Formation is described as a succession of thin-bedded dolomitic ribbon limestone interbedded with limestone conglomerate (Stenzel et al., 1990; Knight and Boyce, 2002). This unit occurs in limited outcrop exposures at two localities, one in the southwestern portion and one in the southeastern portion of the Spruce Brook map area (Figure 2.5 B). At both localities the stratigraphic relationship to adjacent Table Point Formation limestone is ambiguous due to poor exposure and the structurally complex nature of the two areas. Although the stratigraphic sequence is dismembered, the Table Cove occurrences are consistently the highest part of the platform stratigraphy preserved in the Spruce Brook carbonate occurrences; no intact transition to siliciclastic sedimentary rocks (i.e. shales of the Black Cove Formation) is anywhere mapped in the area.

2.7 Goose Tickle Group

The shale and sandstones of the Goose Tickle Group are interpreted as flyschoid rocks deposited over the carbonate platform in upper Middle Ordovician times (Stenzel et al., 1990). On the Port au Port Peninsula the Goose Tickle Group is known as the Mainland Sandstone, whereas the type localities for the unit at Hare Bay are divided into the Black Cove and American Tickle formations (Stenzel et al., 1990). Shale and sandstone successions in the Spruce Brook area are correlated to the American Tickle Formation. These successions locally include limestone

A) Upper Table Point Formation: burrowed lumpy, nodular to stylonodular grey limestone

B) Table Cove Formation: ribbon bedded grey limestone

Figure 2.5: Table Point Formation (Table Head Group) and overlying Table Cove Formation from and western and southern branches of Loggers School Road, respectively.

conglomerate horizons assigned to the Daniels Harbour Member by Knight and Boyce (2002).

The thickness of the American Tickle Formation has been described by previous workers as difficult to assess because of the typically tectonized nature of the unit (Stenzel, 1992). Intact stratigraphic successions defined in Hare Bay and Bonne Bay suggests a highly variable minimum thickness from 80m to 350m (Stenzel, 1992). The thickness of the unit in the Spruce Brook area can not be estimated because its base is not exposed and because the rocks are highly deformed.

2.7.1 American Tickle Formation

Rocks assigned to the American Tickle Formation occurring in the Spruce Brook map area include laminated dark grey siliceous and calcareous shales (Figure 2.6 A). The succession locally includes shales that are highly siliceous and have a distinctive massive appearance. Sandstones of the American Tickle Formation occurring in the map area are typically thin to thick beds or lenses of gritty, dirty brown-weathering, arkosic sandstone. The coarser horizons have mafic volcanic and rare serpentinite clasts, as well as a variety of sedimentary lithic clasts, including chert. The clasts tend to be angular to subrounded, and are generally matrix-supported.

A distinctive lithology of the American Tickle Formation in the Spruce Brook study area is identified in the extreme south immediately above the crest of North Brook Anticline (Insert 1). It is characterized by a succession of brown weathering, thin-bedded, cross-laminated, micaceous sandstone interbedded with black shale (Figure 2.6 B). This sandstone-shale succession is unique to the American Tickle Formation and can be used to differentiate the unit from other shale-dominated units occurring in the map area. The brown sandstone identified in the south can be correlated to similar lithologies in the shale terranes in the central and western portions of the study area; its presence forms the basis of the assignment of these terranes to the American Tickle Formation.

A) Black siliceous shale with silty laminations. Highly cleaved and F1 folded.

B) Thin beds of brown weathering cross-laminated micaceous sandstone.

Figure 2.6: American Tickle Formation (Goose Tickle Group) from western branch of Loggers School Road and from southern map area near the northern closure of the North Brook Anticline respectively.

Tentatively assigned to the American Tickle Formation is a succession of pebble to boulder conglomerate and sandstone in the western portion of the Spruce Brook map area (Insert 1). The conglomerate forms a large lensoid body surrounded by black shale and is composed of well-rounded clasts of vesicular basalt, limestone, chert, shale and siltstone supported by a fine-grained, poorly sorted matrix (Figure 2.7 A). This occurrence was assigned to the Fox Island Group by Williams and Cawood (1989) ('A' Figure 1.4), and although the basalt clasts are likely derived from the Fox Island River Group, the occurrence is clearly sedimentary in origin. This study supports the contention of Knight and Boyce (2002) that the conglomerate was deposited as a thick turbitity flow. Knight and Boyce (2002) suggest a number of possible correlatives for this conglomerate including the Blow Me Down Brook or Irishtown formations of the Humber Arm Supergroup ('A' Figure 1.5), however this study favors their correlation to the Goose Tickle Group particularly the Howe Harbour Member of Quinn (1995). The Howe Harbour Member is described from localities in the Northwest Arm area, in exposures near the stratigraphic top of the American Tickle Formation. It includes meter-thick, scour-based lenses of poorly sorted pebble conglomerate with clasts of mafic volcanic, fine-grained limestone, chert and shale. The lenses are thought to be deposited by debris flows or high-concentration turbidity currents (Quinn, 1995).

The occurrence of volcanic conglomerate in the western part of the map area is unique to the area because of its size and the coarseness of the detrital material, however, compositionally it is very similar to an occurrence of thick-bedded coarse-grained to conglomertatic sandstone outcropping along the road just south of Spruce Ponds ('B' Figure 1.5). This occurrence was mapped by Knight and Boyce (2002) as Irishtown Formation, but is here interpreted as American Tickle Formation and correlated to the volcanic conglomerate in the west because it contains angular clasts of basalt, shale fragments and chert. The similarity of the clast assemblage in the two sandstone occurrences suggests that they may belong to a correlatable horizon in the American Tickle Formation, or occur at various stratigraphic levels, representing deposition from a common source over an extended period of time.

Limestone conglomerate occurs as lenses within grey shale of the American Tickle Formation throughout the Spruce Brook map area. These conglomerates are assigned to the *Daniels Harbour Member* by Knight and Boyce (2002). Lenses are typically less than 1m thick and often have little lateral continuity, but their original shape can only be estimated from deformed successions. The conglomerate is largely comprised of nut-sized irregular-shaped clasts of lime mudstone surrounded by a fine grained dolostone matrix (Figure 2.7 B). The clasts comprising the conglomerate are interpreted to have been derived from the Table Point Formation (Knight and Boyce, 2002). Some occurrences of the Daniels Harbour Member conglomerate in the western part of the map area are very similar to the intraformational breccias in the upper Table Point Formation, in that the conglomerate is monomictic and locally has preserved original layering of the lime mud. The conglomerate occurrences are, however mappable, isolated lenses in black shale and are therefore assigned to the Daniels Harbour Member. Lower Middle Ordovician trilobite *Psedomera barrandei* (W.D. Boyce pers. comm., 2005) was recovered from one such lens in the western Spruce Brook map area. This fossil is typical of the Table Cove Formation. Although the fossil may be detrital in origin, its presence in the conglomerate and the similarity of the conglomerate to litholgies of the upper carbonate platform suggest that the shale-limestone conglomerate successions assigned to the Daniels Harbour Member in the map area were deposited close to the top of the carbonate platform and are roughly coeval with the uppermost Table Point - Table Cove formations.

2.8 Humber Arm Super Group

Rocks of the Humber Arm Supergroup make up the lower structural slices of the Humber Arm Allochthon, which structurally overlies the carbonate platform rocks and rocks of the Goose Tickle Group in the Bay of Islands and Stephenville map areas (e.g.: Williams and Cawood, 1989, Waldron and Palmer, 2000). In the Spruce Brook area, shale and sandstone assigned to the Irishtown Formation are exposed in

A) American Tickle Formation (?): Matrix-supported pebble to cobble conglomerate with well-rounded mafic volcanic clasts.

B) Daniels Harbour Member: limestone conglomerate with irregularly shaped clasts of Table Point lime mudstone in a fine-grained dolomitic matrix.

Figure 2.7: American Tickle Formation (Goose Tickle Group) from western branch of Loggers School Road.

the area east of the platform carbonate occurrences (Insert 1). Several exposures in Spruce Brook along the eastern edge of the limestone occurrences are correlated to the ribbon limestones and calcareous shales of the Cooks Brook Formation.

2.8.1 Irishtown Formation

The Irishtown Formation (Bruckner, 1966) consists of medium- to thick- bedded quartz-rich coarse-grained to conglomeratic sandstone, with intervals of black shale and siltstone. The stratigraphy of the unit is defined from numerous exposures around Humber Arm, including many large outcrops and road cuts in the town of Corner Brook. Macrofossil assemblages in the unit suggest it is late Early to Middle Cambrian in age. The total thickness of the Irishtown Formation has been estimated at 550m (Botsford, 1988), however such estimates are hampered by the intense folding and internal thrust imbrication typical of many exposures.

In the study area the Irishtown Formation underlies a large area immediately east of Spruce Brook. It typically consists mainly of grey shale with white-weathering sandy laminations; locally interbedded with quartz arenite (Figure 2.8 A). Sandstone beds range in thickness from 10cm to 3m and are typically massive but are locally laminated or cross-laminated. Bottom structures such as load-casts are common.

2.8.1 Cooks Brook Formation

Strata assigned to the Cooks Brook Formation outcrop in several localities in Spruce Brook and along a southern branch of Loggers School Road. These occurrences constitute narrow fault-bounded structural slivers that are intensely internally deformed (Insert 1).

The detailed stratigraphy of the Cooks Brook Formation is defined by Botsford, (1988) in the area around Humber Arm. Here the formation overlies Irishtown

A) Thin beds of laminated quartz-rich sandstone in siliceous shale of the Irishtown Formation

B) Deformed ribbon limestone and black shale

Figure 2.8: Irishtown Formation exposed on a southern branch of Loggers School Road east of platform limestone occurrences and deformed Cooks Brook Formation strata occurring in Spruce Brook.

Formation shale and is divisible into five distinct members deposited on a toe-of slope setting during the Late Cambrian to Early Ordovician.

Although the exposed section of the Cooks Brook Formation at Spruce Brook is too incomplete for precise correlation of the units at the member level, several of the typical Cooks Brook lithotypes are present. These include black and green banded shale with intermittent 3-5 cm thick ribbon beds of limestone (Figure 2.8 B); ripple laminated calcareous siltstone and sandstone; buff-weathering calcareous shale and a succession of black shale with limestone pebble conglomerate (Figure 2.9 A).

The assignment of the strata at Spruce Brook to the Cooks Brook Formation is based largely on a condont age derived from a lens of limestone conglomerate in black shale outcropping on a southern branch of Loggers School Road. The sample contained an Early Ordovician conodont assemblage (see Appendix 2). Strata elsewhere in the map area are deemed part of the Cooks Brook Formation based on their structural proximity to, and lithotype association with this key outcrop.

Tentatively grouped with the Cooks Brook Formation is a fault-bounded succession of grey shale with 10 to 20 cm thick lenses of yellow weathering dolomite and sandstone located in the south-central portion of the map area (Insert 1). The succession is poorly exposed and the lithology is determined largely from float mapping. The assemblage of shale and dolomite is somewhat atypical of the Cooks Brook Formation but the dolomite occurrences are reminiscent of those described by Botsford (1988) in the lower portion of the overlying Middle Arm Point Formation. The shales, themselves, however lack the red and green colour that is characteristic of the Middle Arm Point Formation. The affinity of this shale terrain is therefore uncertain, but may represent an atypical lithofacies of the Cooks Brook Formation or a lithology transitional between upper Cooks Brook Formation to Middle Arm Point Formation.

A) Limestone pebble conglomerate forming a thick lens in black silicious shale; contains Early Ordovician conodont assemblage.

B) Massive grey-green weathering serpentinite with brecciated texture.

Figure 2.9: Cooks Brook Formation and altered ultramafic rock outcropping in the southeastern portion of the map area.

2.9 Mafic/Ultramafic Igneous Rocks and Metamorphic Rocks

Mafic and ultramafic rocks outcropping in the Spruce Brook area are largely carbonitized gabbro and serpentinized peridotite. At the Bond Asbestos mine, serpentinized ultramafic rocks are mostly grey-brown to reddish weathering, and are massive or brecciated in appearance with small veins of chrysotile (Figure 2.9 B). Other serpentinite outcrops in the area have schistose, anastomosing cleavage fabrics with lozenge-shaped augen of massive serpentinized peridotite (Figure 2.10 A).

Altered mafic rock occurs as large float southeast of the Bond Mine. These rocks contain microcrystalline serpentinite and course grained epidote and zoesite as pesudomorphs of clinpyroxene and plagioclase crystals. This is indicative of high temperature alteration of medium- to course-grained gabbro.

An occurrence of metamorphic rock consisting mainly of banded amphibolite lies in the northern portion of the Spruce Brook map area, located on Loggers School Road (Insert 1 and Figure 2.10 B). The unit has a well developed foliation fabric that is locally tightly folded. The sheet dip of the foliation suggests that the unit may have a maximum thickness in excess of 150m. Outcrops of this lithology define a curved belt with about 1 km of strike length. Along its length, the amphibolite unit contains a number of outcrop-scale lenses of serpentinized peridotite. This unit was assigned by Williams and Cawood (1989) to the metamorphic sole of the Bay of Islands ophiolite Complex.

A) Serpentinite with anastomosing schistose fabric and augen of more massive serpentinized peridotite

B) Folded foliation in amphibolite assigned to metamorphic sole of the Bay of Islands Complex.

Figure 2.10: Bay of Islands Complex rocks in the Spruce Brook map area Loggers School Road south and north respectively.

Chapter 3

Structure

3.1: Introduction

The carbonate occurrences in the Spruce Brook area form a north-south trending belt with a strike-length of roughly 9km and a width of approximately 5.5km. The carbonate belt is bounded to the west by a belt of shale of the American Tickle Formation (Western Shale Belt) and to the east by clastic rocks of the Irishtown Formation (Eastern Shale Belt). To the south, the carbonate belt is separated from the platform carbonates of the North Brook Anticline by a belt of American Tickle Formation shale denoted as the Southern Shale Belt (Figure 3.1).

The carbonate occurrences are divided into six discrete structural domains. The domains have internally consistent structural style and are bounded by fault contacts. They constitute major thrust slices that are interpreted to form part of an overall westerly verging imbricate thrust stack. The thrust slices are designated, from bottom to top and west to east, as *Spruce Brook 1* through *6* (*SB1-SB6*) (Figure 3.1). This chapter describes the setting, stratigraphy, and internal structural architecture of each of the slices, and the contact relationships of the slices with one another and the adjacent shale belts.

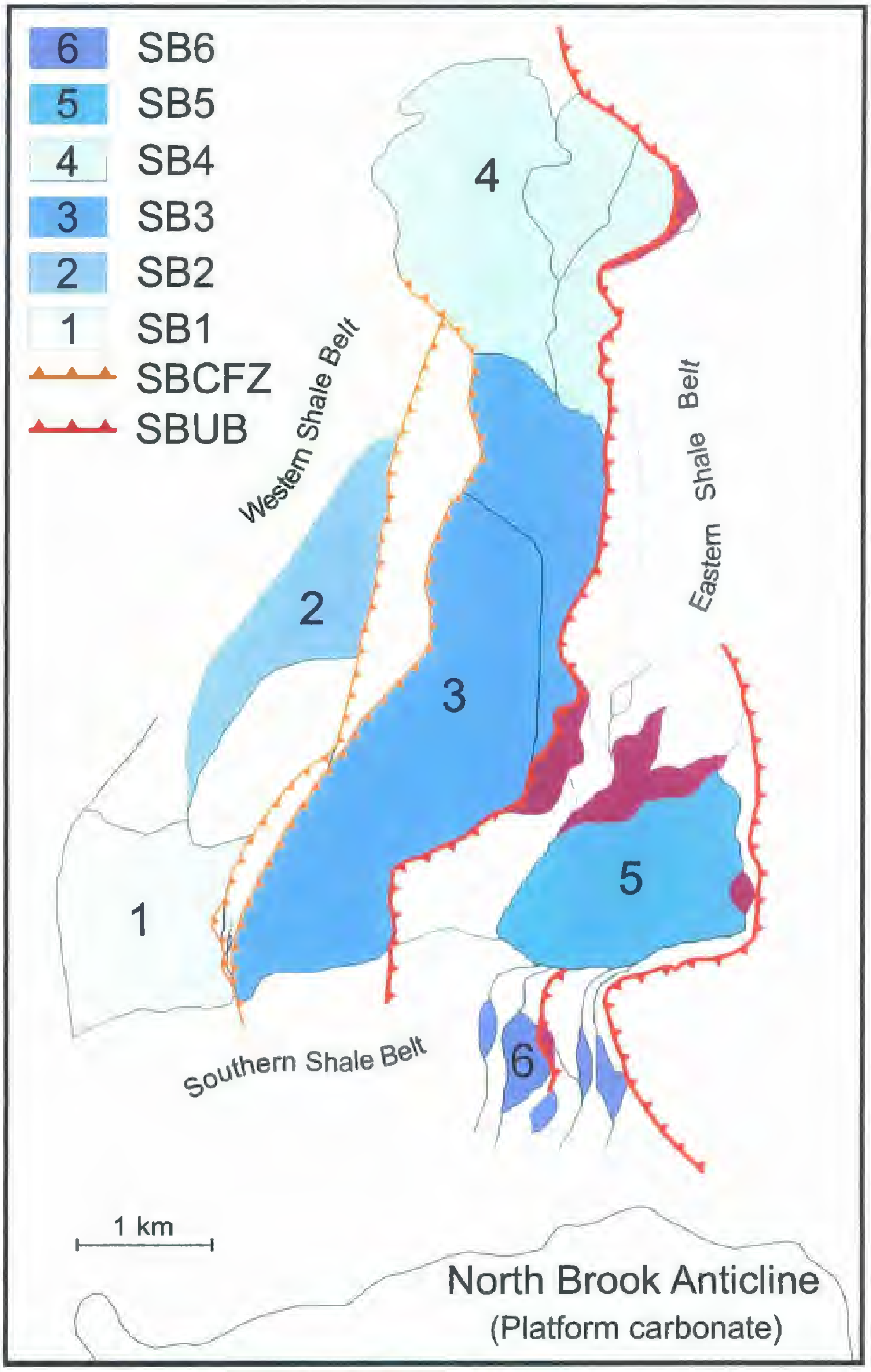


Figure 3.1: Simplified geological map of the Spruce Brook area showing the main structural domains and major fault zones. Structural domains are denoted from top to bottom Spruce Brook 1-6 (SB1-6); fault zones are termed the Spruce Brook Central Fault Zone (SBCFZ) and the Spruce Brook Ultramafic Belt (SBUB)

The Spruce Brook thrust slices are cut by two major fault zones termed the Spruce Brook Central Fault Zone (*SBCFZ*) located in the west-central portion of the map area, and the Spruce Brook Ultramafic Belt (*SBUB*) that forms the eastern upper boundary of the carbonate belt (Figure 3.1). These fault zones are characterized by small-scale duplexing of their footwall and hangingwall terranes. The SBUB is a major regional fault zone that carries slivers of altered mafic/ultramafic igneous rock and metamorphic rocks assigned to the Bay of Islands Complex, as well as dismembered successions of the Humber Arm Supergroup including the Cooks Brook and Irishtown formations.

3.2 Western and Southern Shale Belts

3.2.1 Western Shale Belt

The Western Shale Belt is a north-south trending belt of grey to black shale and micaceous sandstone assigned to the American Tickle Formation with local occurrences of grey limestone conglomerate assigned to the Daniels Harbour Member (Figure 3.1 and Insert 1). The succession is strongly deformed and is characterized by a pervasive steep to moderately east-dipping cleavage fabric.

In the central portion of the Western Shale Belt, exposed west of SB2, the shales exhibit a moderately to steeply east-dipping slatey S1 cleavage fabric (Figure 3.2). Bedding is typically parallel to cleavage, but is only locally observed. In this area intrafolial F1 fold hinges are defined by northeasterly plunging 'fish hook' structures (Ramsay and Huber, 1987) with one attenuated limb representing the steep-limb of a close to isoclinal asymmetrical fold that has been progressively stretched and rotated into parallelism with the cleavage fabric. Unfortunately, the F1 macroscopic fold geometry cannot be reconstructed due to a lack of continuous bedrock exposure, as well as the strong transposition of bedding.

Small-scale F2 folds in the Western Shale Belt are observed near the western edge of the SB4 thrust slice (Insert 1; Figure 3.1; see Section 3.7). The folds are typically 50 cm-scale folds of S1 cleavage with a weakly defined moderately east-dipping axial planar S2 cleavage fabric. Asymmetric fold shapes indicate that the F2 fold system is locally westerly verging with fold axes plunging toward the southeast (Figure 3.2).

At several localities near the northern edge of SB1, the shale contains highly strained lenses of grey limestone conglomerate assigned to the Daniels Harbour Member. The lenses range in structural thickness from less than a meter to several meters. The lenses show well-developed east dipping cleavage fabric that is parallel to the cleavage in the adjacent shale. The conglomerates also show a prominent down-dip stretching lineation defined by elongated limestone clasts. Based on the highly deformed nature of these conglomerates and the transposition of original bedding in the shale, the Western Shale Belt is interpreted to be, at least locally, a zone of high strain.

The contact relationships between the Western Shale Belt and the SB1, SB2 and SB4 thrust sheets are complex, but relatively well constrained in outcrop. The contacts are described in detail in subsequent sections in this chapter. The carbonate thrust slices are interpreted to form a gently northerly plunging imbricate stack based on their internal structural architecture and observed contact relationships. Lithologies of the shale belt occur at three main structural levels along the length of the eastern edge of the imbricate stack: 1) the SB1 footwall, 2) structurally above SB1 in the footwall of the overlying SB2 thrust sheet, 3) the SB4 footwall (Insert 1). These field relationships suggest that the carbonate thrust sheets are structurally interleaved with the shale.

3.2.2 Southern Shale Belt

The Southern Shale Belt is an east-west trending belt of grey to black shale and brown sandstone of the American Tickle Formation that constitutes the low-lying area between the Spruce Brook carbonate occurrences and the northern closure of the North Brook Anticline (Figure 3.1). For this study a sampling of orientation data was collected from three localities in the shale belt, one in the west, one in the central portion of the belt and one in the east near the crest of the North Brook structure. In the west, the shale is not

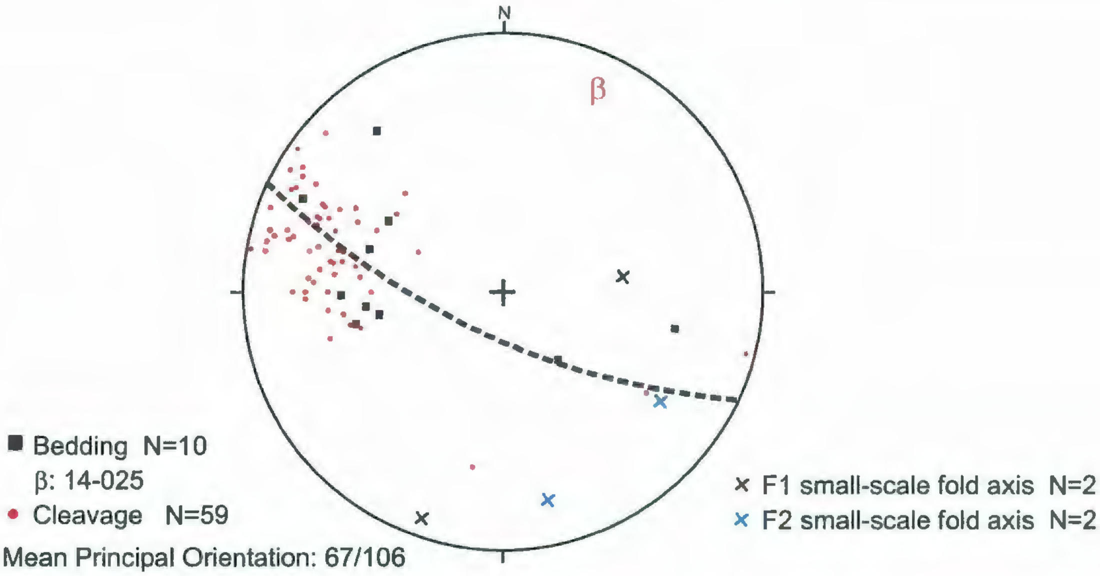


Figure 3.2: Lower hemisphere equal area pole plot of bedding and cleavage in American Tickle Formation shale of the Western Shale Belt. Point maximum for cleavage represents pervasive east-dipping S1 fabric. Bedding is largely parallel to cleavage throughout most of the shale belt but shows a partial great circle girdle distribution indicative of a north plunging asymmetrical F1 fold system.

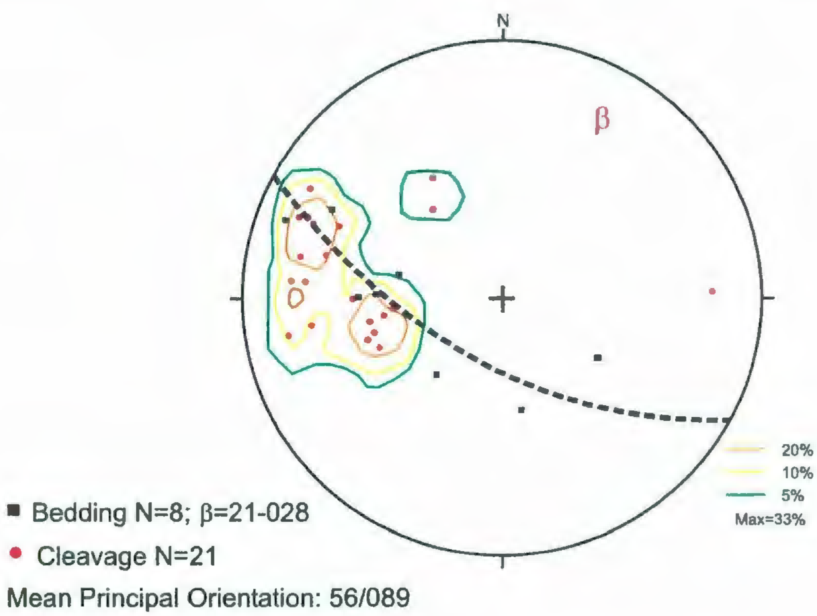


Figure 3.3 : Lower hemisphere equal area pole plot for bedding and cleavage (contoured) in the Southern Shale Belt. Great circle girdle distribution of bedding orientations reflects northeast plunging F1 folds in the belt. Point maximum for cleavage indicates pervasively developed east-dipping S1 cleavage.

well exposed and its occurrence is evidenced principally by subcrop. A number of large occurrences of limestone conglomerate assigned to the Daniels Harbour Member are noted near the southern edge of SB1 (Insert 1) Although the relationship between the conglomerate and the shale is not observed, the conglomerate is interpreted to occur as resistively weathering lenses within the shale. The conglomerates are monomictic, locally resembling auto-brecciated originally thin-bedded nodular limestone. Bedding is locally preserved or defined by long-clast alignment and is moderately east-dipping. The lenses are cut by a moderate to steeply east-dipping cleavage fabric (Figure 3.3). Both bedding and cleavage in the conglomerates lie at a high angle to the perceived long axis of the lenses suggesting that their shape may be a relic of their original sedimentary deposition.

Exposures along a small brook in the central portion of the Southern Shale Belt show consistently moderate to steep east-dipping S1 cleavage. At one locality steep east-dipping beds of sandstone occur in the shale and have an overturned limb relationship with S1. This suggests that the F1 fold system is a west-verging asymmetrical fold system that plunges to the north and is at least locally overturned (Figure 3.3). The S1 fabric at this locality also shows numerous small-scale F2 folds. The F2 fold system is west-verging and plunges to the south.

The basal detachment of the Southern Shale Belt over the top of the North Brook Anticline is observed in the eastern portion of the belt. At this locality a succession of black shale and brown-weathering cross-laminated micaceous sandstone assigned to the American Tickle Formation clearly overlies a gently north-dipping planar limestone surface interpreted to constitute the uppermost surface of the carbonate succession contained within the North Brook Anticline (Figure 3.4A). The shale succession is highly deformed, showing a gently north-dipping penetrative cleavage that is parallel to the limestone surface. The structural relationships along this contact demonstrate that the shale belt is detached and transported over the top limestone surface. The detachment is characterized by a zone of highly sheared and F1 folded laminated dark grey shale with strongly developed S1 axial planar cleavage. Micro-scale F1 folds are

Figure 3.4A: Gently north dipping limestone surface in the foreground represents the crest of the North Brook Anticline. Highly sheared black shale of the American Tickle Formation overlies the detachment surface toward the north. See Appendix 3 for location of photo.

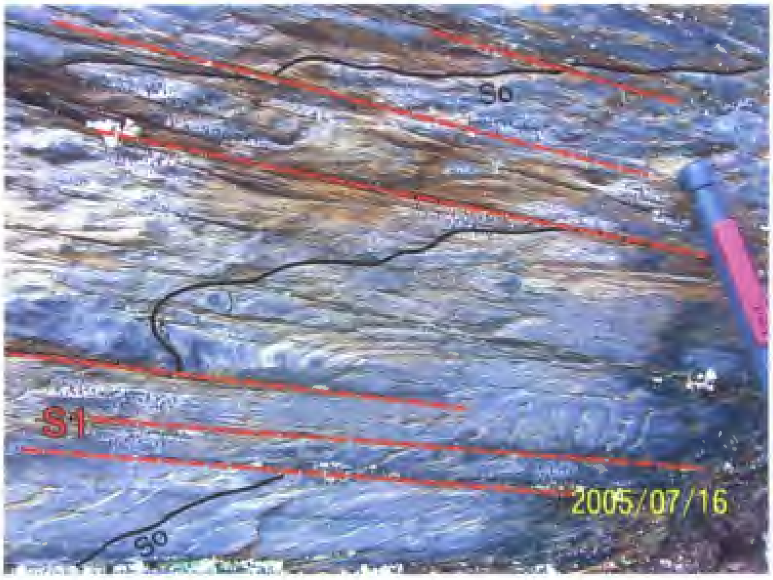


Figure 3.4B: Highly sheared originally laminated American Tickle Formation shale with micro-scale folding and strong S1 cleavage fabric. Note shear offsets along cleavage surfaces. View looking north.

asymmetrical, westerly verging, gently north-plunging folds with tight to isoclinal interlimb angles (Figure 3.4B). The fold hinges are highly crenulated and locally sheared along, or obliterated by, the very strong S1 fabric. Fold limbs show various stages of transposition, particularly in more competent sandy horizons which are dismembered and displaced as a result of cleavage development, forming micro-scale, rhomboid, augen-like lenses within the cleavage fabric. The morphology of these meso-scale folds is characteristic of shear folds or so-called 'Gleitbretter' (Ramsay, 1967), and attests to the pervasive shearing along the S1 cleavage planes parallel to the underlying top limestone surface.

3.3: Spruce Brook Slice 1 (*SB1*)

The leading, lowermost carbonate-cored slice in the Spruce Brook Thrust Stack is exposed in the southwestern corner of the map area (Figure 3.1). The strata contained in SB1 are mostly assigned to the stylonodular to breccia facies of the Table Point Formation (Figure 3.5). Although deformed, the succession is largely complete, with the basal unconformity of the Spring Inlet Member exposed at the southern edge of the slice, along Loggers School Road (Figure 3.5). Bedding orientations collected in the southern portion of the thrust slice define a northeast-plunging fold wave-train made up of a number of small antiform-synform pairs (Figures 3.5 and 3.6A). The fold system is sub-cylindrical and is characterized by sub-rounded fold forms with open to close interlimb angles (Figure 3.7A). The fold train has a moderate to steeply east-dipping axial-planar cleavage fabric and bedding/cleavage intersection lineations are consistent with the gently northeast plunge of the folds (Figure 3.7B).

The northeast-trending fold structures are interpreted as a mildly asymmetric westerly verging fold/thrust system. The thrust slice is interpreted to be emplaced over the Western Shale Belt on a low-angle thrust fault (Figure 3.6 A and B). This relationship is evidenced by exposures along the western edge of SB1, where the contact is well defined in outcrop despite heavy vegetation cover. At numerous locations along strike of the contact, large sinkholes were observed, in which shale of the American Tickle

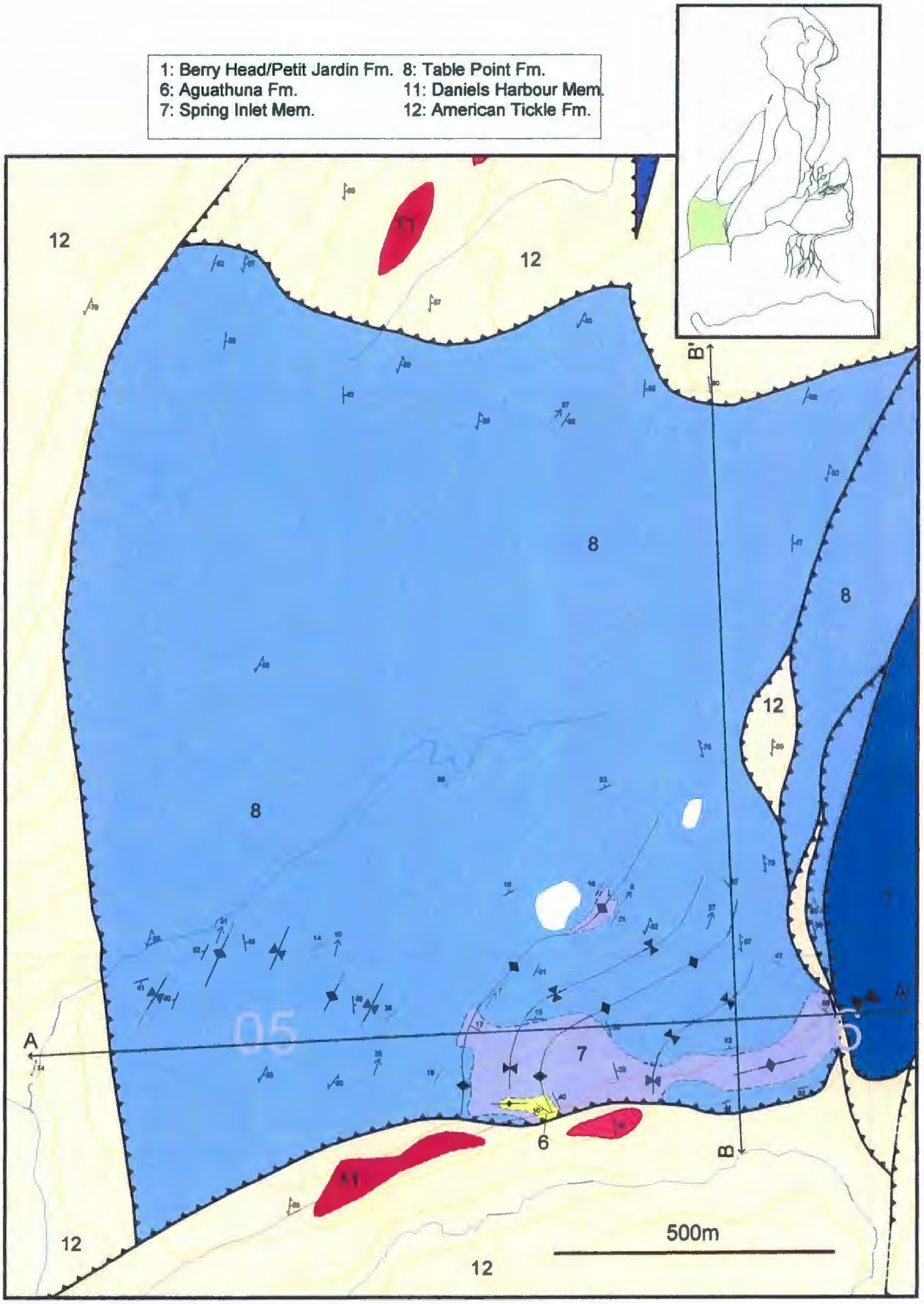


Figure 3.5: Detailed geological map of Spruce Brook thrust slice 1 (SB1). The distribution of the Spring Inlet Member defines the interference of northeast-southwest trending fold system and east-west trending ramp-related antiform.

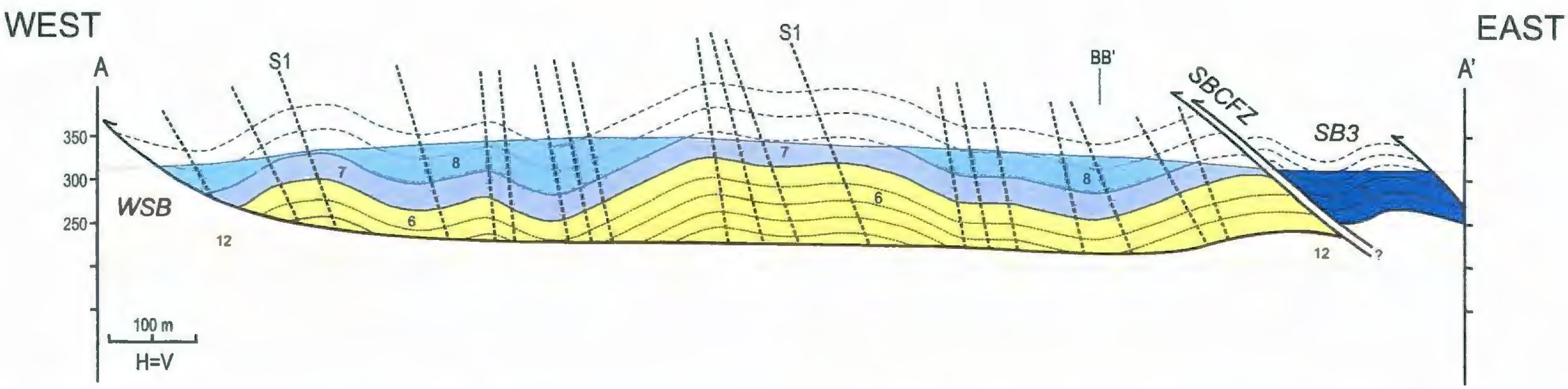


Figure 3.6A: Geological cross section of *SB1* showing west-verging buckle-fold wave-train with pervasive axial planar cleavage and contact relationships with the underlying Western Shale Belt (WSB) and the overlying SB3 structural domain.

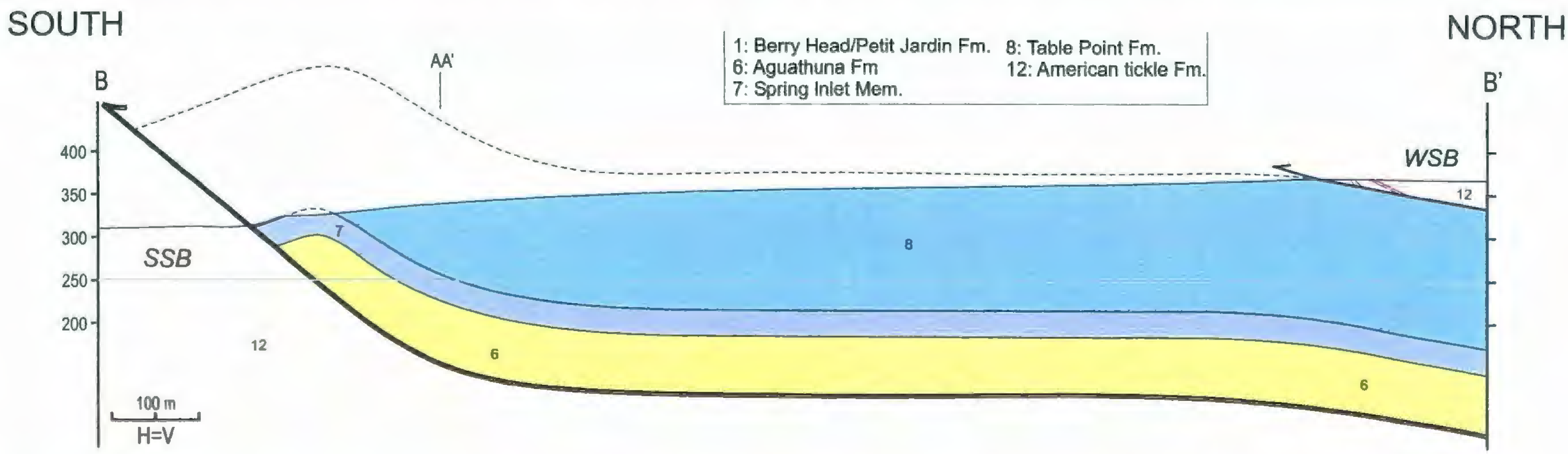
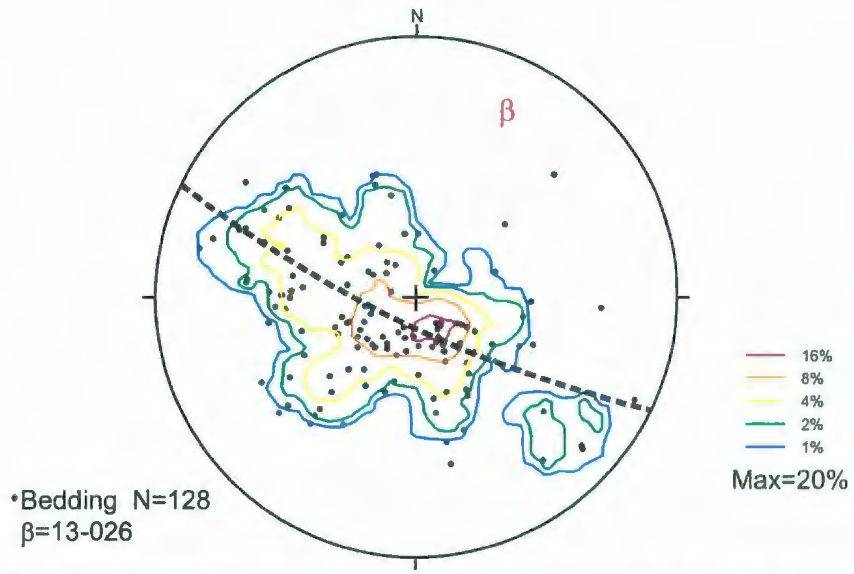
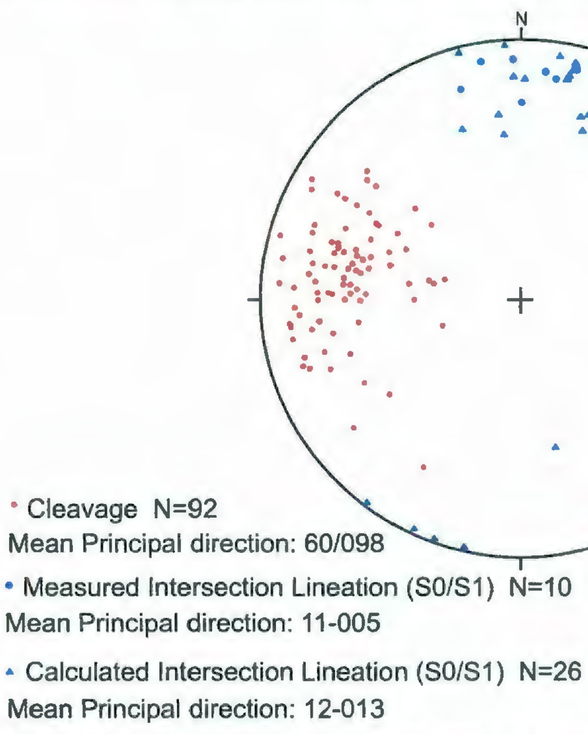


Figure 3.6B: Longitudinal section of *SB1* showing east-west trending anticline above a north-dipping lateral thrust ramp that forms the southern termination of the thrust slice at its contact with the underlying Southern Shale Belt (SSB).



A: Poles to bedding in *SB1* show partial great-circle girdle distribution indicating an open to close,sub-cylindrical northeast-plunging fold system. Note that shallow northeast and northwest dipping planes dominate; southeast dipping planes represent the east-west trending ramp-bend fold.



B: Poles to S1 cleavage planes and L1 bedding/cleavage intersection lineations in *SB1.* Point maximum for S1 suggest pervasive, east-dipping fabric. L1 orientations are coincident with the northeast plunge of the F1 fold system given by Beta in diagram A.

Figure 3.7: Lower hemisphere, equal area pole plots of bedding, cleavage and bedding/cleavage intersection lineations in *SB1*.

Formation has been eroded out from under the overlying limestone, often forming local limestone scarps. The contact is interpreted as a moderately east-dipping thrust fault that carries Table Point Formation limestone over American Tickle Formation shale.

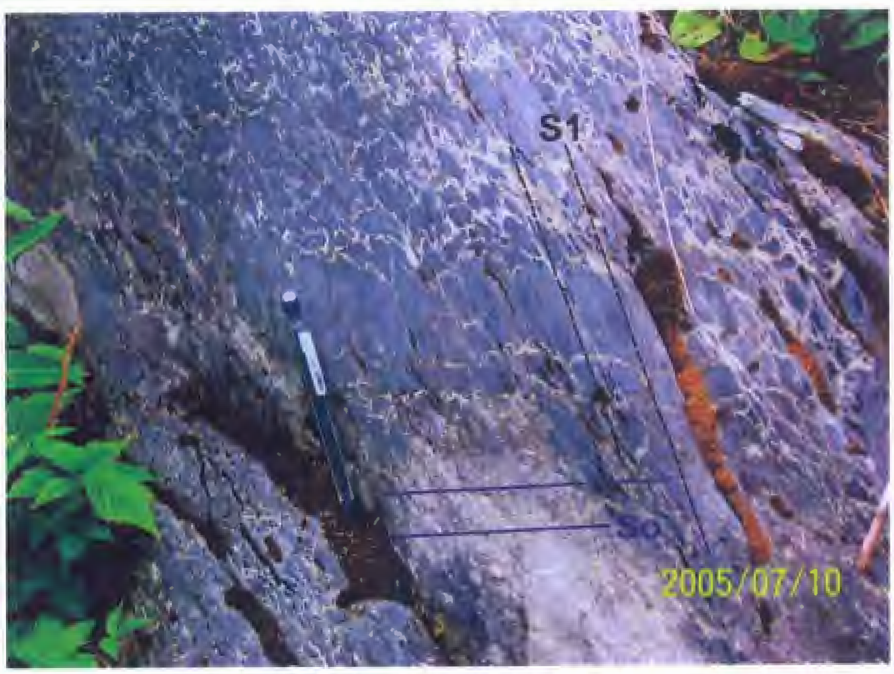
At the southern edge of SB1 the northeast-trending structural grain is superposed by an east-west trending antiformal structure. This structure is delineated by bedding orientations in the upper Spring Inlet Member in the southeastern corner of the thrust slice. Here, the Spring Inlet Member defines the core of the anticline with Table Point Formation limestone exposed to the north and south of the Spring Inlet Member outcrop belt (Figure 3.5). The anticline is interpreted to have a broad, rounded hinge zone, and bedding orientations along the crest of the fold suggest that it is doubly plunging. The fold is asymmetrical with a short, gently south-dipping forelimb in the south and a long moderately north-dipping backlimb that becomes sub-horizontal toward the north (Figure 3.6B). The fold is southerly verging and is interpreted to be located above a moderately north-dipping thrust fault. This fault is interpreted as a lateral ramp in the SB1 basal thrust.

The location of the north-dipping fault is inferred based on exposures along a prominent scarp that defines the southern edge of the limestone slice (Figure 3.5). The scarp is comprised of south dipping Table Point Formation limestone beds that constitute the forelimb of the east-west trending anticline in the hangingwall of the fault. At the southern base of the scarp is a large low-lying area interpreted, based on subcrop, to be underlain by the Southern Shale Belt. The shale terrane is thus interpreted to lie in the footwall of the limestone slice (Figure 3.6B). The footwall terrane is poorly exposed, but several large occurrences of limestone conglomerate assigned to the Daniels Harbour Member are located near the base of the limestone scarp. Bedding and cleavage in these conglomerates strike north-south in marked discordance with bedding orientations in the Table Point Formation limestone exposed in the scarp. This indicates the presence of a structural break between the two terranes.

The northern edge of SB1 is well constrained by outcrops along logging trails that run parallel to the inferred contact. The limestone strata exposed in the north are interpreted to constrain the structural top surface of the SB1 thrust slice based on the northerly plunge of the slice's internal fold systems (Figure 3.7). The uppermost strata in SB1 are assigned to the breccia facies of the Table Point Formation. The breccia has a strongly developed, moderately east-dipping cleavage fabric with a prominent down-dip stretching lineation defined by elongated clasts (Figure 3.8A). Original bedding is rarely preserved, but where visible, it tends to be expressed as an east dipping stylolitic fabric (Figure 3.8B). Because of the local transposition of bedding, fold structures defined in the southern half of the thrust slice are difficult to trace to the north; however, the enveloping surface for the top of the thrust slice is interpreted, based on outcrop distribution, to be fairly non-planar, which may reflect macroscopic folding of the slice. The top surface is not continuously exposed, but the distribution of limestone outcrops suggests that it must lie at slightly different topographic levels along its strike length.

The gently north-dipping enveloping surface of the top of the SB1 thrust slice is interpreted to be structurally overlain by a belt of black shale which is assigned to the Western Shale Belt and is exposed immediately north of the limestone thrust slice. The shale in this portion of the Western Shale Belt has a well developed moderately east-dipping cleavage fabric that is parallel to cleavage fabric in the upper strata of SB1 (Figure 3.5). The shale terrane contains lenses of Daniels Harbour Member conglomerate that are lithologically very similar to the upper strata of the Table Point Formation in the adjacent SB1 thrust slice (see Chapter 2). The conglomerate lenses, like the surrounding shale, typically show well-developed east-dipping cleavage fabric and down-dip elongation lineations. The parallelism of the cleavage fabrics across the shale/limestone contact and the similarities in the state of strain in the upper strata of SB1 and the overlying Daniels Harbour Member lenses suggests that both SB1 and the Western Shale Belt have been subjected to similar strain histories. The deformation histories for the two terranes are treated in greater detail in Chapter 4. At one locality along the eastern portion of the shale-limestone contact, the top surface of the SB1 thrust slice is clearly exposed as a gently north-dipping limestone surface.

A: View of moderately east-dipping cleavage plane in Table Point Formation limestone breccia showing prominent down-dip elongation lineation defined by long axes of clasts.



B: Gently northeast dipping thin-bedded Table Point Formation limestone cut by moderately east-dipping pervasive S1 cleavage fabric.

Figure 3.8: Strongly cleaved limestones of the upper Table Point Formation exposed in SB1

The surface dips beneath an adjacent large outcrop of silicious laminated grey shale assigned to the American Tickle Formation. Bedding data in the shale outcrop define an open asymmetric west-verging fold wave-train. The folding in the shale strata is indicative of detachment-style folding over a low-angle fault, which is inferred to lie at the shale/limestone contact. This contact relationship suggests the shale terrane is, at least locally, detached from the underlying limestone and transported toward the west. The contact is notably similar to the contact between the North Brook Anticline and the overlying Southern Shale Belt, described in Section 3.2.

3.4 Spruce Brook Slice 2 (*SB2)*

SB2 is exposed immediately to the north of SB1 and consists of a narrow north-south trending belt of platform carbonate (Figure 3.1). The limestone is in contact with American Tickle Formation shale and sandstone of the Western Shale Belt along both its western and eastern edges (Figure 3.9). The SB2 thrust slice is generally poorly exposed. Its internal structural and stratigraphic architecture, as well as its contact relationships with the surrounding shale terrane are defined largely in exposures in the southern portion of the thrust slice. The northern extension of SB2 can only be inferred based on limestone subcrop exposed along a disused logging road system extending southwest from Loggers School Road (Insert 1).

The carbonate terrane of SB2 carries strata from Boat Harbour Formation to uppermost Aguathuna Formation (Figure 3.9). The strata have sub-vertical to overturned dips in the west, but become more moderately west-dipping (normal way up) toward the east. The strata of SB2 are cut by a locally developed cleavage fabric that is steeply east-dipping, but is consistently shallower than bedding in the steeply dipping western portion of the slice. This bedding/cleavage relationship indicates that the slice has an overturned limb geometry (Figure 3.10). The strata of SB2 are interpreted to represent the steep forelimb of a large west-verging antiformal fold-structure. The backlimb and hinge domains of this fold are interpreted to be preserved in SB3 as described in Section

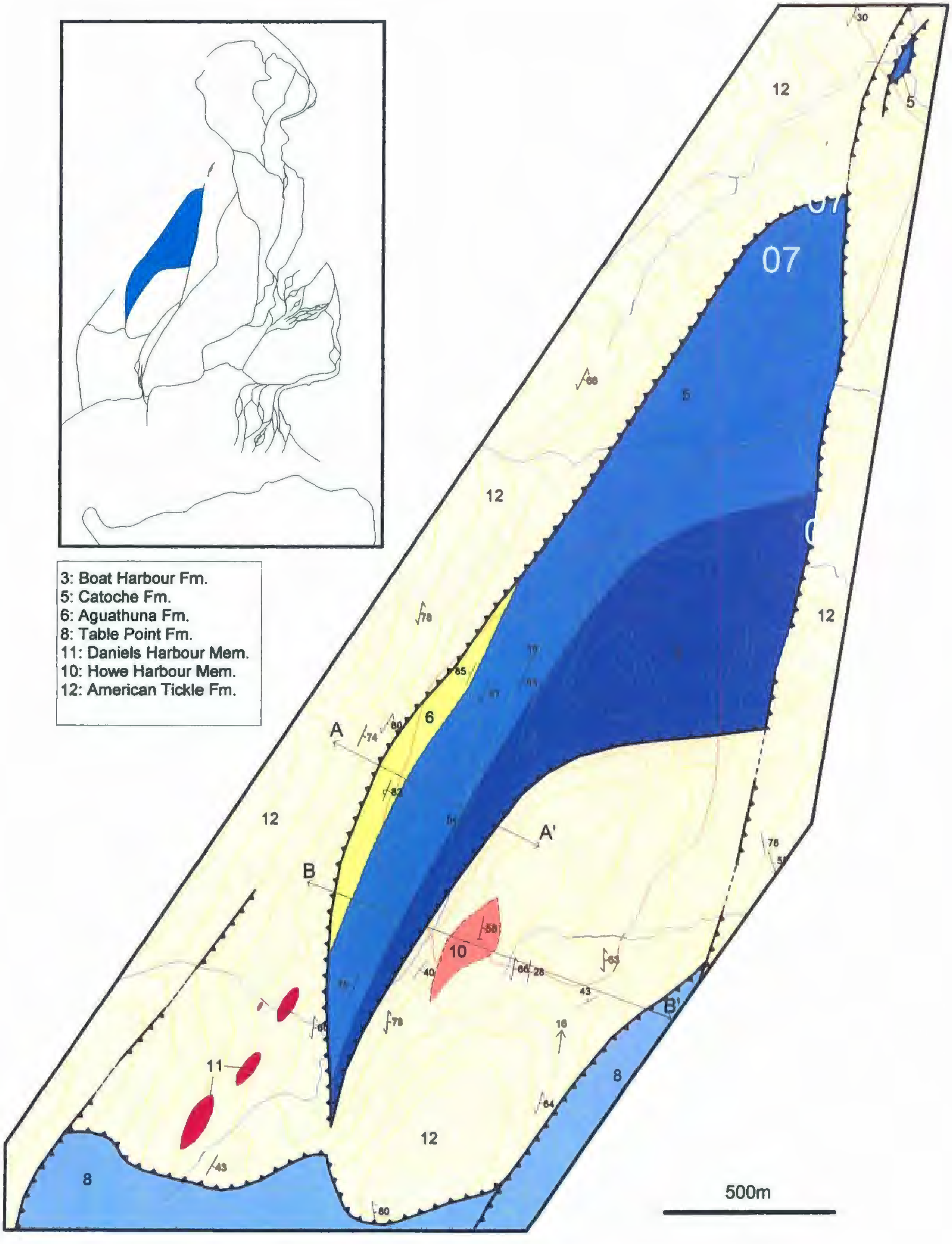


Figure 3.9: Detailed geological map of Spruce Brook thrust slice 2 (SB2)

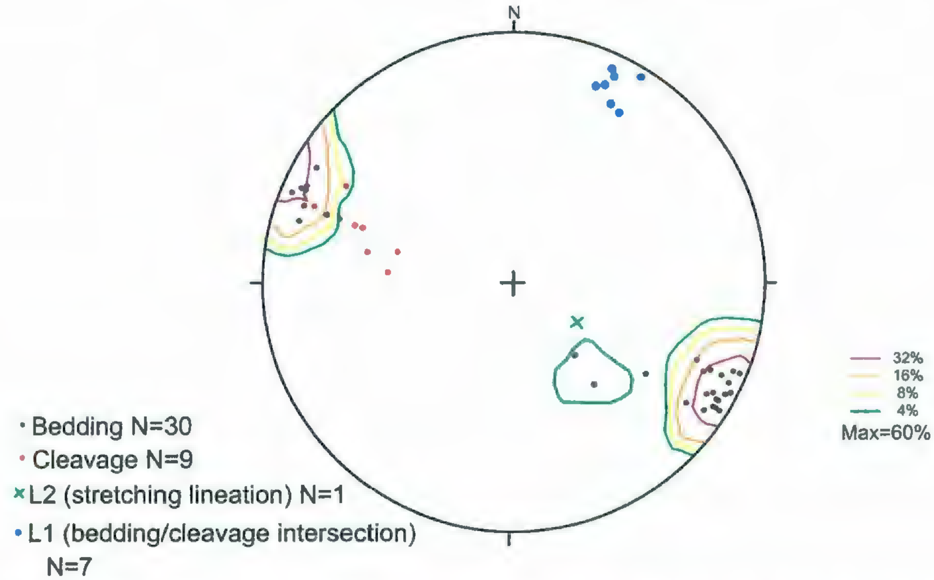


Figure 3.10: Lower hemisphere equal area plot of planar and linear fabrics in carbonate strata of SB2. Poles to bedding show point maximum representing steep to overturned orientations with smaller population of more moderately northwest dipping beds. S1 cleavage is moderately east dipping and consistently shallower than bedding. Partial great circle girdle distribution reflects cleavage fanning. Bedding-cleavage intersection lineations (L1) reflect northerly plunge of the thrust slice. Stretching lineation (L2) occurs on steep east-dipping cleavage plane.

Figure 3.11: Stretching lineation on cleavage plane in east-dipping overturned Aguathuna Formation strata on the western edge of SB2.

3.6. The geometry and origin of the fold structure as a whole will be described in detail in Chapter 4.

The cleavage fabric in SB2 is particularly well-developed in strata of the Aguathuna Formation exposed near the western edge of the SB2. Here the cleavage planes show prominent down-dip stretching lineations (Figures 3.10 and Figure 3.11). Limited orientation data in the Boat Harbour Formation strata exposed in the eastern portion of the thrust slice suggest that the cleavage becomes steeper toward the east defining a cleavage fan (Figure 3.12). The presence of cleavage fanning and stretching lineations suggests that the rocks in the SB2 thrust slice are highly strained. The strain history of SB2 is indicated by the uncharacteristically small thickness of Catoche Formation carried in the thrust slice. The limestone strata are interpreted to have been structurally thinned by extreme shortening during cleavage development and subsequently rotated and further thinned during the progressive strain that produced the cleavage fold. This style of deformation is consistent with the strain patterns developed in the forelimb portions of large thrust-related fold structures (Jamison, 1987).

Calculated bedding/cleavage intersection lineations in SB2 are gently to moderately north-plunging, suggesting that the thrust slice has an overall gentle northerly plunge (Figure 3.10). The basal detachment surface that carries SB2 is not exposed but its southern-most extent is fairly well constrained by outcrop in the area north of the top enveloping surface of SB1. Given the northerly plunge of both SB1 and SB2, and given that the easterly portion of the Western Shale Belt is continuously exposed along the upper portion of SB1 (see Section 3.3) it follows that the SB2 thrust slice structurally overlies both SB1 and its shale cover (Figures 3.9 and Figure 3.13).

The western contact of SB2 with the Western Shale Belt is delineated in the south by a steep ridge of American Tickle Formation shale that has a pervasive steep east-dipping cleavage fabric (Figure 3.9). Sub-vertical beds of Aguathuna Formation limestone at the base of this ridge are interpreted to be in fault contact with the shale. Based on the morphology of the shale ridge, the fault is interpreted to be sub-vertical; however, the

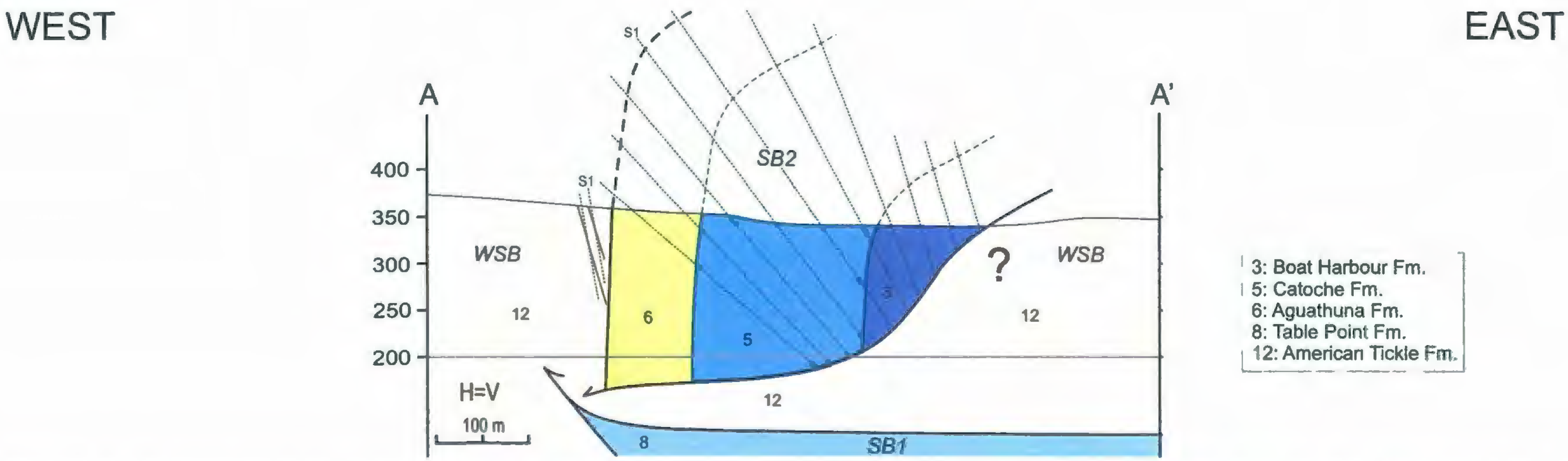


Figure 3.12: Geological cross section of the southern portion of SB2 showing the inferred contacts with the Western Shale Belt. The steep to moderately west-dipping limestone strata define the forelimb and partial hinge zone of an overturned anticline.

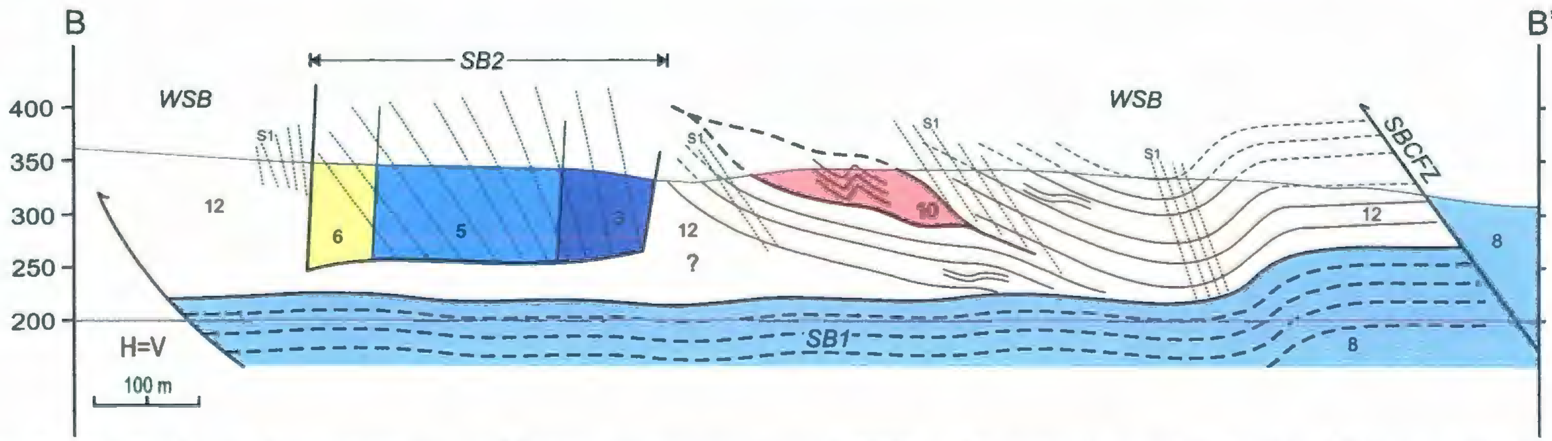


Figure 3.13: Geological cross section of the southern portion of SB2 and the eastern outlier of the Western Shale Belt (WSB).

sense of movement of the fault is not clear at this locality. The nature of the contact can be inferred based on structural relationships in the Spruce Brook Central Fault Zone (see Section 3.5) at the eastern edge of SB2 in the north. The fault zone contains a small structural sliver of Catoche Formation Limestone that dips gently to the west. These strata are clearly overlain by black shale with a strong moderately west-dipping cleavage fabric. This limestone slice and its overlying shale are interpreted to represent a structural slice cut from the down-plunge extension of the upper portion of the SB2 thrust slice that preserves the original structural contact between SB2 and the Western Shale Belt. The original position of this sliver would have been in the crestal region of the overturned anticline contained in SB2. The contact is thus interpreted as a moderately west-dipping thrust fault that becomes sub-vertical toward the south and carries strata of the Western Shale Belt over the SB2 limestone thrust slice. Consequently, SB2, like SB1 is both underlain and overlain by the Western shale belt (Figures 3.12 and 3.13).

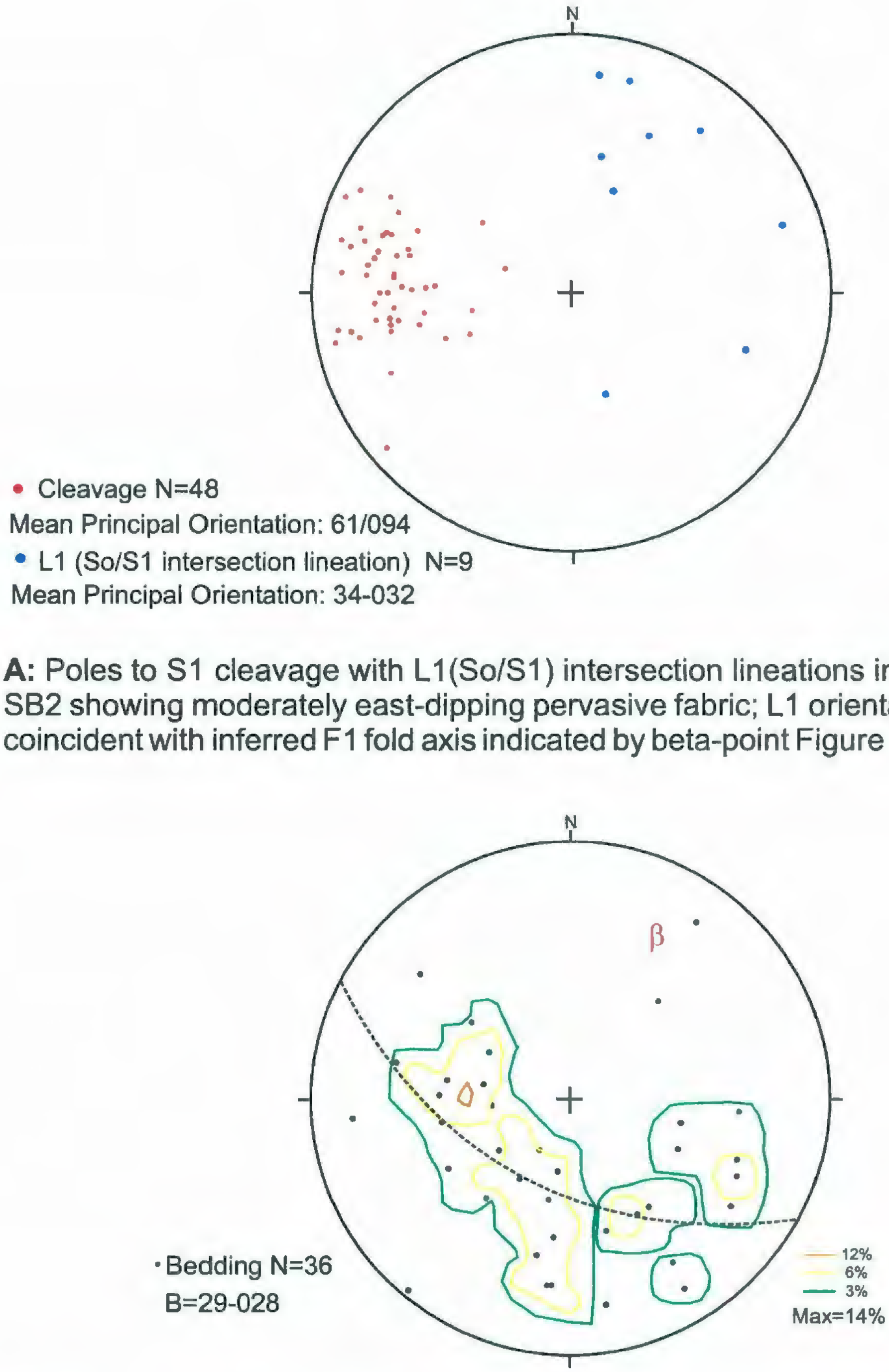
The carbonate succession in SB2 is incomplete since no Table Head Group strata are present in the slice (Figure 3.9). These missing strata are interpreted to be cut-out by the fault that defines the top of the SB2 thrust slice. This fault must have been active prior to imbrication of the slice with the Western Shale Belt since shale is now juxtaposed against the faulted carbonate succession. The early detachment fault cut variably up and down section along its strike, incising into the Boat Harbour Formation and locally preserving portions of the Aguathuna Formation. Although the fault is poorly constrained in SB2, it is thought to be a possible correlative of a similar low-angle fault that deforms the upper strata of the SB3 thrust slice (see Section 3.6).

The eastern contact between limestone strata of SB2 and the eastern portion of the Western Shale Belt is poorly exposed. The contact zone is obscured by heavy vegetation and has very little topographic relief except for a small scarp that defines the edge of the limestone slice along the southern portion of the contact. The scarp consists of moderately to steeply west-dipping beds of Boat Harbour Formation limestone that make up the basal stratigraphic unit in the SB2 thrust slice. Immediately to the east of the scarp are several scattered outcrops of black shale with moderately east-dipping laminations and a well developed east-dipping cleavage fabric. The nature of the contact is somewhat ambiguous but based on the forelimb geometry of the limestone thrust slice, the contact is interpreted as having a hanging-wall flat geometry with the limestone strata structurally overlying the shale on a moderately to steeply west-dipping fault (Figures 3.12 and 3.13).

The portion of the Western Shale Belt exposed east of the SB2 limestone thrust slice consists of lithologies correlated to the American Tickle Formation (Figure 3.9). The shale is locally finely laminated and colour-banded, but some intervals are massive and highly silicious. Thin beds of brown weathering, cross-laminated micacous sandstone occur throughout the shale succession, and there is one large occurrence of conglomerate with mafic-volcanic clasts (see Chapter 2). These lithologies are markedly similar to outcrops of the American Tickle Formation occurring in the Southern Shale Belt that overlies the North Brook Anticline in the southern portion of the map area (Section 3.2). The shales east of SB2 are characterized by a well-developed moderately east-dipping cleavage fabric (Figure 3.14A). Bedding locally shows small-scale folds with axial planar cleavage. The belt contains a west-verging asymmetrical fold system interpreted to be sub-cylindrical, and northeast plunging (Figure 3.14B). The macroscopic fold geometry is interpreted to have a large amplitude with a broadly synformal geometry (Figure 3.10). The east limb of the synform is intensely internally small-scale folded with a moderately west- to northwest-dipping enveloping surface (Figure 3.13). The west limb consists of a thick succession of moderately east-dipping shale and sandstone including the internally folded volcanic-conglomerate lens.

3.5 Spruce Brook Central Fault Zone

The central portion of the map area is transected by a north-south trending fault zone termed the Spruce Brook Central Fault Zone (*SBCFZ*) (Figure 3.1). The fault zone separates SB1 and SB2 in the west from the carbonate-cored SB3 and SB4 thrust slices



A: Poles to S1 cleavage with L1(So/S1) intersection lineations in the WSB east of SB2 showing moderately east-dipping pervasive fabric; L1 orientations are roughly coincident with inferred F1 fold axis indicated by beta-point Figure 3.14B.

B: Poles to bedding in the WSB east of SB2 showing partial great circle girdle distribution suggesting sub-cylindrical, northeast plunging asymmetric fold system with sub-round hinge domains.

Figure 3.14: Lower hemisphere equal area plots of bedding and cleavage in the portion of the Western Shale Belt exposed east of SB2

in the east. The fault zone contains several imbricated structural slices of black shale correlated to the Southern and Western shale belts and two structural slices of limestone, one in the south composed of Table Point Formation limestone and one in the north composed of Catoche Formation limestone (Insert 1). The floor thrust of the fault zone is tightly constrained along most of the eastern edge of SB1, but is not exposed along most of its strike length, including the segment forming the eastern edge of SB2. The roof-thrust is defined in the south at the western base of the prominent north-south trending ridge that forms the main outcrop area of the SB3 thrust slice and its northern extension is interpreted to lie coincident with the leading edge of SB4.

The geometry of the fault zone and its sense of movement are determined from field relationships at the southern extremity of the zone. At this locality the fault zone is defined by a narrow north-south trending valley with scattered outcrops of grey and black shale correlated to the American Tickle Formation of the Southern Shale Belt (Figure 3.15). The western valley wall defines the eastern edge of SB1 and clearly consists of moderately east-dipping beds of Table Head Group limestone. The eastern valley wall is a ridge of distinctly white-weathering moderately east-dipping Berry Head Formation dolostone that constitutes the basal portion of SB3. Based on the morphology of the valley, the SBCFZ appears to be a steeply east-dipping fault zone that truncates bedding in both SB1 and SB3. The fault zone is interpreted to be a westerly-verging thrust emplacing older SB3 dolostone over younger SB1 limestone. The thin veneer of shale riding in the fault zone suggests that the floor and roof thrusts of the SBCFZ root below SB3 in the Southern Shale Belt. Small structural slices of the shale terrane are interpreted to be cut out and transported as small horses by footwall plucking during westerly movement of the SB3 hanging wall over the underlying Southern Shale Belt (Figure 3.16).

Toward the north, the SBCFZ widens, and it contains several laterally discontinuous imbricate thrust slices of shale and a slice of limestone assigned to the Table Point Formation (Figure 3.15). This occurrence of limestone is correlated to the strata of SB1. It is interpreted to have been cut from the eastern trailing edge of SB1 and imbricated

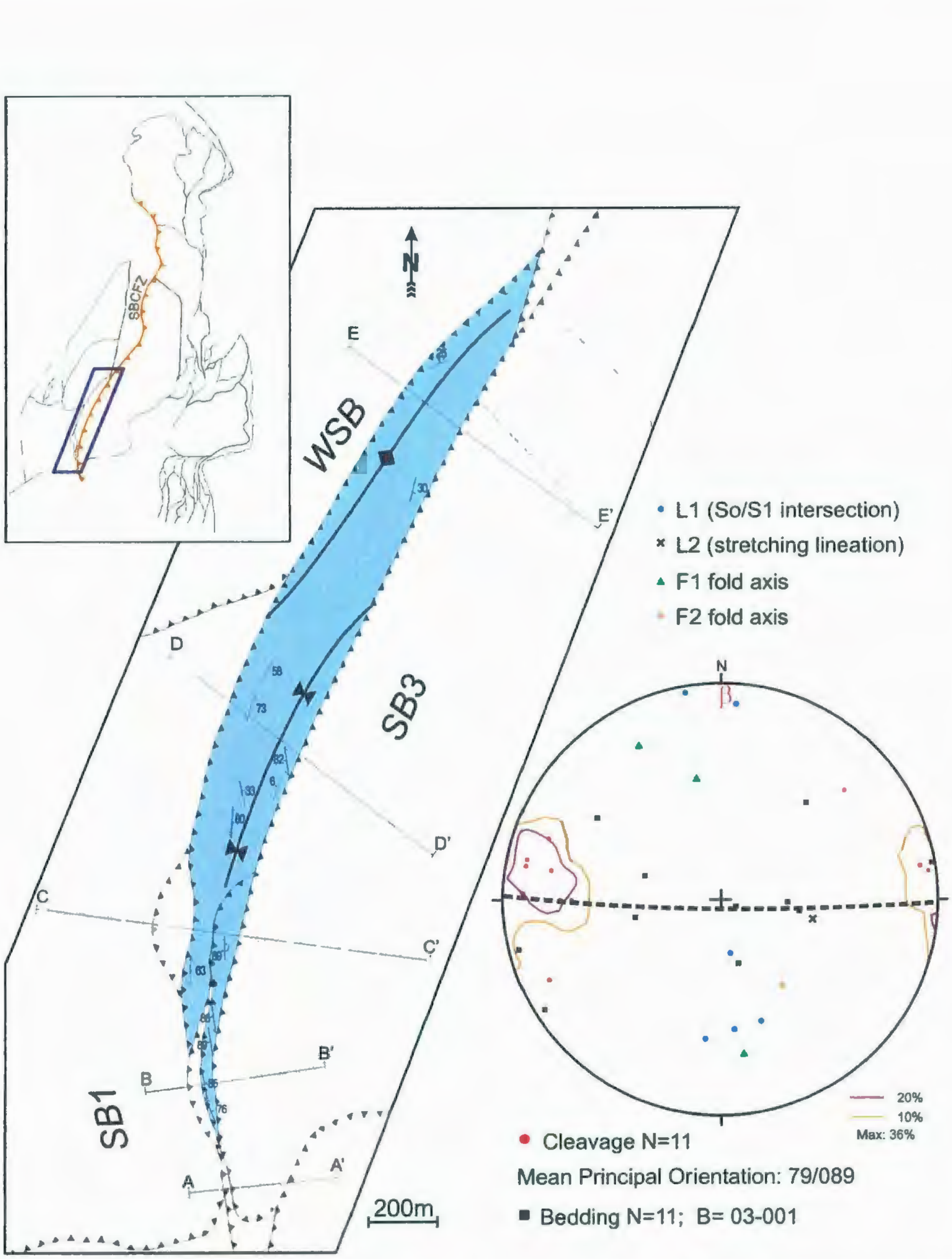


Figure 3.15: Geological map showing a structural slice of Table Point Formation limestone occurring in the Spruce Brook Central Fault Zone; Lower hemisphere equal area pole plot of bedding and cleavage in the limestone slice. Partial great circle girdle distribution of poles to bedding indicate that the F1 fold system is gently north plunging. The fold system is interpreted to be locally asymmetric based on sub-vertical to overturned bedding orientations in the south. Point maxima for east and west dipping S1 fabric suggests that the cleavage locally fans across mesoscopic F1 fold closures.

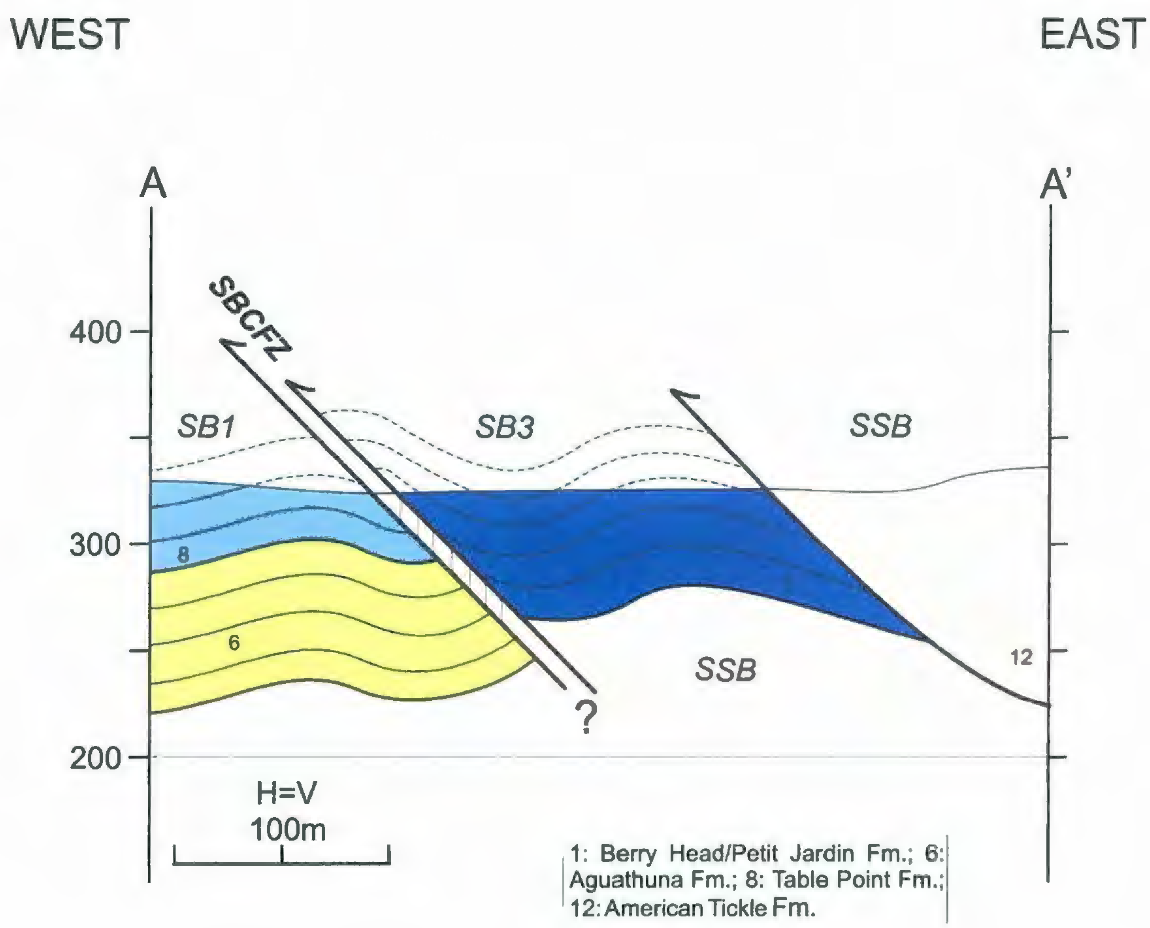


Figure 3.16: Geological cross section of the southern portion of the Spruce Brook Central Fault Zone (*SBCFZ*). Imbricating thrusts are west-verging emplacing older Berry Head Formation dolostone of SB3 over younger Table Head Group limestones of SB1. The fault zone carries structural slivers of black shale correlated to the underlying Southern Shale Belt (SSB). See Figure 3.15 for location of section.

within the fault zone. The limestones are intensely internally deformed and contain a north-south trending fold system. Unfortunately, the slice is poorly exposed along much of its strike-length and the morphology of the fold system is not well resolved; however, scattered bedding measurements indicate the presence of a map-scale antiform-synform pair (Figure 3.15). The folds contain a north-south trending cleavage fabric that appears to fan across the fold system (Figure 3.15). Bedding/cleavage intersection lineations indicate that the plunge of the fold system is variable, from moderately south to moderately north plunging.

In the south, the limestone slice contains small-scale tight to isoclinal folds with steep east-dipping axial planar cleavage fabric (Figure 3.17). Bedding in the originally laminated limestone is locally transposed into parallelism with the cleavage, but where the two fabrics are discernable, bedding is consistently steeper than cleavage. This relationship suggests that the southern portion of the limestone slice has an overturned limb geometry, although no younging indicators are preserved (Figure 3.18 BB'). Bedding/cleavage intersection lineations and small-scale F1 and F2 fold axes in the overturned panel are dominantly southerly plunging (Figure 3.15). A narrow structural slice of shale is exposed immediately west of the highly deformed overturned limestone panel. The presence of the shale indicates that the overturned limestone panel is carried on a thrust splay and is imbricated with shale slivers cut from the underlying Southern Shale Belt (Figure 3.18 BB'). The thrust splay is interpreted to extend northeast to root against the SBCFZ roof thrust (Figure 3.15). This splay locally emplaced the overturned limestone panel over more moderately east-dipping beds of Table Point Formation limestone (Figure 3.18 CC'). The juxtaposition of overturned and moderately east-dipping limestone panels reflects internal shortening by folding and imbrication of the limestone thrust slice within the SBCFZ. The limestone slice is interpreted to have had an original geometry of a west-verging overturned synform that formed in the trailing edge of SB1 above the tip-line of a major east-dipping fault during the initial propagation of thrusts in the SBCFZ. The fold would have developed a break-thrust geometry as the slice was cut from SB1 and became internally deformed within

Figure 3.17: Highly transposed, originally laminated Table Point Limestone exposed on the eastern edge of SB1 within the SBCFZ; S1 trends north-south, So is highly deformed and small-scale folded and locally shows sub-vertical dips with overturned limb bedding/cleavage relationships. See Appendix 3 for location.

the fault zone. Relative timing of key structural relationships in the Spruce Brook area is treated in greater detail in Chapter 4.

Structurally below the internally imbricated portion of the limestone slice is a laterally discontinuous occurrence of shale interpreted as a small structural slice riding on the floor thrust of the SBCFZ. The shales typically show strong cleavage development and original laminations are locally preserved. At one locality steeply plunging bedding cleavage intersections are observed indicating that the cleavage may be axial planer to a fold system that refolds the steep limb of an older, pre-cleavage fold system in the shale. The deformation history of the shale slivers is thought to be complex, but is unfortunately poorly resolved due to lack of exposure. The two occurrences of shale interleaved with the limestone in the south are correlated to lithologies of the Southern Shale Belt. As described above, the shale belt is though to be the root-zone of the SBCFZ, but structural sections depicting the shale-limestone imbricate zone show a greater vertical displacement of shale slices compared to the limestone panels with which they are imbricated (Figure 3.18 CC' and 3.18 BB'). This apparent offset can be attributed to a significant component of oblique-slip during some stage in the slip-history of the SBCFZ. Since the fault-zone cuts an early north-plunging fold structure, a phase of sinistral strike-slip movement could potentially produce an apparent normal-sense displacement within the imbricate fault-zone. Unfortunately, no field evidence of the sense of movement on the fault zone could be obtained, since no fault surfaces are exposed. It should be noted, however, that strike-slip movement is known to occur in the map area based on fabric relationships in schistose rocks of the SBUB (see Section 3.8); possible commonalities between these major fault zones are outlined in Chapter 4.

The Table Point Formation limestone imbricate slice in the SBCFZ is not well exposed in the north. It is interpreted to have a moderate easterly sheet-dip and is folded by up-right moderately north-plunging folds. The central portion of the slice is interpreted to have a broadly synformal geometry indicated by bedding orientation measurements that resolve a gently west-dipping east limb and a more moderately east-dipping west limb (Figure 3.18 DD'). The northern-most portion of the limestone slice is interpreted to have a broadly antiformal geometry although the morphology of the fold is not well constrained in outcrop (Figure 3.18 EE').

North of the Table Point Formation limestone slice, near the northern end of SB2, the SBCFZ contains a small structural slice of limestone assigned to the Catoche Formation based on conodont analysis (see Chapter 2 and Appendix 2) (Figure 3.19 and Insert 1) . A cross section through the slice is exposed in Spruce Brook, but the area is otherwise devoid of bedrock exposure, and the lateral extent of the limestone slice can only be inferred. The slice consists of a succession of gently west-dipping strata that are approximately 25 m thick. Exposed immediately to the west of the limestone is a highly cleaved succession of black, locally calcareous shale assigned to the American Tickle Formation constituting the Western Shale Belt (Figure 3.19). The cleavage fabric in the shale dips moderately toward the west suggesting that the shale structurally overlies the limestone on a moderately west-dipping fault (Figure 3.19). As described in Section 3.4, this composite limestone/shale slice is interpreted to represent a dismembered part of the upper portion of the SB2 thrust slice including its roof thrust with the overlying shale terrane. The branch points for the splays of this slice must, therefore, lie on the roof thrust of the Western Shale Belt. The limestone and overlying shale constitute a structural slice within the SBCFZ that is cut from the northeastern, down-plunge extension of SB2 and imbricated toward the west within the fault zone. The imbrication of the trailing-edge portions of both SB1 and SB2 is interpreted to reflect deformation in the footwall of the SBCFZ that was punctuated by short-cut faulting and duplexing during shortening.

The area northeast of the Catoche Formation thrust slice exposed in Spruce Brook is a low-lying marshy area with no bedrock exposure. Based on its geomorphology, the area is interpreted to be underlain by recessively weathering shale that lies within the SBCFZ (Figure 3.19). Based on the amount of displacement suggested by the location of the Catoche Formation sliver relative to the down-plunge projection of the SB2 thrust slice, the inferred shale slice likely correlates to the portion of the Western Shale Belt the overlies SB1 (Insert 1).

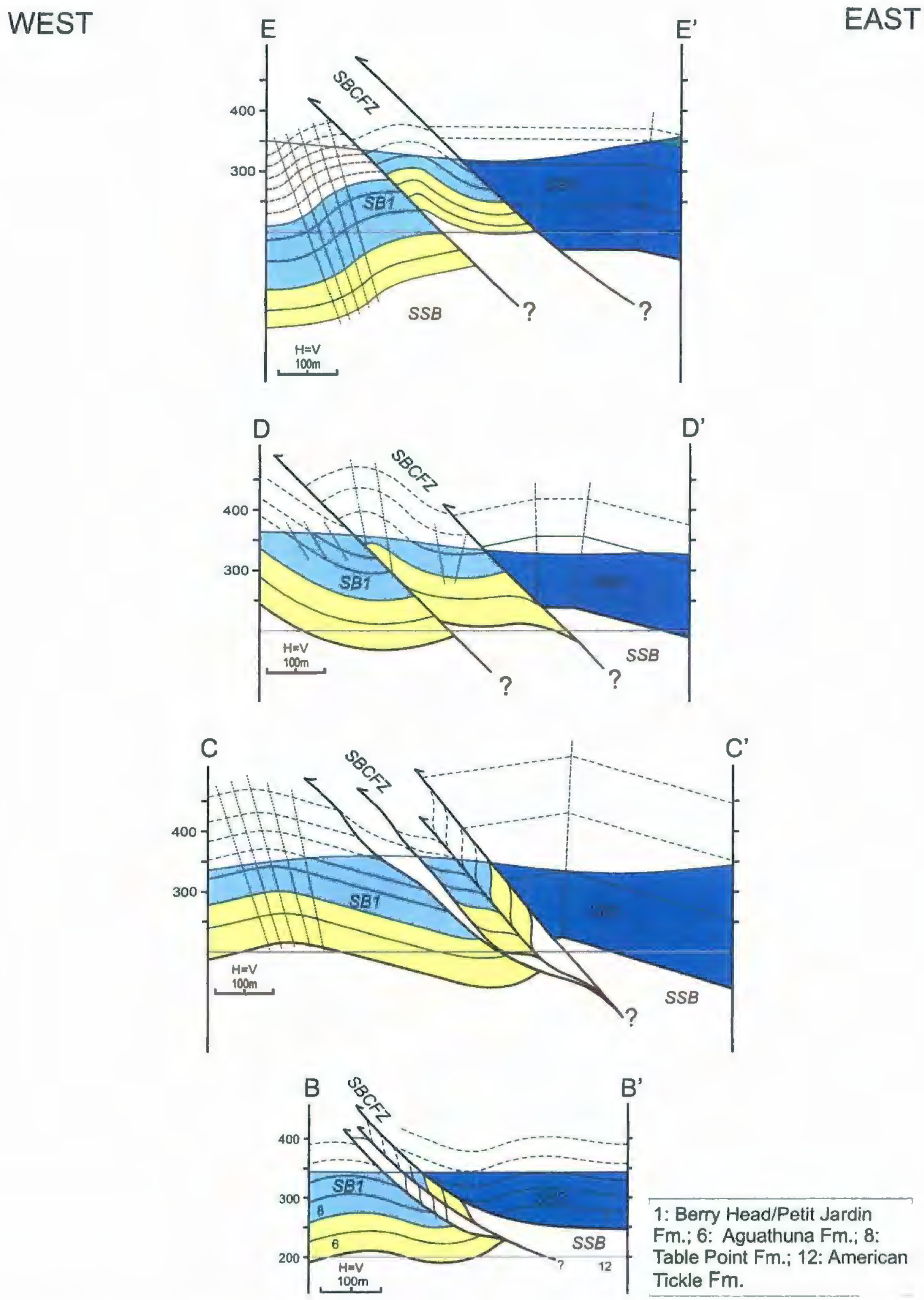


Figure 3.18: Geological cross sections through the Spruce Brook Central Fault Zone. See Figure 3.15 for section locations.

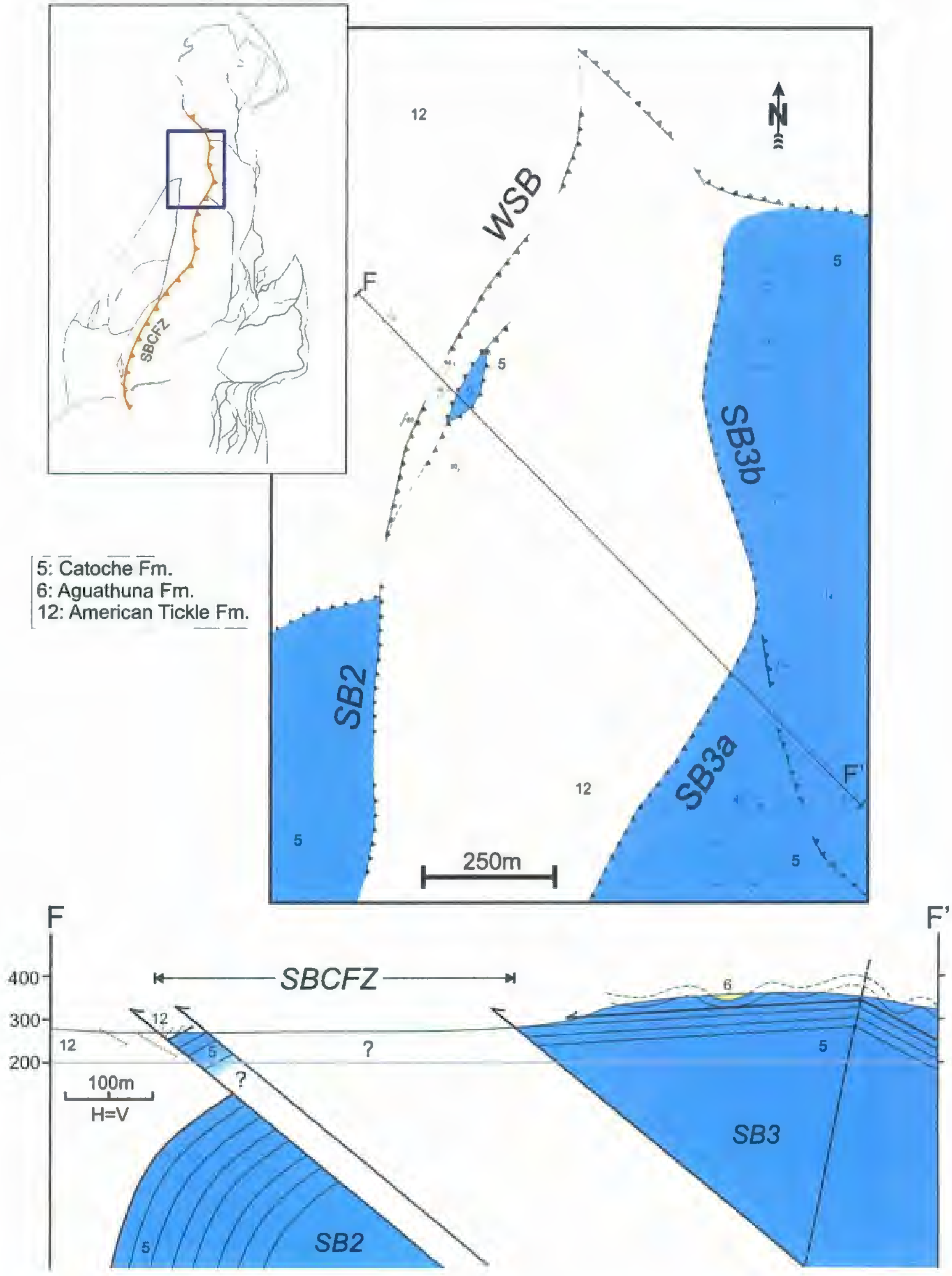


Figure 3.19: Geological map and cross-section of a small structural sliver of Catoche Formation limestone occurring in the Spruce Brook Central Fault Zone just north of the northern end of SB2.

3.6 Spruce Brook Slice 3: *SB3*

SB3 is the largest occurrence of platform carbonates in the Spruce Brook map area (Figure 3.1 and Insert 1). It is expressed as a prominent morphological ridge defining a narrow north-south trending belt that is bounded to the east and west by the SBUB and the SBCFZ, respectively. SB3 contains a simple succession of platform carbonate from upper Port au Port Group (Berry Head/Petit Jardin formation) to the upper strata of the St. George Group (Aguathuna Formation) (Figure 3.20).

SB3 is divided into two sub-domains denoted SB3a, in the south, and SB3b, in the north (Figures 3.20 and 3.21). The sub-domains are differentiated based on the styles and orientations of fold systems defining their internal structural architecture, and they are separated by an inferred thrust fault. The architecture of SB3a is characterized by a major polyclinal kink-style fold structure. In contrast, SB3b contains a locally overturned mesoscale fold train. The eastern edges of both SB3a and SB3b contain north-south trending cleavage folds that reflect deformation in the immediate footwall of the SBUB fault zone.

3.6.1 SB3a

The SB3 thrust slice contains a number of distinct planer dip domains of bedding, defining a prominent polyclinal kink-style fold structure (Figure 3.20). The main axis of the fold trends north-south and is gently northerly plunging. It separates gently northwest and northeast dipping panels in the west from gently to moderately east-dipping panels in the east (Figures 3.21A and 3.22). The fold has an antiformal geometry and is asymmetrical, with a wide east-dipping planar backlimb domain and a narrow northeast dipping planar crest region. The kink-style geometry of the anticline structure suggests that folding is related to movement of the SB3a thrust sheet over a series of thrust ramps. The structure may therefore be described as a ramp-anticline. Its asymmetry indicates that it formed during west-directed transport over an east-dipping frontal thrust fault.

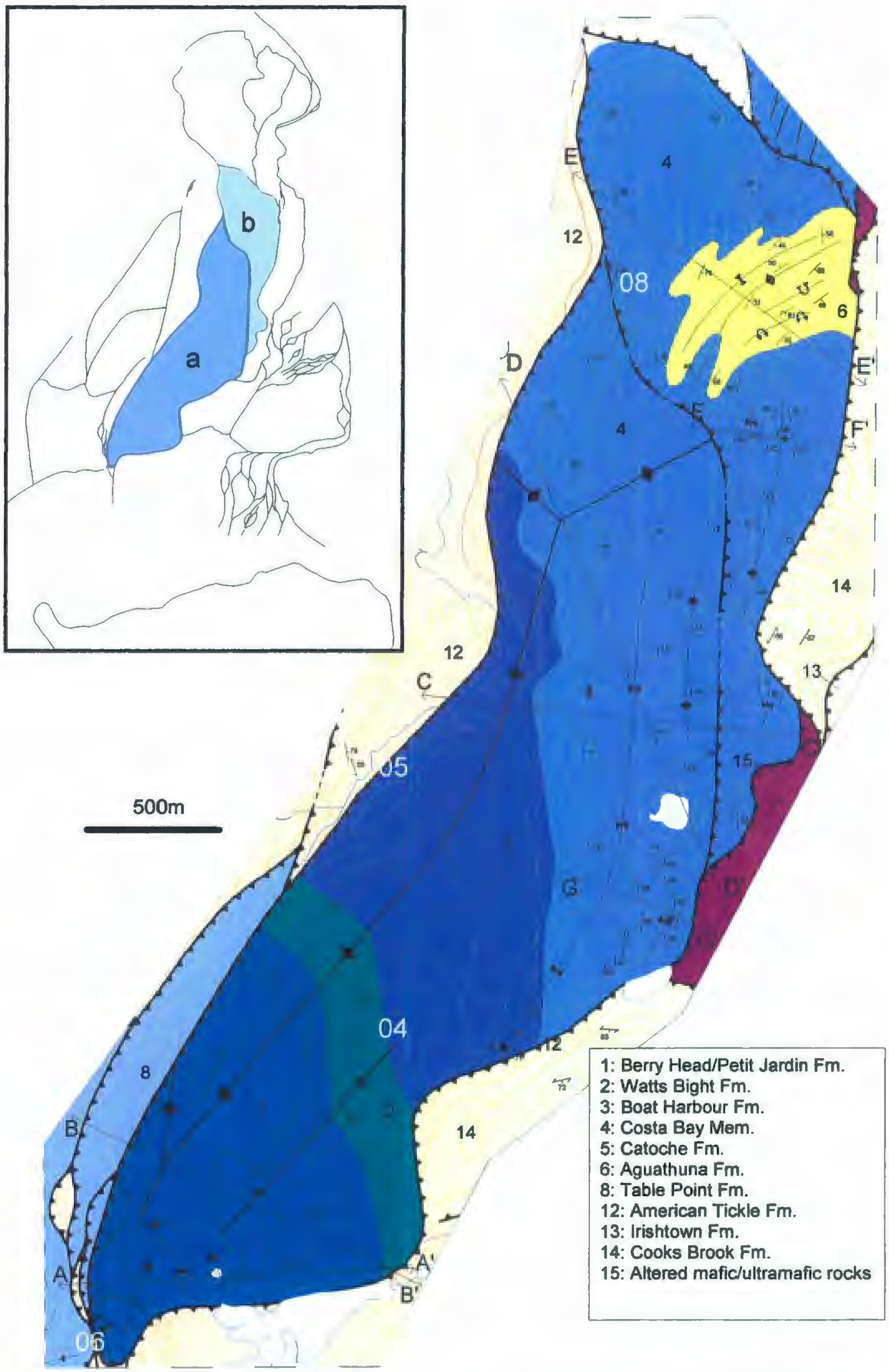
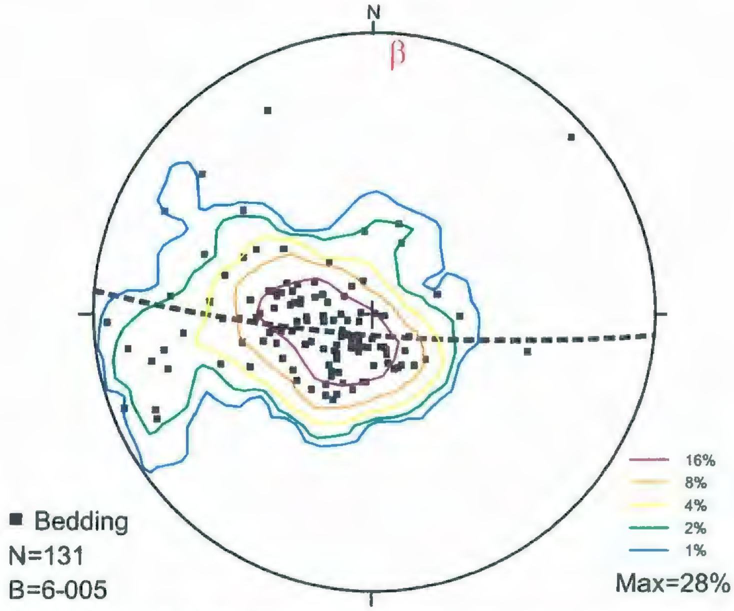
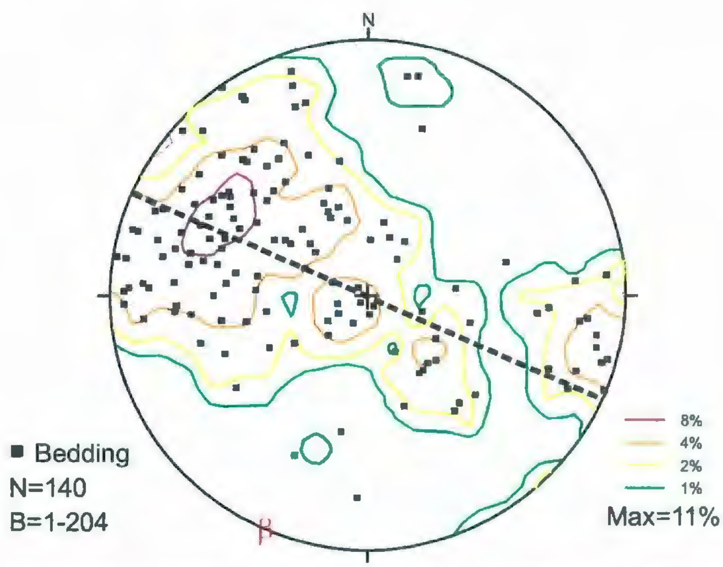


Figure 3.20: Geological map of SB3 showing sub-divisions SB3a and SB3b



A: Poles to bedding in *SB3a* showing broad point- maximum for moderately east- and northeast-dipping beds located on the crest and backlimb domains of a northerly plunging polyclinal anticline structure.



B: Poles to bedding in *SB3b* showing diffuse great circle girdle distribution suggesting a non-cylindrical fold system. Point maxima for east-dipping backlimbs and steep forelimbs define tight asymmetrical fold wave trains. Calculated B-axis plunges southwest, but observed small-scale folds suggest fold axes vary from southwest to northeast plunging.

Figure 3.21: Lower hemisphere equal area pole plots of bedding in *SB3a and SB3b* showing contrasting fold systems in the two sub-domains.

In the southern portion of SB3a, the ramp anticline has an open, polyclinal geometry with a gently northwest-dipping forelimb and a broad flat-crested hinge area defined by a pair of gently northeast-dipping panels (Figure 3.22 and 3.23 BB'). The fold has a demonstrable 'kink' style constrained by densely populated bedding orientation data across well exposed portions of the fold structure. These data indicate that the transitions between dip-domains are abrupt, defining sharp narrow hinge zones that are best described as kink axes. This style of deformation is consistent with the rigid mechanical nature of the thick-bedded dolomite successions of the Berry Head and Watts Bight formations that form the core of the anticline in the south.

In the extreme south of SB3a the core of the anticline is exposed, although outcrop control in the area is generally poor. The core of the anticline contains a series small of antiforms and synforms defined from limited orientation data and patterns visible on aerial photographs that show folded bedding traces in the well-bedded Berry Head Formation. The fold system consists of open, roughly north-south trending antiforms and synforms (Figure 3.23 AA'). The folded Berry Head Formation strata at this locality do not show evidence for pervasive axial planar cleavage development, but some micritic horizons in the dolostone locally show a crudely developed steep east-dipping cleavage fabric.

The fold wave train loses expression to the east where beds of Berry Head Formation are gently to moderately east-dipping (Figure 3.23 AA'). This planar east-dipping panel is interpreted to reflect a hangingwall flat geometry overlying an east-dipping thrust fault. The basal thrust fault of the slice is interpreted to be sub-horizantal below the fold wave-train in the core of the ramp-anticline and the folds are attributed to hangingwall ramp-to-flat transitions occurring in the strata overlying the fault (Figure 3.23 AA'). The fold wave-train is terminated in the north by an east-west trending antiform (Figure 3.22 A). This structure, although poorly resolved in outcrop, is interpreted to be similar to the east-west cross-fold in the southern edge of SB1; in that it must be related to a local east-west trending lateral thrust ramp occurring below the basal detachment of the thrust slice.

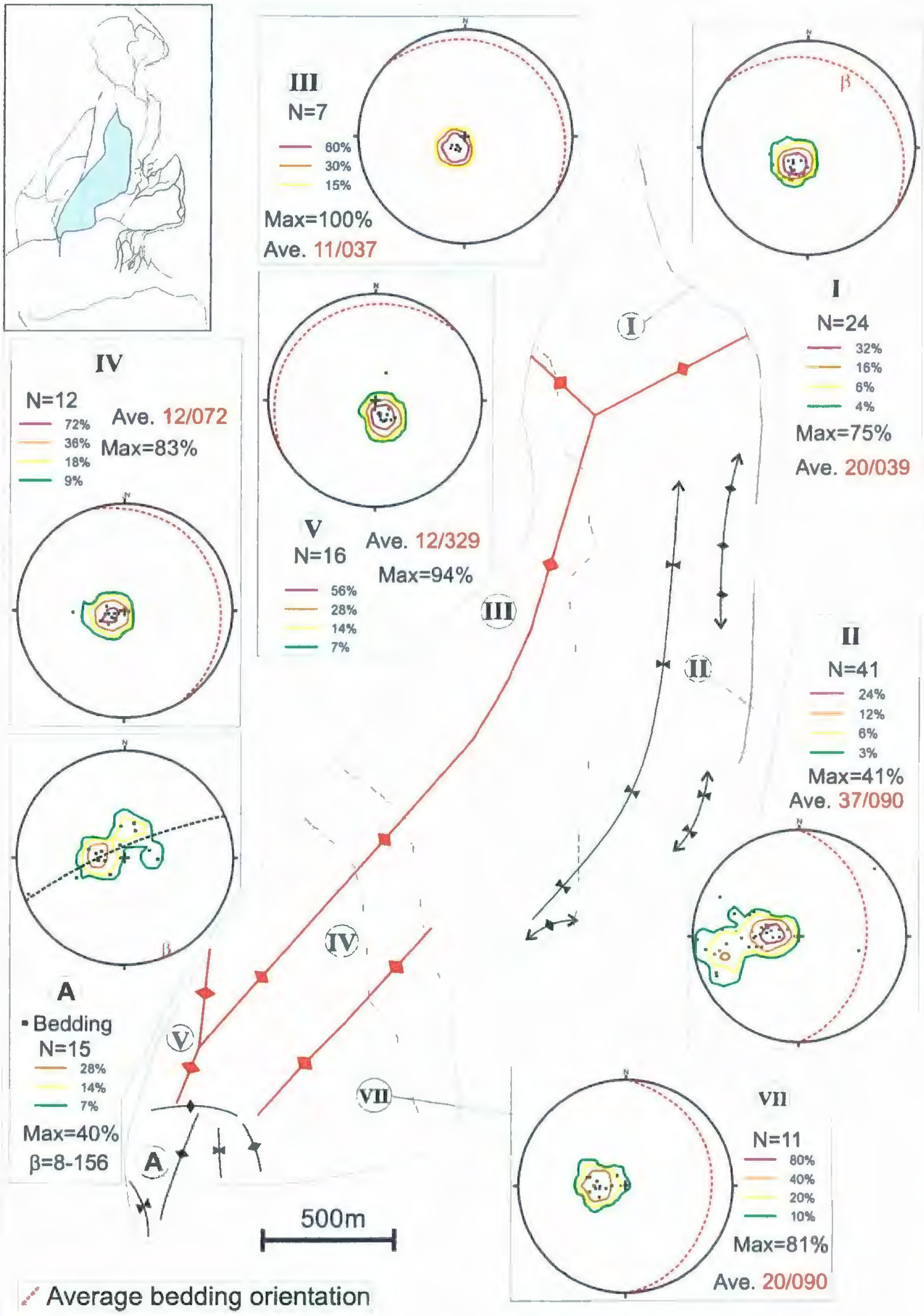


Figure 3.22: Lower hemisphere equal area pole plots of bedding in each of the six major dip domains describing the *SB3a* ramp anticline structure.

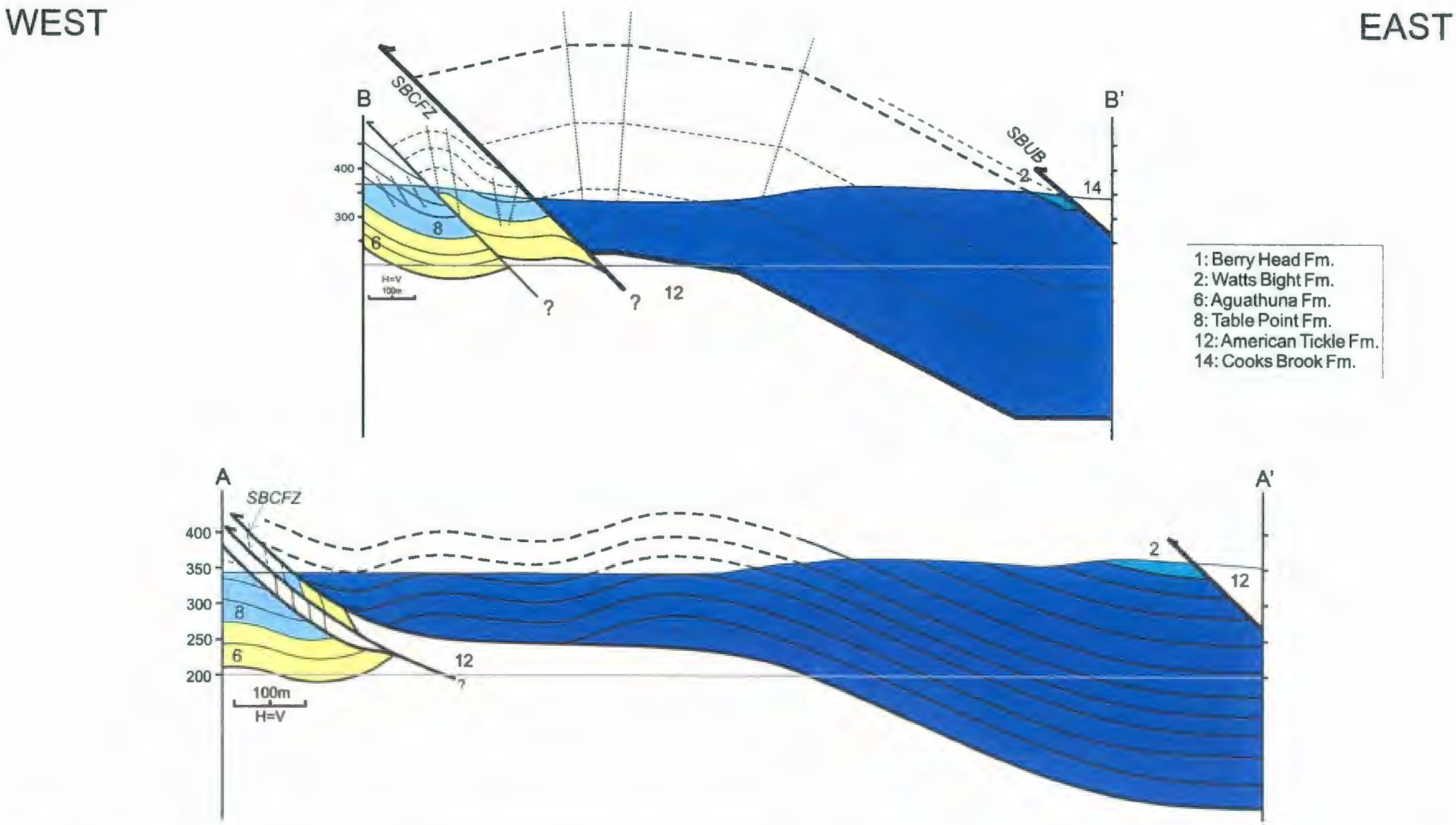


Figure 3.23: Geological cross-sections through the southern portion of the SB3a ramp anticline. AA' shows upright buckle fold wave-train in the core of the fold; BB' shows its asymmetrical polyclinal, kink-style morphology. The ramp anticline is cored by limestone and dolostone of the Berry Head and Watts Bight formations.

The gently dipping crestal dip-domain that characterizes the fold in the south is interpreted to die-out toward the north (domain IV, Figure 3.22). The central portion of SB3a is poorly exposed because the area underlain by the recessively weathering Boat Harbour Formation. The upper and lower boundaries of the formation are roughly constrained by outcrops of the underlying Watts Bight and overlying Catoche formations, but this indicates that SB3a contains an unusually thick succession of Boat Harbour Formation strata (See Chapter 2). Scattered bedding orientation data show dip variations in Boat Harbour Formation strata suggesting that the strata are folded. The succession may thus be structurally thickened by internal fold wave trains that remain unresolved due to lack of outcrop. Furthermore, the thin-bedded nature of the Boat Harbour Formation also makes it amenable to the formation of detachment surfaces that could potentially thicken the succession by fault repetition. The geometry of the crestal portion of the ramp anticline in this part of the carbonate succession is nevertheless inferred to be uniform with the exposures of the crestal dip-domain in the south, having a gentle northeasterly dip (Figures 3.20 and 3.23).

Toward the north, the gently east-dipping backlimb portion of the ramp anticline becomes a wide dip-domain comprised of strata of the Catoche Formation (domain II, Figure 3.22). The backlimb panel is well exposed and is interpreted to be internally folded based on numerous orientation data collected along the eastern side of the SB3a outcrop ridge. The data show dominantly north-south striking beds, but the dip amounts define discrete linear zones of alternately steeply and moderately east-dipping beds (Figure 3.24 and Figure 3.25). This pattern is interpreted to define a monoclinal asymmetrical, west-verging fold with narrow kink-style hinge zones. The axial surfaces of the folds are roughly north-south trending and dip moderately westward, while the fold axes are interpreted to be doubly plunging since the folds laterally transition into areas of shallow east-dipping beds. The folding is parasitic to the SB3a ramp anticline structure and is attributed to bending of the backlimb over asperities in the floor thrust during emplacement of the thrust sheet.

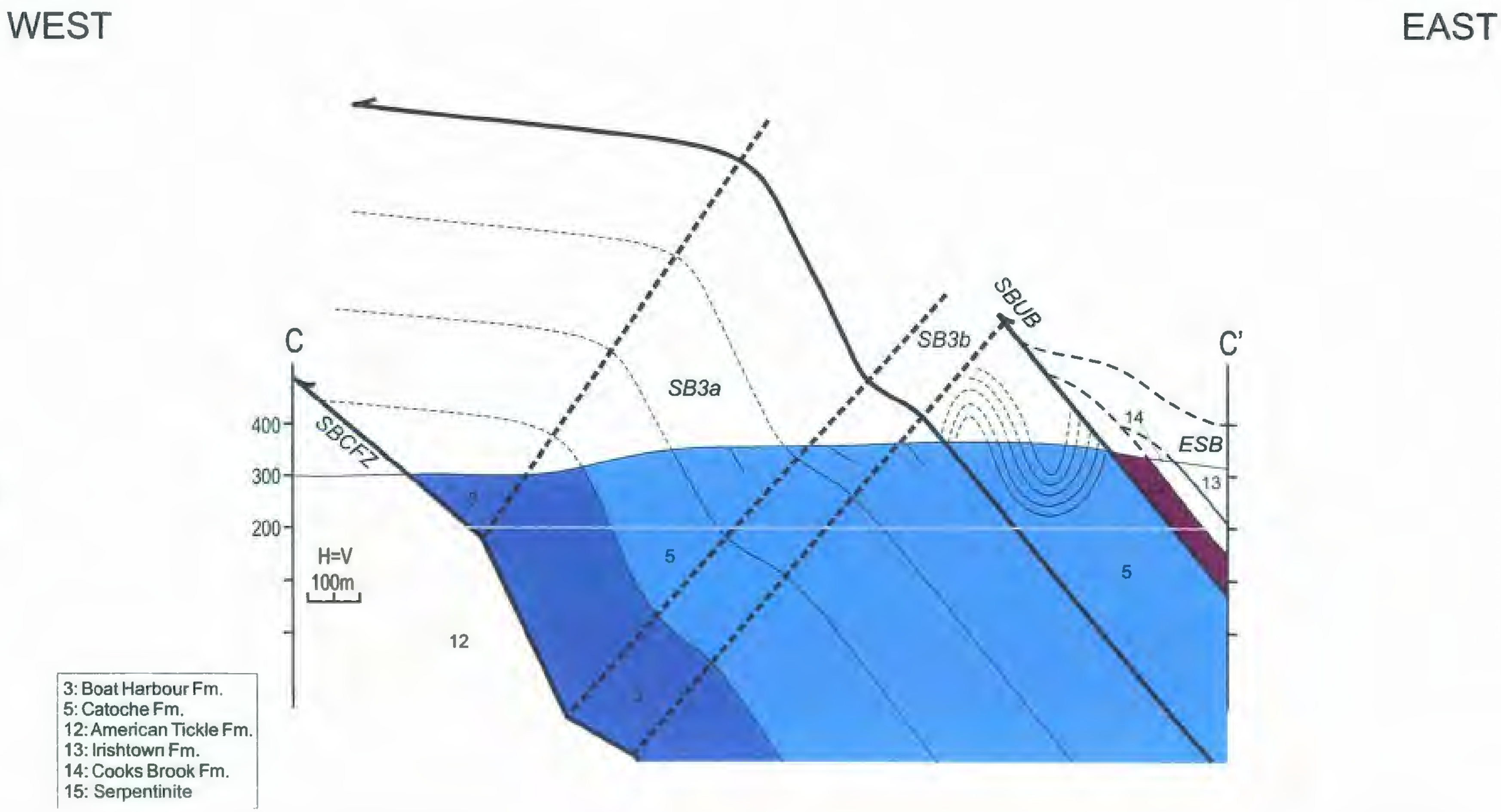


Figure 3.24: Geological cross-section through SB3 showing open kink-style folds in Catoche Formation limestone of SB3a overlain by bed-parallel detachment surface carrying tightly folded sub-vertical beds of Catoche Formation limestone constituting SB3b. Note also contacts with SBCFZ in the west and SBUB and Eastern Shale Belt (ESB) in the east.

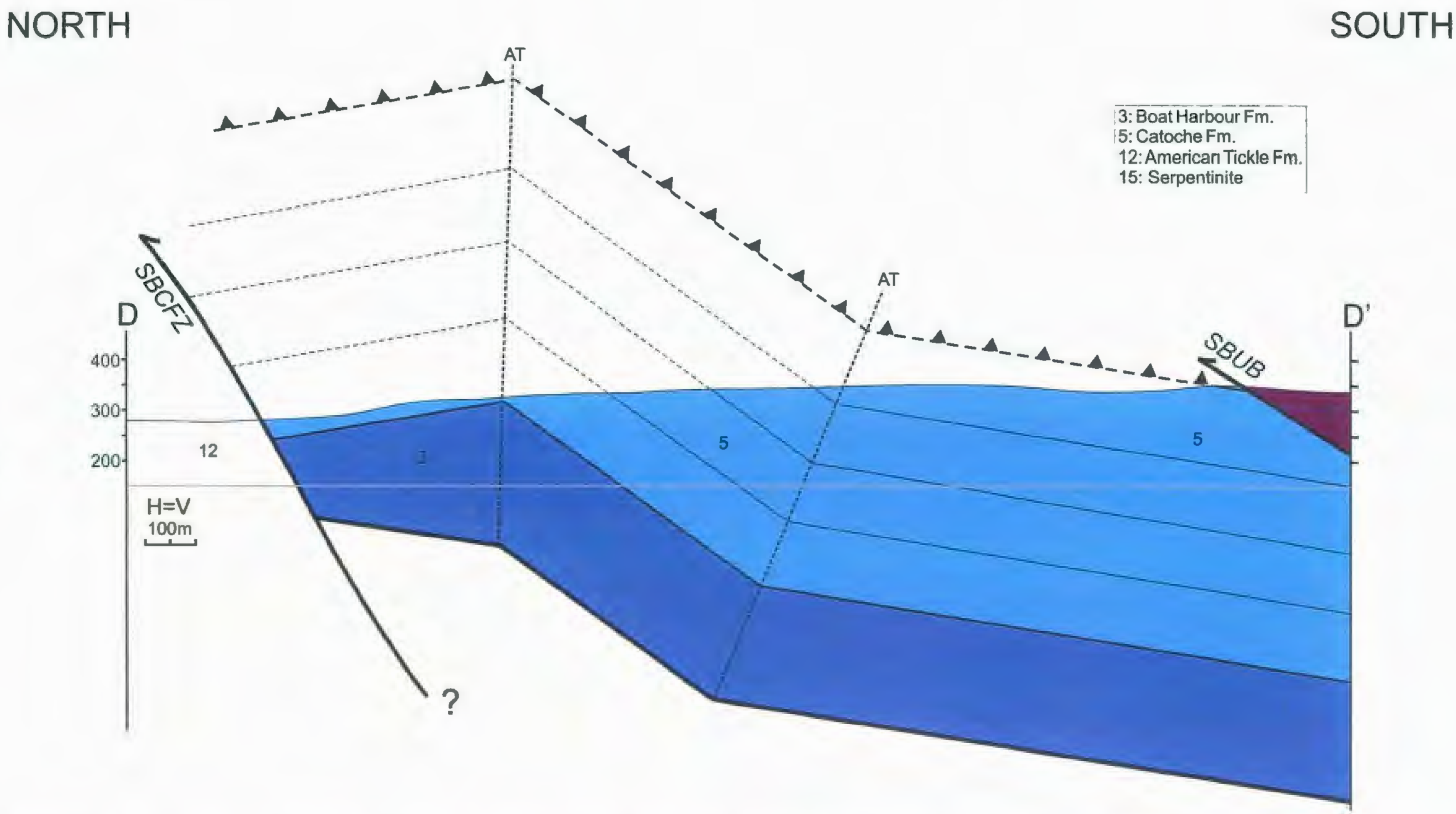


Figure 3.25: Oblique vertical section of SB3a ramp anticline showing northern closure of the large polyclinal fold structure with moderately northeast dipping crestal panel formed over south-dipping lateral thrust ramp.

In the northern portion of SB3a, the morphology of the ramp anticline changes as the crest portion of the structure becomes a wider dip-domain (domain III, Figure 3.22). Bedding in this panel dips toward the northeast and is about ten degrees steeper than that in the crestal domain to the south (domain I, Figure 3.22). The change in morphology is interpreted to reflect a change in shape of the underlying basal thrust, namely a transition from a moderately east-dipping frontal thrust ramp in the south to a moderately south-dipping lateral thrust ramp toward the north (Figure 3.25).
As the crestal portion of the anticline widens, the trace of the main north-south trending axis of the anticline branches into two fold axes, one axis trending northeast-southwest and the other northwest-southeast (Figure 3.20). The northeast-southwest trending hinge zone is clearly defined in aerial photographs by thick-bedded Catoche Formation limestones that form a prominent set of northwest-southeast trending morphological ridges in the crestal dip-domain and north-south trending ridges in the backlimb dip domain. Based on air-photo analysis, the hinge zone is interpreted to be more rounded than the kink-axes defining the fold in the south. The axis of the hinge zone is interpreted to plunge toward the northeast as the fold loses expression toward the northeast (Figure 3.20).

The backlimb and crest regions of the SB3a ramp anticline are abruptly truncated by steep faults constituting the SBUB and SBCFZ respectively (See Sections 3.5 and 3.8 for descriptions of the geometry of the fault zones). As described in Section 3.4, the ramp anticline is interpreted to have a steep forelimb represented by the SB2 thrust slice that is preserved in the footwall of the SBCFZ exposed to the west of SB3. The fold structure as a whole and its dismemberment by major fault zones will be treated in greater detail in Chapter 4.

3.6.2 SB3b

The northern portion of SB3 is denoted a separate structural sub-zone because it has a distinctly different internal structural architecture (Figures 3.20 and 3.21). Unlike SB3a, the strata in SB3b are intensely meso-scale folded and, although no structural break is mappable, a low-angle thrust fault is inferred, separating SB3a from the overlying SB3b (Figure 3.20). The inferred fault is interpreted to lie roughly parallel to bedding in the backlimb and crestal portions of the SB3a ramp anticline.

The internal structural architecture of SB3b is characterized by a northeast-southwest trending fold system. The most prominent part of this fold system is a synclinorium defined by the outcrop distribution of the Aguathuna Formation (Figure 3.26). The thin-bedded character of the Aguathuna Formation coring the map-scale synform allows for several orders of folds to be resolved, particularly in exposures along a logging road that transects the structure. Second-order folds define a tight, asymmetrical and locally overturned west-verging fold wave-train with wavelengths of about 100m (Figure 3.27). Meter scale (third order) folds are also noted at several localities in the synform and are similarly tight asymmetrical folds (Figure 3.28). The small-scale fold axes plunge variably northeast and southwest (Figure 3.21B).

The synclinorium is highly non-cylindrical, showing a diffuse and broad partial great circle girdle distribution of bedding orientations in lower hemisphere projection (Figure 3.26). Based on the orientation of second order folds, the synclinorium is interpreted to be non-planar since the folds have slightly arcuate axial traces that trend northeast-southwest in the west, but become more east-west toward the east (Figure 3.21). Furthermore, the variable plunge of third order folds indicates that the axis of the synclinorium is also somewhat curvilinear and doubly plunging.

The area north of the Aguathuna-cored synform is underlain by thick-bedded Catoche Formation limestone (Figure 3.20). Bedrock exposure is generally poor in this area, but scattered orientation data suggest that beds are moderately east-dipping. These strata constitute the west limb of the synclinorium; however, their apparent thickness suggests that the succession is repeated, or thickened, likely by a series of tight folds (Figure 3.27). Unfortunately the morphology of the folding in this portion of the thrust slice cannot be resolved. The fold system is interpreted to decrease in amplitude toward the

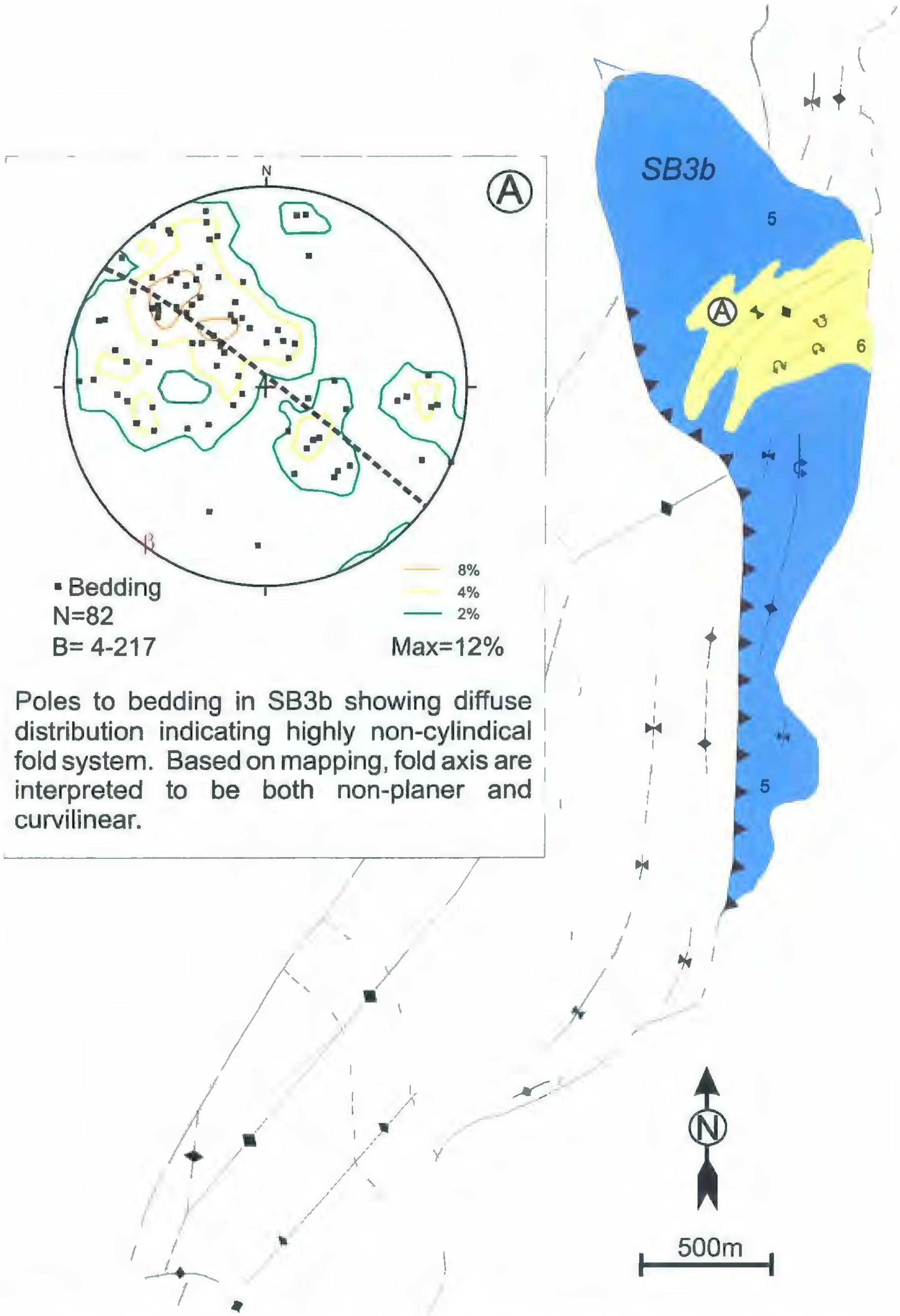


Figure 3.26: Detailed map of the fold system in the SB3b subdomain and annotated lower hemisphere equal area plot of poles to bedding. 5: Catoche Fm.; 6: Aguathuna Fm.

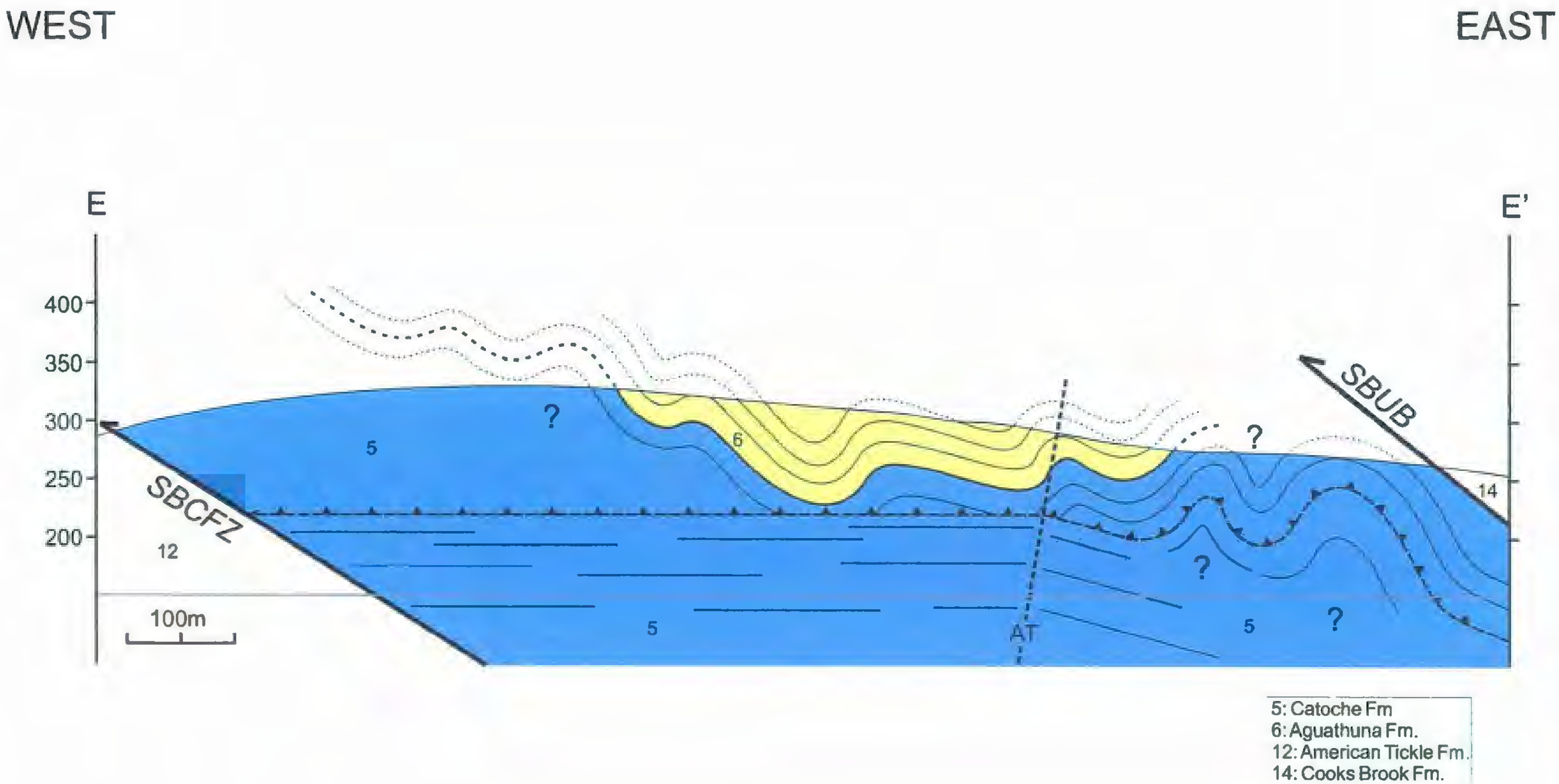


Figure 3.27: Geological cross section of SB3b showing down-plunge view of detachment fold system in SB3b and the kink-style ramp-bend fold in the underlying SB3a. Folding on the eastern edge of the thrust slice is interpreted to overprint both fold systems. Section is a profile view of the synclinorium in SB3b, and is oriented 70/216 (dip-dip direction)

Figure 3.28: Tight fold in laminated limestone of the Aguathuna Formation occurring within a broadly synformal structure that exposes the unit in the northern portion of *SB3b.*

Figure 3.29: Strong S1 cleavage fabric in east-dipping beds of Boat Harbour Formation limestone exposed in SB3a.

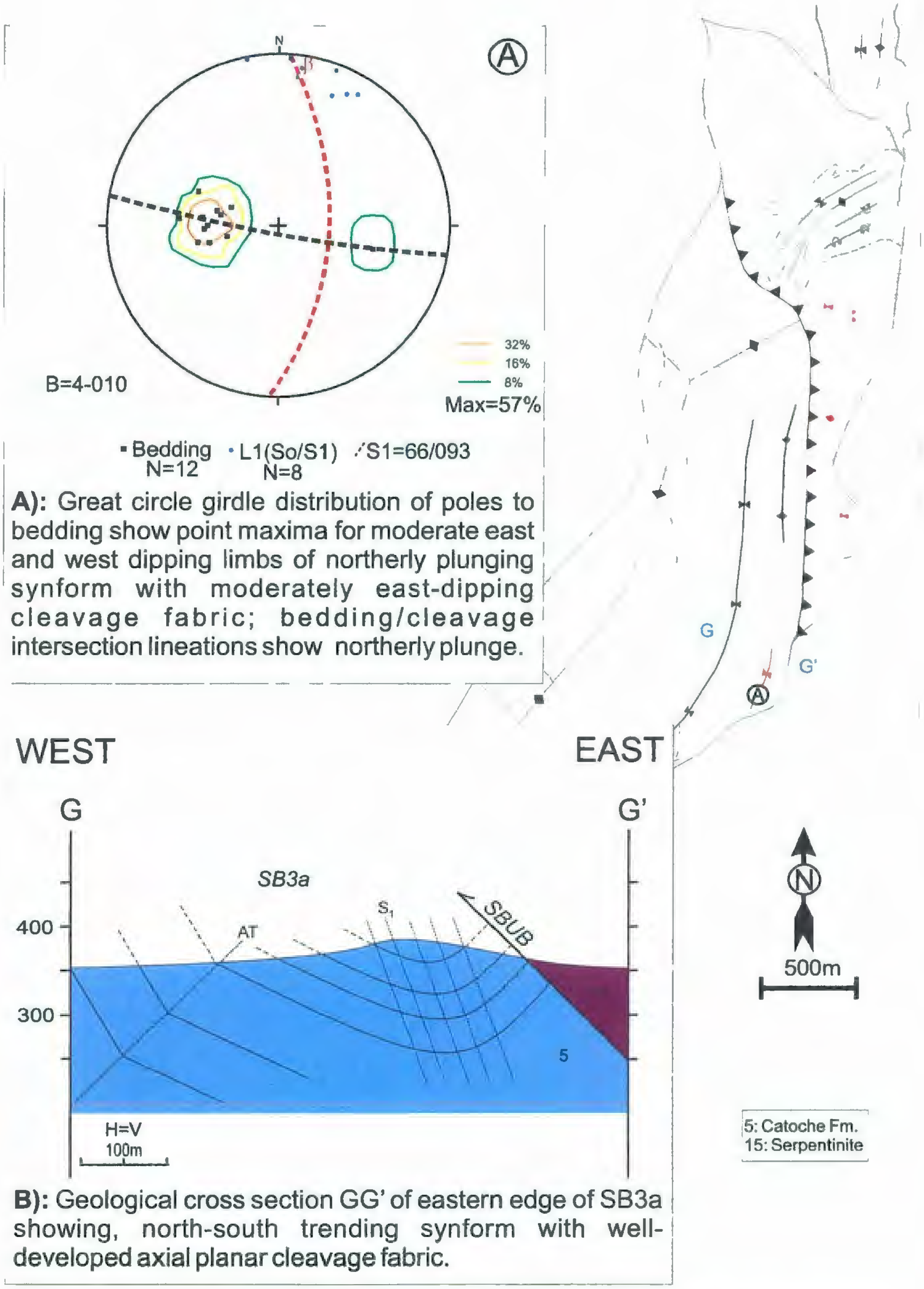
north, based on exposures of SB3b in Spruce Brook that are characterized by sub-horizontal stylo-bedded Catoche Formation limestone (Figure 2.2 B).

The detachment surface that carries SB3b is interpreted to be relatively planar and likely originated as a low-angle, bed-parallel fault, since it does not show significant stratigraphic separation. The fault is overall north dipping; however outcrops constraining the location of the fault suggest that it is folded about the axis of the SB3a ramp anticline (Figure 3.27). Furthermore, the fault surface is interpreted to be truncated by the SBUB and SBCFZ. This suggests that the fault formed early in the emplacement history of the Spruce Brook Thrust Stack and was deformed by subsequent internal shortening of the stack. The timing of major deformation events will be treated more fully in the following chapters.

3.6.3 Late folds

The eastern edge of SB3 in the immediate footwall of the SBUB is characterized by tight, locally overturned north-south trending folds (Figures 3.20 and 3.24). There is also a well-developed, east-dipping, locally slatey cleavage that is axial planer to folding and is interpreted to be parallel to the fault zone (Figure 3.29).

The fold system in the south is developed within the eastern portion of the SB3a ramp anticline backlimb dip domain. At the southeastern edge of SB3a, exposed between two small ponds, is a succession of Catoche Formation limestone that is folded by a tight north-south trending synform (Figure 3.30A). Although the eastern limb of the synform is poorly exposed, limited bedding data indicate that it has a moderate westerly dip (Figure 3.30A). The fold is characterized by a well-developed moderately to steeply east-dipping axial planar cleavage fabric and bedding/cleavage intersections indicate that the fold is gently north plunging (Figure 3.30A). The cleavage fabric observed at this locality is thought to be only locally developed and genetically related to this particular synform, because cleavage is generally not pervasively developed in the Catoche Formation strata in the SB3a backlimb domain, and does not appear to be axial



A): Great circle girdle distribution of poles to bedding show point maxima for moderate east and west dipping limbs of northerly plunging synform with moderately east-dipping cleavage fabric; bedding/cleavage intersection lineations show northerly plunge.

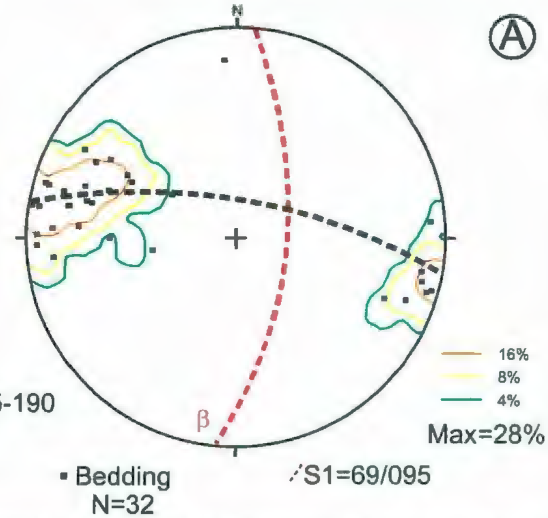
B): Geological cross section GG' of eastern edge of SB3a showing, north-south trending synform with well-developed axial planar cleavage fabric.

Figure 3.30: Pole-plot (A) and geological cross section (B) of late fold system located along the eastern edge of SB3.

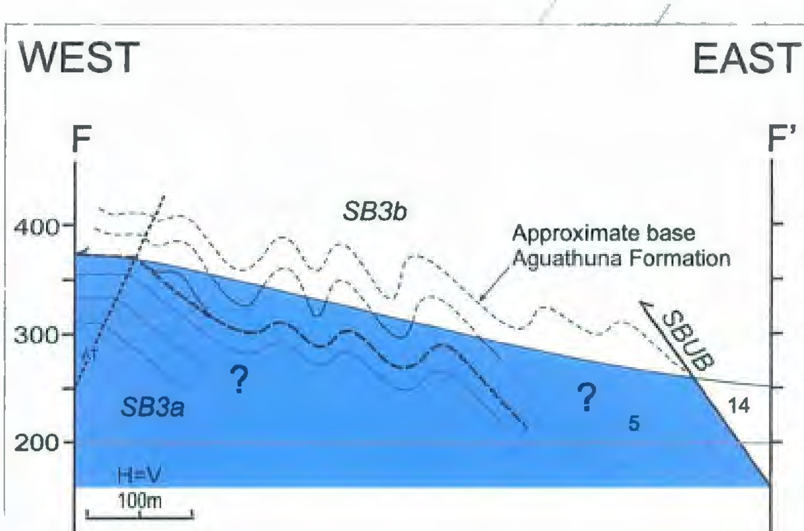
planar to the kink-style folds (Figure 3.30B). The cleavage fabric is, however, well expressed in the lime mudstone of the underlying Boat Harbour Formation exposed just to the south near the eastern edge of the SB3a thrust slice. Here the cleavage dips moderately to steeply toward the east, parallel to the axial planar fabric observed in the folded Catoche Formation succession (Figure 3.20 and Insert 1). The fabric is notably of a slatey nature suggesting that it formed under considerable load-pressure (Figure 3.29). The deformation is, therefore, interpreted to be caused by straining of the SBUB footwall during westerly emplacement of imbricate thrust slices over the eastern edge of SB3.

In the north, the north-south trending fold system is also expressed along the eastern edge of SB3b (Figure 3.20). Here the fold system includes a prominent antiform defined by a belt of steeply dipping to sub-vertical north-south striking beds of Catoche Formation limestone (Figure 3.31A). In the south the fold is upright and symmetrical but becomes more asymmetric toward the north. In the north, the west limb of the fold is interpreted to be locally overturned and the east limb has a more moderate easterly dip giving the fold a west-verging asymmetrical geometry. The area east of the antiform is not well exposed except for a small area in the south where a tight upright synform is defined by steeply dipping beds of Catoche Formation (Figure 3.31B). This structure is most notable for its locally developed axial planar cleavage fabric, which dips steeply toward the east. The area west of the antiform is characterized by steeply dipping to sub-vertical limestone beds that are interpreted to constitute a succession of tight north-south trending antiforms and synforms (Figure 3.31B).

The north-south trending folds that deform the eastern edge of SB3b lie at an angle to the northeast-southwest trending synclinorium that exposes strata of the Aguathuna Formation toward the northwest; the two fold systems are thus interpreted to be genetically different (Figure 3.20). The northeast-southwest trending folds are thought to be related to buckling over the inferred low-angle detachment that separates SB3b from the underlying SB3a, whereas the north-south trending folds at the slice's eastern edge are interpreted to be related to deformation along the edge of the SBUB, reflecting



A): Poles to bedding in Catoche Formation with point maxima for moderately to steeply east dipping and locally overturned orientations, defining an asymmetrical, west-verging antiform. Average cleavage orientation moderately to steeply east-dipping.



B): Geological cross section of eastern edge of SB3b showing tight, north-south trending folds in Catoche Formation limestone

Figure 3.31: Pole-plot (A) and geological cross section (B) of late fold system located along the eastern edge of SB3.

footwall strain during shortening on the fault zone. It is furthermore interpreted that the curvature of the fold axial traces in the SB3b synclinorium and the variable plunge of small-scale folds within the synclinorum may reflect interference between this fold system and the north-south folding in the SBUB footwall. Unfortunately, this inferred interference pattern is not well constrained due to limited orientation data across the two fold systems. The relative timing of the key structural elements in SB3 is treated more fully in Chapter 4.

3.7 Spruce Brook Slice 4 (*SB4*)

Carbonate occurrences north of SB3 are assigned to a separate structural domain termed SB4 (Figure 3.1). The main outcrop area of SB4 consists of two heavily vegetated hills north of Loggers School Road. It is isolated from the outcrop area of SB3 by a low lying marshy area that is unfortunately devoid of outcrop (Figure 3.32). The southern extension of SB4 is inferred to underlie the marshy area, giving it a total areal extent of approximately 5 km^2. In contrast to SB3, the carbonate succession of SB4 consists mostly of upper platform stratigraphy, namely the upper Catoche Formation through Table Point Formation (Figure 3.32). Based on their structural architecture, which will be described in this section, the strata are interpreted to constitute a large west-verging thrust sheet.

The leading edge of the SB4 thrust slice is interpreted to lie coincident with the roof thrust of the Spruce Brook Central Fault Zone (SBCFZ) in the west. The trailing edge of the thrust slice is clearly truncated by the Spruce Brook Ultramafic Belt (SBUB) in the east (Figure 3.1). A detailed description of this contact zone is given in Section 3.8. Internally the SB4 thrust slice is imbricated by west-verging thrust faults that repeat the stratigraphic succession in the slice at three main localities. The slice is therefore divided into three sub-domains, each defining a discrete imbricate thrust slice. They are denoted *SB4a*, *b* and *c*, from west to east (Figure 3.32).

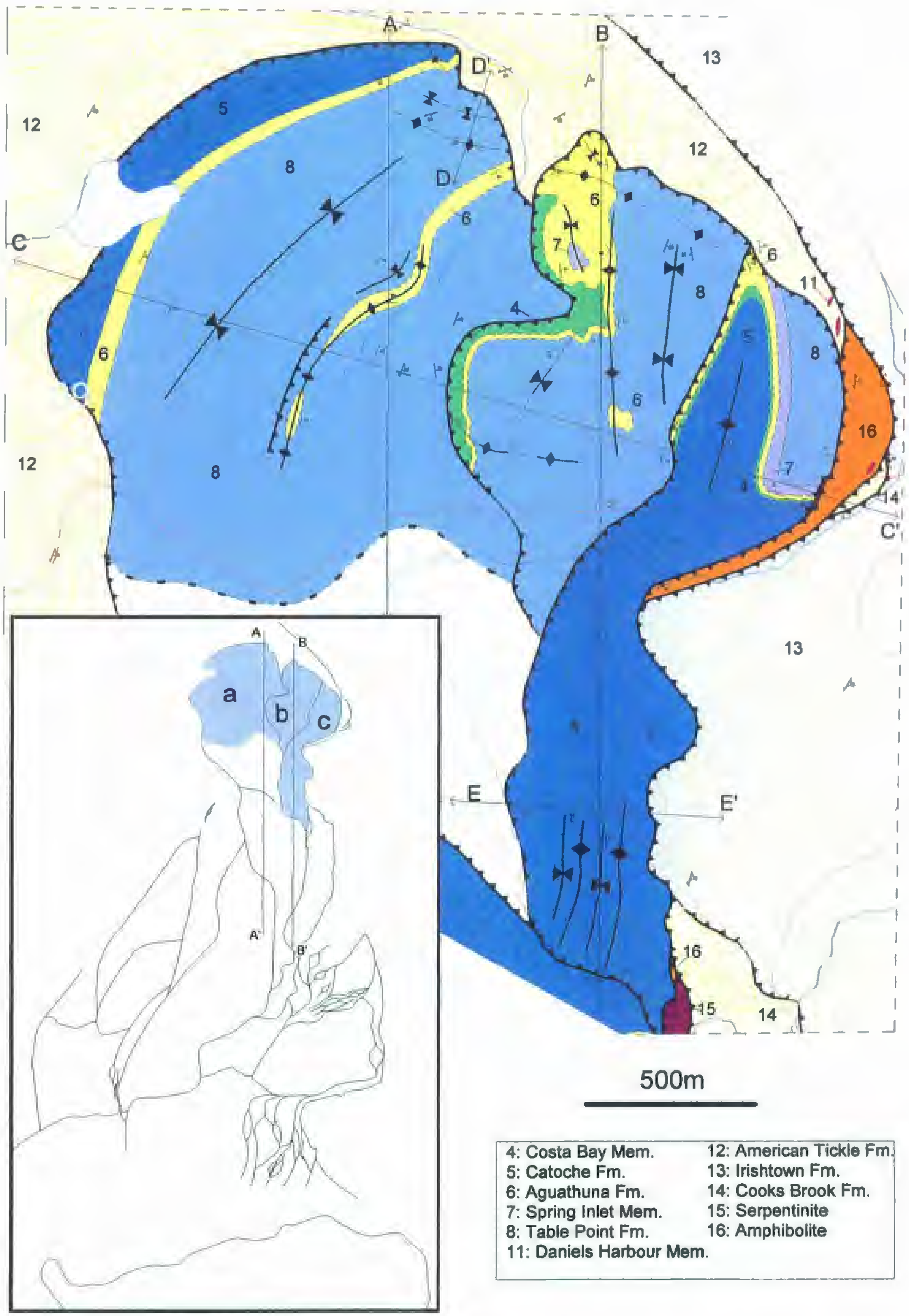


Figure 3.32: Geological map of SB4. Index map shows sub-domains: SB4a, SB4b and SB4c and location of regional longitudinal sections AA', BB'

The contact relationships between SB4 and SB3 must be inferred based on the internal architecture of the thrust slices, since the contact zone is largely obscured by vegetation and is not exposed in outcrop. SB3a and the overlying SB3b thrust slices plunge toward the north, becoming sub-horizontal where their strata are exposed in Spruce Brook in the northern-most extent of the structural domain (Figure 3.33 and Insert 1). Since SB4 lies north of SB3, it maybe concluded that SB4 structurally overlies the northern end of SB3, but given the small plunge amounts and the relatively small structural relief between the top of SB3 and the inferred basal thrust of SB4, it is likely that the two thrust slices lie roughly adjacent to one another at approximately the same structural level (Figure 3.33). The juxtaposition of SB3 and SB4 is treated in greater detail in Chapter 4.

The basal thrust of SB4 is best constrained by exposures of the slice's trailing edge near Spruce Brook in the southern portion of the domain (Figure 3.34C). At this locality, beds of Catoche Formation limestone exposed in the brook are sub-horizontal to gently northeasterly dipping and are interpreted as the top of the SB3b thrust slice. Directly up section from these outcrops, on the north side of Spruce Brook is a tightly folded succession of Catoche Formation strata which are assigned to the basal portion of the trailing edge of SB4. A major low-angle thrust fault is thus interpreted to lie immediately north of the brook emplacing SB4 limestone over the SB3 succession. This fault is interpreted as the basal thrust of the SB4 thrust sheet (Figure 3.33).

3.7.1 SB4a

The leading edge of SB4a is well defined in the west where it forms a prominent limestone scarp consisting of east-dipping beds of Catoche Formation limestone (Figure 3.32). At the northeast and southwest ends of the scarp, several outcrops of American Tickle Formation shale (assigned to the Western Shale Belt) are located below the limestone scarp, in the footwall of the thrust slice. Based on the distribution of shale outcrops, the thrust carrying the limestone slice is interpreted to be moderately east-dipping (Figure 3.34A). The shale footwall of SB4a is also exposed in the steep hillside defining the northeastern edge of the thrust slice. The shale can be traced into the base

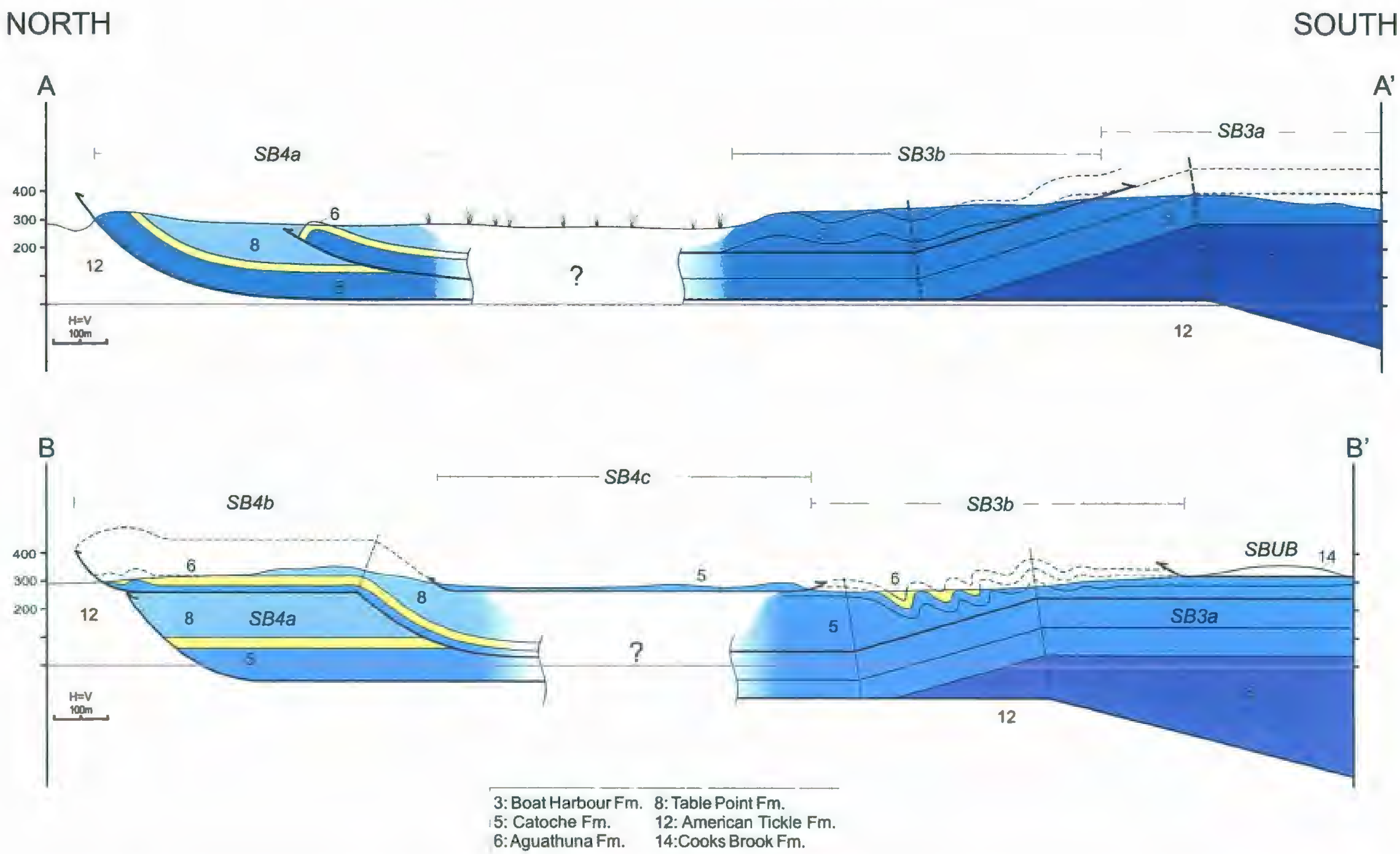


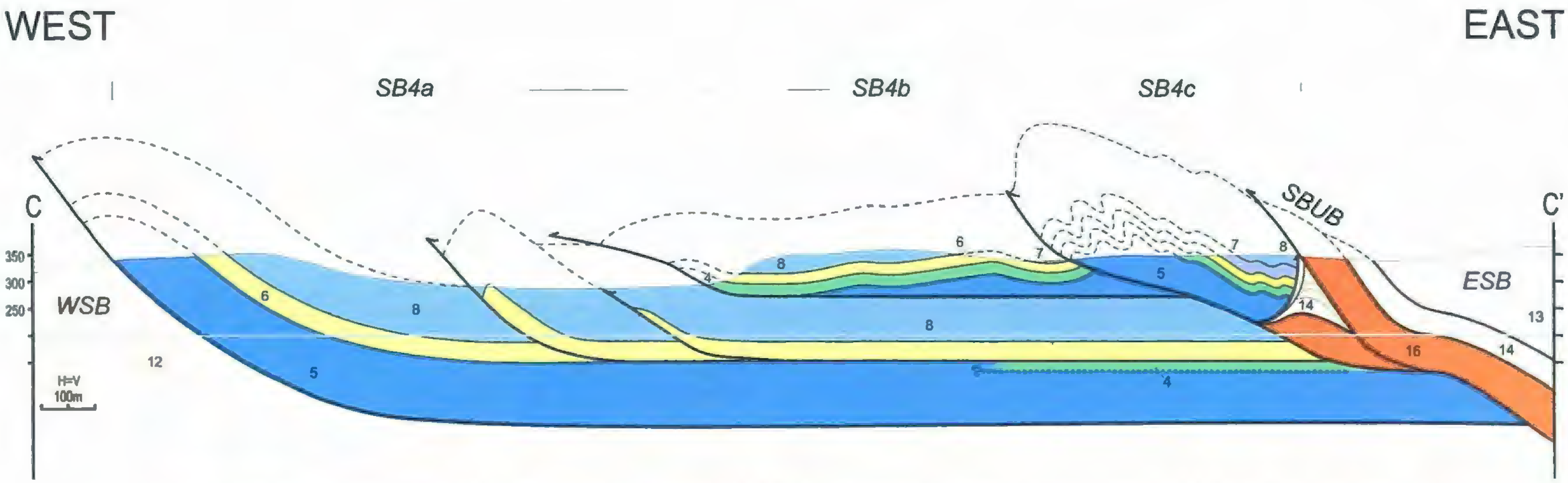
Figure 3.33: Longitudinal sections of SB4 and the northern portion of SB3. The contact zone between the structural domains is largely obscured by a low-lying marshy area; the structural slices are interpreted to lie adjacent to one another at roughly similar structural levels. See Figure 3.32 for location of sections.

of the hill toward the south suggesting that the basal thrust of SB4a dips to the southeast at this locality. This portion of the thrust is interpreted as a major lateral thrust ramp that forms the northeastern termination of the SB4 thrust slice (Figure 3. 34B).

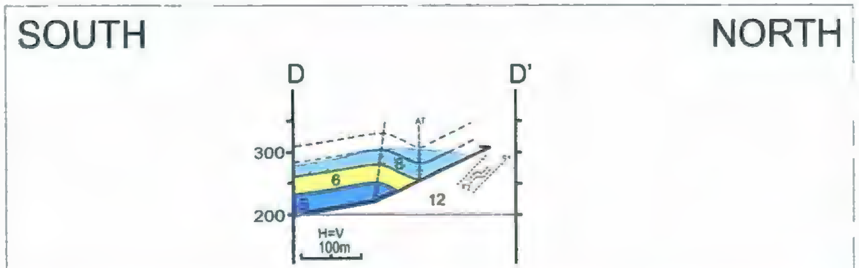
SB4a has a broadly synformal geometry and is interpreted as the leading syncline of the SB4 thrust slices (Figure 3.35A). The west limb of the syncline is exposed along the crest of the limestone scarp forming the leading edge of SB4a. It is moderately east dipping and its trend curves slightly along strike from north-south in the south to northeast-southwest toward the north (Figure 3.32). The west limb of the syncline is expressed morphologically as a gentle east-sloping hillside. The slope is heavily wooded and outcrop exposure is poor. Subcrop in the slope is dominated by Table Point Formation limestone suggesting that the stratigraphic succession on the west limb of the synform is largely complete up to the upper portion of this unit. The succession is, however, interpreted to be internally deformed and structurally thickened by disharmonic meter-scale buckle-fold wave trains (Figure 3.36). These folds are only locally observed, but tend to be variable in their fold axis orientations suggesting that the internal deformation in SB4a is somewhat non-cylindrical (Figure 3.35B).

The synform terminates at the northeastern edge of the thrust slice where limestone beds dip moderately toward the northeast (population iii, Figure 3.35A). These beds define the forelimb of a low amplitude antiform-synform pair that is interpreted to have formed in response to movement of the thrust slice over the lateral thrust ramp that forms the northern termination of the slice (Figures 3.32 and 3.34B).

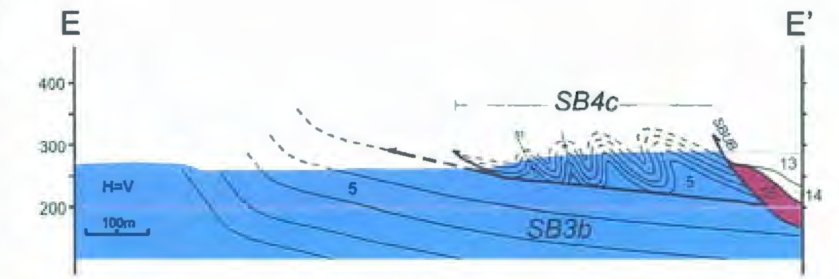
The morphological slope underlain by the synform transitions into a low-lying marshy area toward the east. Here a tight, locally overturned, antiform is observed in strata of the upper Aguathuna Formation (Figures 3.32 and Figure 3.35A). The tightness of the fold and the occurrence of Aguathuna Formation at this locality suggest that the stratigraphic succession is repeated by a thrust fault and that the fold formed above the tip-line of the fault (Figure 3.34A). The fold loses its expression toward the north where Aguathuna Formation strata dip more uniformly to the southeast (Figure 3.32). East of



A): Cross section CC' of the central portion of SB4 showing internal imbrication of the thrust sheet

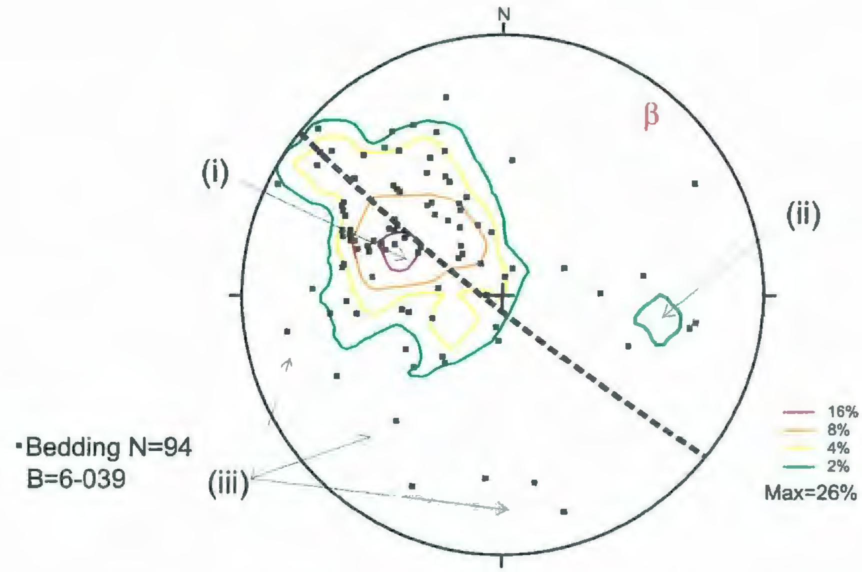


**B): Cross section DD' of northeastern edge of SB4a showing antiform-synform pair formed over a west-dipping lateral thrust ramp that terminates the thrust slice in the north.

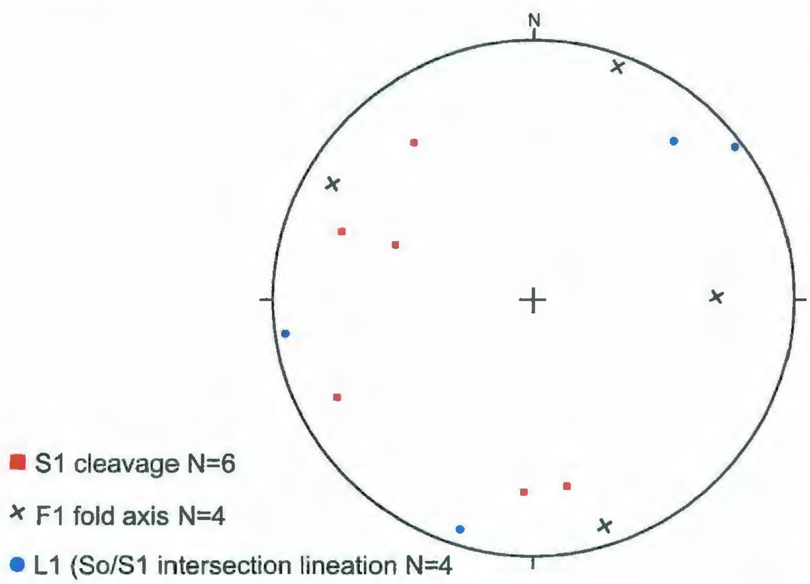


C): Cross section EE' of the southern portion of SB4c showing inferred contact zone with SB3b as exposed in Spruce Brook.

Figure 3.34: Geological cross sections of SB4 showing internal structural architecture of subdomains SB4a, SB4b, SB4c and contacts with Spruce Brook Ultramafic Belt (SBUB), Western Shale Belt (WSB) and Eastern Shale Belt (ESB). See Figure 3.32 for location of sections and lithology legend.



A: Poles to bedding showing point maximum (i): moderately east-dipping limb of north plunging synform; point maximum (ii): west dipping beds reflect folding over thrust tip that repeats the Aguathuna Formation in the central portion of the slice; population (iii): steep northeast-dipping beds define forelimb of ramp anticline above the lateral ramp at northern edge of slice.



B: Poles to S1 cleavage indicate moderate to steep, dominantly east-dipping fabric; bedding/ cleavage intersections plunge gently northeast and southwest; small-scale fold axis orientations are highly variable.

Figure 3.35: Lower hemisphere equal-area plots of bedding, cleavage and small-scale fold axes in SB4a

Figure 3.36: View looking east of meter-scale synformal fold in Catoche Formation Limestone located on the west limb of the SB4a syncline. Hinge plunges gently to the east and has disharmonic asymmetrical parasitic folds.

Figure 3.37: Small-scale west-verging polyclinal kink folds in Costa Bay Member limestone, in the basal portion of SB4b.

the inferred tip-line fold are several large outcrops of Table Point Formation that are interpreted to lie in the hangingwall of the imbricating thrust (Figures 3.32 and 3.34A). The limestones at this locality show a crudely developed cleavage fabric that dips steeply to moderately toward the east (Figure 3.35B). The thickness of the Table Point Formation in this portion of SB4a suggests that the succession is structurally thickened. An imbricating thrust is thus inferred, although this faulting is not documented in outcrop due to lack of exposure.

3.7.2 SB4b

The Table Point Formation in *SB4a* can be traced eastwards to the leading edge of the SB4b thrust slice, which is delineated by a prominent cliff that has over 50m of topographic relief (Figure 3.32). The base of the cliff face contains strata assigned to the Costa Bay Member of the Catoche Formation. This unit is interpreted to have been emplaced over the Table Point Formation by a west-verging thrust fault having a stratigraphic separation on the order of 100m (Figure 3.34A). The limestone strata in the immediate hangingwall of the thrust are gently east-dipping and show prominent small scale polyclinal, kink-style folds (Figure3.37). The folds are asymmetrical west-verging structures and plunge gently to the northeast (See Insert 1).

In the north, SB4b overlies black shale and limestone conglomerate of the American Tickle Formation in the footwall of the southeast dipping lateral thrust ramp that forms the northern termination of the SB4 thrust slice (Figure 3.32). Similar to that of SB4a, limestone strata at the northeastern edge of SB4b dips steeply toward the north, suggesting that the slice is deformed by an east-west trending ramp-bend fold that is coincident with the inferred underlying lateral thrust ramp (Figure 3.38A). The basal thrust of SB4b is exposed near its transition from a north-south trending frontal ramp to an east-west trending lateral ramp. At this locality the limestone strata have a well-developed cleavage fabric and are structural interleaved with several meter-thick lenses of highly cleaved black shale. The shale lenses are interpreted as duplex horses cut from the shale footwall of the lateral ramp and imbricated with the limestone in the fault zone.

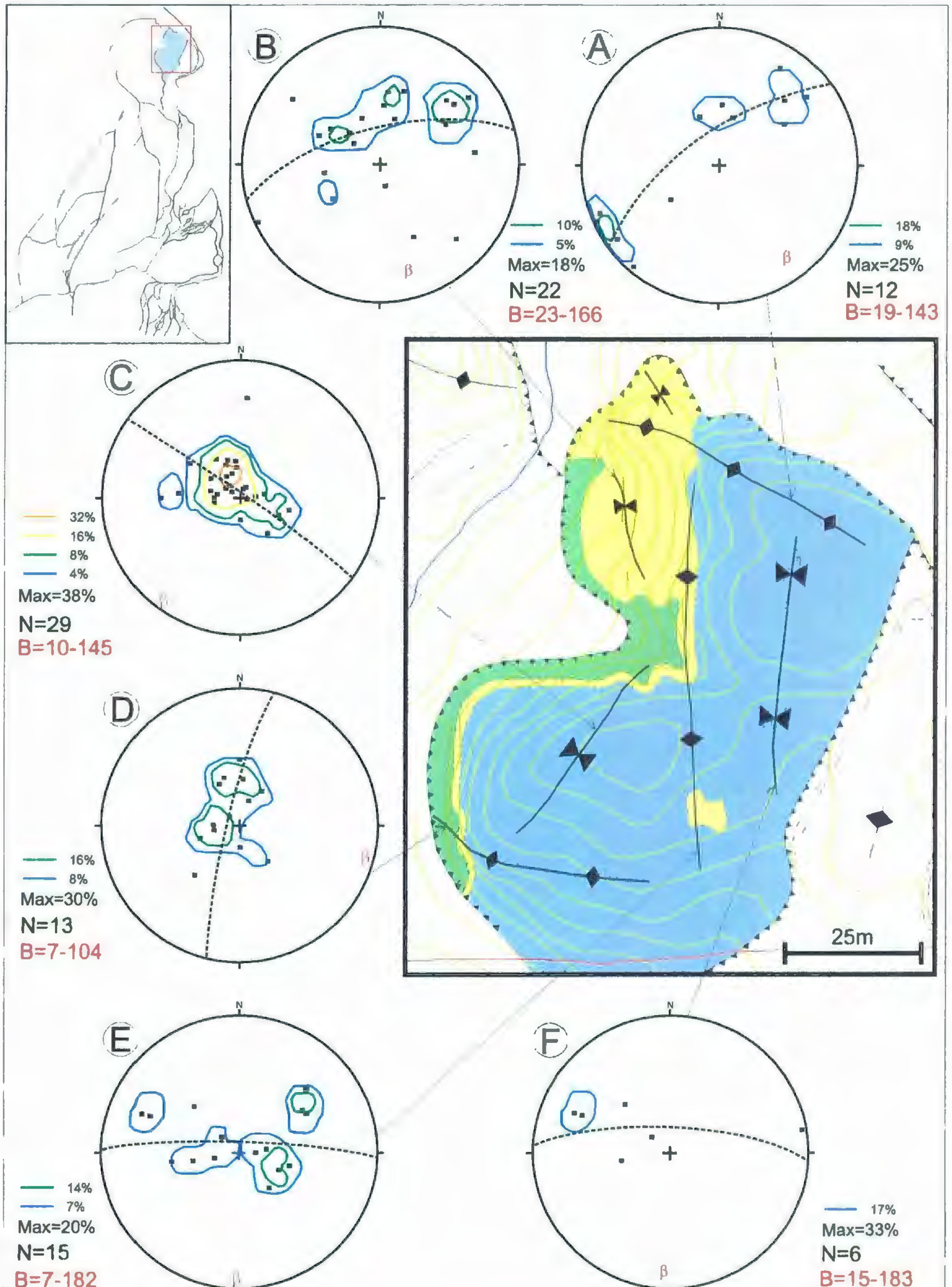


Figure 3.38: Lower hemisphere equal area plots of poles to bedding defining the major fold structures in SB4b.

The presence of shale in the footwall of SB4b suggest that the imbricating thrust that transported SB4b toward the west must have had a significant component of sinistral oblique slip to emplace the limestone thrust slice over the adjacent shale.

The SB4b thrust slice contains a series of synforms and antiforms (Figure 3.38). Immediately up-section from its basal thrust, the folded strata of SB4b constitute a leading syncline defined by two main structural depressions, a northwest-southeast trending depression in the north and a southwest plunging depression in the south. The synform in the north is cored by Aguathuna and Table Point formations and is non-cylindrical (Figure 3.38 B). The Aguathuna Formation strata at this locality typically show small-scale detachment style folds with variable orientations. In the south, the syncline is cored by Table Point Formation limestone and has well defined east-, south-, north- and west- dipping flanks defining a symmetrical upright structural depression (Figure 3.38 C).

The leading syncline of SB4b is terminated in the south by an east-west trending antiform defined by its north-dipping northern limb and south-dipping limestone beds exposed along Loggers School Road. The fold is a gently east plunging upright and symmetrical antiform that is interpreted to be formed over a lateral thrust ramp (Figure 3.38 D).

The central portion of SB4b is interpreted to have an antiformal geometry defined by sparse orientation data (Figure 3.38 E). The fold is upright, north-south trending, and very gently south plunging. The moderately east-dipping eastern limb of the fold is exposed north of Loggers School Road near the inferred basal thrust of the overlying SB4c structural slice. Further north, the antiform is interpreted to be flanked by a synform, but this structure is poorly constrained due to lack of outcrop (Figure 3.38 F).

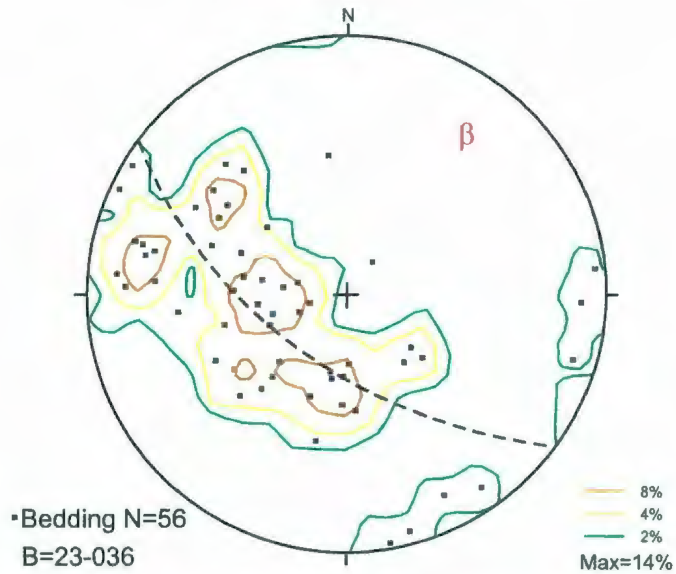
The north-south trending folds in SB4b are indicative of detachment-style folding by westerly-directed layer-parallel compression. SB4b is thus interpreted to be a thin thrust sheet emplaced to the west over a low angle thrust surface (Figure 3.34 A). The thrust surface is thought to be somewhat irregular with several lateral thrust ramps that created the east-west trending fold structures in the slice.

3.7.3 SB4c

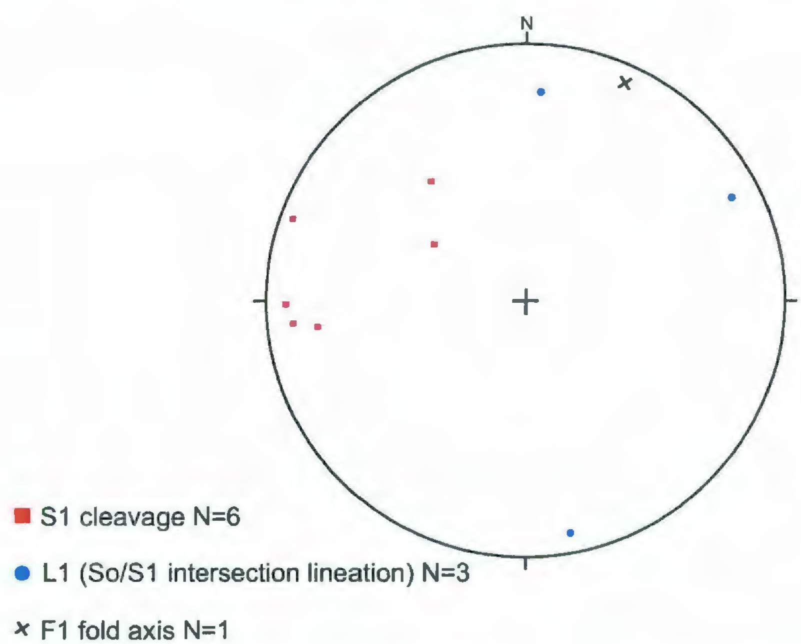
The eastern edge of *SB4b* is an inferred thrust fault that carries in its hangingwall the folded limestone succession of Catoche through Table Point formations constituting the SB4c thrust slice (Figure 3.32). SB4c is interpreted as the deformed trailing edge of SB4. The thrust splay that carries it is interpreted to root in the basal detachment of SB4 and to cut up-section toward the north (Figures 3.34A and 3.34C). The surface trace of this fault is poorly constrained in the eastern and central portion of SB4c due to lack of bedrock exposure. The internal structural architecture of SB4c and the location of its basal thrust are identified from two important localities, one in the north along Loggers School Road and one near Spruce Brook in the south.

In the north, the thrust fault carrying SB4c is inferred below a belt of steeply dipping Aguathuna Formation strata. These strata are interpreted to be part of a tight, westerly-verging fold wave-train that structurally overlies gently east dipping beds of Spring Inlet Member limestone assigned to SB4b outcropping immediately to the west (Figure 3.34A). The main outcrop area of SB4c in the north is poorly exposed, but the fold system is interpreted as a non-cylindrical system of northeast-plunging, westerly-verging asymmetrical folds based on scattered orientation data (Figure 3.39A). Mesoscopic folds observed in the northern portion of SB4c along Loggers School Road are typically characterized by northeast plunging asymmetrical, west-verging folds with broad, rounded hinge domains.

South of Loggers School Road, the along-strike continuation of SB4c is interpreted to lie along a low north-trending ridge that extends to Spruce Brook (Figure 3.32). The ridge is poorly exposed along most of its length, but exposures in a prominent small scarp immediately north of Spruce Brook suggest that it is largely composed of Catoche Formation limestone. The strata show a locally developed moderately to steeply east-



A: Poles to bedding in *SB4c* showing partial great circle girdle distribution describing non-cylindrical, northeast-plunging fold system characterized by tight asymmetrical and upright fold forms. Overall moderate and steep east-dipping orientations reflect west-verging asymmetry of fold system.



B: Poles to S1 cleavage describe crudely developed moderate to steep east-dipping fabric interpreted to be roughly axial planar to west-verging fold system; bedding/cleavage intersection lineations plunge gently north and south, rare small-scale fold plunges gently north.

Figure 3.39: Lower hemisphere equal area pole plots of planar and linear fabrics in in SB4c

dipping cleavage fabric (Figure 3.39B). The fold system in this portion of SB4c is interpreted to be westerly-verging and is characterized by tightly folded strata with locally sub-vertical to overturned bedding orientations (Figure 3.34C). Based on the similarity of the deformation style, the folded Catoche Formation strata north of Spruce Brook is interpreted to constitute the up-plunge continuation of the northeast-plunging fold system defined on Loggers School Road. These folded strata directly overly the basal detachment of SB4, which is interpreted to be sub-horizontal to gently east dipping as described above (Figure 3.34C).

3.8 The Spruce Brook Ultramafic Belt (*SBUB*)

The eastern edge of the SB3 and SB4 thrust slices is defined by the Spruce Brook Ultramafic Belt (SBUB). It is a major north-south trending fault zone with a strike length of approximately 9 km (Figure 3.40). The SBUB is characterized by numerous small, discontinuous structural slices of altered mafic and ultramafic plutonic rocks correlated to the Bay of Islands ophiolite Complex, and metamorphic rocks correlated to the metamorphic aureole of the Bay of Islands Complex. The fault zone also carries structural slivers of black siliceous and calcareous shale with ribbon limestone and limestone conglomerate assigned to the Cooks Brook Formation. These structural slices are typically internally deformed by westerly verging fold systems with pervasive moderately east-dipping axial planar cleavage fabric. The fault zone is interpreted to be moderately to steeply east-dipping based on cleavage orientations in sedimentary units and schistose serpentinite occurring within the fault zone (Figure 3.40). Exposed east of the fault zone, its hanging wall succession consists of sandstone and shale assigned to the Irishtown Formation and defined as the Eastern Shale Belt (ESB) (Figure 3.40).

The SBUB is a narrow zone along most of its strike length in the north. Imbricate slices within the fault zone rarely exceed 100-200m in thickness and are laterally discontinuous, locally pinching out to make the floor and roof thrusts of the fault zone coincident (Figure 3.40). In the southern portion of the map area the SBUB becomes a wide imbricate zone termed the Spruce Brook Ultramafic Belt Imbricate Zone

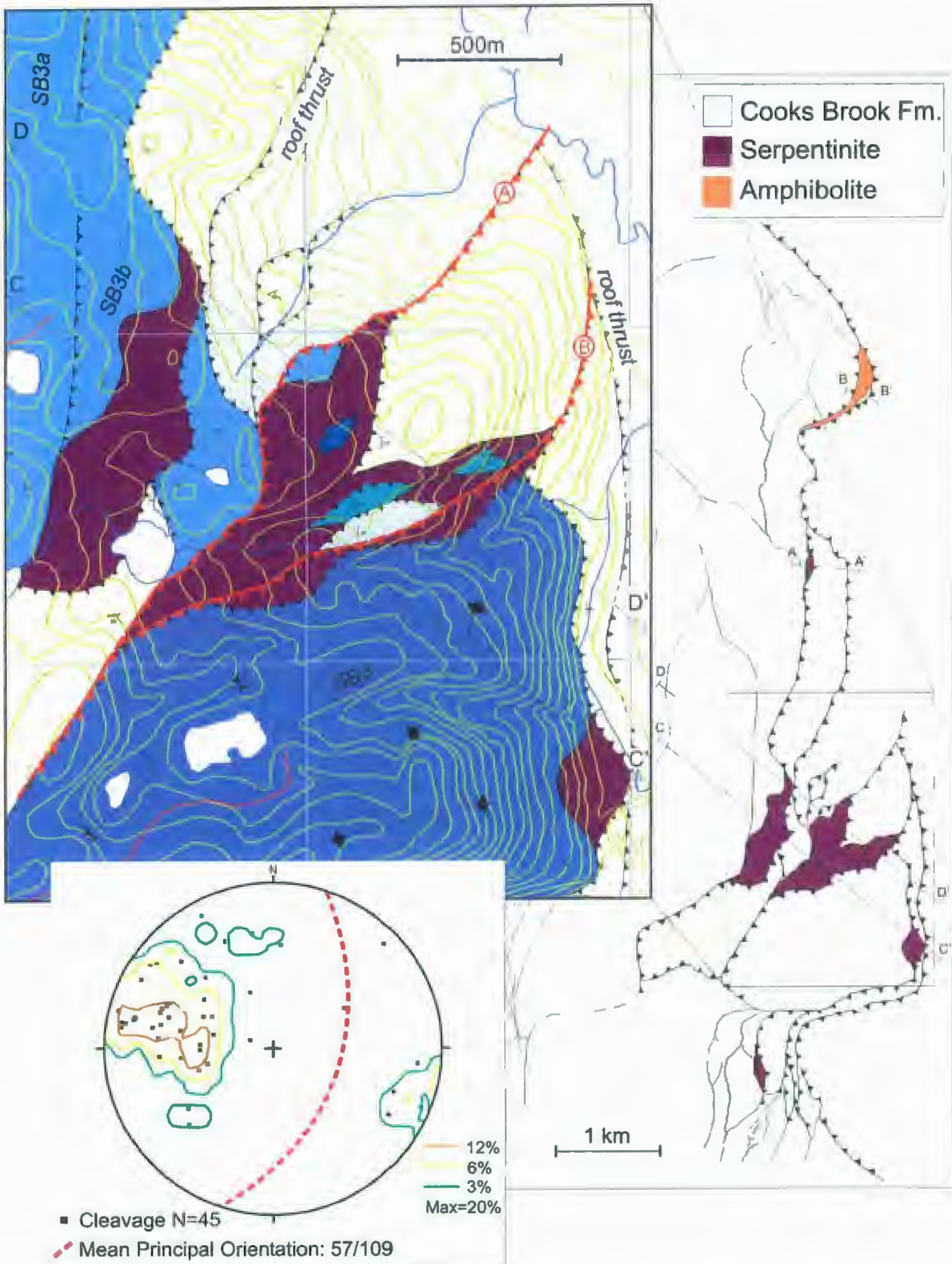


Figure 3.40: Geological map of the Spruce Brook Ultramafic Belt with detailed geology map for the SBUB imbricate zone. Lower hemisphere equal area pole plot for schistosity in structural slices of serpentinite and amphibolite occurring within the fault zone shows an overall moderate to steep easterly dip.

(SBUBIZ) characterized by a complex east-dipping stack of small fault-bounded structural slices. Major west-verging thrust faults within this zone repeat the footwall and hangingwall successions of the SBUB. The imbricate zone encompasses the SB5 structural domain and continues to the south where it is an integral part of the SB6 structural domain.

The floor thrust of the SBUB is observed at several localities long the east side of SB3 in the immediate footwall of the fault zone. The fault is delineated by a narrow belt of rusty weathering platform carbonate that is highly fluid-altered and silicified with some minor sulphide mineralization (Figure 3.41). The altered rocks typically have a moderately to steeply east-dipping stylolitic fabric and are locally cross-cut by quartz/calcite stockwork veins.

The roof-thrust of the SBUB carries the Eastern Shale Belt, a thick succession of polydeformed sandstone and shale of the Irishtown Formation (Figure 3.40). This unit is exposed east of Spruce Brook, and its internal structural architecture is treated in Section 3.11. The roof thrust is generally not well defined where the Eastern Shale Belt is in structural contact with shales of the Cooks Brook Formation; however it is observed in outcrop at two localities in the map area, most notably in the southern portion of Spruce Brook where Irishtown Formation sandstone is in contact with serpentinite (Figure 3.42). Like the floor thrust, the roof thrust is typically characterized by a zone of stockwork quartz veining and is fluid altered, giving the wall rocks a rusty-weathered appearance.

The type section of the SBUB fault zone is identified in Spruce Brook near the contact between SB3 and SB4 (Figure 3.40 AA'). Here the floor thrust of the fault zone is clearly marked by a steep east-dipping zone of rusty weathering, highly veined limestone. Immediately east of the altered limestone is an occurrence of highly cleaved schistose serpentinite (Figure 3.43). The fabric in the serpentinite is steeply east-dipping and locally shows well-developed C-S fabric indicating sinistral-reverse sense shear.

Figure 3.41: Rusty weathering fluid-altered platform carbonate defining the floor thrust of the SBUB along the eastern edge of SB3. Altered zone locally has poorly developed steep east-dipping cleavage fabric and stockwork veining

Figure 3.42: View looking east in Spruce Brook showing steeply east-dipping contact between Irishtown Formation sandstone and sepentinite defining the roof-thrust of the SBUB at the trailing edge of SB5.

The schistose serpentinite contains rotated augen of massive serpentinite that indicate a reverse sense of shear.

To the east, the brook exposes a succession of highly deformed calcareous shale correlated to the Cooks Brook Formation. This occurrence is interpreted as a north-south trending, east-dipping structural panel that overlies the serpentinite in the SBUB fault zone (Figure 3.44). The southern continuation of the slice is exposed on a logging road that runs along the hill side immediately west of the brook. The succession in this structural slice shows a well-developed steep S1 cleavage fabric that is typically parallel to bedding in the shale. Small-scale F1 folds are not exposed, but based on bedding/cleavage relationships, it is inferred that the F1 system is tight to isoclinal with steeply inclined limbs. The S1 cleavage is deformed by a tight, moderately inclined, moderately southeast-plunging and northwest-verging asymmetrical F2 fold system (Figure 3.45). The fold axial planes of the F2 system locally strike nearly east-west, lying at a high angle to the inferred bounding faults of the Cooks Brook Formation thrust panel (Figure 3.45). This indicates that the panel was, at least locally, deformed by a compressive stress oriented roughly north-northwest within the overall north-south striking SBUB which suggests that the fault zone had a significant component of sinisitral strike-slip during a portion of its movement history. This strike-slip movement is also indicated by shear fabrics in the serpentinite exposed adjacent to Cooks Brook Formation strata in Spruce Brook.

The southern portion of the Cooks Brook Formation panel shows well-developed F2 fold wave-trains with moderately east-dipping F2 fold axes which are locally crenulated by F3 folding (Figure 3.46). Based on limited data, the F3 fold system is interpreted to consist mostly of large open fold structures that are only locally expressed as interference patterns in the more prominent F2 fold system. F3 folds exposed on the logging road are moderately inclined and plunge toward the southeast (Figure 3.45). S2 axial planar fabrics are not well developed in the structural panel, but are locally expressed as a widely spaced southeast dipping crenulation cleavage.

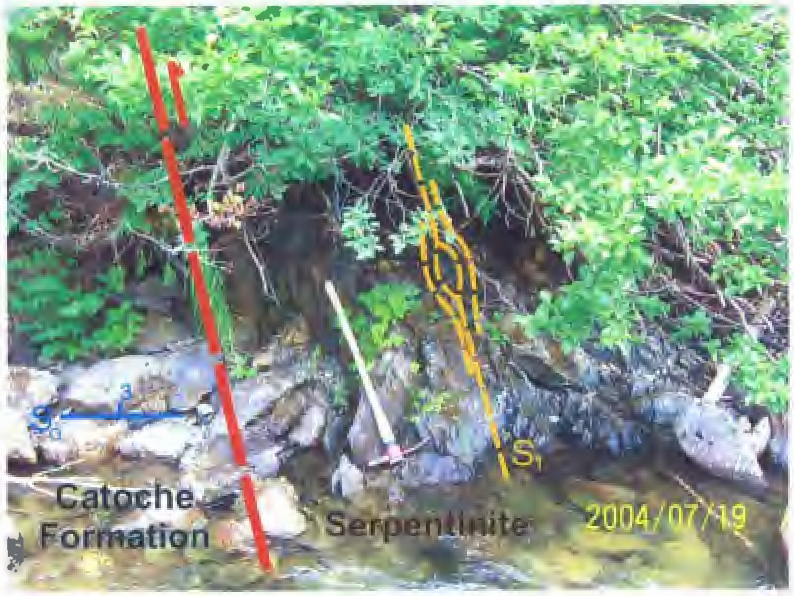
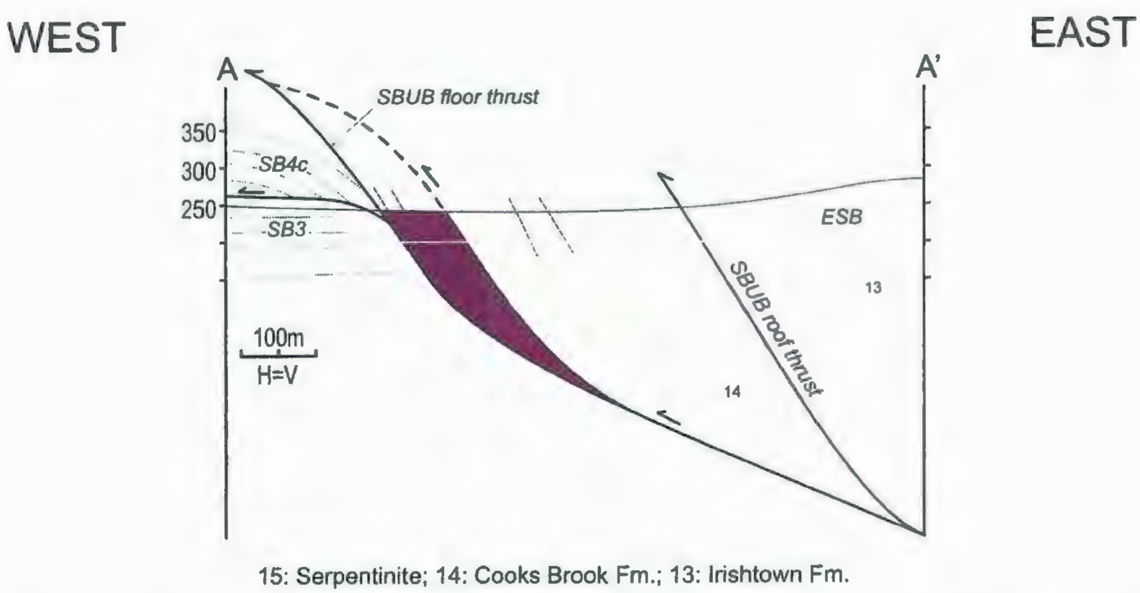


Figure 3.43: View looking north in Spruce Brook showing east-dipping schistose serpentinite near the floor-thrust of the SBUB. Beds of Catoche Formation limestone in the footwall are sub-horizontal.



15: Serpentinite; 14: Cooks Brook Fm.; 13: Irishtown Fm.

Figure 3.44: Geological cross-section showing the type-section through the SBUB exposed in Spruce Brook near the contact between SB3 and SB4. The floor-thrust of the SBUB emplaces imbricated structural slices of serpentinite and Cooks Brook Formation shale over platform carbonate (Catoche Formation). The roof thrust of the SBUB carries Irishtown Formation shale and sandstone constituting the Eastern Shale Belt (ESB). See Figure 3.40 for location of section.

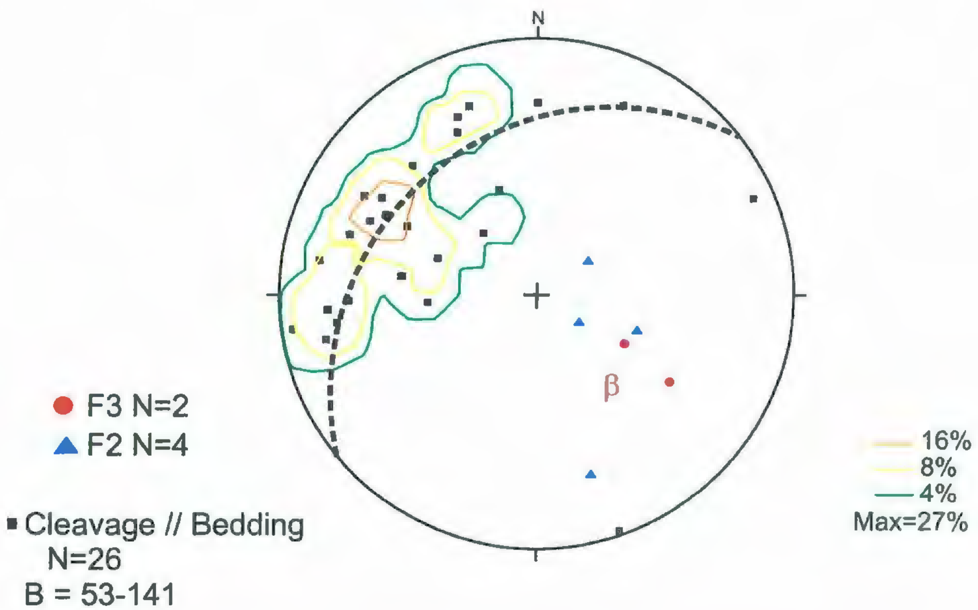
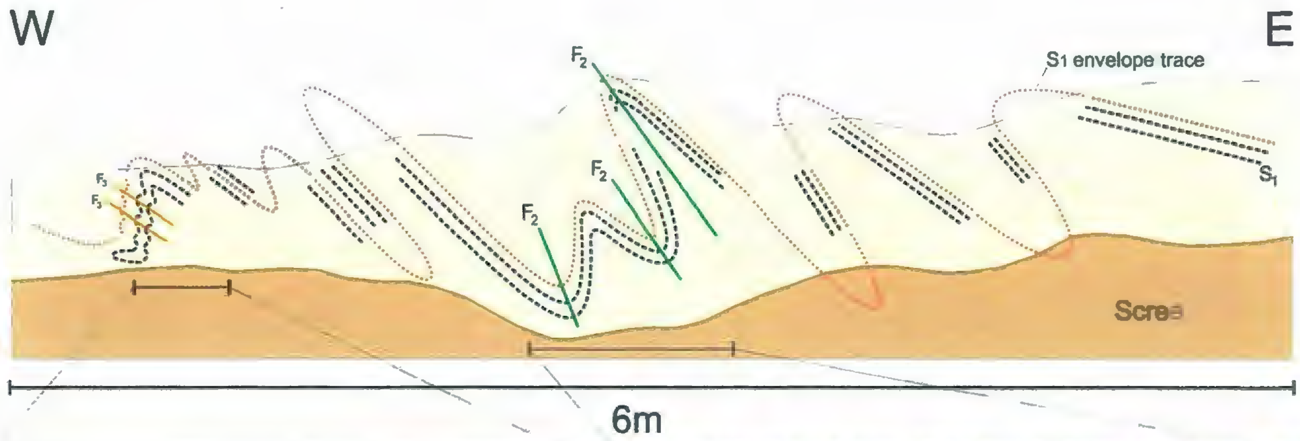
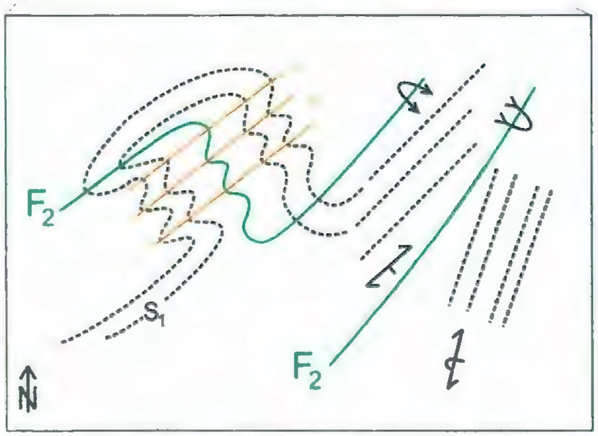


Figure 3.45: Lower hemisphere equal area plot of poles to cleavage parallel to bedding and small-scale fold axes in thrust panel of Cooks Brook Formation within the north-central portion of the SBUB at its type locality (see Figure 3.44). Partial great circle girdle distribution with point maxima for east and southeast dipping fabric indicates sub-cylindrical southeast plunging F2 fold system (see Figure 3.29). Measured small scale F2 and F3 fold axis plunge to the southeast; they lie reclined within the overall orientation of the fault zone.





Plan-view sketch of F2 antiform re-folded by moderately southeast-plunging F3 fold axes

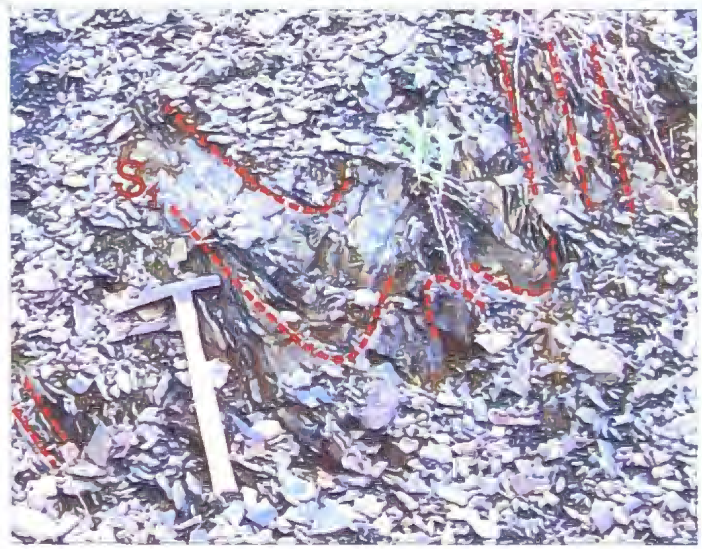


Figure 3.46: Field sketches and photo of F2 fold system in black shale assigned to Cooks Brook Formation outcropping on a logging road immediately west of Spruce Brook. Fold system defined by west-verging asymmetrical folds of S1 cleavage fabric. F2 axial planes locally crenulated by southeast plunging F3 folds. See Appendix 3 for location.

The Cooks Brook Formation panel is interpreted to be overlain by the Eastern Shale Belt which is delineated by outcrops of laminated siliceous shale of the Irishtown Formation exposed along logging roads in the hillside east of Spruce Brook (Figure 3.44). The roof thrust of the SBUB is, however, not exposed in the northern portion of Spruce Brook.

In the north, a cross-section through the SBUB is exposed along Loggers School Road. At this locality the fault zone carries a large structural slice of banded amphibolite and a small structural sliver of shale and ribbon limestone of the Cooks Brook Formation. (Figure 3.40 BB'). The amphibolite has a strong moderately to steeply east-dipping foliation and is locally internally imbricated with small (~ 1 meter thick) slivers of serpentinized ultramafic rock. The amphibolite thrust slice is internally deformed by folds that are locally tight meter-scale structures, but are more typically broad open wave trains.

The contact between the amphibolite and the eastern edge of the SB4 limestone succession is well exposed along the road; however, the contact zone is markedly different from exposures of the SBUB footwall in Spruce Brook to the south. On Loggers School Road the limestone immediately west of the amphibolite slice lacks the rusty-weathering fluid-altered character that typifies the SBUB floor thrust in the south; the gently east-dipping strata are unaltered and sharply truncated by a west-dipping fault (Figure 3.47). The limestone is separated from the amphibolite by a narrow belt of black shale that demonstrably lies in the footwall of the west-dipping fault and has a prominent sub-vertical cleavage. The shale is tentatively correlated to the Cooks Brook Formation and the fault is interpreted to be a back-thrust that displaces SB4c toward the east, bringing it to overly the SBUB floor thrust (Figure 3.48). The back thrust is thought to have formed in response to shortening in the footwall during movement on the SBUB fault zone. The relative timing of major deformation events is treated in greater detail in Chapter 4.

Figure 3.47: View looking northwest on Loggers School Road showing gently east-dipping beds of Spring Inlet Member limestone truncated by a west-dipping fault. Highly cleaved black shale lies in the immediate footwall of the fault. A large structural slice of banded amphibolite occurs just to the east of outcrop.

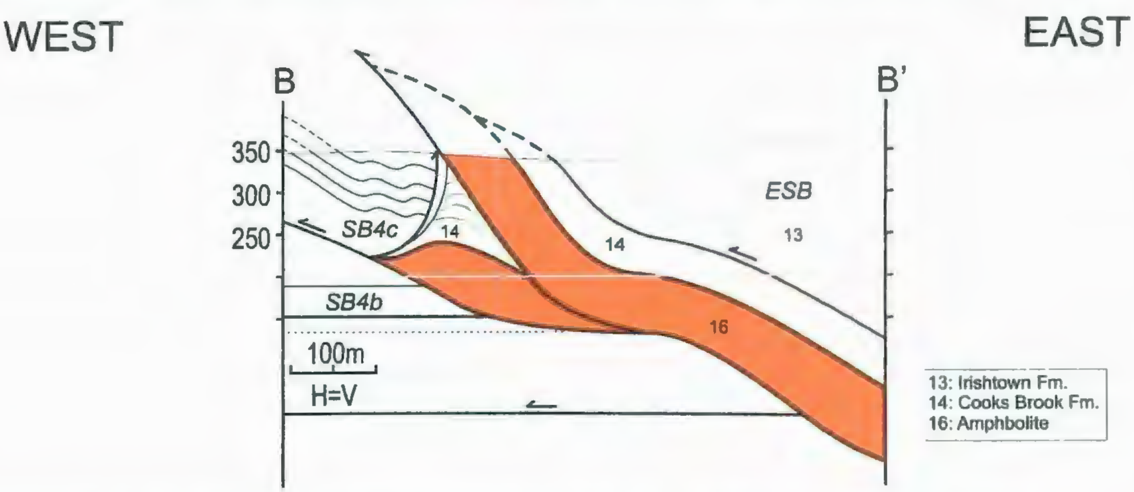


Figure 3.48: Geological cross-section of the SBUB as exposed on Loggers School Road at the eastern edge of SB4. The fault zone carries a large slice of banded amphibolite, but the floor-thrust is interpreted to be overlain by SB4c, which is thrust to the east on an antithetic fault. Shale occurring in the footwall of the back-thrust is assigned to the Cooks Brook Formation which clearly overlies the amphibolite toward the east.

The contact between the amphibolite and the overlying Cooks Brook Formation is tightly constrained by outcrops on Loggers School Road. A highly deformed succession of black shale and ribbon limestone is exposed immediately east of the amphibolite. The succession is deformed by small-scale west-verging asymmetrical folds with a well-developed moderately east-dipping axial-planar cleavage fabric (Figure 3.49). This occurrence of Cooks Brook Formation is interpreted to constitute a discontinuous structural sliver that pinches out toward the south. This is based on outcrops of the SBUB roof thrust just south of the road where Cooks Brook Formation strata are notably absent. At this locality, a low ridge composed of foliated amphibolite has a steeply east-dipping scarp on its eastern edge that is composed of rusty weathering, highly deformed quartzose sandstone assigned to the Irishtown Formation of the Eastern Shale Belt.

3.8.1 Spruce Brook Ultramafic Belt Imbricate Zone (SBUBIZ)

In the southeastern portion of the map area the SBUB becomes a wide fault zone as its roof-thrust steps abruptly to the east. This part of the SBUB is a complex moderately to steeply east-dipping imbricate zone that carries several structural slices of altered ultramafic rock, Cooks Brook Formation, and platform carbonate, including the *SB5* structural domain (Figure 3.40). Irishtown Formation strata of the Eastern Shale Belt in the hangingwall of the SBUB are exposed to the east and north of the imbricate zone. The strata are locally overlain by structural slivers of serpentinite and carbonate that constitute the underlying imbricate succession. This suggests that thrust splays carrying serpentinite slivers within the imbricate zone locally breach the roof thrust of the SBUB to incorporate slivers of the ESB into the imbricate stack.

The lowermost structural slice in the SBUBIZ occurs in the west, and is juxtaposed against the eastern edge of the SB3 carbonate thrust slice. It is the largest occurrence of altered ultramafic rock in the map area and is composed mostly of schistose serpentine that locally shows well developled C-S fabrics (Figure 3.50). The slice also includes massive serpentinized peridotite with veins of fibrous chrysotile that where exploited by

Figure 3.49: View looking north on Loggers School Road showing west-verging small-scale fold in ribbon limestone of the Cooks Brook Formation overlying the structural slice of banded amphibolite within the SBUB.

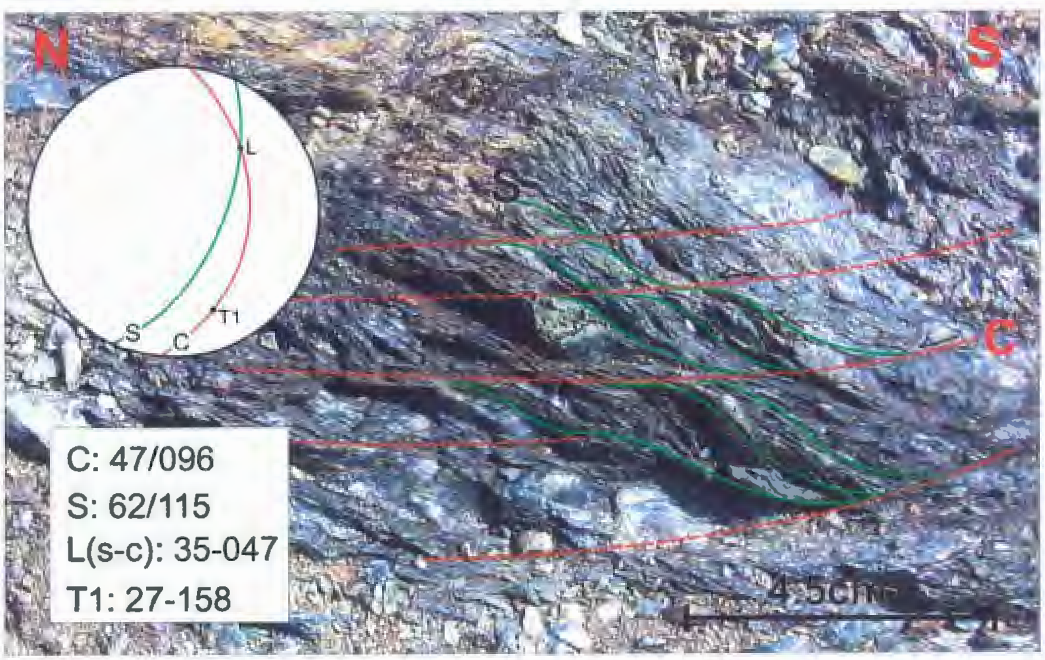


Figure 3.50: C-S fabrics in serpentinte exposed in the SBUB showing planar, moderately east-dipping C planes and anastomosing, steeper southeasterly dipping S planes. T1 defines the transport direction and has a pitch of 36 S on the C-plane, indicating a reverse-sinistral sense of movement (lower hemisphere equal area plot). See Appendix 3 for location.

the Bond Asbestoses Mine (Walther, 1949). The occurrence of altered ultramafic rock is coincident with a large magnetic anomaly that encompasses a sizable area east from its surface exposure, suggesting that the slice has a substantial sub-surface extension toward the east and southeast (Figure 3.51).

The floor thrust of the SBUB is not exposed at this locality, but the contact between the serpentinite slice and Catoche Formation limestone of SB3 is tightly constrained by scattered outcrops in a marshy area east of the SB3 ridge. Limestone strata in the immediate footwall of the serpentinite slice have well-developed east-dipping cleavage that is sub-parallel to C-S fabrics in the adjacent serpentinite. The fabric in the serpentinite are characterized by C-planes that dip moderately to the east and are planar, while S-planes are anastamosing and dip more steeply toward the east-southeast. The intersection lineation of the C-S planes is calculated to be moderately northeast plunging, therefore the movement direction plunges to the south, indicating a reverse-sense of displacement with a significant component of sinistral strike-slip (Figure 3.50).

The serpentinite slice tapers out to the south where platform carbonates of SB3 are in contact with a narrow belt of shale characterized by east-dipping bedding and cleavage fabrics. The shale panel structurally overlies both the limestone and the serpentinite slice (Figure 3.40) in the fault zone. The affinity of this shale unit is uncertain (see Chapter 2), but it is tentatively assigned to the Cooks Brook Formation. The contact between SB3 and the shale terrane lies along the edge of a broad valley that has a western scarp formed of Boat Harbour and Catoche formation limestone and an eastern wall composed of black shale. A logging trail that crosses the valley in the south exposes a succession of highly deformed Boat Harbour Formation limestone in the valley floor. The deformed limestone is clearly structurally overlain by black shale exposed in a nearby scarp at the base of the eastern valley wall. This contact is interpreted as a moderately east-dipping thrust fault constituting the SBUB floor thrust. Together the Bond Mine serpentinite slice and the Cooks Brook Formation slice constitute the imbricate succession of the SBUB as defined at its type locality in Spruce Brook (Figure 3.44). These two slices are structurally overlain by a small structural

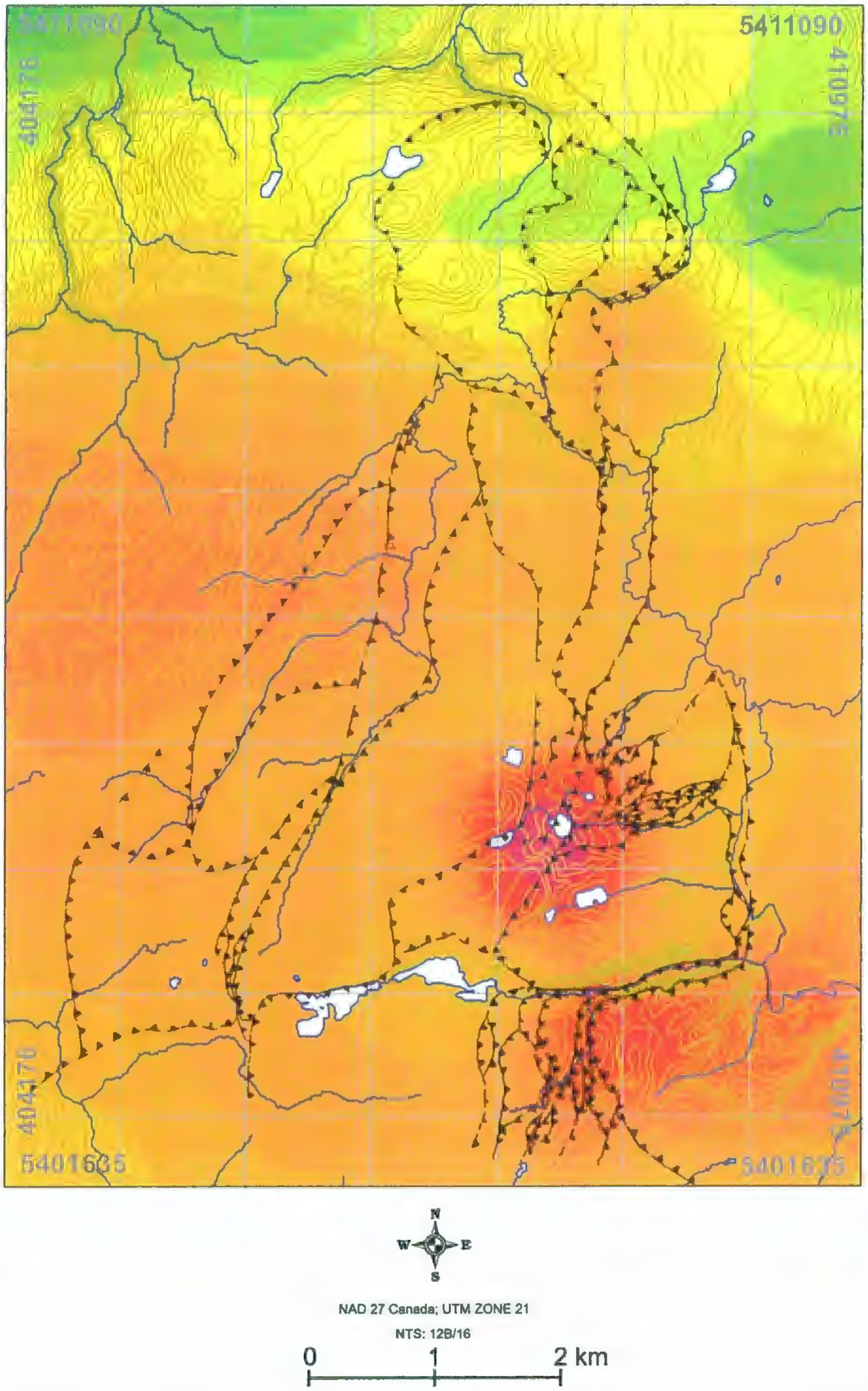


Figure 3.51: Residual total field magnetics map (200m resolution) of the Spruce Brook map area showing anomaly in the area of the Bond Asbestos Mine, SBUB (courtesy of the Geological Survey of Canada).

sliver of Catoche Formation limestone (Figure 3.40). The contact zone between the slices is exposed north of a small round pond near the Bond Mine. The fault zone is characterized by outcrop-scale imbricates of limestone, serpentine, and highly deformed laminated silicious shale, all of which show well-developed east-dipping cleavage fabrics. The structural slice of Catoche Formation limestone is internally strongly deformed. Bedding orientations across the slice are highly variable and no coherent fold system could be identified. This suggests the slice maybe internally imbricated and possibly poly-deformed. The slice is thought to have been cut from the down-dip extension of SB3 and incorporated into the SBUBIZ along with typical SBUB imbricate slices of serpentinite and Cooks Brook Formation exposed to the north and south (Figure 3.52).

The western imbricate slices are interpreted to be overlain by a succession of Irishtown Formation exposed along a logging road to the north of the limestone slice (Figure 3.40). This occurrence is interpreted as an outlier of the Eastern Shale Belt preserved as a portion of the breached SBUB roof thrust that became incorporated into the SBUBIZ. The slice of Irishtown Formation strata is internally imbricated with a small occurrence of calcareous laminated shale assigned to the Cooks Brook Formation; the latter is interpreted to be a small structural sliver riding in the underlying imbricate zone on a thrust fault that locally breaches through the SBUB roof thrust (Figures 3.52 and 3.53).

The Irishtown Formation panel and underlying imbricates are structurally overlain by a repeated succession of SBUB lithologies including serpentinite, minor altered gabbro, Cooks Brook Formation, and small slivers of platform carbonate. These lithologies are carried by a major northeast-southwest trending fault labeled 'A' in Figure 3.40. This fault is interpreted to root at depth below SB5 cutting up-section to the southwest, and ultimately breaching the roof thrust of the SBUB. The imbricated succession of serpentinite and carbonate carried on breaching thrust A pinches out toward the south and fault 'A' becomes coincident with the basal thrust of SB5 (Figures 3.40, 3.52 and 3.53). The imbricate stack in the hanging wall of thrust A includes a large structural slice of serpentinite, which is itself internally imbricated by faults that carry small

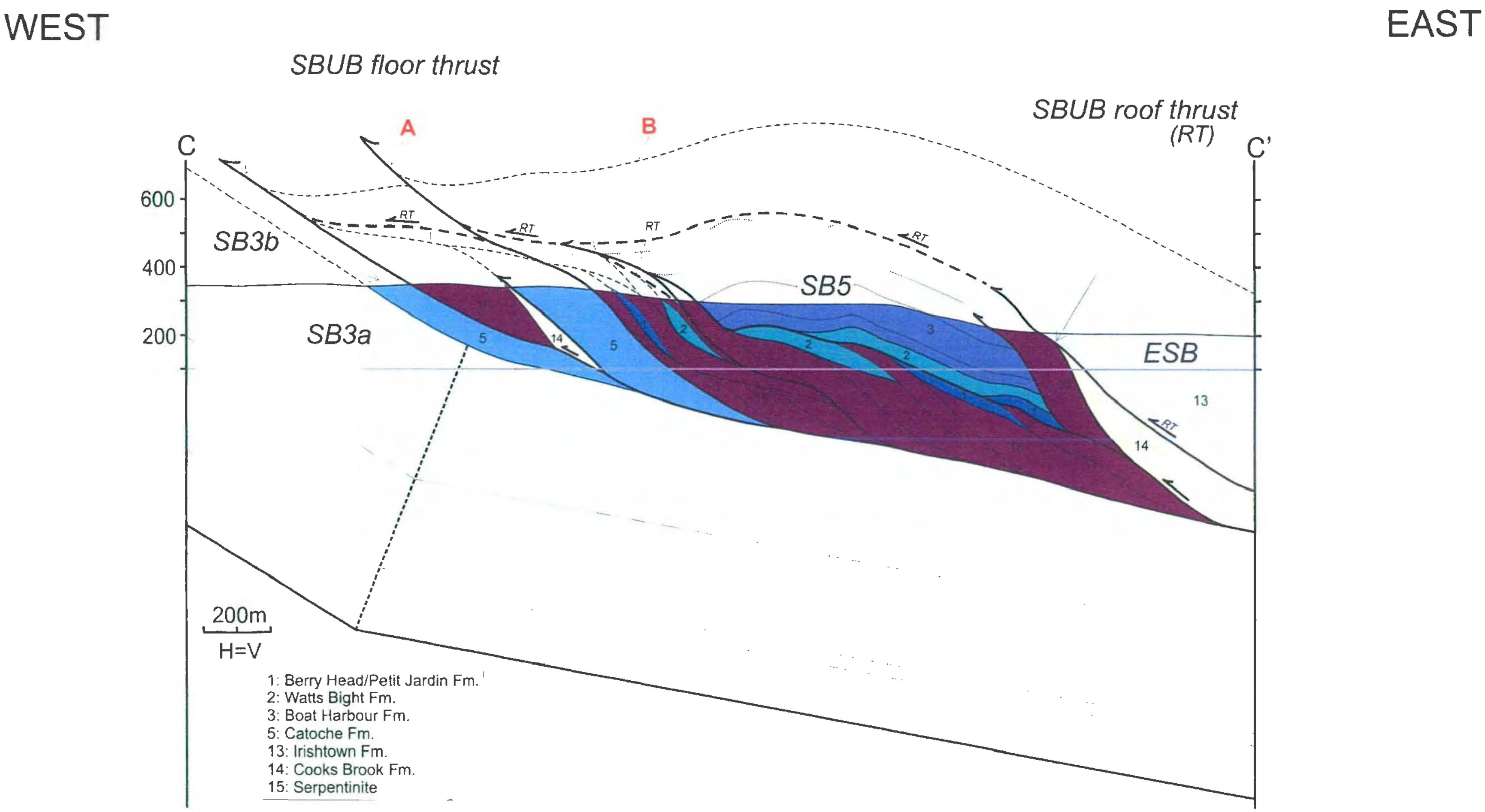


Figure 3.52: Geological cross section of SBUBIZ showing east-dipping imbricate slices of Catoche Formation limestone imbricated with slices of serpentinite, Cooks Brook Formation, and Irishtown Formation of the SBUB. Boat Harbour Formation limestones of SB5 constitute a large imbricate slice within the SBUBIZ. Stuctural slivers of Watts Bight and Berry Head formation carbonate occur in a small-scale duplex structure located beneath the SB5 thrust slice. (Roof thrust: *RT*)

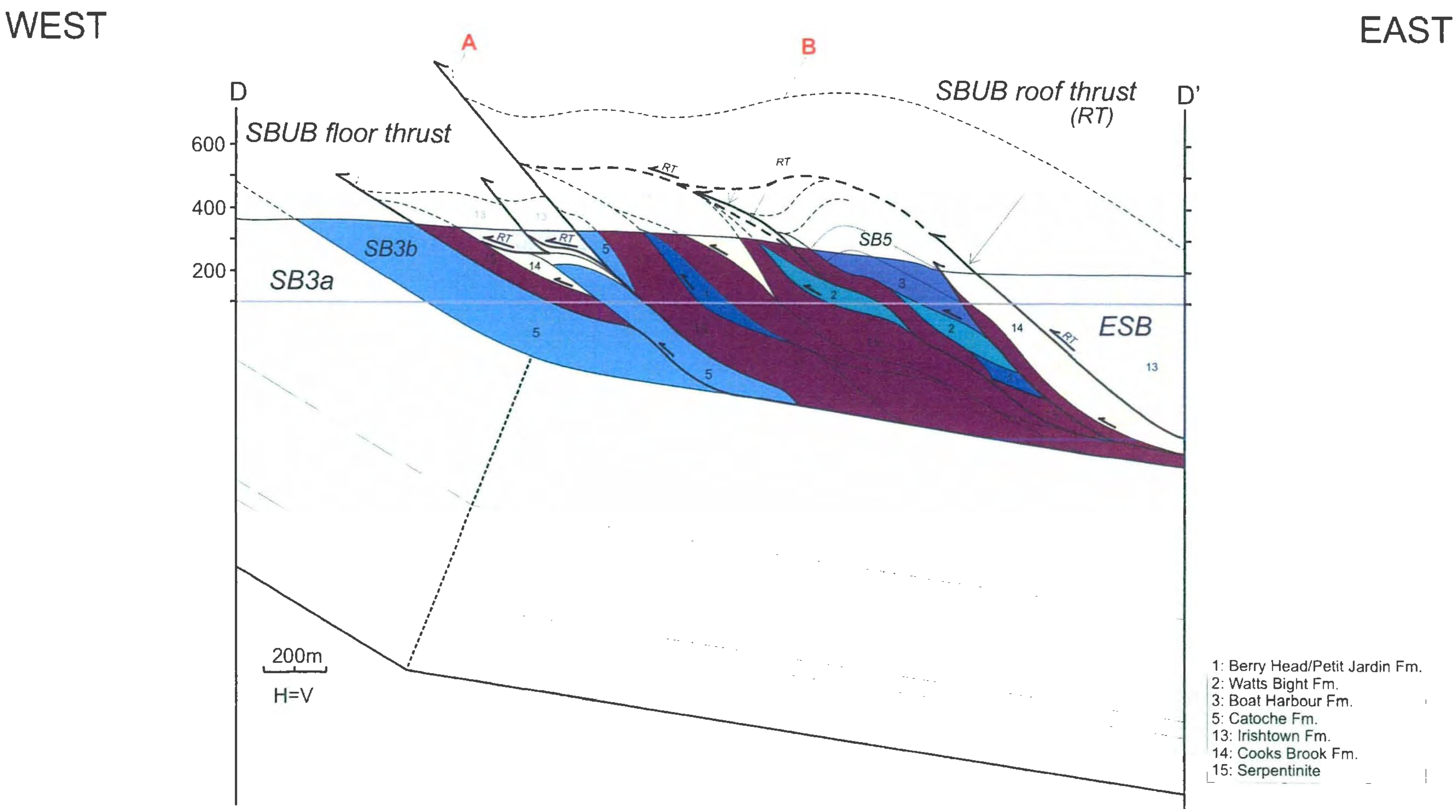


Figure 3.53: Geological cross section of SBUBIZ showing east-dipping imbricate slices of Catoche Formation limestone imbricated with structural slices of serpentinite, Cooks Brook Formation,and Irishtown Formation of the SBUB. Boat Harbour Formation limestones of SB5 constitute a large imbricate slice within the SBUBIZ. Stuctural slivers of Watts Bight and Berry Head formation carbonate occur in a small-scale duplex structure riding beneath the SB5 thrust slice.

structural slivers of platform carbonate. The outcrop area of this part of the fault zone is largely obscured by marshy cover and the limestone slices are exposed as small hillocks in the marsh. The distribution of the outcrops suggests an overall northeast-southwest trending structural grain for this part of the main fault zone. The limestone slivers from west to east are assigned to the Catoche Formation (?), the Berry Head Formation (see Appendix 2), and Watts Bight Formation. Bedding orientations in the slivers are markedly discordant with the bounding fault traces of the slivers indicating that the limestone strata were folded prior to being imbricated within the fault zone.

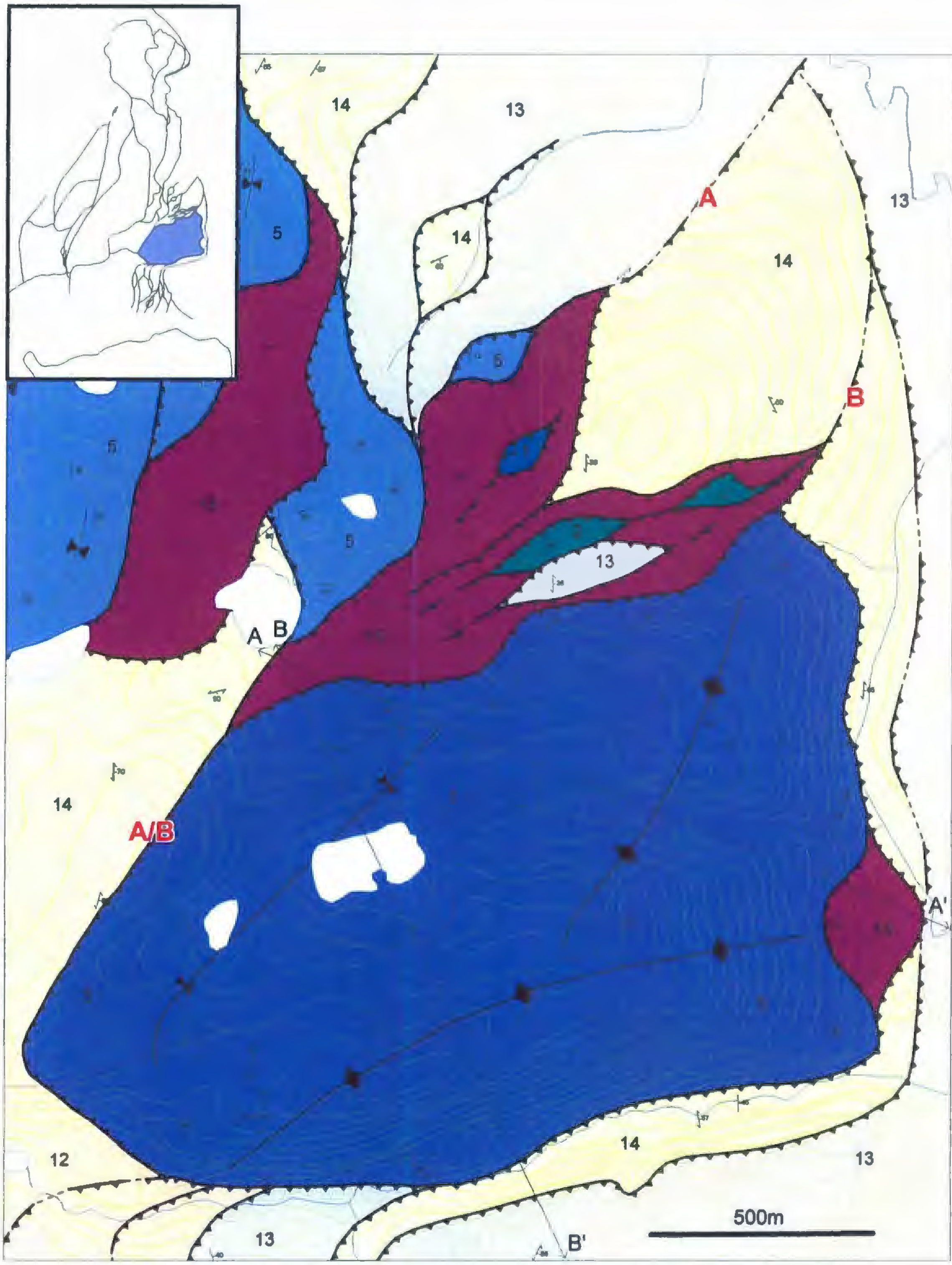
A wedge-shaped slice of Cooks Brook Formation is also imbricated with the serpentinite in the north. This succession constitutes a rounded hill-top northeast of the leading edge of SB5 (Figure 3.40). The shale is interpreted to overlie serpentinite along the western base of the hill and is overlain by the serpentinite exposed to southeast of the hill (Figure 3.53). Along the northeastern edge of the hill, the Cooks Brook Formation is interpreted to be overlain by Irishtown Formation of the Eastern Shale Belt along an intact segment of the SBUB roof thrust.

Near the leading edge of SB5 is a small occurrence of Irishtown Formation sandstone and shale (Figure 3.40). The shale is finely laminated and shows small-scale north-plunging F1 folds with a moderately east-dipping axial planar cleavage. The occurrence is interpreted to constitute a structural sliver that is imbricated with serpentinite, which outcrops to the west and east of the occurrence. Its presence in the imbricate stack suggests that a second major thrust fault (marked 'B' in Figure 3.40) breached through the roof thrust of the SBUB to incorporate a portion of the hanging-wall succession, namely strata of the Eastern Shale Belt, into the imbricate zone. Like Fault A, Fault B is interpreted to root at depth near the basal thrust of the SB5 thrust sheet (Figures 3.52 and 3.53).

The imbricate succession of serpentinite and limestone carried between breaching thrusts A and B is interpreted to be an overall steeply east-dipping thrust stack that lies in the footwall of the SB5 thrust slice. The contact relationships at the leading edge of SB5 are described in detail in the following section. The imbricate stack is interpreted to be a duplex structure that formed as the SB5 thrust slice was emplaced over serpentinite. The Watts Bight and Berry Head formation limestone slices that are incorporated in the duplex are thought to represent structural slivers plucked from the lower portion of the SB5 thrust sheet that is composed of the overlying Boat Harbour Formation (Figure 3.52). The presence of these carbonate slivers within the serpentinite occurrences indicates that the serpentinte is cut by several major thrust faults. The thick serpentinite successions are thus interpreted to be small imbricate stacks consisting of thin thrust-repeated slivers, rather than a single contiguous body as indicated by the geophysical anomaly represented in Figure 3.51. Structural relationships between the serpentinite/carbonate imbricates with the adjacent Cooks Brook and Irishtown formations indicate that the structural mixing of carbonate and serpentinite occurred mostly below the structural level of the Cooks Brook Formation slices that where carried in the SBUB fault zone. Incorporation of the Cooks Brook and Irishtown formation into the imbricate stack suggests that imbricating thrusts within the duplex breached the panels of Cooks Brook Formation and locally breached the roof thrust of the SBUB to imbricate slivers of the originally structurally overlying Irishtown Formation (Figure 3.52 and Figure 3.53). The sequence of major west-directed thrust faulting in the imbricate zone and its relationship to major deformation events affecting the Spruce Brook thrust stack will be discussed in Chapter 4.

3.9 Spruce Brook 5 (*SB5*)

SB5 is an occurrence of limestone and dolostone assigned to the Boat Harbour Formation that is located in the southeast corner of the map area (Figures 3.1 and 3.54). It is interpreted to constitute a broadly flat-lying thrust slice, since none of the upper or lower platform carbonate units are exposed in the slice. The slice is bounded to the east by the roof thrust of the SBUB, and its western edge is defined by a major imbricating thrust splay within SBUBIZ labeled B in Figure 3.54. The northwestern edge of SB5 is in fault contact with serpentinite of the SBUBIZ. Fault B is interpreted to be steeply southeasterly-dipping based on the distribution of serpentinite outcrops and sub-crop



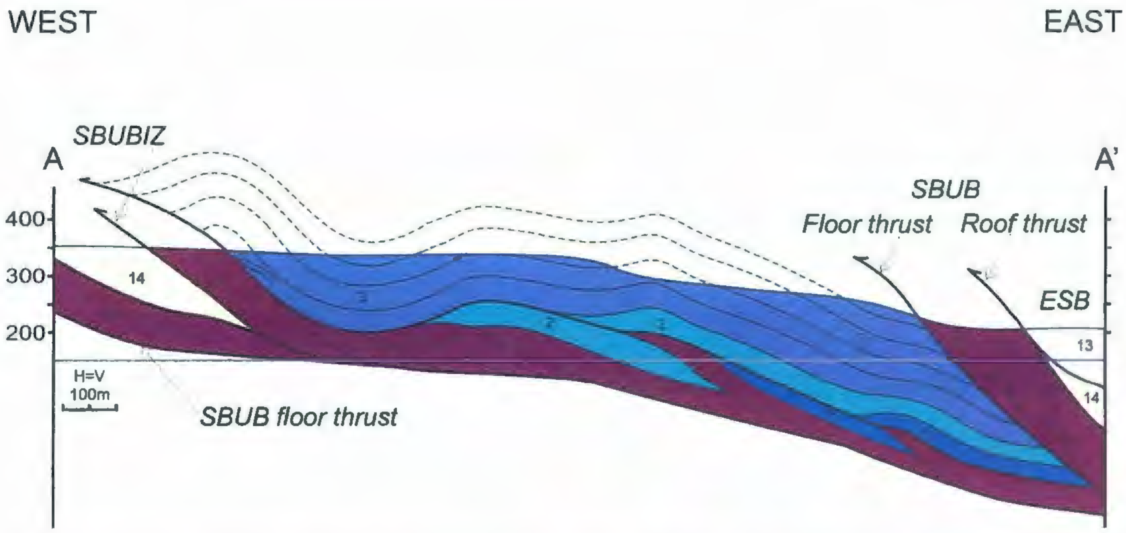
1: Berry Head/Petit Jardin Fm.	5: Catoche Fm.	14: Cooks Brook Fm.
2: Watts Bight Fm.	12: American Tickle Fm.	15: Altered mafic/ultramafic rocks
3: Boat Harbour Fm.	13: Irishtown Fm.	

Figure 3.54: Geological map of Spruce Brook structural domain 5 (SB5) Imbricating faults A and B in the SBUBIZ labled in red.

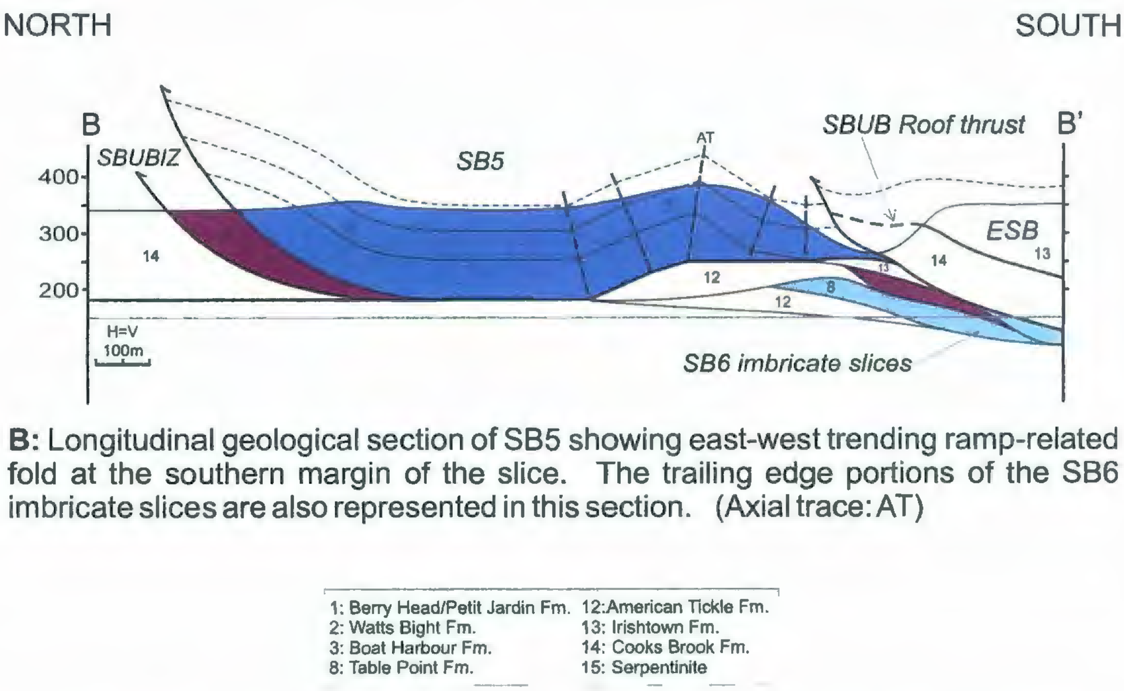
along logging trails in the north slope of a small valley near the northern edge of the slice (Figure 3.55A). The serpentinite sliver tapers out toward in the southwestern edge of SB5, where the limestone is in fault contact with black shale and dolostone assigned to the Cooks Brook Formation (Figure 3.53). The fault is defined here by a ridge of brecciated Boat Harbour Formation limestone with a steep east-dipping cleavage fabric (Figure 3.56). Immediately northwest of the carbonate ridge, in the footwall of the fault, are a number of scattered outcrops of black shale that exhibit a well-developed, southeast dipping cleavage fabric.

The eastern and southern edges of SB5 are defined by steep-walled valleys. Spruce Brook runs through the eastern valley and the southern valley is drained by a brook running east from the Spruce Ponds (Figure 3.54). Exposures in Spruce Brook clearly show the structural relationship of SB5 with the imbricate slices of the SBUB at its north-south striking roof thrust. In the south, east-dipping limestone beds are in contact with a small structural sliver of serpentinite and altered gabbro (Figures 3.54 and 3.55A). This sliver is constrained mainly by subcrop along a disused logging path that runs down the eastern side of SB5. The serpentinite sliver outcrops in Spruce Brook where it can clearly be seen in contact with quartzose sandstone of the Irishtown Formation constituting the roof thrust of the SBUB. North of the serpentine exposure, east-dipping limestone beds of the Boat Harbour Formation are clearly overlain by deformed black shale and ribbon limestone of the Cooks Brook Formation (Figure 3.57).

The valley forming the southern edge of SB5 has numerous outcrops on the valley walls and in the brook itself. Limestone beds dip moderately to the south in the northern valley wall and become shallower dipping going down slope to the brook, where beds are sub-horizontal (Figure 3.54 and 3.55B). The south valley wall is dominated by silicious and calcareous black shale assigned to the Cooks Brook Formation which clearly overlies the Boat Harbour Formation exposed in the brook. The southern continuation of the SBUB roof thrust is inferred to lie high in the southern valley wall based on outcrops of Irishtown Formation sandstone in the hill top above the valley (Figure 3.54). This fault can be traced to the south where it curves to follow the north-



A: Geological cross section of westerly-verging SB5 thrust slice showing northeast-southwest trending internal fold system and contact relationships with the SBUB and overlying Eastern Shale Belt (ESB). Simplified footwall geometry is inferred based on structural relationships in the underlying SBUBIZ exposed to the northwest.



B: Longitudinal geological section of SB5 showing east-west trending ramp-related fold at the southern margin of the slice. The trailing edge portions of the SB6 imbricate slices are also represented in this section. (Axial trace: AT)

1: Berry Head/Petit Jardin Fm.	12: American Tickle Fm.
2: Watts Bight Fm.	13: Irishtown Fm.
3: Boat Harbour Fm.	14: Cooks Brook Fm.
8: Table Point Fm.	15: Serpentinite

Figure 3.55: Geological cross sections of the SB5 thrust slice located in the southeastern portion of the Spruce Brook map area. See Figure 3.54 for location of sections.

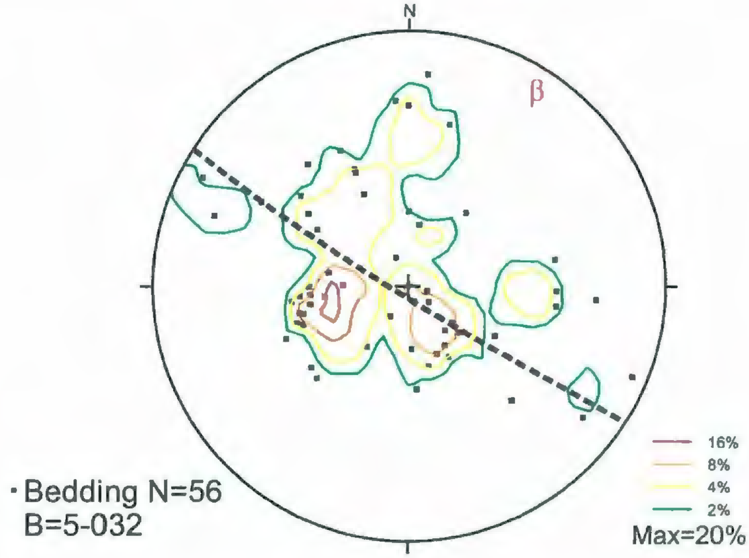
Figure 3.56: Western edge of SB5: tectonized Boat Harbour Formation limestone with steep east-dipping fabric; Cooks Brook Formation shale outcrops immediately west of this outcrop.

Figure 3.57: View looking south in Spruce Brook showing east-dipping beds of Boat Harbour Formation limestone. Black shale assigned to the Cooks Brook Formation lies immediately east of outcrop.

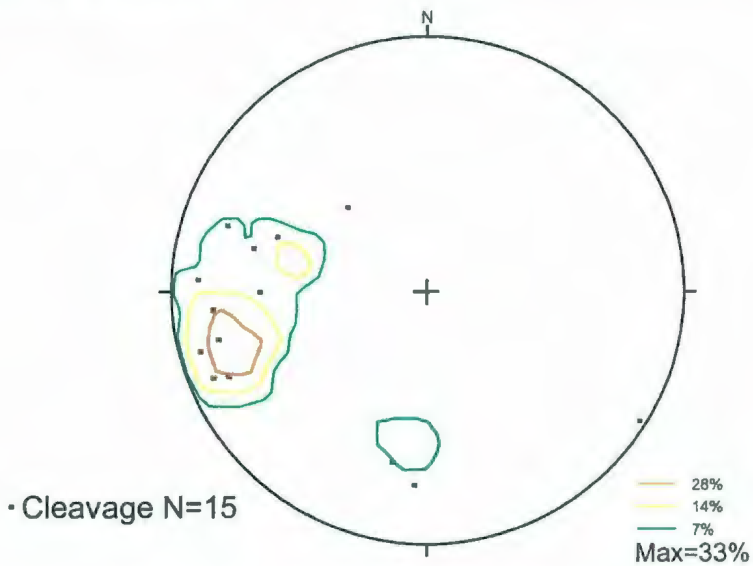
south trend of the SB6 structural domain. The internal structural architecture of the SB5 thrust slice is characterized by two main fold systems: 1) a northeast-southwest trending fold system that is pervasive across the slice and, 2) an east-west trending anticline that is situated near the southern margin of the slice (Figures 3.54 and 3.55 A and B).

The northeast-southwest trending fold system is a west-verging asymmetrical fold wave train that includes a pair of macroscopic structures defined as the leading synform of the thrust slice in the northwest and a corresponding trailing antiform in the southeast (Figure 3.55A and 3.58A). The leading synform has a prominent morphological expression with its west limb defining the leading edge of the thrust slice. The limb panel is locally internally deformed by small-scale folds that are parasitic to the macroscopic synform. The axis of the leading synform is expressed as a narrow marshy valley with two small ponds. Southeast of the valley, bedding orientations define a large antiform with a moderately east-dipping backlimb that forms the prominent morphological slope at the eastern edge of the slice. This fold system has a locally developed axial-planar cleavage that is moderately to steeply southeast-dipping in the northern part of the thrust slice (Figure 3.58B). Based on fold asymmetry, the northeast-southwest trending fold system is interpreted to have been formed as the slice was emplaced toward the west. The prominence of the east-dipping backlimb dip domains that characterize the fold system suggests the slice is emplaced over a low-angle thrust with a moderately east-dipping frontal ramp.

The two macroscopic northeast-southwest trending folds are overprinted in the south by a broad, open east-west trending antiform with a prominent south-dipping limb that constitutes the southern edge of the slice. This fold structure rotates the orientation of the S1 axial planar cleavage of the northeast-southwest fold system. S1 is consistently east-dipping in the north, but becomes easterly-dipping over the crest of the ramp-anticline (Figure 3.54 and Figure 3.58B). The geometry of this structure is markedly similar to the ramp-bend fold at the southern edge of the SB1 thrust slice and the structure is similarly interpreted to be related to emplacement of the thrust slice over a major north-dipping lateral thrust ramp (Figure 3.55B).



A: Poles to bedding in SB5. Partial great-circle girdle distribution with point maxima for east and west dipping beds describe northeast plunging fold system characterized by asymmetrical fold forms. Point maximum for South-dipping beds represents the forelimb of east-west trending ramp-anticline structure at the southern edge of SB5.



B: Poles to S1 cleavage in SB5. Point maximum for northeast-dipping cleavage represents axial planar fabric of the northeast-southwest trending fold system. Diffuse distribution of poles reflects interference of east-west trending anticline in the southern portion of the thrust slice.

Figure 3.58: Lower hemisphere equal area plot of poles to bedding and cleavage in SB5.

3.10 Spruce Brook Slice 6 (*SB6*)

The SB6 structural domain is situated in the southeastern corner of the map area. It consists of six small north-south trending occurrences of Table Head Group limestone that straddle the structural contact between the Southern Shale Belt, the SBUB and the Eastern Shale Belt (Figure 3.1 and Figure 3.59). The strata in the occurrences are correlated to the well-bedded to stylo-nodular facies of the Table Point Formation with one occurrence of thin-bedded limestone and ribbon limestone assigned to the Table Cove Formation. The limestone is locally heterogeneously replaced by secondary dolomite that gives the rock an uncharacteristic yellow weathered surface. Exposed immediately adjacent to the limestone occurrences are lithologies of the SBUB, including serpentinite, Cooks Brook Formation, Irishtown Formation of the Eastern Shale Belt, and American Tickle Formation of the Southern Shale Belt.

The strata that make up the limestone occurrences of SB6, although locally folded, are dominantly east-dipping suggesting that they constitute east-dipping structural panels (Figure 3.60A). This is supported by the geomorphological expression of the limestone panels as east-sloping hills separated by narrow valleys. Siliciclastic and crystalline rock units exposed adjacent to the limestone strata are similarly interpreted to be east-dipping panels that are structurally interleaved with the limestone panels. The entire SB6 structural domain, is characterized by a pervasive moderately to steeply east-dipping cleavage (Figure 3.60B). Based on their internal structure and contact relationships, the east dipping panels are interpreted to be imbricate thrust slices (horses) in a small east-dipping, westerly verging duplex structure (Figure 3.61). The geometry of the duplex is illustrated by outcrop relationships in a small thrust slice of Table Point Formation limestone in the south-central portion of SB6 (Figure 3.59). Exposures on a southern branch of Loggers School Road show that the slice is internally imbricated by east-dipping faults, and the west and east portions of the limestone slice are separated by a small sliver of American Tickle Formation shale containing Daniels Harbour Member limestone conglomerate (Figure 3.62).

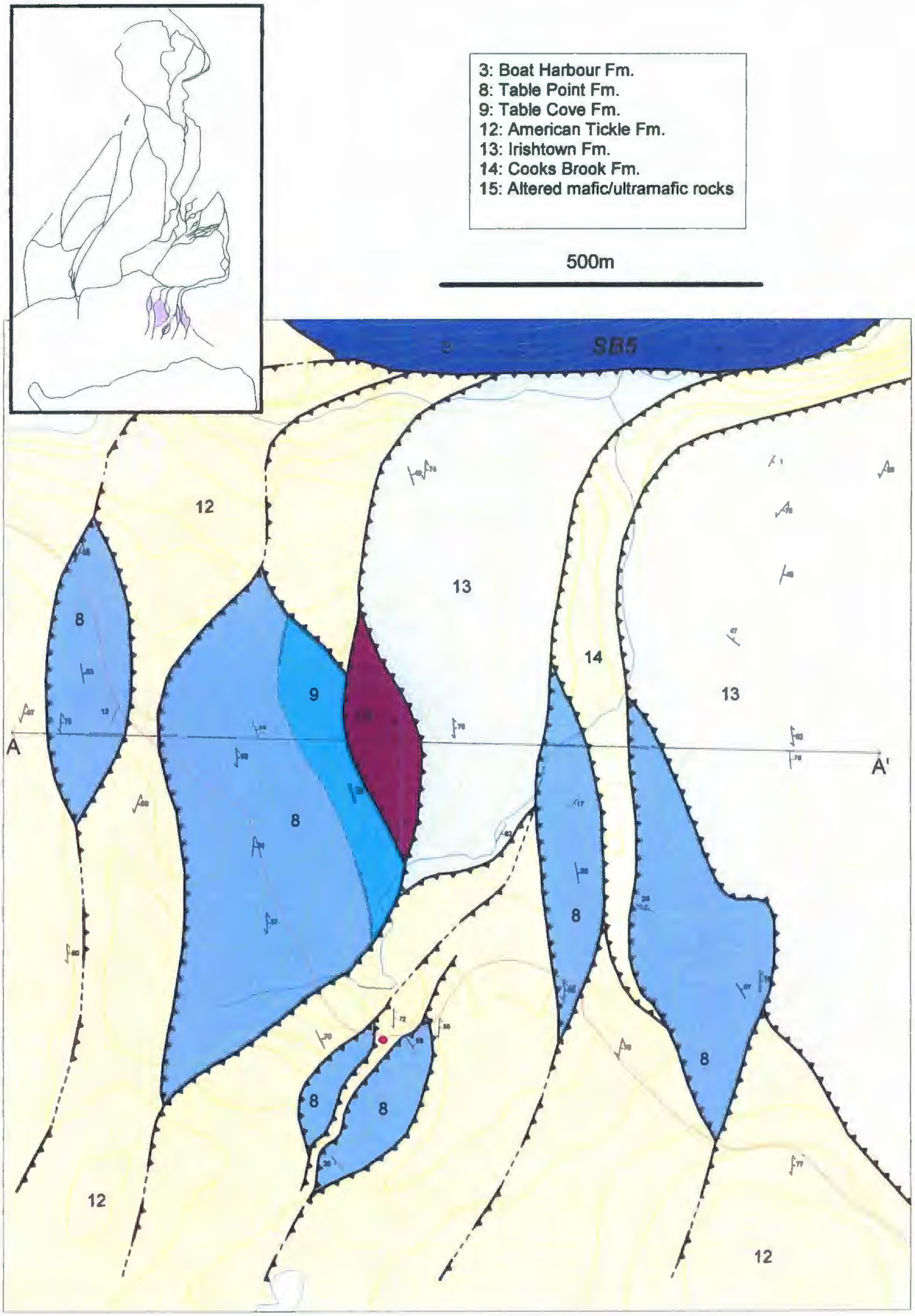
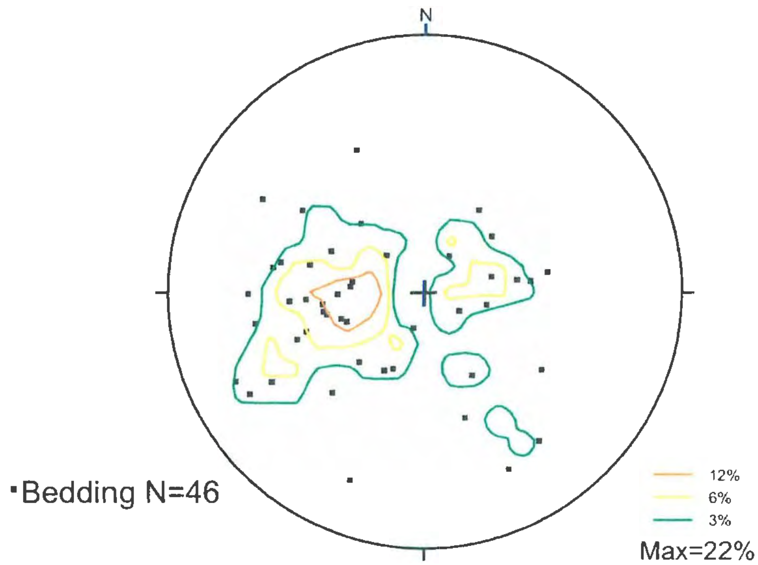
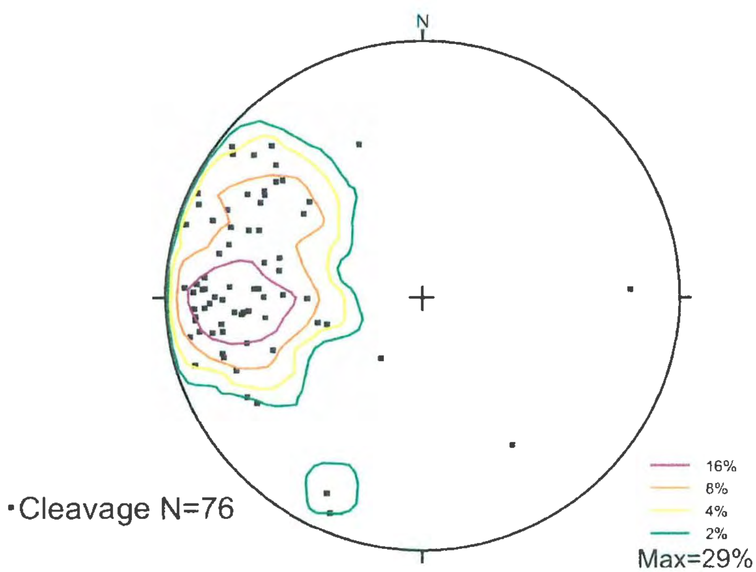


Figure 3.59: Geological map of Spruce Brook structural domain 6 (SB6)



A: Poles to bedding in the carbonate thrust slices of SB6. Point maximum for moderately east-dipping orientations defines the overall sheet-dip of the slices. Smaller population of west-dipping beds reflects folding within the thrust slices.



B: Poles to S1 cleavage in SB6. Point maximum for steeply east-dipping orientations show pervasively developed fabric in the carbonate, clastic, and crystalline rocks of SB6.

Figure 3.60: Lower Hemisphere equal area plots of poles to bedding and cleavage in SB6.

The area immediately west of SB6 is underlain by black shale and sandstone of the American Tickle Formation that constitutes the Southern Shale Belt (Figure 3.59). Lithologies of the American Tickle Formation occur in the valley east of Spruce Ponds along the northwestern contact of SB6. This indicates that easterly dipping panels of shale constituting the Southern Shale Belt lie in the footwall of the SB6 duplex, and are imbricated with easterly dipping panels of Table Point Formation limestone in the lower levels of the duplex (Figure 3.61).

The occurrences of serpentinte and Cooks Brook Formation shale in SB6 are similarly interpreted to be imbricated with the limestone and American Tickle Formation shale (Figure 3.59). This is supported by the pervasive east-dipping cleavage fabrics developed in both the serpentinite and Cooks Brook Formation slices. The serpentinite slice is discontinuous having a strike length of about 500m while the structural slice of Cooks Brook Formation occurs as a thin veneer within the imbricate stack that is thought to be continuous toward the north and is correlated to the Cooks Brook Formation strata exposed in Spruce Brook (Figure 3.59).

SB6 includes an occurrence of sandstone and shale assigned to the Irishtown Formation constituting a small outlier of the Eastern Shale Belt (Figure 3.59). Moderate to steep east-dipping bedding and cleavage fabrics in the shale suggest that the occurrence is an east-dipping panel. Its field relationships with limestone occurrences exposed to the east indicates that it is imbricated within the SB6 duplex structure. The roof thrust of the SB6 duplex is interpreted to be coincident with the roof thrust of the SBUB (Figures 3.59 and Figure 3.61). It is delineated by the western edge of exposure of the Irishtown Formation in the Eastern Shale Belt that structurally overlies the SB6 duplex. SB6 is interpreted to have been formed by deformation in the footwall of the SBUB. Short-cut faulting into the footwall during shortening imbricated the limestone and shale succession, but during progressive deformation the imbricating thrusts are thought to have breached through the floor and roof thrusts of the SBUB to incorporate structural slivers of SBUB lithologies (serpentinite, Cooks Brook Formation and Irishtown Formation) into the SB6 imbricate stack.

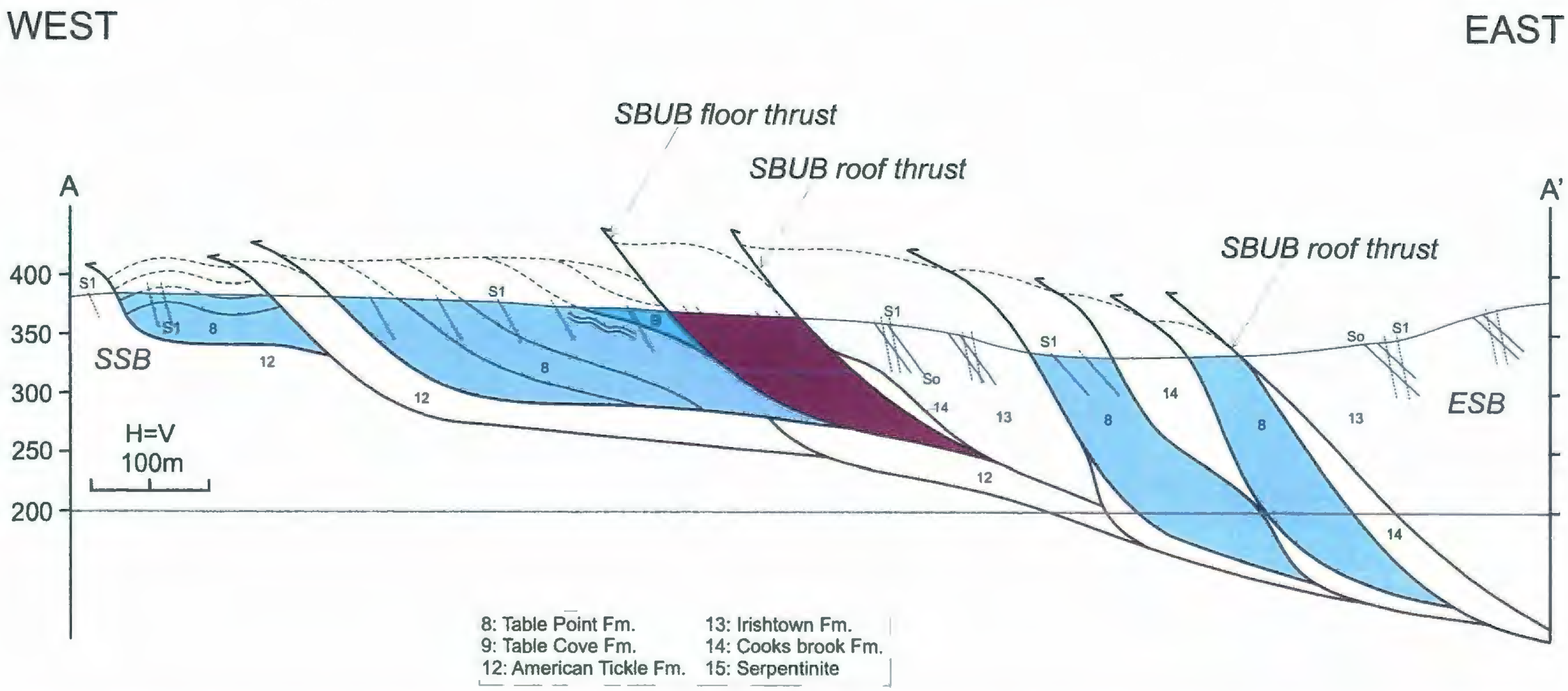


Figure 3.61: Geological cross section of SB6 showing east-dipping imbricate slices of Table Point Formation limestone, serpentinite, Cooks Brook Formation, Irishtown Formation and American Tickle Formation. See Figure 3.60 for location of section.

The SB6 structural domain is terminated in the north at the major east-west trending lineament that forms the southern termination of SB1, SB3 and SB5. As described in earlier sections, this lineament is the contact between the Southern Shale Belt and the southern edges of the overlying carbonate thrust sheets (Insert 1). The thrust slices, particularly SB1 and SB5 have prominent east-west trending fold structures at their southern edges suggesting that the major lineament is coincident with a north-dipping thrust ramp. In the northern portion of SB6, the lineament is defined by a steep-walled valley with a brook that runs east from the Spruce Ponds (Figure 3.59). This valley is the inferred contact zone between SB6 in the south and SB5 in the north. The contact is poorly exposed in the valley except in one short segment of the brook which exposes beds of Boat Harbour Formation limestone of the southern edge of SB5. These beds are overlain by calcareous shale of the Cooks Brook Formation exposed in the southern valley wall. The shale is interpreted to be the down-dip extension of the east-dipping structural slice of Cooks Brook Formation that occurs below the roof thrust of the SB6 thrust stack (Figures 3.59 and Figure 3.55B)

The continuity of the Cooks Brook and Irishtown formation structural slices of the SBUB across the contact between SB5 and SB6 with little or no vertical displacement from north to south suggests that the SB6 duplex and the SB5 thrust slice lie at approximately the same structural level and have comparable structural relief (Figures 3.61 and 3.55B). This observation is consistent with the interpretation that both SB6 and SB5 have been formed by deformation related to movement on the SBUB. Despite their structural proximity, SB5 and SB6 contain markedly different stratigraphic successions. The juxtaposition of Boat Harbour Formation and Table Point Formation strata from north to south in the footwall of the SBUB may be attributed to a vertical displacement across the east-west lineament that pre-dates movement on the SBUB. The significance of the east-west lineament and the structural relationships between SB5, SB6, and the Southern Shale Belt are treated in greater detail in Chapter 4.

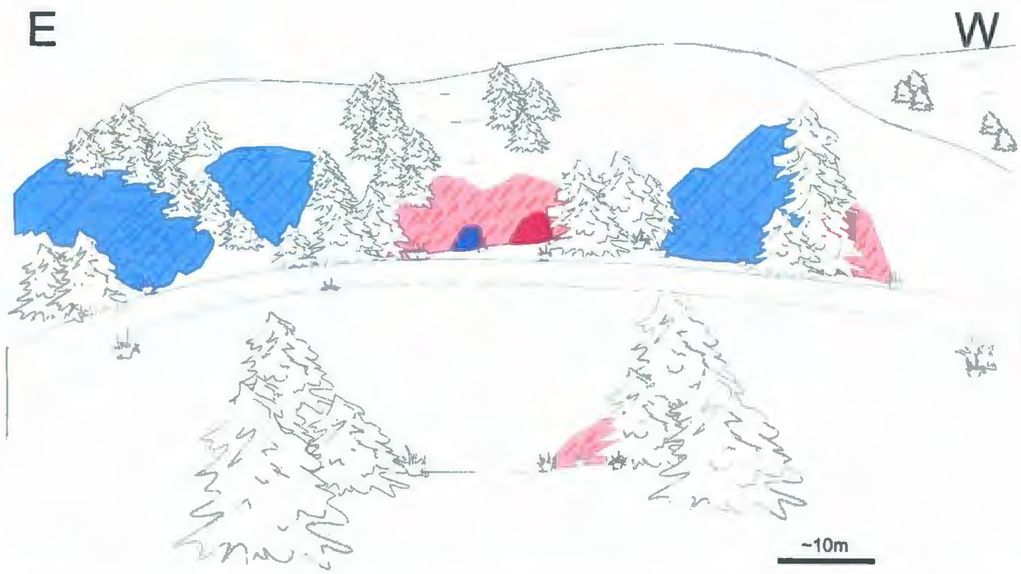


Figure 3.62: Field sketch of view looking south on southern branch of Loggers School Road showing east-dipping imbricates of Table Point Formation limestone (in blue) and American Tickle Formation shale (in pink) in the south-central portion of the *SB6* duplex structure. Note the occurrence of Daniels Harbour Member conglomerate (dark pink) and massive limestone (dark blue) within the central shale slice. Shale also outcrops below the roadbed suggesting that the limestone slices do not extend north of the road.

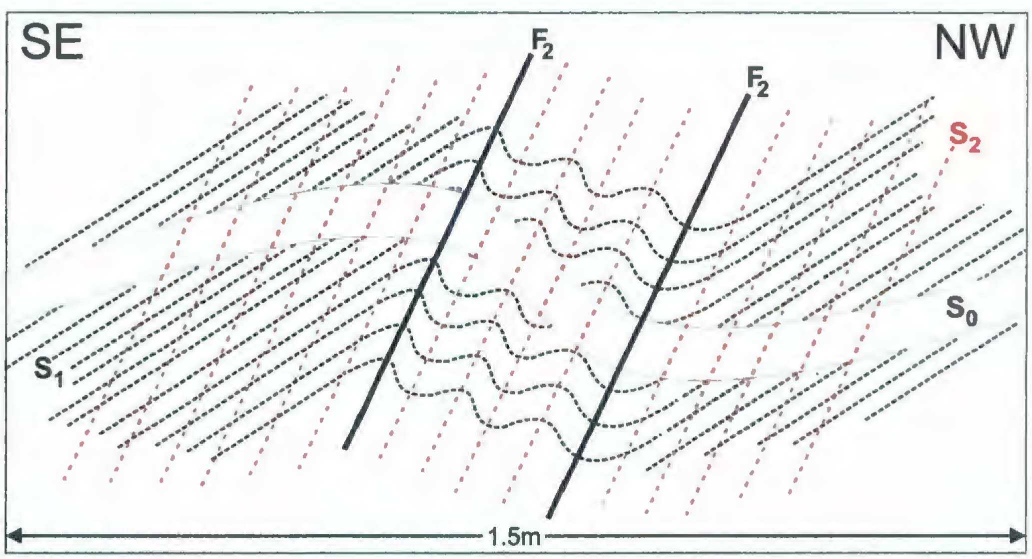


Figure 3.63: Field sketch showing typical example of a folded Irishtown Formation sandstone and shale succession in the Eastern Shale Belt exposed in the southeast corner of the map area. West verging asymmetrical F2 fold with steep east-dipping S2 axial planar cleavage; it clearly crenulates an older S1 fabric that lies at a small angle to bedding suggesting that the F2 fold is formed on a gently east-dipping F1 normal limb.

3.11 Eastern Shale Belt

The Eastern Shale Belt consists of a thick succession of interbedded sandstone and shale of the Irishtown Formation that underlies a large area east of Spruce Brook (Figure 3.1). The fold systems in the Eastern Shale Belt have not been extensively resolved by this study, but the fold geometry and deformation history in this structural panel is documented in detail by Murphy (2005) in an area just east of the Spruce Brook study area. This worker describes the Irishtown Formation succession as penetratively F1 and F2 folded with minor F3 folding. The F1 and F2 fold systems are described as polyharmonic with several orders of mesoscopic and macroscopic folds. Macroscopic F1 folds are defined by Murphy (2005) as a series of regularly spaced, north-south trending antiforms and synforms with slightly asymmetric geometry. The orientation of the F1 fold system is strongly influenced by the superposed F2 system; however, it is interpreted to have originally had moderately southeast-dipping axial surfaces with gently to moderately northeast and southwest plunging fold axes. The F2 fold system that affected the Irishtown Formation is oriented at a small angle oblique to the F1 folds, and is comprised of westerly verging asymmetrical folds with moderately to steeply east-dipping axial surfaces. This fold system is associated with the development of pervasive S2 cleavage fabric, and is genetically related to a number of low-angle, west-verging imbricating thrust faults that repeat the stratigraphic succession (Murphy, 2005). The superposition of the F1 and F2 fold systems is interpreted as having an oblique Type 2 (Ramsay, 1967) or 'mushroom' to 'crescent' shape interference pattern which is expressed locally in macroscopic structures. The F3 fold system is highly variably developed, and is only locally defined by kink-style folding of the S2 cleavage fabric about moderately to steeply east-dipping axial surfaces (Murphy, 2005).

In the Spruce Brook map area, macroscopic fold structures in Irishtown Formation strata are not readily observed, and are only locally resolved from outcrop relationships. Mesoscopic F1 and F2 folds are documented at several localities along Spruce Brook, most notably in the southeastern corner of the map area. F2 folds are best defined in successions of laminated shale and thin sandstone beds, where both bedding and S1 are well preserved. They are typically defined by west-verging asymmetrical folds of bedding with well developed S2 axial planar cleavage that clearly crenulates the older S1 fabric (Figure 3.63).

The plunge directions of mesoscopic F2 fold axes are highly variable, but the axes are demonstrably parallel to the F2 axial plane. This is shown by their distinct great-circle girdle distribution in Figure 3.64A The pi-girdle for small-scale F2 fold axes is coincident with the orientation of the F2 axial surface as defined by the average orientation for the steeply to moderately east-dipping S2 axial planar cleavage (Figure 3.64B). This pattern of distribution for F2 fold axes is typical of Type 2 fold interference patterns where the F2 axial plane is at a moderate to high angle to the pre-existing F1 fold axis. In such an arrangement, both limbs of a macroscopic F1 fold may be folded about a single F2 axial plane, so that any one macroscopic F2 fold closure will contain a series of variably dipping packages of rock layers corresponding to the limb domains of the F1 system. Each package of layers will make a unique line of intersection with the F2 axial plane; in other words, the F2 fold will have variably plunging fold axes. Similarly, smaller scale F2 folds will have different fold axis orientations, because the strike and dip of their enveloping surfaces is dependent on whether they form on a first-order F1 steep limbs, normal limbs, or hinge domains within the F1 fold system.

The interference of the F1 and F2 fold systems in this way is demonstrated by the distribution of F2 fold axis along the F2 axial surface (Figure 3.64A). The distribution is defined by three main point maxima that are interpreted to represent average F2 fold axis orientations for three unique F1 dip-domains affected by the F2 fold system.

The point clusters representing shallow northerly and southerly plunges represent small-scale upright folds with doubly plunging sub-horizontal axes. These folds although not observed, are interpreted to be symmetrical based on the bedding pole distribution in Figure 3.65 which shows that bedding orientations are mostly steeply east-dipping with a smaller population of moderately west-dipping beds. The west dipping beds are

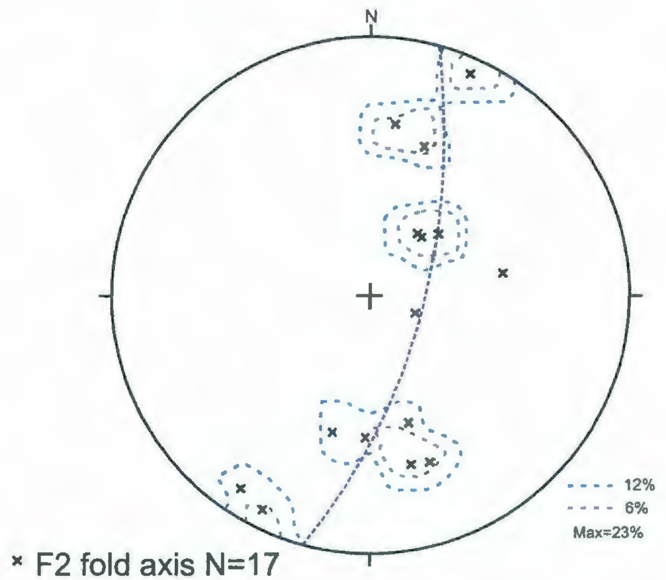


Figure 3.64A: Lower hemisphere equal area plot of small-scale F2 fold axes measured on bedding with great circle girdle distribution corresponding to the F2 axial plane. Shallow north and south plunging axes represent re-folded gently dipping F1 crestal layers, while moderately northeast and southeast plunging axes are interpreted to have formed on beds located on F1 fold limbs.

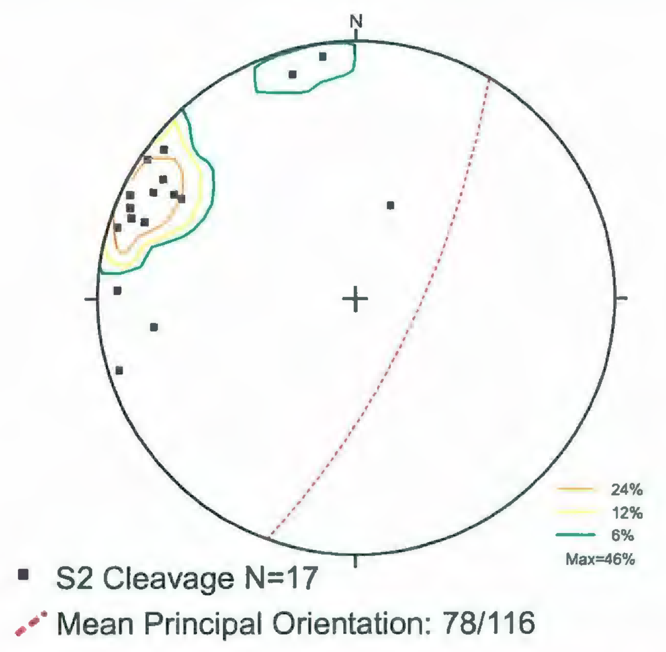


Figure 3.64B: Lower hemisphere equal area plot of S2 cleavage fabric showing point maximum for east-dipping orientations. Mean orientation parallels axial plane of F2 fold system.

interpreted as an F2 short limb orientation and, although grossly under-sampled, this is consistent with folding about a gently plunging F2 fold axis. These folds formed where the F2 axial plane is nearly orthogonal to bedding and since the F2 axial plane is moderately to steeply dipping, the original beds must have been shallow dipping. Such a bedding orientation would characterize the crest/trough domain of a gently plunging F1 fold system. The gently plunging F2 folds are therefore interpreted to represent a re-folded F1 crest/trough domain. Because the plunge of F2 fold axes is predicated on the original dip direction of the folded layers, the doubly plunging nature of the F2 system indicates that the F1 crest/troughs must have dipped gently to both the north and south; i.e. the F1 fold system was gently doubly plunging.

The trend of the F1 fold system is inferred based on the fold interference pattern represented by bedding pole distributions in Figure 3.65. The moderately north-dipping and moderately south-dipping bedding orientations shown in Figure 3.65 are interpreted to represent the 'lobes' of the transitional Type 2, mushroom to crescent, interference pattern formed by refolding of beds originally located on F1 fold hinge domains. The point maximum for north-dipping orientations indicates that the interference pattern is asymmetrical (Figure 3.65). This is typical of crescent folds where the F2 axial plane is oriented at an acute angle to the F1 axial plane. Given that the F1 axial plane lies perpendicular to crestal layers that must be gently north and south dipping (based on F2 fold axis orientations, described above) and lie at an acute angle to the F2 axial plane, it is interpreted that the F1 fold system was southwest-northeast trending.

Figure 3.64A shows a point maximum for moderately to steeply northeast plunging F2 fold axes and one for moderately southeast plunging axes. These are interpreted to represent F2 folds formed on originally moderately to steeply west- and moderately east-dipping beds (respectively) that constitute two discrete limb domains in the F1 fold system. Northeast plunging axes are slightly steeper plunging compared to southeast plunging axes and therefore likely formed on moderately to steeply west-dipping F1 limb domain whereas the southeast plunging axes are located on moderately east-dipping F1 limb domain (Figure 3.64A). The distribution of F2 axes in two discreet

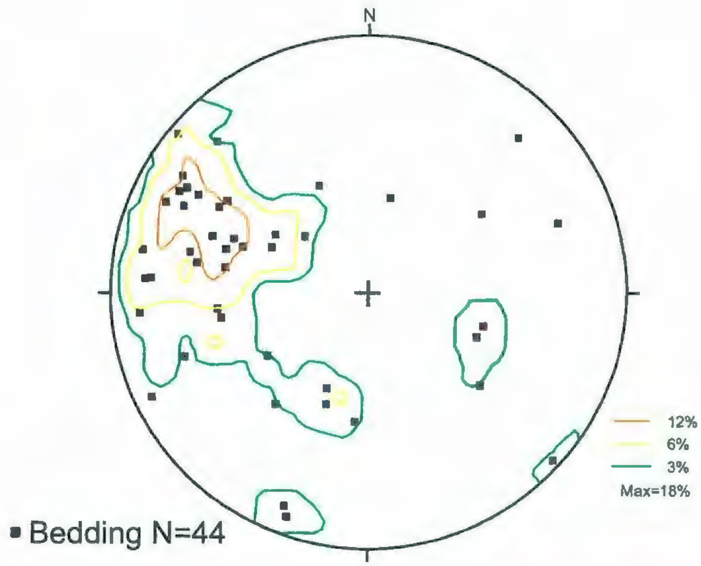


Figure 3.65: Lower hemisphere equal area pole plot for bedding in the Eastern Shale Belt. Point maximum for east-dipping orientations suggests that F1 and F2 normal limb geometries dominate. Point maximum for west dipping beds represent F2 short limb geometry.

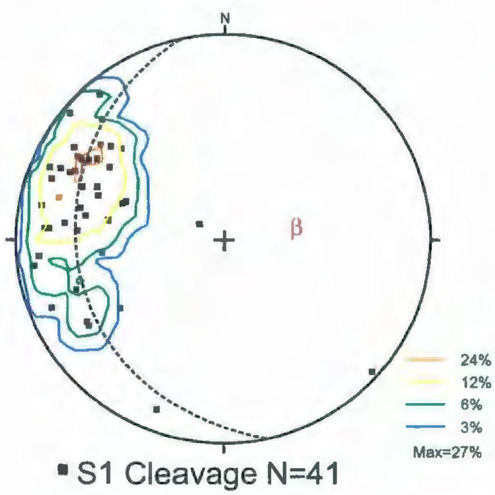


Figure 3.66: Lower hemisphere equal area pole plot for S1 cleavage fabric in the Eastern Shale Belt. Point maximum for east-dipping orientations define F1 normal limb geometry where S1 is sub-parallel or slightly steeper than bedding. Partial great circle girdle distribution reflects folding of S1 about the F2 axial plane requiring that the S1 and S2 planes lie at a small angle to one another.

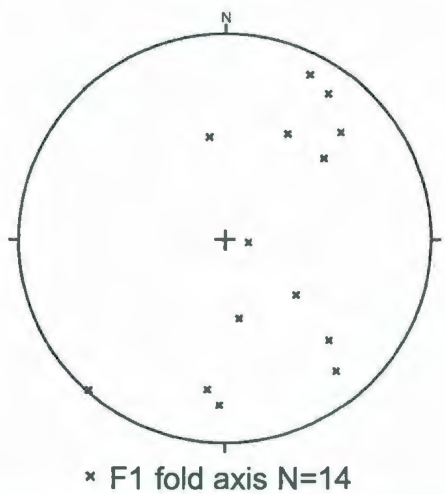


Figure 3.67: Lower hemisphere equal area plot of small-scale F1 folds in the Eastern Shale Belt. Diffuse distribution reflects interference of the F1 and F2 fold systems, but the F1 axis locus is under-sampled.

point maxima suggests that the F1 limb domains had a consistent orientation throughout the fold wave train, which suggests that the F1 fold system was relatively cylindrical. The larger population of southeast plunging F2 fold axes reflects the over sampling of refolded east-dipping F1 limbs suggesting that the F1 system had a moderately inclined west-verging asymmetry with longer east-dipping backlimb dip domains. The degree of inclination of the F1 fold system is difficult to assertain in the absence of S1-S2 intersection lineations which where unfortunately poorly preserved in the map area. The interlimb angle of the F1 fold system can be inferred based on the angle between the point maxima for F2 fold axes on the two F1 limb domains. This angle is a minimum inter-limb angle for the F1 folds because F2 lies at an acute angle to the F1 axial plane, but based on this pattern, the F1 fold system was likely characterized by fairly open fold forms with broad, flat-crested hinge domains (Figure 3.64A).

The inferred geometry of the F1 fold system is supported by locally preserved F1 structures, in particular the preserved angular relationships between S1 cleavage and bedding. Bedding orientations in the Eastern Shale Belt show a wide range of orientations (Figure 3.65), but are most commonly steeply east-dipping. These orientations are interpreted to be strongly influenced by the F2 fold system, but they nevertheless show a strong correlation to orientations of S1 cleavage fabric (Figure 3. 66). This demonstrates that the S1 axial planar fabric commonly occurs at a small angle to, or is parallel to, bedding in the F1 fold system. This relationship is interpreted to indicate that the portion of the Eastern Shale Belt sampled in this study is dominated by a macroscopic east-dipping F1 normal limb geometry and that the F1 fold system is overall west verging with moderately inclined axial surfaces. Meso-scale F1 fold structures in the shale belt demonstrate the prevalence of this normal limb geometry (Figure 3.68), but more typically show S1 cleavage sub-parallel to bedding, indicating that the meso-scale F1 fold system has at least locally tight interlimb angles. Meter-scale F1 fold hinges are locally preserved in outcrops along Spruce Brook (Figure 3.69), and are common as intrafolial folds where tightly folded bedding is transposed into a strong, bed-parallel S1 cleavage fabric (Figure 3.70). These small-scale F1 folds tend to have highly variable fold axis orientations (Figure 3.67) suggesting that they occur near a macroscopic F1 hinge domain that has had its axial plane folded by the F2 fold system, giving rise to an irregular distribution of small-scale F1 hinge lines. Unfortunately, small-scale F1 folds are not sufficiently well-exposed to produce a statistically reliable orientation data set for the fold system.

S1 orientations show a well-defined point maximum with moderate to steep easterly dips (Figure 3.66). It is noteworthy, however, that S1 has a greater range of orientations than S2, and its distribution can be described as a partial great circle girdle distribution with a beta-axis that lies roughly on the mean F2 fold axial plane (Figure 3.64A). This is interpreted to reflect the deformation of the S1 fabric by the F2 fold system, in particular, the kink-style offsets of the S1 fabric that are caused by overprinting of the S2 axial planar fabric which strikes at a small angle to S1 (Figure 3.66).

Figure 3.68: Thick-bedded Irishtown Formation sandstone and shale exposed in Spruce Brook shows well developed S1 cleavage that is steeper than bedding, indicating F1 normal limb geometry.

Figure 3.69: View looking north in Spruce Brook showing moderately north-plunging F1 fold hinge with well developed S1 axial planar cleavage. Marker pen for scale. See Appendix 3 for location.

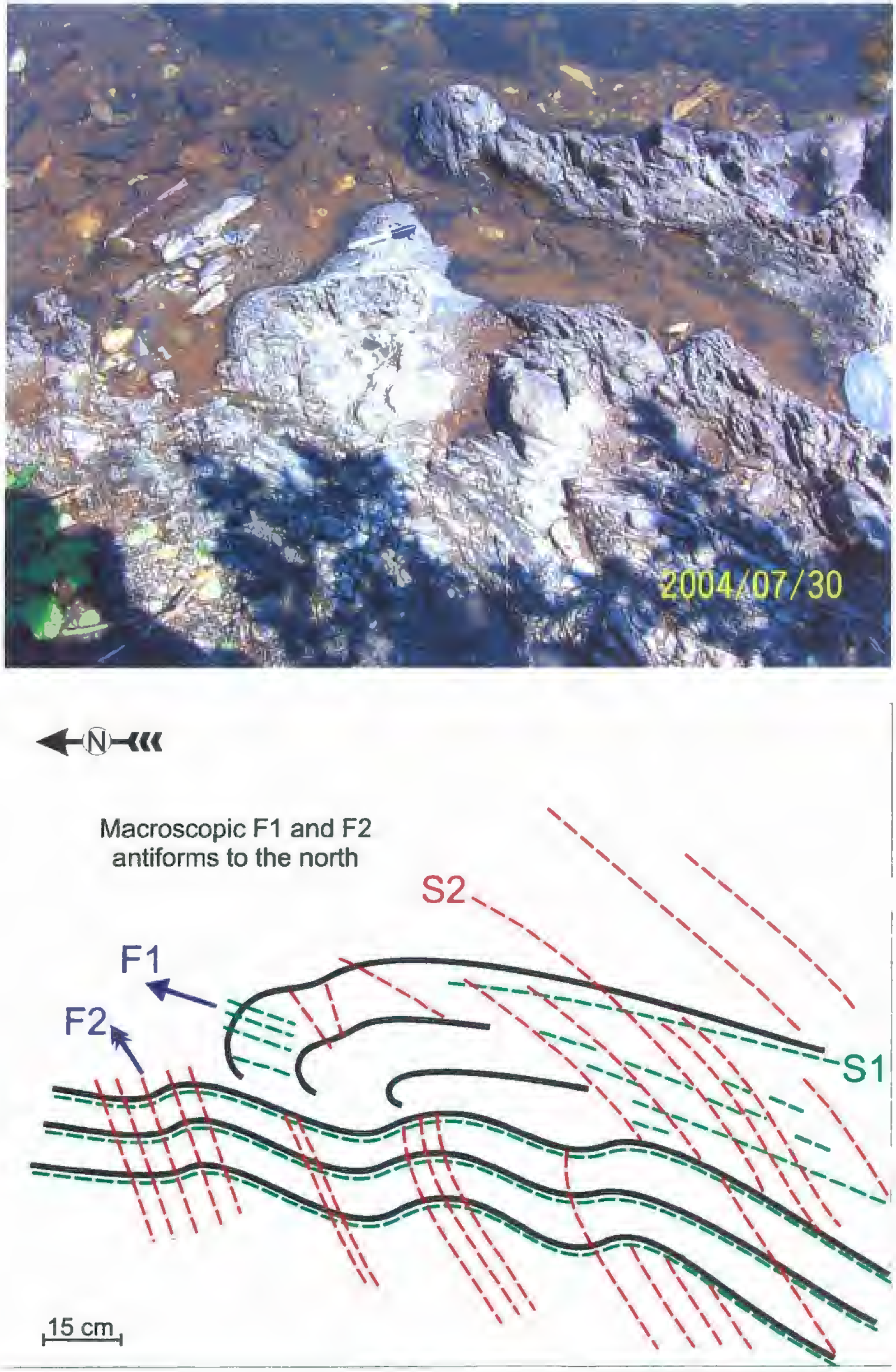


Figure 3.70: Field photo and interpretation of folded Irishtown Formation sandstone and shale of the Eastern Shale Belt exposed in Spruce Brook. F1 fold limb with S1 parallel to bedding and detached, tight F1 fold hinge are deformed by north-verging F2 asymmetric small-scale folds with weakly defined S2 axial planar cleavage.

Chapter 4

Style and History of Deformation

4.1: Introduction

Based on detailed analysis of the structure of the Spruce Brook carbonate occurrences and adjacent shale terranes, several conclusions can be made about their setting and geometry. The carbonate occurrences are bounded by observed, or inferred, gently to moderately east-dipping faults. Fold systems in the carbonate strata are inclined with east-dipping axial surfaces. The orientation of bounding faults and internal fold systems defines an overall easterly sheet-dip for the carbonate occurrences. The basal portions of the occurrences are not exposed other than along their outcrop edges; however, based on geometric constraints derived from detailed section construction, the carbonate occurrences are interpreted to constitute overall planar east-dipping panels. Furthermore, the distribution of bounding faults suggests that the panels are typically thin, containing carbonate strata on the order of only a few hundred meters in maximum thickness.

Fold systems within the carbonate panels have marked asymmetry with long, moderately east-dipping backlimb domains and shorter west-dipping forelimb domains that are locally overturned with steep easterly dips. Axial planar cleavage is only locally developed, but is consistently east-dipping. This morphology indicates that the fold systems are overall west-verging, and that the east-dipping carbonate panels are transported from east to west on east-dipping, reverse-sense faults. This is consistent with the vergence of observed faults which cut up stratigraphic section toward the west indicating west-verging thrust trajectories. Contact relationships between the thrust-bounded carbonate panels indicate that they are imbricated from west to east: SB1 is overlain by SB2 and both are overlain by SB3 and SB4 which in turn are overlain by SB5 and SB6. The panels constitute an overall east-dipping thrust stack, termed here the Spruce Brook Thrust Stack (SBTS).

The distribution of Goose Tickle Group shale in the map area suggests that it occurs at several structural levels in the SBTS, and this is exemplified by the contact relationships of the Southern and Western shale belts. The Southern Shale Belt (SSB) overlies the North Brook Anticline on a tectonized stratigraphic contact suggesting that it is itself a transported panel. The SSB is overlain by the SBTS including the Western Shale Belt (WSB), which is interpreted to represent a thrust repetition of the SSB strata. The WSB is interleaved with the carbonate thrust slices at the leading edge of the SBTS. It occurs above and below SB1 and SB2 and, in the north, it also underlies SB4. This suggests that the SBTS lies as a duplex within the succession of Goose Tickle Group shale. Structurally, the duplex lies between the par-autochthonous carbonate platform, defined in the south by the North Brook and Philip's Brook anticlines and the overlying Humber Arm Allochthon. Incorporation of Goose Tickle Group, as well as lithologies of the Humber Arm Allochthon, into the SBTS is a fundamental feature of the thrust stack, and has important implications for the emplacement history of the stack (see Section 4.4).

Internally the deformation of the Spruce Brook Thrust Stack is complex, showing evidence for several phases of shortening including the development of major out-of-sequence thrust faults (the SBUB and SBCFZ) that re-imbricate the carbonate thrust panels. Fold overprinting relationships are also locally indicated by detailed mapping and are the basis for the deformation history presented in Section 4.4.

The style of folding that characterizes the internal deformation of the Spruce Brook Thrust Stack is typical of fold-thrust belts, consisting of a combination of detachment style folding (e.g. Dahlstrom, 1970), fault propagation folding (e.g. Elliott, 1976), and ramp-bend folding (e.g. Rich, 1934 and Suppe, 1983). The style of folding can be related in part to the timing of deformation, but is also intrinsically controlled by the variability in the rheolgical response of the different stratigraphic units contained in the thrust sheets.

4.2 Mechanical Stratigraphy

The formation of major thrust faults and the style of folds formed in the carbonate strata at Spruce Brook are strongly predicated by the mechanical nature of the stratigraphic succession. The competency and ductility of carbonate units is a function of their lithological characteristics including composition, grain size, and bed thickness. These characteristics vary considerably from unit to unit in the platform succession, creating several key contrasts in competency of adjacent units, and in their ductility, as indicated by the style and pervasiveness of the internal deformation of the units (Figure 4.1). Contacts between carbonate units with highly contrasting competency are important root zones for major fault systems in the Spruce Brook Thrust Stack. The style of folding and fabric development within the thrust slices can be related to the ductility of the carbonate units carried in the sheet. The heterogeneity of structural styles across the thrust slices can, therefore, be accounted for in part by variations in the ductility of the carbonate succession.

4.2.1 Formation of Fault Zones

The main detachment surface of the carbonate duplex of the SBTS lies at the base of the contiguous SB2/SB3/SB5 thrust panel. It occurs within bedded dolostones of the Berry Head/Petit Jardin formations and propagated with a staircase trajectory, giving rise to the kink-style folding that characterizes the internal deformation of SB3. The formation of the large SB3 ramp anticline with SB2 as its forelimb domain requires that the basal detachment of the thrust slice had a ramp-flat geometry with a major ramp relief in the upper part of the carbonate succession (St. George to Table Head groups). Smaller kink folds exposed in the SB3 backlimb domain suggest that the underlying thrust also has

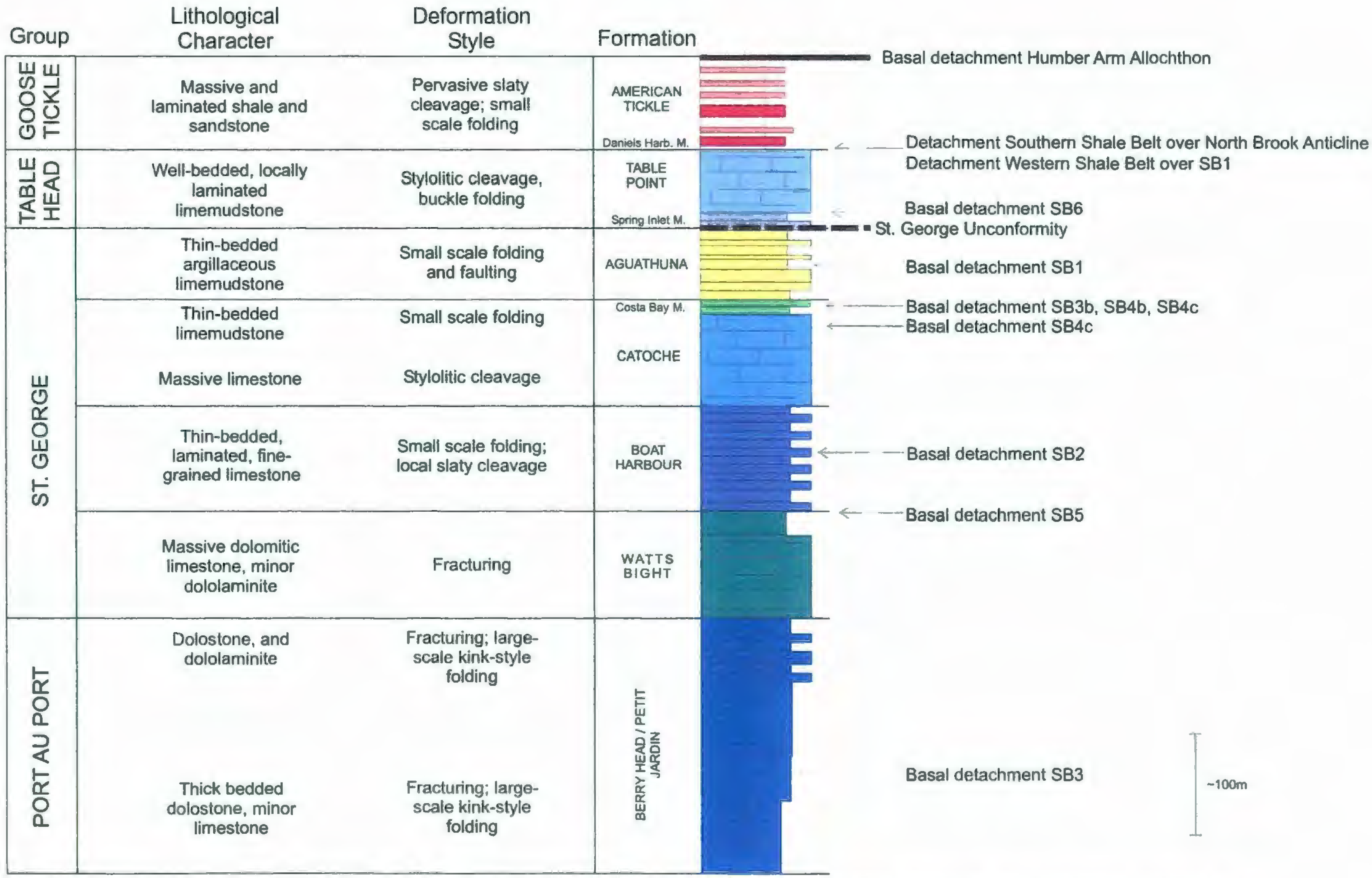


Figure 4.1: Schematic stratigraphic column showing lithological character and internal deformation styles of autochthonous units and approximate locations of major detachment surfaces in the Spruce Brook Thrust Stack

ramp-flat geometry in the lower portion of the carbonate succession (Port au Port to St. George groups), but with significantly smaller amounts of ramp relief.

The lowest strata carried by SB2 at the leading edge of the thrust slice are assigned to the Boat Harbour Formation suggesting that the basal thrust ramps up-section within Berry Head strata through the Watts Bight Formation and becomes a footwall flat within the Boat Harbour Formation. This thrust trajectory clearly illustrates the competency contrast between massive dolostone of the Berry Head and Watts Bight formations and the overlying laminated limestone of the Boat Harbour Formation. It is thought to be related to the rigid mechanical nature of the well-bedded Port au Port Group dolostone succession in comparison to the overlying St. George and Table Head group limestones, which are more mechanically heterogeneous and less competent than the underlying thick massive dolomite succession (Figure 4.1).

The occurrence of major thrust faults within the bedded limestones of the St. George and Table Head groups is strongly influenced by competency contrasts between the units in these successions. The Catoche and Table Point formations are the most competent units in this succession, and both are underlain by markedly less competent strata: the Boat Harbour and Aguathuna formations, respectively (Figure 4.1). Because the low competency limestone units act as decollement zones, their occurrence at regular intervals throughout the carbonate succession has lead to formation of a thrust stack which is characterized by thin, planar thrust sheets.

The Boat Harbour Formation is conducive to forming bed-parallel detachments because of its laminated bed intervals. In several localities in the map area, the presence of such detachments is observed, or inferred, such as the basal and upper detachments of the SB5 thrust sheet (see Chapter 3, Figure 3.55). The Aguathuna Formation consists of thinly bedded, fine-grained, locally agillaceous lime mudstone. The transition into this unit is marked in the upper Catoche Formation by the Costa Bay Member, which is also a fine-grained lime mudstone. This stratigraphic contact is the site of key detachment surfaces in SB3 and SB4 (Figure 4.1). In SB3, the floor thrust at the base of the SB3b subdomain lies near the top of the Catoche Formation (Figure 3.27). It forms the low-angle detachment between the less competent lime mudstones and the underlying, more competent, massive limestones during bulk shortening of the SB3 panel. In SB4, the trailing edge of the thrust slice is telescoped above the level of its basal detachment, which is interpreted to lie in the Catoche Formation (Figure 3.34 C). The Costa Bay Member constitutes a zone of weakness from which imbricating, out-of-sequence thrust faults formed during post-emplacement internal shorting of the SB4 thrust slice (See Section 4.4). This is evidenced by the occurrence of small-scale folded Costa Bay Member strata at the base of the SB4b subdomain (Figures 3.34A and 3.37).

The Aguathuna Formation is the site of the basal detachment of SB1 and the unit plays an important role in the development of buckle-folds in the overlying Table Point Formation (Figure 4.1). The ductility contrast between the two units allows the Aguathuna formation lime mudstones to flow in close to tight folds, filling the spaces opened by folding of the stiffer overlying Table Point Formation limestone (Figure 3.6 A).

The most important mechanical horizon in the autochthonous carbonate platform succession is the contact between the top of the Table Head Group limestones and the overlying shales of the Goose Tickle Group (Figure 4.1). This is a major zone of weakness created by the large competency contrast between shale and limestone. It is significant, because the Goose Tickle Group is structurally overlain by the Humber Arm Allochthon; therefore, the deformation of the shale succession is directly related to emplacement of the allochthon as it forms the easy glide horizon (Boyer and Elliott, 1982) for the floor thrust of the allochthon. Exposures of the basal portion of the Goose Tickle Group in the Southern Shale Belt near the crest of the North Brook Anticline show strong cleavage development and poly-phase west-verging small-scale folds (Figure 3.4). In contrast, the underlying Table Head Group limestones at the contact zone show little or no evidence of deformation indicating that the shale succession is detached from the limestone and transported toward the west.

In the SBTS, strata of the Goose Tickle Group constitute the footwall of the stack and are structurally interleaved with the carbonate thrust panels in duplex fashion. The tectonized shale-limestone contact is structurally repeated by thrust imbrication; it occurs at the top of SB1 and SB2 where it acts as a roof thrust, separating the limestone thrust sheet from the detached overlying shale (Figures 3.12 and 3.13). The floor-thrusts of SB1 and SB2 are interpreted to have ramped up-section through the limestone succession, but assumed a footwall flat geometry upon entering the less competent shale. The limestone thrust slices can thus be described as horses, riding above and below shale of the Goose Tickle Group.

The occurrence of mechanically weak Goose Tickle Group strata at several structural levels in the SBTS is interpreted to have played a role in the internal shortening of the thrust stack. In SB2, the limestone strata and their basal detachment define a large overturned cleavage fold in which the limestone strata dip steeply to the west and the cleavage fabric in the underlying shale is steeply east-dipping. The basal thrust of SB2 is interpreted to have originated as a shallow east-dipping thrust surface that became folded during progressive shortening after initial emplacement of the contiguous SB2/SB3/SB5 thrust slice. This shortening is accommodated in large part by the ductility of the shale terrane; since the shale is detached from the underlying SB1 thrust slice it was free to flow and fill the core of the macroscopic SB2 cleavage fold.

The Goose Tickle Group also occurs as small horses between the floor and roof thrusts of the SBCFZ (Figure 3.16). These horses are interpreted to be cut from both the SSB that underlies SB3, and the WSB that overlies SB1. The incorporation of the shale into the fault zone is mechanically important, because the shale preferentially accommodates flow within the fault zone, acting as a lubricant to facilitate movement of the hangingwall.

4.2.2: Fold Styles and Fabric Development

The internal deformation of the Spruce Brook thrust slices is heterogeneous in structural style: some domains are chiefly characterized by detachment style folding, while others are dominated by thrust surface-related fold structures, including ramp-bend folds and fault propagation folds. The main styles of folding in each of the structural domains of the SBTS are summarized in Table 4.1. This contrast in fold styles is due in part to the timing of deformation, as will be discussed in Section 4.4, but is also controlled by the variability in the rheological response of the different stratigraphic units contained in the thrust sheets. In principle, the style of folding depends on the ductility of the unit; for example, the thick-bedded, coarse-grained carbonates tend to deform in a more brittle fashion, forming ramp-related, kink-style, flexural slip folds; whereas thin-bedded, fine grained limestones preferentially deform by flexural flow, giving them a stronger propensity to form buckle-fold wave trains.

Generally, the carbonate succession increases up-section in overall ductility. This contrast is best exemplified by the change in fold style down the plunge of the SB3 ramp anticline. The anticline is cored by the stiffest, most rigid units in the carbonate succession, namely the thick-bedded dolostones of the Berry Head/Petit Jardin formation, and the limestone/dolostone succession of the Watts Bight Formation (Figure 4.1 and Figure 3.23). These units deform chiefly by the formation of discrete narrow kink-zones, and do not typically show evidence for internal distortion except for the local development of fracture sets. This suggests that the dolostone units mainly show brittle behavior during deformation. The portion of the anticline occupied by the overlying Catoche Formation limestone, in contrast, is characterized by a more rounded fold closure (Figure 3.24). Although discrete planar crest and backlimb domains are preserved, the transition between the domains is markedly more gradual, indicating that the thick-bedded massive limestones are able to deform in a slightly more ductile fashion. The Catoche Formation is also more amenable to cleavage formation, locally showing weakly developed stylolitic fabric.

The style of folding in the Catoche Formation of SB3 is similar to large-scale ramp-bend folds in the Table Head Group strata of SB4 where the leading syncline of the thrust slice has an open, rounded morphology (Figure 3.34 A). The Table Head limestones are locally lithologically similar to the Catoche Formation in that both units have thick-

Domain	Detachment-Style Folding	Ramp-bend Folding	Fault Propagation Folding
SB1	N-S to NE-SW trending buckle fold wave train with steep E-dipping axial planar cleavage	E-W trending, S-verging lateral ramp anticline at S edge of domain	Trailing edge folded and imbricated with shale in SBCFZ
SB2	Tight, overturned cleavage fold formed over low angle detachment in underlying shale	-	-
SB3	SB3b: detached upper strata of panel; tightly folded including Aguathuna Fm. in core of synclinorium	SB3a: large W-verging ramp anticline formed over east-dipping frontal ramp	Asymmetrical W-verging folds with east-dipping axial planar cleavage along E edge of domain related to footwall strain on SBUB
SB4	Open small-scale folds in bedded limestone (SB4a, SB4b); tight, steeply inclined folds in trailing edge (SB4c) with axial planar cleavage	Leading syncline formed over E-dipping frontal ramp; E-W trending low amplitude lateral-ramp-related folding	Internally imbricated; folding over buried thrust tips; break thrusts repeat limestone units
SB5	Large-wavelength NW-verging antiform-synform pair with axial planar cleavage	E-W to NE-SW trending ramp-bend fold; E-dipping backlimb panel formed over footwall ramp	-
SB6	Small panels are detached and internally buckled with heterogeneously developed axial planar cleavage	-	Limestone panels imbricated into moderately easterly dipping thrust stack

Table 4.1: Summary of main fold systems characterizing the internal deformation of the carbonate thrust panels in the Spruce Brook map area. See also Figure 4.2 for orientation patterns.

bedded massive sections (Figure 4.1). Internally, the Table Head Group also accommodates strain by local development of stylolitic cleavage fabric.

In contrast to the large ramp-related fold structures, thrust slices such as SB3b, SB4c and SB1 have a structural style characterized by buckle folding associated with shortening over planar detachment surfaces (Table 4.1). These domains are underlain by thin-bedded muddy limestone units such as the Aguathuna Formation, Costa Bay Member, and thin-bedded portions of the Table Point Formation (Figure 4.1). Fold wave trains in these domains are typically on the order of a few tens of meters in wavelength and are locally close to tight. The folds are often associated with a moderately east-dipping axial planar cleavage, particularly in the Table Point Formation strata of SB1 (Figure 3.6A). The cleavage shows diverging and converging fanning patterns over culminations and depressions, respectively, indicating that the strata have been significantly strained. Detachment-related fold structures in SB3b include the synclinorium cored by Aguathuna Formation strata. These strata are thin- to ribbon-bedded, and several orders of parasitic folds are present. In the core of the synclinorium, folds are tight and are locally overturned, showing west-verging asymmetry. Argillaceous portions of the unit are most ductile and often appear chaotic, showing disharmonic fold patterns. They are also locally characterized by small-scale space accommodation faults and localized detachment surfaces. This style of deformation is also observed in the underlying Costa Bay Member which has a similar lithological character (Figure 4.1). This incompetent unit constitutes the lowest strata of the SB4b and SB4c structural slices and is tightly folded over their basal detachments (Figure 3.34 A and C).

The clear correlation between detachment surfaces and tight fold wave trains formed preferentially in thin-bedded, muddy limestone units illustrates that the mechanical nature of these units controls the style of deformation of the thrust slice. This is particularly true of structural domains such as SB3 where large ramp-bend folds and tight detachment folds occur adjacent to one another. The transition from thick-bedded, massive limestone (Catoche Formation) to thin-bedded limestone (Aguathuna Formation) is clearly coincident with a change in structural style from large open folds to tight buckle folds and is the site of an inferred detachment surface.

The heterogeneous development of cleavage fabric in the Spruce Brook Thrust Stack is also attributed in part to the variable mechanical stratigraphy of the carbonate succession. Generally the fine-grained carbonate units show more pervasive development of axial planar cleavage fabrics compared to the coarser-grained units. The same can be said of siliciclastic successions in the map area that typically show strong cleavage development in shaley portions, but fabric development is less pervasive in more sandstone-dominated sections. The best defined cleavage fabrics in carbonate strata are typically observed in strata of the Table Point, and Boat Harbour formations. They tend to show well-developed stylolitic cleavages that may locally be characterized as slaty cleavage, particularly in Boat Harbour Formation strata. The formation of stylo-fabrics verses slaty fabrics is attributed to the mechanical nature of the rock, but may also be influenced by differences in state of strain affecting the strata. In contrast, units like the Catoche Formation which are coarse and massive do not typically show cleavage, but where visible, the fabric tends to take the form of a wispy, non-planar stylolitic cleavage.

Localized cleavage development in the SBTS can be related to the development of zones of high strain. One such location is in the immediate footwall of the SBUB where cleavage is parallel to the trace of the fault and is interpreted to be a local effect of thrust loading on the footwall combined with shear imposed by the overriding thrust slices (Figure 3.30). Cleavage is also strongly developed in SB2, particularly in subvertical to overturned strata of the Aguathuna Formation which show prominent stretching lineations oriented down-dip on the cleavage planes (Figure 3.11). This is typical of the flattening in forelimb domains of large fold structures and implies that the carbonate succession in SB2 underwent significant structural thinning during folding.

4.3 Fold Orientation Patterns

The Spruce Brook carbonate thrust panels constitute a north-south trending linear belt, and many of the major fold systems within the thrust sheets follow this general trend. Figure 4.2 shows that the folds in most structural domains have overall north to northeast plunging fold axes, indicated by beta axis orientations defined by poles to bedding, parasitic small-scale fold axis orientations, and bedding-cleavage intersection lineations. These data are for the most part internally consistent for each structural domain, with beta, L1, and F1 all lying within 5 degrees of each other and plotting consistently on the girdle for average S1 orientation. Exceptions to this pattern occur for SB1, SB5 and SB3b, in which cases the deviation of beta-axis orientations from the S1 girdle is interpreted to reflect the influence of fold overprinting; this is discussed in the following section. The plunge of the fold systems is gentle, rarely exceeding 15 degrees. This reflects the planar, nature of the basal detachments of the thrust slices and their relatively low dip angles, which is consistent with the interpretation that the detachments originated as roughly bed-parallel faults that formed along zones of mechanical weakness within the carbonate succession.

Figure 4.2 also shows the similarity of S1 cleavage orientations in the structural domains. Although not pervasively developed (due in part to the variable lithological character of the stratigraphic units), S1 is consistently moderately east-dipping. This is indicative of the inclined nature of the internal fold systems and, since the mappable folds show west-verging asymmetry with broad east-dipping backlimbs, the orientation of S1 demonstrates the overall easterly sheet-dip of the thrusts slices.

The overall north-northeast trend of fold axes in the SBTS holds true for structural domains such as SB3, which is dominantly deformed by ramp-bend style structures, and for domains such as SB1 which is characterized by a detachment style fold system (Figure 4.2). This shows that, although structural style may vary across the domains, the thrust slices were emplaced as part of a contiguous thrust stack with an overall westerly transport direction. Large-scale ramp-bend folds in the carbonate thrust

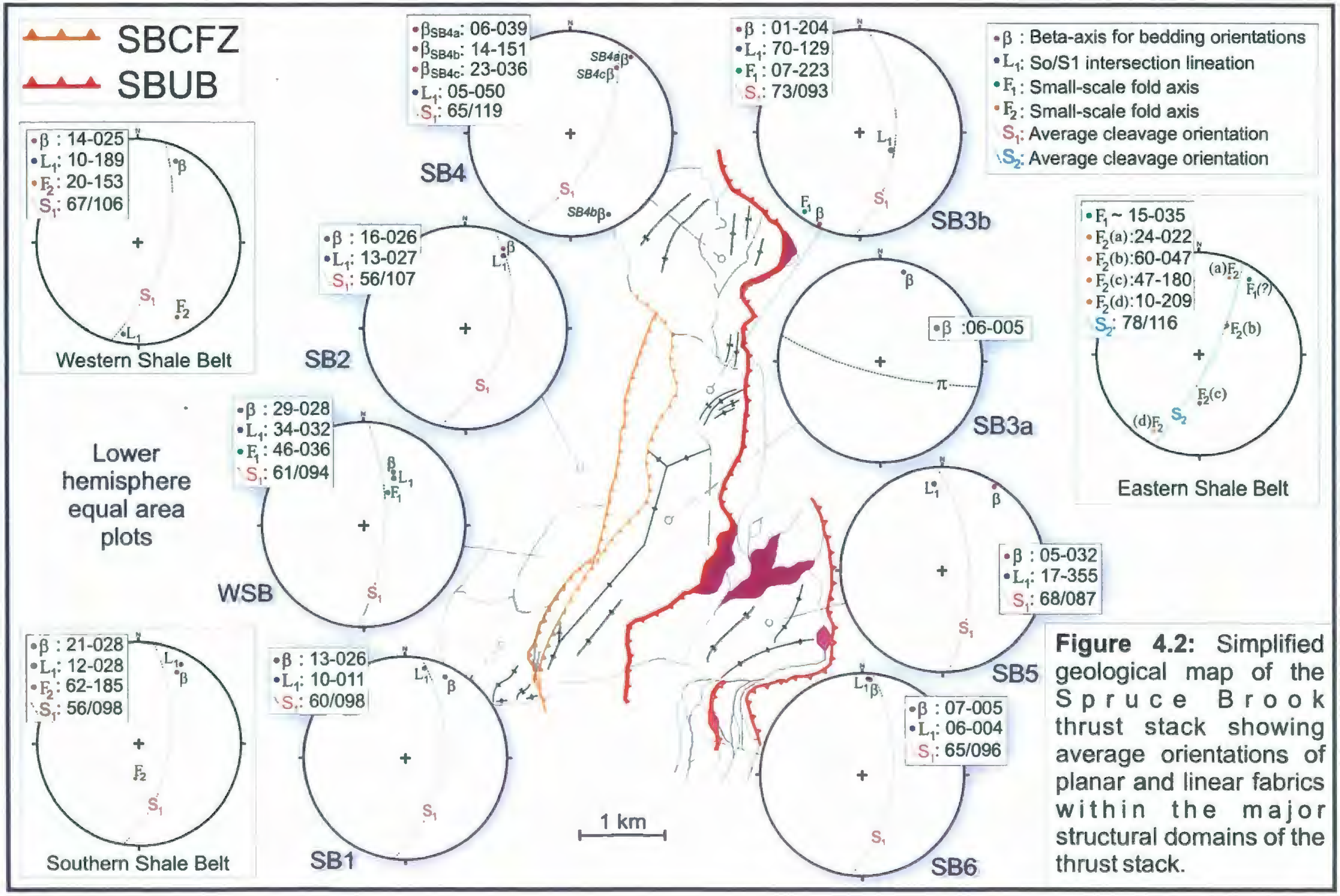


Figure 4.2: Simplified geological map of the Spruce Brook thrust stack showing average orientations of planar and linear fabrics within the major structural domains of the thrust stack.

slices fall into one of two main categories: 1) north-south to northeast-southwest trending folds, and 2) east-west trending folds. North-south to northeast-southwest trending folds include the large SB3 ramp anticline and the leading syncline that constitutes most of SB4 (Table 4.1). These ramp-bend folds are interpreted to have been formed by movement of the Spruce Brook thrust slices over east-dipping frontal thrust ramps during emplacement; they share similar orientations with the emplacement-related buckle folds. East-west trending ramp-bend structures include the antiforms situated at the southern margins of SB1 and SB5 as well as the folds at the northern margin of SB4 (Table 4.1). These structures are interpreted to be local effects created by the presence of lateral footwall thrust ramps. The dip direction and dip amount of lateral ramps in the map area is interpreted to be highly variable based on the variable morphology of east-west trending folds. In the south, the east-west trending anticlines in SB1 and SB5 are prominent structures and the underlying lateral ramps dip to the north. In contrast, small folds in the northern edge of SB4 are formed over a steeply south-dipping lateral ramp. The ramps are interpreted to be related to pre-existing east-west lineaments that affected the upper portion of the autochthonous succession prior to emplacement of the SBTS.

Like the frontal ramp-bend fold structures, north-south to northeast-southwest trending buckle-fold wave-trains are attributed to deformation of the thrust slices during west-directed emplacement of the thrust slice along east-dipping thrust faults. These fold trains are the primary emplacement related structures in SB1, SB3b, SB4b, SB4c, and SB5 (Table 4.1)

4.3.1 Fold Interference

The overprinting of north-south and east-west trending folds is the main cause of fold interference in the carbonate thrust slices, and this is indicated by discrepancies in the pole-plots presented in Figure 4.2. In SB1, the beta axis for folded bedding lies off the girdle for the average S1 orientation, despite local outcrop observations indicating that S1 is axial planar to the fold system. This is interpreted to be caused by a slight statistical skew in the beta point orientation because of the presence of north- and south-dipping beds defining the east-west trending anticline at the southern margin of the thrust slice. A similar effect is observed in SB5 where the main northeast-southwest trending fold system is overprinted by an east-west trending anticline. The orientation of the northeast-southwest trending fold system is best described by the beta-axis, but the S1 axial planar fabric appears to be more north-south striking (Figure 4.2). This is because the S1 fabric is folded about the axis of the east-west trending anticline so that the value for the average S1 orientation is influenced by a dominantly east-dipping population of orientation data on the south limb of the anticline.

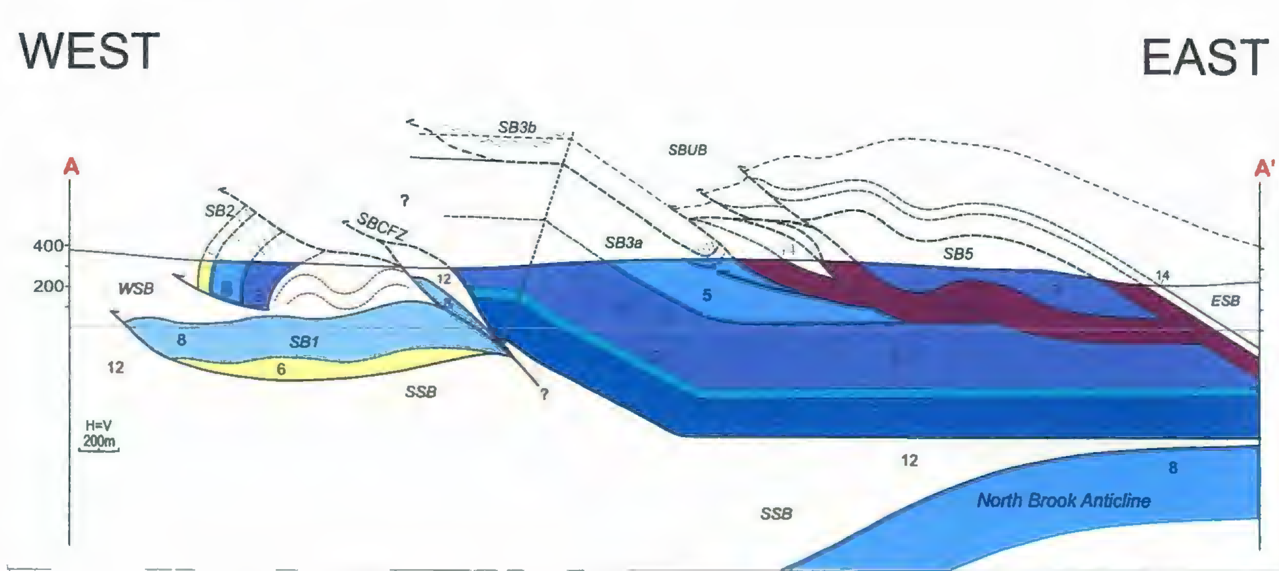
The main fold system in SB3b, including the Aguathuna Formation cored synclinorium is oriented northeast-southwest. The plunge amount of the fold system is generally small, with a plunge of less then 10 degrees and small-scale fold orientations suggest that the plunge direction varies from northeast to southwest, whereas the average fold axis orientation based on bedding is toward the southwest (Figure 4.2). This orientation is in marked discordance with the average S1 orientation which strikes north-south. This is because the northeast-southwest trending fold system does not have a well developed axial planar cleavage fabric; rather S1 in SB3b is axial planar to folds along the southeastern edge of the slice which are attributed to footwall straining in the SBUB. This indicates that northeast-southwest trending folds and north-south trending folds constitute two different fold systems. The interference of these two fold systems is not well exposed, however their relative ages can be inferred based on the association of north-south trending folds with the SBUB. As described in Section 4.4, the SBUB is part of a thrust array that is interpreted to have formed late in the deformation history of the thrust stack based on cross-cutting relationships in the carbonate strata. North-south trending cleavage folds associated with the fault zone in SB3b are therefore interpreted to be younger than the northeast-southwest folds which are likely related to the initial emplacement of the thrust slice. Furthermore, folding of the northeast-southwest trending fold system about north-south trending fold axes may account for the highly non-cylindrical nature of the Aguathuna Formation cored synclinorium.

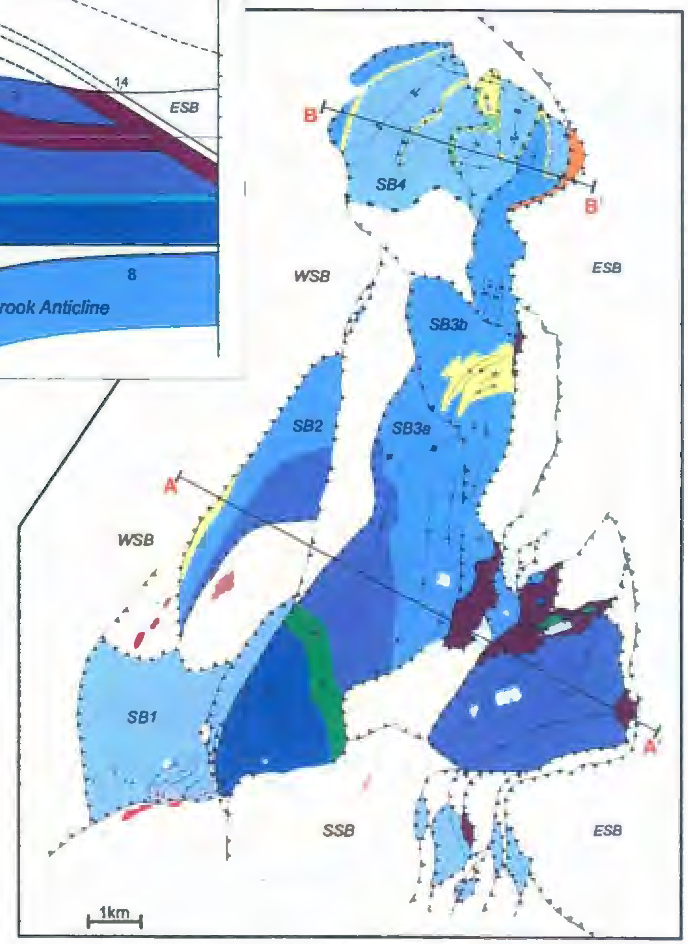
Generally, mapping indicates interference between individual fold structures within any single thrust panel. Unfortunately, the discontinuous nature of outcrop exposure in the map area inhibits the correlation of fold elements to specific sub-cylindrical fold systems on the scale of the thrust stack as a whole. Mesoscale folds often occur in isolation over a small area, limiting orientation data-sets to a minimum of measurements. Fold elements can only be correlated based on similarities in fold style and orientation, but because mesoscale overprinting patterns are rare and poorly exposed, and fabric relationships are not observed, it is difficult to conclusively assign fabrics and fold structures to uniquely defined fold generations.

Fold overprinting relationships are best resolved in the Eastern Shale Belt (ESB). Unlike the adjacent carbonate strata, the Irishtown Formation sandstone and shale show two generations of cleavage fabric and numerous small-scale folds, allowing a more robust data set to be collected despite the relatively small area sampled by the study. In the ESB, bedding orientation data are indicative of an asymmetrical mushroom to crescent (transitional Type 2) interference pattern. This shows that the moderately to steeply east-dipping F2 axial surface is oriented at a small angle to the pre-existing F1 fold axial plane which is interpreted to trend more toward the northeast-southwest. Both F1 and F2 fold systems are characterized by west-verging asymmetrical fold forms, but the F1 fold system is interpreted to be more moderately inclined with broad hinge domains and is gently doubly plunging.

4.4 Deformation History

Formation of the Spruce Brook Thrust Stack (SBTS) is thought to have initiated during emplacement of the Humber Arm Allochthon with the excision of a large panel of limestone and dolostone from the carbonate platform. The basal detachment of the carbonate panel is interpreted to represent a foreland propagating thrust splay rooted in the footwall of the basal thrust of the allochthon. The carbonate panel was subsequently dismembered, but is largely preserved in SB2, SB3, and SB5 (Figure 4.3). The lateral along strike continuation of this panel in the north is preserved as SB4, which is





1: Berry Head/Petit Jardin Fm.
2: Watts Bight Fm.
3: Boat Harbour Fm.
5: Catoche Fm.
6: Aguathuna Fm.
8: Table Point Fm.
12: American Tickle Fm.
13: Irishtown Fm.
14: Cooks Brook Fm.
15: Serpentinite

Figure 4.3: Geological cross section AA' through the southern portion of the Spruce Brook Thrust Stack showing interpreted structural relationships between the North Brook Anticline, SB1, SB2, SB3, and SB5. See Figure 4.4 for restoration of this section. BB' shows location of cross section in Figure 4.5.

interpreted as a separate thrust sheet because its stratal architecture is not continuous with the SB2/3/5 composite sheet. The basal detachments for both sheets are, however, interpreted to lie at approximately the same structural level (Figure 3.33). The discontinuity of the two main sheets is attributed to variables controlling the pre-deformation morphology of the carbonate platform; this is discussed in greater detail in Section 4.4.4. It is nevertheless clear that both carbonate thrust panels were emplaced together as part of the Spruce Brook Thrust Stack.

The carbonate panels were excised by west-propagating thrust faults locally following a stair-case trajectory up stratigraphic section toward the inboard portion of the lower Paleozoic continental margin. The thrust trajectory is best exemplified in the south where SB1 lies on a low-angle thrust fault that formed as a footwall short-cut splay that propagated toward the foreland of the overall east-dipping basal thrust of the SB2/3/5 composite thrust panel (Figure 4.3).

The fine-scale imbrication of the carbonate thrust slices that characterizes their internal structural architecture is attributed to progressive internal shortening of the carbonate strata during their emplacement. Two main phases of thrusting can be identified in the thrust stack. The first is related to the excision of the carbonate strata on a foreland propagating array of the low-angle thrusts including the basal detachments of the thrust slices. The second phase is characterized by a steeper array of thrust faults that propagated into the assembled thrust stack from a deep root zone located in the hinterland portion of the thrust stack.

Major west-verging fold systems in the carbonate strata are interpreted to have formed during the first phase of thrusting as the thrust slices were cut from the platform and transported toward the west. These folds are termed emplacement-related structures and include ramp-related and detachment-style fold systems. Fold overprinting relationships in the deformed carbonate strata indicate that some fold systems developed early in the emplacement of the thrust stack, while others formed as the structure of the thrust stack evolved. This suggests that the emplacement of the thrust stack occurred over a protracted period of time. In SB1, SB5, and SB3b prominent northeast-southwest trending fold wave trains formed by layer-parallel shortening during detachment of the carbonate strata. As these strata were transported to the west, they moved over frontal and lateral footwall ramps causing the fold wave trains to bend, creating fold interference patterns. Both buckle-folds and ramp-bend folds are thus both classified as emplacement-related structures, but their relative timing is variable across the thrust stack.

The second phase of thrusting is chiefly responsible for the internal imbrication of the thrust slices; it demonstrably deforms pre-existing, emplacement-related folds in the thrust sheets. They are, therefore, interpreted as an out-of-sequence thrust array that includes the SBCFZ and SBUB. In the south, out-of-sequence faults dismember the large ramp-anticline that formed during emplacement of the SB2/3/5 composite thrust slice. The hinge and backlimb portions of the anticline are preserved in SB3, while the sub-vertical carbonate strata in SB2 preserve the forelimb of the fold (Figure 4.3). SB5 is interpreted to have been cut from the hinterland extension of the backlimb of the anticline. SB4 is also internally imbricated by an array of thrust faults that are interpreted to be out-of sequence based on their inferred timing relative to the basal thrust of the carbonate sheet. The out-of-sequence array is rooted above the basal detachment of the thrust slice. This indicates that, prior to its formation, deformation stepped back toward the hinterland of the thrust sheet and restarted at a slightly higher structural level within the sheet (Figure 3.34). In addition to the out-of-sequence fault array, SB4 includes a pop-up structure at its trailing edge that shows intense internal deformation. This structure is interpreted to root from the out-of-sequence fault array and is attributed to late telescoping of the trailing edge of the thrust slice (Figure 3.34).

Out-of-sequence faults in the SBTS are interpreted to have formed when the thrust stack was internally shortened as the Humber Arm Allochthon advanced over it. The occurrence of serpentinite and amphibolite in the SBUB demonstrates that the SBTS was part of the wide fault zone that constitutes the basal thrust zone of the allochthon. Shortening within this fault zone and the formation of imbricate structures such as the

SBTS demonstrate a process of duplexing by hangingwall and footwall plucking at the contact between the upper portion of the autochthonous succession and the basal portion of the allochthon. Imbrication of thrust slices within the duplex by in-sequence and out-of-sequence thrusting represents a process of shortening of the footwall terrane that incrementally advanced the allochthon towards its foreland.

4.4.1 Section Restorations

Fold overprinting relationships and relative timing of imbricating faults observed in the field are the basis for the schematic restoration of the structural cross sections presented in Figures 4.4 and 4.5, which depict the southern and northern portions of the belt, respectively. It should be noted that these cross sections can not be considered true balanced cross sections because area is not everywhere conserved from the deformed state to restored-state sections. This is due to thickness changes in stratigraphic units that cannot be explained by field relationships because of lack of exposure. In several cases, the positions of the upper and lower boundaries of stratigraphic units can be reasonably inferred, whereas the internal structure of the unit remains largely unresolved. The restoration is carried out sequentially beginning with the youngest structures that deformed the thrust stack: the out-of-sequence thrust faults (SBCFZ and SBUB).

Out-of-sequence fault displacements can be restored in the south using the inferred cut-offs in the trailing edge of SB2 and leading edge of SB5 to correlate with the truncated strata in the forelimb and back limb of the SB3 ramp anticline, respectively (Figure 4.4). Some error is introduced at this step since the cut-offs lie above the erosional surface so that not all original bed length can be accounted for by field mapping. Removing the displacement on the SBUB and SBCFZ restores the composite SB2/3/5 thrust panel to the time of its initial emplacement (Figure 4.4 II). This stage in the restoration shows the geometry of the ramp-anticline and the original shape of the basal detachment of the thrust slice. A line length balance of the strata constituting the anticline is then carried out to illustrate to total internal shortening of the thrust panel (Figure 4.4 III).

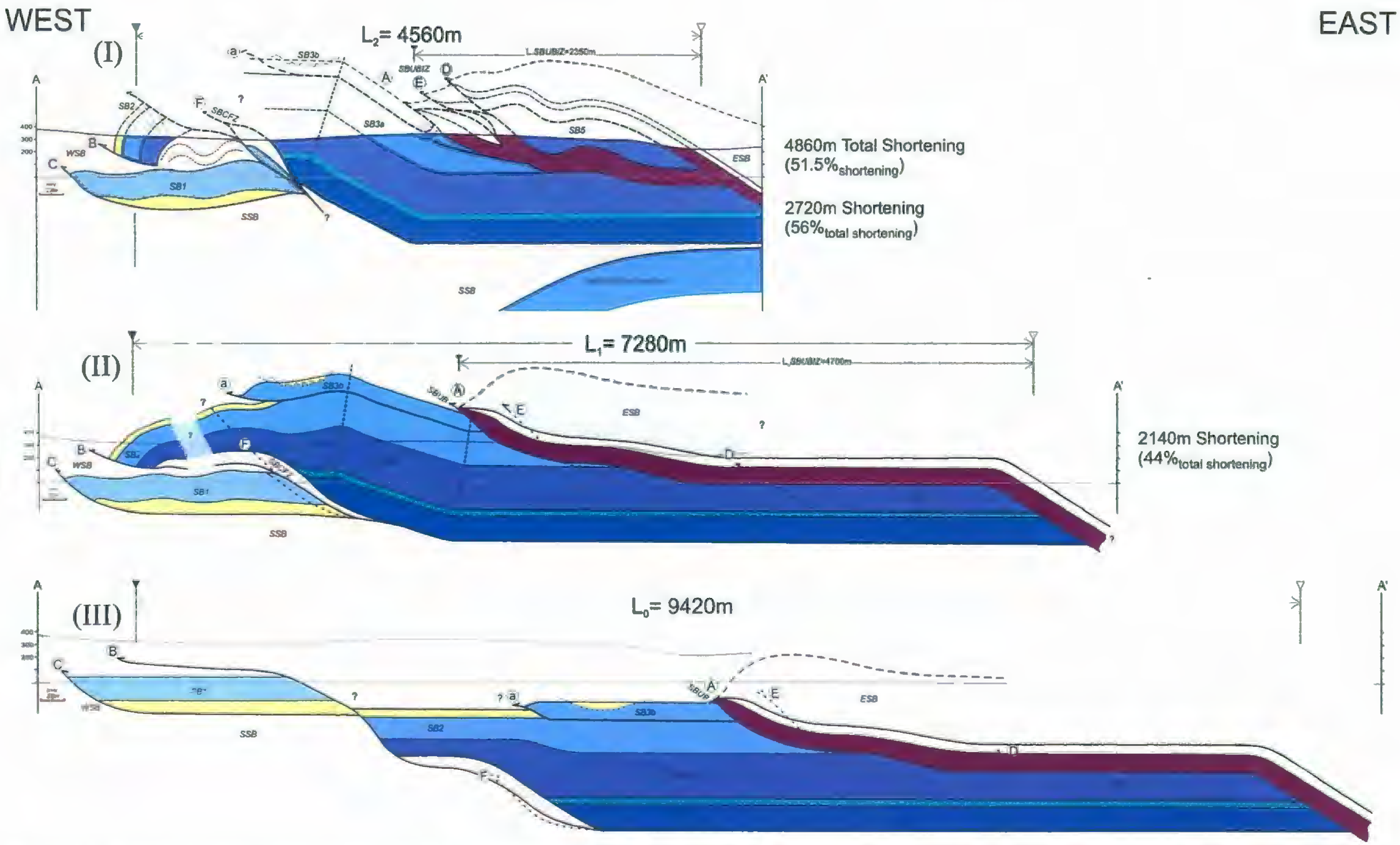


Figure 4.4: Schematic restored structural sections of the southern portion of the Spruce Brook Thrust Stack. (I) shows deformed state section; (II) restores shortening by out-of-sequence thrusting; (III) shows the pre-emplacment geometry of the slice. Internal shortening measured from pin line in basal detachment of SB1and loose line at trailing edge of SB5. See Figure 4.3 for location of section.

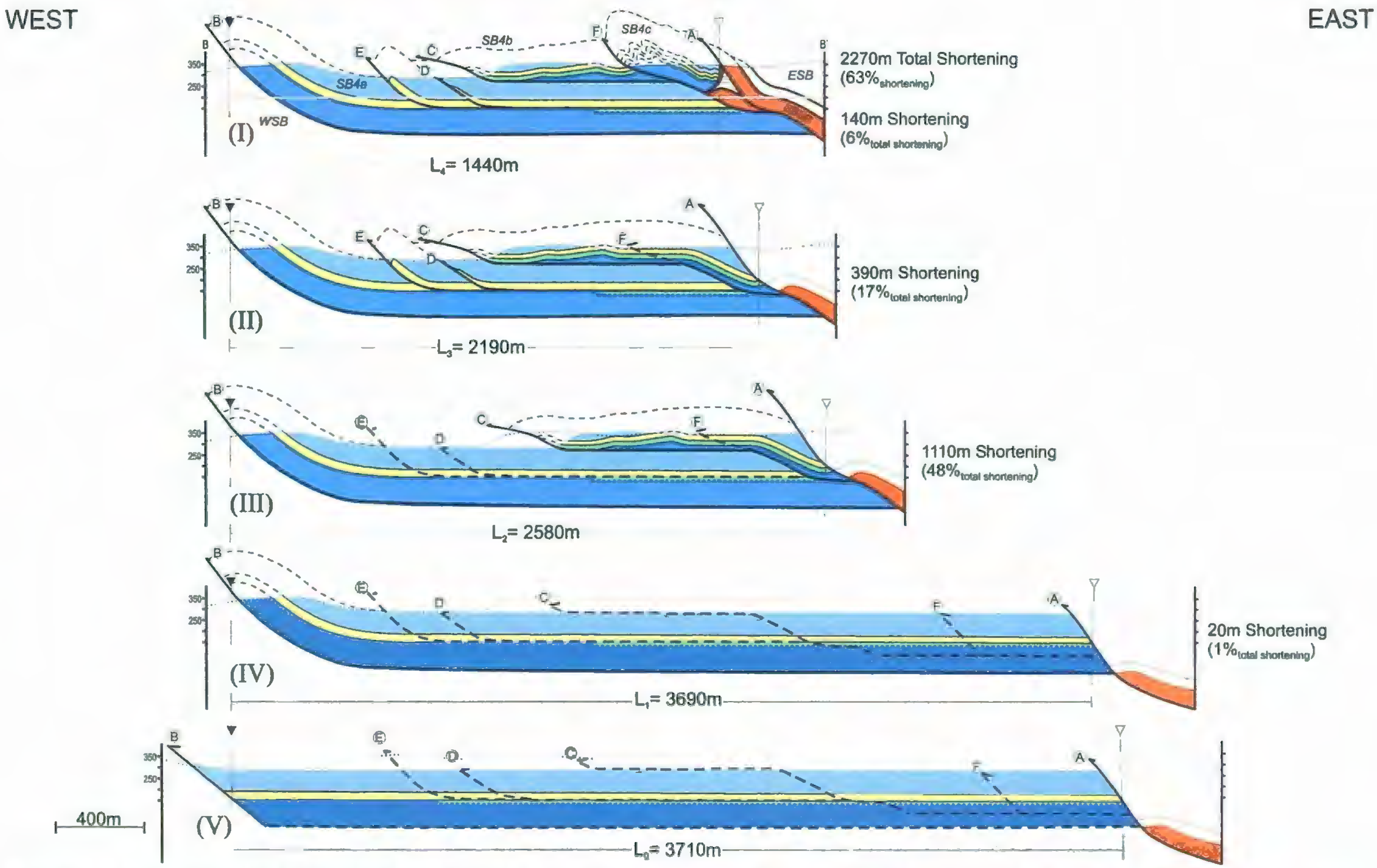


Figure 4.5: Line-length balance for the SB4 structural domain using reconstructed base of Aguathuna Formation. Stages (I) through (V) restore structures in the order in which they are interpreted to have formed. See Figure 4.3 for location of section.

For the northern section (Figure 4.5) the deformation at the trailing edge of the thrust slice is interpreted to be the last phase in the internal shortening of the slice. SB4c is restored first followed by the thrust array that includes the basal thrust of SB4b and the splays in its foreland. This array is interpreted to be foreland propagating so splays E and D are restored first, followed by splay C (Figure 4.5 II and III). The restoration uses the base of the Aguathuna Formation to restore bed length within the thrust slice. This gives a reasonable depiction of the restored basal thrust of the slice because the fault is interpreted to be roughly planar and bed parallel. The last step in the restoration resolves the SB4a syncline, which is interpreted to represent the initial response of the thrust slice to emplacement on an east-dipping frontal thrust ramp.

The final restored-state sections locally indicate that the pre-emplacement geometry of the thrust slices may be controlled in part by an earlier phase of deformation, or is strongly influenced by the paleo-topography of the carbonate platform prior to detachment and emplacement of the Spruce Brook thrust slices. Unfortunately, the original location of the thrust slices on the carbonate platform cannot be restored because cut-offs of the carbonate strata on their basal detachment cannot be correlated to exposures of the underlying par-autochthon (i.e. the North Brook Anticline in the south of the map area). The amount of displacement of the SBTS can, therefore, not be resolved; however, the cross sections illustrate the potential minimum amount of internal shortening that has occurred in the belt.

To restore the cross sections presented in Figures 4.4 and 4.5, pin lines are placed perpendicular to bedding at the exposed leading edge of the thrust slices. In the north (Figure 4.5), this is represented by the inferred position of the hanginwall cut-off of the Aguathuna Formation on Fault B. In the south (Figure 4.4), the pin line is placed near the leading edge of the basal detachment of SB1. This surface is restored to horizontal by removing deformation associated with the SBCFZ; then it is taken to approximate the base of the Aguathuna Formation and is correlated to the cut-off of this unit in SB2 for the final restoration of SB2 to horizontal bed-length. Figure 4.5 also restores to the base of the Aguathuna Formation, so the loose line for this part of the restoration is placed at the footwall cut-off of the unit against the SBUB at the eastern trailing edge of the thrust slice. In the southern cross section, the loose line is placed at the trailing edge of the SB5 thrust slice near the base of the Boat Harbour Formation where it is truncated by the original floor thrust of the SBUB (Figure 4.4). This allows restoration of shortening caused by duplexing in the SBUB and provides the most accurate reference for total shortening, because it represents the eastern-most extension of the original SB2/3/5 composite thrust slice.

The sequential restoration of the structural cross sections is explained in detail in the following sections.

4.4.2 Out-of-Sequence Faults

In the northern cross section two major out-of-sequence thrusts carry the SB4b and SB4c thrust slices and are labeled ‘C’ and ‘F’, respectively (Figure 4.5). Fault C is rooted in upper Catoche Formation strata and cuts the carbonate sheet above the level of its basal detachment in the southern portion of the sheet. It, therefore, represents a hinterland back-stepping, foreland propagating thrust fault, and is by definition out-of-sequence. Furthermore, fault C emplaces SB4b over a portion of the lateral footwall ramp that terminates the SB4 sheet in the north. The thrust carries a thin horse of the footwall shale (WSB?), indicating that it deforms the limestone sheet and the underlying shale terrane irrespective of the internal geometry of the thrust slice. This suggests that the fault formed during a phase of shortening in the thrust belt occurring after initial emplacement of the SB4 thrust slice over the WSB. Faults D and E (Figure 4.5) are interpreted as foreland-propagating thrusts that are in-sequence relative to out-of-sequence thrust C, since they cut up-section from the root zone of fault C to deform Aguathuna and Table Point formation strata. Faults C/D/E together constitute a foreland-propagating thrust array that formed out-of-sequence relative to the basal thrust of SB4. Shortening caused by formation of the out-of-sequence fault array was significant, accounting for 48% of the total internal shortening of the SB4 thrust slice (Figure 4.5 III).

Fault 'F' carries the SB4c thrust slice and is interpreted as a second out-of-sequence thrust fault that splays from fault C during a second hinterland-back stepping deformation event that followed the formation of the C/D/E array (Figure 4.5). Movement on fault F is thought be genetically related to the moderately west-dipping back-thrust that emplaces the eastern edge of the carbonate slice over the adjacent shale and serpentinite of the SBUB. SB4c is interpreted as a local 'pop-up' style structure that accommodates about 5% of the total internal shortening in SB4; it likely formed in response to final stages of shortening in the trailing edge of the slice (Figure 4.5 I). The antithetic fault at the eastern edge of SB4c is unique to the northern exposure of the contact zone and is attributed to a localized response to some irregularity in the geometry of the fault zone or the original shape and pre-existing structure of the carbonate block.

The presence of the out-of-sequence thrusts and 'pop-up' structures in SB4 reflects the extreme amount of shortening in the immediate footwall of the SBUB. In the south, the shortening is accommodated by duplexing of the hanging wall succession with structural slices of the underlying carbonate (Figure 4.4). Major imbricating thrusts in the SBUB Imbricate Zone (SBUBIZ) in the southern portion of the map area are considered to be out-of-sequence relative to the basal detachment of the composite SB2/3/5 carbonate thrust slice. Figure 4.4 highlights faults D and E that carry Boat Harbour Formation of SB5 and strata assigned to the Catoche Formation, respectively. The faults are roughly correlatives of the imbricating thrusts that carry SB6 in the south. As described in Chapter 3 (Section 3.9), SB5 and SB6 are emplaced contemporaneously across a pre-existing high-angle fault. Thrusts D and E are out-of sequence relative to the original floor thrust of the SBUB (thrust 'A'), but together they represent a phase of back-stepping followed by renewed foreland-propagating (in-sequence) thrusting. The faults cut up-section through the assembled thrust stack with a stair-case trajectory mobilizing slices of carbonate by footwall plucking. This is likely controlled to some degree by zones of mechanical weakness in the carbonate succession, particularly the upper and lower contacts of the Boat Harbour Formation. The imbicating thrusts demonstrably breach pre-existing faults that separate lithologies of the SBUB hanging wall succession. Duplexing of carbonate strata as isolated small horses at various structural levels within the SBUB further suggests that the breached thrusts were active during footwall plucking of the carbonates in the footwall below the original position of thrust A.

The SBUB and SBUBIZ clearly have complex deformation histories that include several generations of in-sequence and out-of-sequence fault arrays which evolved over protracted periods of deformation. Out-of-sequence duplexing in the SBUBIZ is interpreted to constitute over 2 kilometers of shortening based on schematic restored structural sections (Figure 4.4 II) The thickening of the imbricate zone by shortening created considerable structural relief in the hinterland of the Spruce Brook Thrust Stack. This effect was compounded by shortening in the Eastern Shale Belt which is characterized by imbrication and refolding of thick Irishtown Formation sandstone/shale successions. This growth within the allochthonous thrust stack exerted considerable load-pressure on the underlying carbonate succession, causing deformation along the eastern edge of SB3. Here, slaty cleavage fabrics are noted in Boat Harbour Formation limestone and tight, north-south trending cleavage folds developed in strata of the Catoche Formation (Section 3.6.3) (Figure 4.4 I).

The SBCFZ, marked 'F' (Figure 4.4) and exposed in the southern portion of the map area, is also demonstrably out-of-sequence, because it deforms a pre-existing thrust slice after its emplacement. The SBCFZ truncates the crestal portion of the SB3 leading ramp anticline including the overlying SB3b thrust panel. It displaced the crest and backlimb portions of the anticline relative to its forelimb which is preserved in SB2 to the west. Unfortunately, no reliable estimate of the displacement on the SBCFZ can be made, because hangingwall and footwall cut-offs in SB2 and SB3 across the fault zone are ambiguous due to the apparent change in thickness of stratigraphic units in the two domains (see Section 4.4.4). The fault zone is interpreted to root below the basal detachment of the original composite SB2/3/5 thrust sheet; it imbricates structural slices cut from the footwall shale terrane over SB2. The roof thrust of the SBCFZ lies at the base of the SB3 thrust slice and its along-strike continuation to the north is interpreted to become coincident with the basal thrust of SB4. Movement on the SBCFZ is thought to be roughly contemporaneous with the initiation of out-of-sequence movement on the

SBUB and represents re-activation of the original floor thrusts of SB3 and possibly SB4. This implies that the SBUB and SBCFZ constitute a major back-stepping phase of foreland-propagating out-of-sequence thrusting.

4.4.3 Structures related to excision and initial emplacement of carbonate thrust sheets

The main thrust faults related to the emplacement of the Spruce Brook Thrust Stack are highlighted in Figures 4.4 and 4.5. In both the northern and southern portions of the thrust belt, the fault that initiates deformation is the SBUB (marked 'A' in Figures 4.4 and 4.5), which is interpreted to have a long, multi-stage deformation history as a splay that rose from the basal detachment of the Humber Arm Allochthon (see Chapter 5). For the purpose of the balanced section construction, Figure 4.5 (III) is restored to a partially deformed state interpreted to represent the initial emplacement of the SBUB thrust stack over an outboard portion of the carbonate platform. This early emplacement stage of the SBUB is interpreted to have been roughly coincident with the mobilization of the carbonate thrust slices and to have acted as the trigger for detachment of the Spruce Brook Thrust Stack. The SBUB is depicted as a low-angle thrust fault that transports serpentinite, metamorphic aureole rocks and Irishtown Formation, separated by a veneer of Cooks Brook Formation, to the west over, the carbonate succession. It should be cautioned that the structural slices of altered mafic-ultramafic rock in the SBUB are shown as continuous, thin sheets in the structural sections for the purposes of the restoration. They are, however, more likely to be highly irregular in shape, with variable thickness and little lateral continuity based on the exposures of the unit and its geophysical character (Figure 3.51).

The partially restored structural section presented in Figure 4.4 (III) suggests that the basal thrust of the SBUB followed a stair-case trajectory so that serpentinite came to overly carbonate strata at various stratigraphic levels. The geometry of the footwall cut-offs in the SBUB, as presented in Figure 4.4, indicates that a sizable section of carbonate stratigraphy appears absent from the hanging wall of the SBUB. Such missing section could lie in the now exhumed leading edge of the SBUB, but this would require an extremely complex additional thrust stack component. Alternatively, the truncation of the carbonate strata may pre-date the formation of the SBUB; in other words, the footwall of the SBUB may have been an erosive slope in the paleo-topography of the outboard carbonate platform. This contingency would explain how allochthonous rock units may be juxtaposed with various stratigraphic units of the carbonate platform without a complex early phase of duplexing into the carbonate succession. Evidence for such early processes is somewhat tenuous given the bedrock exposure in the area; however, the early formation of thrust splays from the SBUB into the carbonate succession is consistent with the stair-case trajectory of the thrust. Footwall shortcut faulting is evidenced by structures such as the SB3b thrust panel (Fault 'a' in Figure 4.4 III). This thrust forms early in the deformation history of the SBTS since it becomes subsequently folded by the underlying SB3a ramp anticline and is truncated by the SBCFZ. It repeats carbonate strata from middle-upper Catoche Formation, and this accounts for some of the missing section above the SBUB. The stratigraphic succession in SB3b is, however, not complete since it contains no Table Head Group strata; this must be attributed to either erosion that pre-dates the SBUB, or a higher level thrust splay that is not preserved in the map area. The structural style of SB3b suggests that short-cut faulting in the footwall of the SBUB may have mobilized multiple thin structural panels of carbonate, forming a composite duplex structure near the leading edge of the fault zone. The presence of this structure would account for the missing carbonate section above the SBUB but it is not resolved by this study since it lies above the erosional level of the map area.

The basal detachment of the main carbonate thrust panels, labeled B in Figures 4.4 and 4.5, is thought to have formed as a foreland propagating thrust array initiated in the carbonate succession by emplacement of the impinging SBUB thrust panels. The root zone of the basal carbonate detachment is thus thought to be coincident with that of the SBUB in the hinterland of the thrust stack. The basal detachment of the carbonate slice lies at a higher stratigraphic level in the north: Petit Jardin/ Berry Head Formation in SB3 to middle-base Catoche Formation in SB4, suggesting that the fault is overall gently south-dipping and cuts up-section toward both the north and west. It is unclear, however, what role the pre-deformation morphology of the carbonate platform may have played in controlling the geometry of this fault. It is possible that the basal Catoche Formation strata of SB4 were juxtaposed with the basal portion of SB3 prior to their detachment by vertical displacement on a pre-existing high-angle fault, similar to the fault which must have juxtaposed SB5 and SB6 in the south (Section 3.9).

In the south, the basal thrust ('B' Figure 4.4 II) ramps up-section toward the west, emplacing the composite SB2/3/5 thrust sheet over Table Head Group limestone and Goose Tickle Group shale. The imbrication of SB1 and the composite SB2/3/5 thrust sheet is interpreted to account for about 44% of the total internal shortening of the southern portion of the thrust stack. The basal detachment of SB1 ('C' Figure 4.5 II) is interpreted to have formed in the relatively incompetent lime mudstones of the upper Aguathuna Formation by a footwall short-cut fault propagating 'in sequence' to fault 'B', into the foreland of the main carbonate thrust sheet. Both slices are subsequently transported to the west over the Western and Southern Shale Belts by continued activity on faults B and C (Figure 4.4 II). Foreland propagating thrusts are also likely to have propagated into the WSB, both in the southern and in the northern portions of the leading edge of the carbonate thrust slices. Although these faults are not mappable, they are an important element in the development of the SBTS and the westward continuation of the fold and thrust belt.

In the north, the emplacement of SB4 is thought to be contemporaneous with the mobilization of the composite SB2/3/5 sheet. SB4 is emplaced over the Western Shale Belt on an east-dipping thrust ramp ('B' Figure 4.5 V) and its leading anticline/syncline pair is formed in response to movement of the sheet over the ramp (Figure 4.5 IV). The southern along-strike continuation of the basal thrust of SB4 is interpreted to become roughly coincident with the basal thrust of SB3b as part of the overall gently south-dipping floor thrust of the SBTS (Figure 3.33).

The footwall cut-offs of the Spruce Brook carbonate thrust panels in the par-autochthonous portion of the carbonate platform are not observed in the map area. However, one important stratigraphic marker is noted in both the SBTS and the underlying par-autochthon. This is the contact between Table Head Group limestone and the overlying Goose Tickle Group. The contact is exposed in SB1 in the west and also on the northern portion of the underlying North Brook Anticline in the southeast. Although strongly tectonized, this contact is thought to be a correlable stratigraphic horizon based on the occurrence of distinctive sandstone units. The presence of the contact at the top of the SB1 thrust slice suggests that SB1 and its shale cover form a thrust-repeated portion of the northern, down-plunge continuation of the North Brook Anticline. This is an important constraint for palinspastic restoration of the SBTS because it indicates that the leading edge of the stack would restore to the north and east of the eastern subsurface continuation of the carbonate strata exposed in the North Brook Anticline. It also suggests that the Western Shale Belt may include several imbricate panels of shale, giving the belt its marked thickness and large areal extent. The thrust faults that potentially repeat the stratigraphy of the Western Shale Belt are not mappable because of the monotonous nature of the lithology and the lack of bedrock exposure. The horizontal component of displacement of SB1 remains unknown since no precise cut-offs are observed, but the vertical displacement of the slice can be estimated to be on the order of 600m based on the minimum estimated stratigraphic separation of the carbonate succession in SB1 and the North Brook Anticline (Figure 4.4 I). This estimate must also take into account the non-planar nature of the upper platform, particularly since the pre-deformation morphology of the SB1 strata is unknown.

After initial detachment of the carbonate thrust slices, their westerly transport was punctuated by the internal shortening of the sheets by folding and further thrusting. The response of the thrust sheets to emplacement was heterogeneous. In the south, the leading edge of the main carbonate thrust slice evolved as a large, locally overturned cleavage fold (preserved in SB2) and the central portion of the composite SB2/3/5 thrust panel developed as a broad flat-crested ramp anticline (preserved in SB3) (Figure 4.4 II). Shortening is also accommodated in the south by detachment of the SB1 thrust sheet and development of its internal buckle-fold wave train with axial planar cleavage. Lateral footwall asperities also influence the emplacement of the thrust sheets at this time, forming the lateral east-west trending ramp-bend structures as the sheets were transported.

Deformation in the SBTS is interpreted to have intensified after initial emplacement, culminating in the development of major out-of sequence fault zones. This is evidenced by structures at the leading edge of the thrust belt which show evidence of significant straining accommodated by formation of high-amplitude folds. In the southwest, the leading edge of the composite SB2/3/5 thrust sheet overlies black shale that is partially indigenous to the SB1 thrust slice (i.e. the WSB) and partially transported from the underlying SSB by footwall plucking (Figure 4.4 II). Both SB2 and the shale slices are emplaced over the top of SB1, and are progressively deformed together with SB1 to form the large-amplitude shale-cored SB2 cleavage fold. At the leading edge of SB4 in the north, the hangingwall strain does not appear to be as high, but the attitude of the west limb of the SB4 leading syncline, and its marked asymmetry, suggest that the fold limb is somewhat over-steepened. This geometry is thought to reflect the intensity of deformation at the leading edge of SB4 (Figure 4.5 IV). As ramp-related folds and detachment folds in the leading portion of the thrust stack grew in amplitude, they exerted a buttressing effect on the thrust stack causing deformation to stall and shift toward the hinterland. Hinterland propagating out-of-sequence thrust faults formed as a result, causing re-imbrication of the thrust sheets.

4.4.4 Pre-emplacement Structures

Figure 4.4 (III) approximates the partially restored shape of the main carbonate thrust panel constituting the southern portion of the Spruce Brook Thrust Stack prior to its detachment from the platform and subsequent westerly transport. It is clear that there is a significant change in the thickness of the Catoche and possibly the Boat Harbour formations from east to west. This may be explained in one of two ways: 1) the change in thickness may be related to an unusual variation in deposition of the carbonate units over an uneven paleo-topography, or 2) the strata have experienced structural thinning in the SB2 portion of the thrust slice, while the SB3 portion of the slice may be structurally thickened by repetition of carbonate strata during an early phase of deformation on the platform.

Scenario 1 necessitates that the SB2 structural domain was a high-standing block on the carbonate platform during deposition of the upper St. George Group and the adjacent SB3 area was more basinal; as such, SB2 would carry a thinned version of the St. George stratigraphy exposed in SB3. It should be noted, however there is no precedent for this style of deposition in other exposures of the St. George Group elsewhere in the Humber Zone. Although it is unlikely that block faulting affected the carbonate platform at the time of deposition of the St. George Group; the paleo relief of SB2 during deposition of the Table Head Group could explain the absence of this unit from the upper portion of the thrust slice. The block may have been basinal, however, during deposition of the Goose Tickle Group since SB2 is interpreted to be overlain by shale. The nature of the upper contact of SB2 is unfortunately not resolved due to lack of exposure.

Scenario 2, which attributes thickness variations to deformation, is more plausible. This is particularly true for SB2, which shows evidence for forelimb thinning based on strong S-L fabric development. Whether this structural thinning was significant enough to account for the geometry presented in Figure 4.4 is, however, questionable. Strong evidence also exists for early deformation that could account for structural thickening of SB3. The SB3b panel, for example, is interpreted to be a thin package of strata that was detached from SB3 early in its deformation history. The structure of SB3b is resolved by mapping in large part because its internal deformation is accentuated by the thin-bedded nature of the Aguathuna Formation in the upper portion of the panel, but a similar panel occurring within the massive limestones of the Catoche Formation would be potentially undetectable given the level of exposure in the area. Figure 4.4 (III) suggests that the additional thickness of Catoche Formation in SB3 could be accounted for by the presence of just such a thrust slice with a thickness roughly the same as that of SB3b. Furthermore, structural thickening of the carbonate units at Spruce Brook is plausible considering that the thickness of the units documented by this study are anomalous compared to those established by previous workers in the nearby par-autochthonous structures. This applies particularly to the Philip's Brook Anticline where the Catoche Formation is on the order of 125 m in thickness (Knight and Boyce, 2000) compared to a thickness in excess of 200m locally found in the Spruce Brook Thrust Stack.

Deformation on the carbonate platform prior to transport of the Spruce Brook Thrust Stack is inferred in order to explain major discontinuities in the belt along its strike, most notable the juxtaposition of SB5 and SB6. As described in Chapter 3, SB5 and SB6 are separated by a major east-west trending lineament, but the roof thrust of the SBUB, which straddles the lineament, does not show significant vertical or horizontal separation across it (Figure 3.55B). This suggests that the Boat Harbour Formation of SB5 and the upper Table Point Formation strata of SB6 were situated at approximately the same structural level during imbrication in the SBUB, and were therefore juxtaposed prior to initial emplacement. The lineament is also coincident with lateral ramp-bend folds at the southern margin of SB1,SB3 and SB5, indicating that the lineament pre-dates the emplacement of the main carbonate thrust slice. The lineament is interpreted to be a steep east-west trending fault that formed on the carbonate platform in response to peripheral bulge migration. Such faults would act as transfer zones between arrays of normal faults during uplift and subsidence of the platform. Some of these faults may have been reactivated as thrusts in the subsequent development of the Taconic foreland, or may have remained quiescent, but would nevertheless act as important footwall asperities influencing the emplacement of platform carbonate thrust sheets at or near the base of the Humber Arm Allochthon.

4.5 Summary

Important steps in the deformation history of the Spruce Brook area interpreted from field mapping are outlined as follows:

1) The SBUB developed as a splay from the basal portion of the Humber Arm Allochthon as it is emplaced to the west over the carbonate platform. The initial

response of the platform may have locally included the formation of low angle detachments in the carbonate succession, exemplified by the SB3b structural slice.

2) Short-cut faults propagated into the foreland of the SBUB mobilizing thin sheets of carbonate. The geometry of the transported sheets is predicated on zones of mechanical weakness in the carbonate succession and the presence of pre-existing high-angle faults that gave the platform edge a morphology characterized by high- and low-standing blocks.
3) Westerly transport of the carbonate slices took place on low-angle detachments rooted in the Southern Shale Belt. It was punctuated by formation of the SB4 leading syncline in the north, cleavage folding in SB2, and ramp-bend folding of SB3.
4) Foreland-propagating thrusts detached SB1 and buckle-folds within the slice were subsequently formed to accommodate strain in the footwall of the overriding SB2 sheet.
5) The late stages of shortening occurred along out-of-sequence fault zones including the SBCFZ that re-imbricates the SB2 and SB3 portions of the thrust sheet in the south. SB4 is internally imbricated by the emplacment of the SB4b slice. Telescoping of the trailing edge portion of the carbonate thrust sheets is accommodated by the SB4c pop-out structure in the north, and duplexing within the SBUB in the south that includes the emplacement of SB5 and SB6.

Chapter 5

Tectonic Synthesis

5.1 Tectonic Setting

The Spruce Brook Thrust Stack (SBTS) is an example of a small imbricate stack of thin-skinned thrust sheets containing stratigraphic units of the lower Paleozoic carbonate platform of the Laurentian margin. The strata in the thrust stack have undergone significant internal shortening during polyphase deformation punctuated by discrete pulses of in-sequence and out-of-sequence thrusting.

The basal detachment or floor thrust of the SBTS is interpreted to lie within shales of the Goose Tickle Group at or near the stratigraphic contact between the shale and the underlying Table Head Group limestone. The thrust stack is interpreted to lie structurally below the main units of the Humber Arm Allochthon, which is readily envisaged in the field since the Spruce Brook area is a topographic lowland that sits between the Lewis Hills and Blow Me Down ophiolite massifs to the west and north, respectively, and the hills of resistively weathering allochthonous Irishtown Formation sandstone to the east. Contact relationships between the Spruce Brook Thrust Stack and the lower structural slices of the allochthon are locally observed east and west of the map area. The basal portion of the allochthon can be divided into two main structural terranes consisting of 1) the Blow Me Down Brook and Fox Island River formations which occur immediately below the ophiolite massifs, and 2) the imbricated thrust slices of Humber Arm Supergroup strata at the base of the allochthon.

Sandstone and shale of the Blow Me Down Brook Formation do not occur in the Spruce Brook map area, nor do mafic volcanic rocks of the Fox Island River Formation. These units are interpreted to constitute a discontinuous duplex with variable structural thickness that carries the Bay of Islands Complex on its roof thrust (Gilles, 2006; Williams and Cawood, 1989). The strata occur most notably west of the study area, along the western and eastern margins of the Blow Me Down Brook and Lewis Hills massifs (Figure 1.4). They are exposed near the northern closure of the Philip's Brook Anticline (Knight and Boyce, 2000). The duplex is interpreted to be discontinuous because units of the Bay of Islands Complex are locally in direct structural contact with the platform carbonate and flysch successions, most notably at Phillip's Brook, Cache Valley, and Spruce Brook (Figure 1.4). The Blow Me Down Brook and Fox Island River formations structurally overly the Humber Arm Supergroup including the Cooks Brook and Irishtown formations (Buchanan, 2004). They are carried on a thrust that is interpreted to lie above the level of erosion in the Spruce Brook area.

The structural slices of Irishtown and Cooks Brook formation in the map area constitute the leading edge of a large, internally folded and re-imbricated thrust stack that underlies most of the area southeast of Humber Arm (Waldron et al. 2003). This thrust stack is interpreted to have the geometry of a large antiformal stack that formed as the Humber Arm Allochthon was internally shortened during its emplacement. The basal detachment of the antiformal stack constitutes a preserved portion of the original floor thrust on which the Humber Arm Allochthon was transported. Along the eastern edge of the SBTS, strata of the Cooks Brook and the Irishtown formations clearly structurally overly east-dipping beds of platform carbonate, indicating that the thrust slices in the SBTS lie in a duplex situated directly below the Humber Arm Allochthon (Insert 1). The roof thrust of the duplex is the basal detachment of the Humber Arm Allochthon. The floor thrust is defined as the basal detachment of the Spruce Brook Thrust Stack and is rooted deep in the carbonate platform succession. The structural panels of carbonate and shale contained in the SBTS are, therefore, horses riding within a lower duplex, which is situated at the base of the allochthon and above the fold/thrust panels of the par-autochthonous carbonate platform exposed in the North Brook and Phillips Brook anticlines.

5.2 Tectonic Synthesis

5.2.1 Thrust Mechanics

The formation of the Spruce Brook Thrust Stack (SBTS) is interpreted to be directly related to deformation in the immediate footwall of the Humber Arm Allochthon during its emplacement. The precise age of deformation of the SBTS can not be determined in the field from stratal relationships, however, based on structural relationships between the carbonate thrust slices and the syn-tectonic flysch succession, as well as units of the allochthon, the SBTS is interpreted to have formed early in the deformation history of the allochthon, during the Taconic Orogeny.

The structural architecture of the SBTS is presented as an example of the style of deformation that occurred in the upper portion of the autochthonous succession during the emplacement history of the allochthon. It highlights the importance of in-sequence and out-of-sequence thrust propagation, which lead to significant shortening in the footwall of the allochthon. The development of fold-thrust structures near the basal portion of the allochthon is one of the chief mechanical processes by which the Bay of Islands ophiolite massif was emplaced. The Spruce Brook Thrust Stack also exemplifies how lithologically different panels from various structural levels of the allochthon and par-autochthon have been juxtaposed by a multi-stage process of thrust imbrication and duplexing.

The kinematics of the emplacement of large thrust sheets or nappes has been modeled by, among others, Platt (1986) and Morely (1988). In principal, the kinematic evolution of the orogenic thrust wedge is controlled by the mechanical behavior of the units in the wedge, most notably by the angle of taper of the wedge (Platt, 1986). To progress toward the foreland, an orogenic wedge must maintain a critical angle of taper defined by the angle of its frontal thrust ramp and by the angle of the top surface of the wedge. According to the model, the thrust nappe is transported on an array of foreland-propagating thrust splays. The array successively mobilizes and imbricates small structural slices in the footwall of the nappe, incrementally displacing the orogenic wedge toward its foreland each time a new imbricate thrust sheet is added to the base of the wedge. As a consequence, the wedge is thickened, increasing the angle of taper of the wedge. This causes the wedge to buttress against its now over-steepened frontal ramp. For the wedge to continue to move toward the foreland, its shape must be modified to regain the critical angle of taper. This may occur by shortcut faulting through the footwall ramp or by internal deformation of the thrust nappe, such as extensional collapse of the toe of the wedge. These processes modify the ramp angle and the top surface slope, respectively, thereby thinning the wedge and giving it a shallower angle of taper.

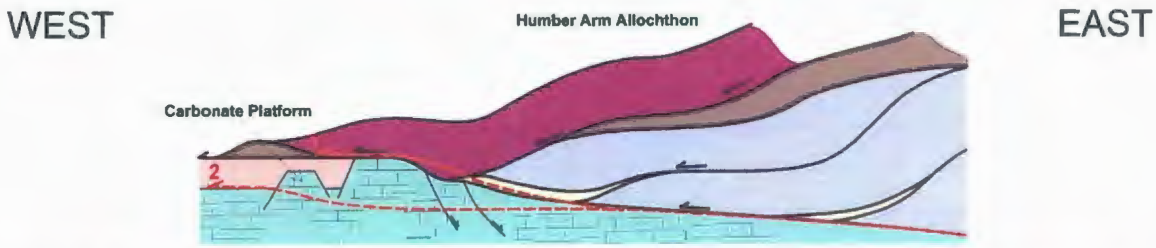
The emplacement of large thrust nappes by thickening and thinning of the orogenic wedge leads to an episodic, punctuated emplacement history. It can be described locally in terms of phases or pulses of deformation related to periods of in-sequence or out-of-sequence faulting. Generally, a thrust nappe thickens as it is transported by its foreland-propagating, in-sequence thrust array until such time that its critical taper becomes unstable, causing the nappe to stall. At this time, the locus of deformation shifts away from the thrust front toward the hinterland as contraction continues. The formation of major hinterland-propagating, out-of-sequence fault systems is therefore often coincident with periods of internal deformation in the thrust nappe that occurs in order to modify the shape of the wedge and thereby maintain its critical taper. As a consequence of hinterland-back-stepping, in-sequence faulting that resumes as a second phase of movement produces a new thrust array that truncates and re-imbricates the earlier thrust slices at the base of the nappe.

The basal thrust of an orogenic wedge is often characterized by a wide, complex fault zone, because ramp angles in the advancing thrust nappe are continually being modified by in-sequence and out-of sequence faulting. Strata within the fault zone are, therefore, typically polydeformed. They are often characterized as 'broken formation', because the original stratigraphic successions become dismembered as the strata are repeatedly folded and faulted. When structural mixing incorporates exotic material, the rocks within the fault zone may be described as 'tectonic mélange'. This is possible because out-of-sequence faults cut through both the transported thrust slices, which are part of the allochthon, and the par-autochthonous slices excised from the nearby footwall. Displacement on these faults can juxtapose units from the middle of the allochthon with units from the upper portion of the autochthon that were originally separated by hundreds of meters in the pre-deformation lithostratigraphy.

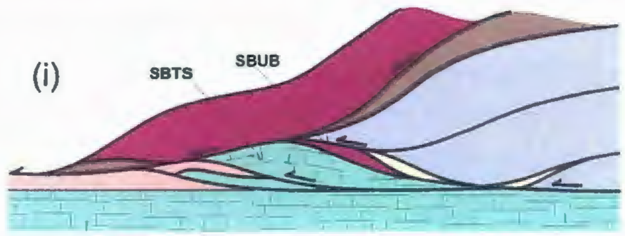
Faulting within thrust stacks is characterized by processes of footwall and hangingwall plucking. Footwall plucking occurs in foreland propagating thrust systems during progressive footwall collapse, when a thrust splays from the floor thrust then shortcuts through a footwall ramp and rejoins the main thrust surface. This mobilizes a structural panel of footwall rock and attaches it to the base of the overlying hangingwall. Hangingwall plucking occurs when a splay from the main thrust ramps up-section into the hangingwall, then cuts across the lower portion of the stack, assuming a flatter trajectory, and rejoins the main thrust. This splay would act as a hangingwall shortcut or 'smooth out' fault and would emplace footwall rocks over a small sliver of the hangingwall rock (Figure 5.1 A). Although hangingwall and footwall plucking typically occur as part of progressive in-sequence propagation of rejoining thrust splays, the processes may also occur during out-of-sequence faulting when a late fault crosscutting an imbricate stack, shortcuts by re-activating a pre-existing imbricating thrust.

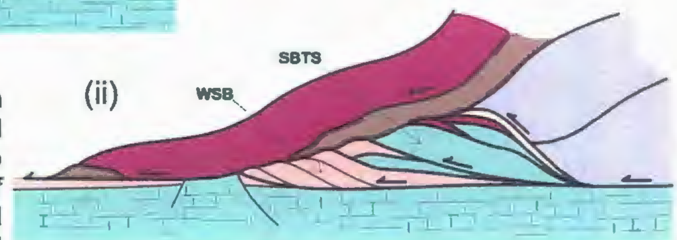
5.2.2 Formation of the Spruce Brook Thrust Stack

The carbonate thrust slices in the SBTS are interpreted as footwall plucked slivers cut from the outboard portion of the carbonate platform. The altered ultramafic and metamorphic rocks of the SBUB, on the other hand, were cut from the base of the overriding allochthon by hangingwall plucking. Figure 5.1 is a schematic drawing that illustrates the processes by which this may have occurred.

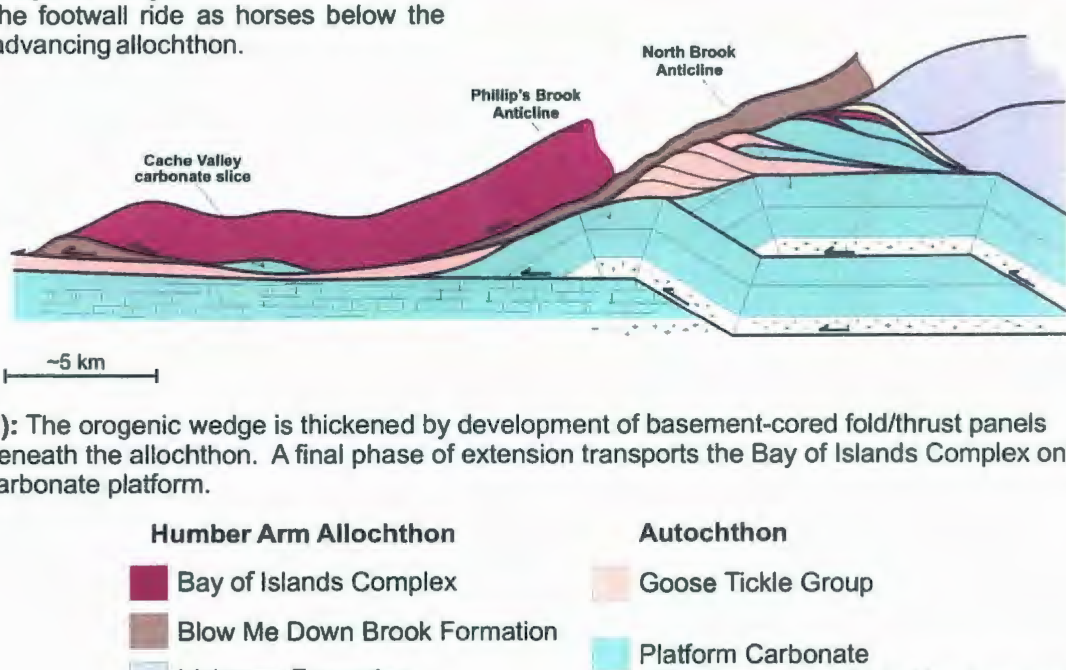


A): The Humber Arm Allochthon is buttressed by high-standing blocks on the carbonate platform. Dashed red lines show the trajectories of thrust splays 1 and 2 that form the SBUB and basal detachment of the SBTS, respectively.





B): Growth of the Humber Arm Supergroup antiformal stack and underpinning of the SBTS leads to westward transport of the Bay of Islands Complex by extensional collapse at the toe of the over thickened orogenic wedge. Thrust slices cut from the footwall ride as horses below the advancing allochthon.



C): The orogenic wedge is thickened by development of basement-cored fold/thrust panels beneath the allochthon. A final phase of extension transports the Bay of Islands Complex onto the carbonate platform.

Humber Arm Allochthon

- Bay of Islands Complex
- Blow Me Down Brook Formation
- Irishtown Formation
- Cooks Brook Formation

Autochthon

- Goose Tickle Group
- Platform Carbonate (St. George and Table Head groups)
- Crystalline Basement

Figure 5.1: Simplified schematic tectonic model for emplacement of the Bay of Islands ophiolite massif including development of the Spruce Brook Thrust Stack

During the Taconic Orogeny the Humber Arm Allochthon is interpreted to have developed as a foreland-tapering orogenic wedge with the Bay of Islands Complex riding near the toe of the wedge in advance of the telescoping continental rise prism (Figure 5.1 A). Telescoping in the more interior portion of the allochthon led to formation of a large antiformal stack in the lower structural slices composed of Humber Arm Supergroup. This portion of the allochthon is preserved in the map area by the Eastern Shale Belt including Irishtown and Cooks Brook formations. The footwall of the antiformal stack contains the carbonate platform and its indigenous flysch that was incised to form the carbonate thrust panels of the SBTS. As described in Chapter 4, schematic section restorations of the SBTS indicate that the thrust slices likely originated as high-standing blocks on the carbonate platform. This is indicated by the internal stratigraphic architecture of the slices and the stratigraphic levels at which the carbonate succession was incised. The basal detachment of the main carbonate thrust slice lies in strata of the Port au Port Group, suggesting that the carbonate strata carried in the SBTS must have had considerable structural relief above the basal detachment of the allochthon which lies above the Table Head Group (Figure 5.1 A).

The carbonate blocks acted as large footwall asperities and are interpreted to have had a significant effect on the geometry of the orogenic wedge. Firstly, the outboard edges of the carbonate blocks abruptly steepened the angle and increase the height of the frontal thrust ramp in the basal detachment of the allochthon. Secondly, the footwall asperities led to an increase in the top angle of the orogenic wedge by creating a localized buttressing effect that caused the growth of the trailing basal antiformal stack. The modified orogenic wedge geometry became unstable, leading to the extensional collapse of the toe of the wedge. The upper slices of the allochthon, including the Bay of Islands Complex and the underlying Blow-Me-Down Brook Formation subsequently slid onto the outboard portion of the carbonate platform (Figure 5.1 A).

The structural contact between the carbonate strata and serpentinite plus metamorphic rocks at Spruce Brook indicates that at the time of formation of the SBTS, the Bay of Islands Complex was in direct contact with the carbonate platform. This requires that at this locality in the Humber Arm Allochthon, the ophiolite complex was also directly overlying the Humber Arm Supergroup with omission of the duplex of Blow-Me-Down Brook Formation in between. It furthermore requires that carbonate in the footwall consisted of high-standing erosive blocks since no (or only very thin) flyschoid strata occur in the contact zone (Figure 5.1 A).

When the upper slices of the allochthon moved from the leading western flank of the antiformal stack onto the carbonate platform, the angle of taper of the orogenic wedge decreased to an angle less than that of the critical taper. The wedge thus began to thicken again as continued contraction caused the locus of deformation to shift toward the hinterland of the ophiolite massif. This phase of shortening was characterized by further amplification of the Humber Arm Supergroup antiformal stack and formation of a foreland-propagating array of thrust faults that cut 1) the basal portion of the allochthon, and 2) the carbonate platform footwall ramp (Figure 5.1 A). Movement on this thrust array caused 1) the stacking of the SBUB assemblage by hangingwall plucking of altered ultramafic rock as faults cut into the sole of the Bay of Islands Complex, and 2) the mobilization of the Spruce Brook carbonate thrust slices by short-cut faulting into the platform (Figure 5.1 B(i)).

The SBUB is interpreted as a thrust splay that formed out-of-sequence relative to the original basal detachment of the allochthon following a period of extensional collapse and hinterland back-stepping. It rose from the basal detachment of the allochthon at a level below the Irishtown Formation, cutting up-section into the Bay of Islands Complex and then rejoining the active basal detachment. The splay emplaces Irishtown and Cooks Brook formation strata over a thin hanging-wall plucked sliver of serpentinite and metamorphic aureole (Figure 5.1 A and B).

The excision of the main Spruce Brook carbonate thrust slice occurred by propagation of a low-angle fault into the steeply-dipping carbonate thrust ramp (Figure 5.1 A). The basal detachment of the carbonate block propagated in–sequence relative to the SBUB as the leading splay in a foreland-propagating array. It formed as a short-cut fault in response to the localized buttressing effect the frontal ramp exerted on the basal portion of the allochthon and is thought to be contemporaneous with thrust imbrication and F2 folding in the Humber Arm Supergroup antiformal stack. The structure of the antiformal stack is thought to be directly related to buttressing against the carbonate footwall ramp since the base of the ramp is preserved as the trailing edge of the SBTS that marks the western-most limit of Humber Arm Supergroup strata exposed in the study area.

The internal shortening of the SBTS continued until the critical taper of the orogenic wedge increased to a point of instability. During this time the SBTS was re-imbricated by a second phase of out-of-sequence thrusting that was characterized by thrust repetition of the SBUB assemblage and imbrication in the SBCFZ (Figure 5.1 B(ii)). The bulk shortening of the thrust stack adds significant structural relief to the hinterland of the Bay of Islands complex, renewing the critical taper angle of the orogenic wedge (Figure 5.1 B(ii)). Extensional collapse of the toe of the wedge after this phase of growth moved the Bay of Islands complex further west, where it again came into direct contact with a portion of the carbonate platform now preserved in the northern portion of the Phillip's Brook Anticline. As the upper slices of the allochthon moved west, the imbricate slices of the SBTS acted as a thin-skinned duplex carrying the allochthon on its roof thrust. The leading portion of the roof thrust dipped toward the foreland and because the allochthon moved by gravity-driven extension, no hangingwall plucking occurred at the leading edge of the SBTS, allowing the Western Shale Belt to be preserved (Figure 5.1 B(ii)).

At Philip's Brook, near the eastern base of the Lewis Hills, small structural slices of serpentinite, metamorphic rocks, and Humber Arm Supergroup are imbricated with Blow-Me-Down Brook and Fox Island River formations within a belt of shale assigned to the American Tickle Formation. Altered ultramafic rocks also occur in structural contact with limestone strata of the Catoche Formation (Knight and Boyce, 2000; Palmer et al., 2000). The structural relationships at Phillip's Brook are interpreted to represent a third phase of growth and collapse in the orogenic wedge that moved the Bay of Islands complex to its ultimate location (Figure 5.1 C). At this time the Bay of Islands Complex was again in direct structural contact with the carbonate platform. This is indicated by the excision of the Cache Valley carbonate slice from the platform by footwall plucking and its displacement to the west as part of the basal portion of the allochthon (Palmer et al, 2000). The increase in critical taper angle that drives the final phase of gravity sliding of the Bay of Islands Complex is interpreted to have been due to formation of the Phillip's Brook and North Brook anticlines which are deep-rooted, basement cored ramp-anticlines. These structures are interpreted to have formed in the Devonian by a post-Taconic phase of thick-skinned deformation (Cawood and Williams, 1988). The Phillip's Brook Anticline is interpreted to fold the basal detachment of the allochthon; the missing section of the upper part of the carbonate succession at the crest of the anticline is correlated to the section exposed in the Cache Valley sliver (Figure 5.1 C). This suggests that the anticline formed in the footwall of the Humber Arm Allochthon and its growth resulted in the continued west-ward movement of the Bay of Islands Complex after the top of the carbonate platform at Phillip's Brook was excised by the floor thrust of the allochthon.

5.3 Conclusions

Several important conclusions can be drawn from the detailed structural, stratigraphic and tectonic analysis of the carbonate occurrences in the Spruce Brook area.

1) The carbonate occurrences are allochthonous thrust slices cut from the platform and transported near the base of the Humber Arm Allochthon during the Taconic Orogeny. They can thus be likened to the carbonate occurrences at Cache Valley and Serpentine Lake, in contrast to the interpretation of Williams (1973) who interpreted the occurrences as an outlier of the par-autochthonous platform of the North Brook Anticline.

2) The carbonate occurrences are thrust-bounded, east-dipping imbricated structural panels occurring as a duplex lying within the foreland basin flysch succession and structurally below the Humber Arm Allochthon. This is contrary to the interpretations of Williams and Cawood (1989) and Knight and Boyce (2002) who described the carbonate

occurrences as klippe within a belt of undifferentiated tectonic mélange. These workers have proposed that the basal thrust of the carbonate occurrences is a low-angle detachment and that the adjacent shale terranes are erosional windows through an originally contiguous carbonate thrust sheet. This interpretation does reflect the overall thin-skinned nature of the carbonate thrust stack, however, it requires that stratigraphic boundaries in the carbonate succession be continuous across the shale terranes that separate the carbonate occurrences, and that the basal thrust of an individual carbonate occurrence dips toward the center of the occurrence. These criteria are not supported by the detailed mapping of this study; therefore, the carbonate occurrences cannot be classified as klippe. The interpretation of the Spruce Brook region as a tectonic mélange terrane is not supported by the detailed mapping of this study. The area clearly consists of mappable structural panels containing discrete stratigraphic successions that can be confidently assigned to known stratigraphic units.

3) The history of internal shortening in the SBTS is presented as an example of thickening in the Humber Arm Allochthon orogenic wedge (Platt, 1986). It illustrates how in-sequence and out-of-sequence fault arrays (Morely, 1988) imbricate and re-imbricate duplex horses at the base of the allochthon leading to an extreme amount of shortening over a relatively small portion of the footwall terrane. Although the thrust panels are thin and the displacements on individual thrusts are relatively small, the emplacement of the SBTS as a whole represents significant growth of the orogenic wedge and substantially contributed to the overall westward displacement of the allochthon. It can therefore be concluded that the fine-scale process of thrust imbrication at the base of the allochthon was an important mechanism of its emplacement.

4) The emplacement of Humber Arm Allochthon was punctuated by complex internal deformation of the allochthon that led to direct juxtaposition of the Bay of Islands ophiolite complex and the underlying platform carbonate succession. This structural relationship was attributed by Cawood (1988) to gravitational sliding of the ophiolite thrust sheet from the culmination of the assembled Humber Arm Allochthon after it was deformed and uplifted by development of basement- and platform-cored fold and thrust

structures in the Acadian Orogeny. This interpretation was based on structural relationships in the area east of the Lewis Hills near Phillip's Brook. While it accounts for the final emplacement of the ophiolite onto the carbonate platform, it does not explain structural contacts between slivers of ophiolitic rocks and carbonate in the hinterland area east of the exposed ophiolite complex. Structural relationships in the Spruce Brook area show that the ophiolite came into contact with the outboard carbonate platform during its emplacement in the Taconic. This suggests that gravitational sliding of the upper ophiolite thrust slices occurred periodically as one of the principal emplacement mechanisms of the allochthon.

5) The carbonate platform at the time of the Taconic Orogeny was characterized by localized high-standing, erosive carbonate blocks with intervening flysch basins. The carbonate blocks were controlled, in part, by a system of steeply dipping east-west trending faults. The presence of high standing blocks is indicated by the direct structural contact between platform carbonate with ultramafic and metamorphic rocks of the sole of the Bay of Islands Complex and also by the internal stratigraphic architecture of the restored Spruce Brook carbonate occurrences. The model presented by Quinn (1995) suggests that the carbonate platform was completely buried by flysch in the Taconic foreland. This however, could not have been everywhere the case since there was clearly structural interaction between the allochthon and the carbonate succession with no intervening flyschoid rocks, as documented by this study. The existence of major east-west trending high-angle faults on the Laurentian margin carbonate platform is inferred based on the presence of prominent east-west trending lateral thrust ramps beneath the SBTS. The ramps are interpreted to represent preserved fault blocks originally controlled by high-angle faults that trend east-west. The structural relief of the thrust ramps reflects the original stratigraphic separations on the high-angle faults, therefore, based on the amplitude of folds developed other the lateral ramps, it can be concluded that the early faults where significant structures on the carbonate platform when they were active prior to emplacement of the SBTS.

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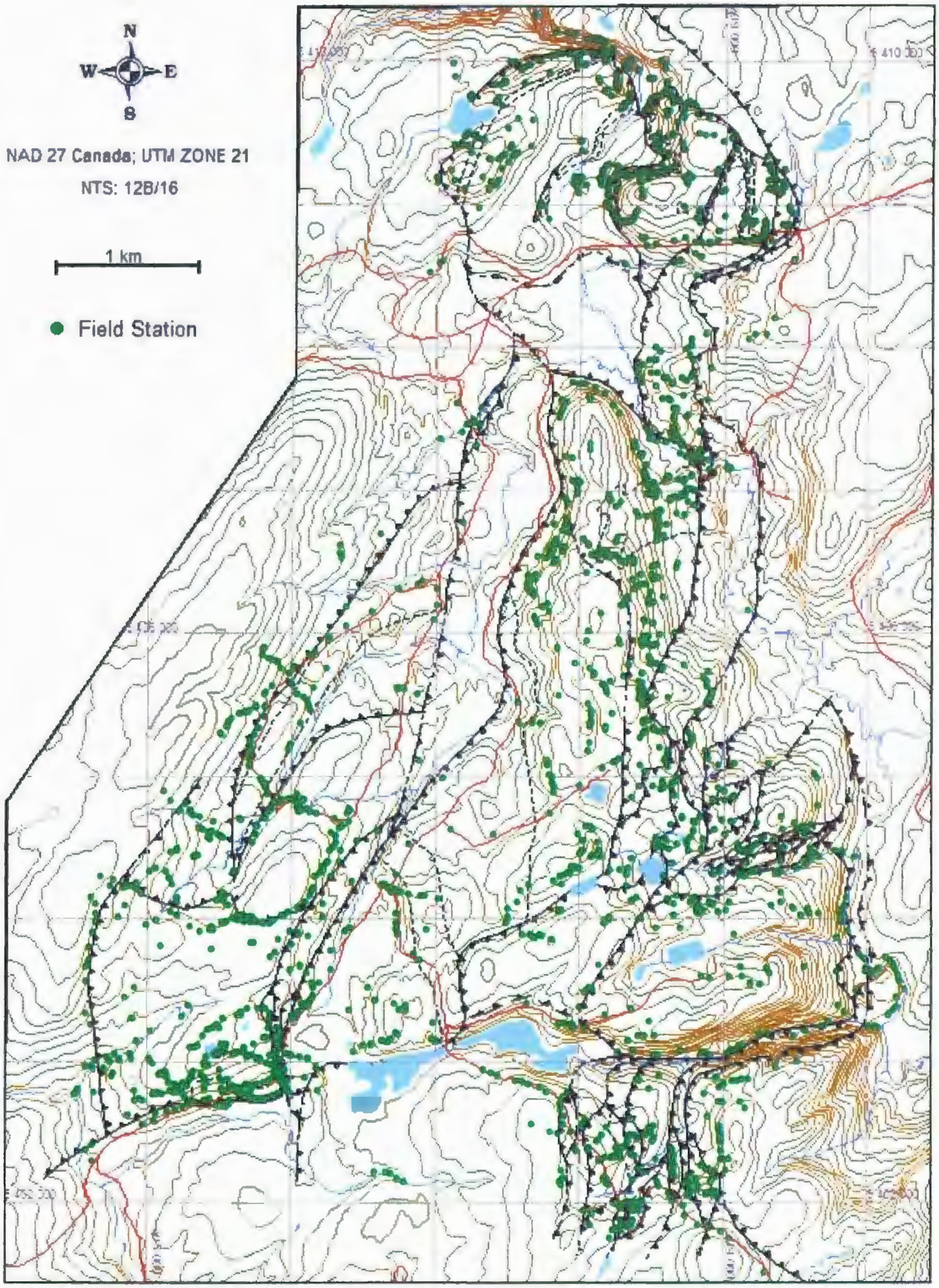
Appendix 1: List of Field Stations

Locations of field observation stations are presented on Map1 and are included in digital format on the enclosed Compact Disk as a Microsoft Excel 97-2003 spreadsheet and as a Mapinfo 7.5 table file. These files include UTM coordinates for field stations (NAD27, Zone 21), and their elevation in meters above sea level. The lithology observed at the station is also listed in the file using a code system presented in Table 1.

Table 1	
Lithology	**Code**
Aguathuna Fm.	AG
American Tickle Fm.	AT
Berry Head Fm.	BH
Boat Harbour Fm.	BHr
Catoche Fm.	Cat
Coasta Bay Mem.	CB
Cooks Brook Fm.	CBF
Irishtown Fm.	IT
St. George Gr.	SG
Spring Inlet Mem.	SIM
Table Cove Fm.	TC
Table Head Gr.	TH
Table Point Fm.	TP
Watts Bight Fm.	WB
Platform Carbonate	PLT
Serpentinite	SERP



Appendix 1

Map 1: Locations of field observation stations; Spruce Brook map area, Western Newfoundland.

Appendix 2: Conodont Analysis Results

For this study seven limestone samples collected in the Spruce Brook map area were processed for conodont analysis by Nowlan (2006) and are the subject of GSC Report No.006-GSN-2006. Of the seven samples, four proved barren of conodonts. The three samples that yielded conodonts are described below and their locations are given in Table 1 and shown on Map 1.

SRM05-425 (GSC loc. C-450623)

This sample is located in the upper course of Spruce Brook near the northern end of the SB2 thrust slice. The sampled was taken from a large isolated outcrop of massive, weakly stylolitic, dark grey limestone exposed in an otherwise marshy section of the brook.

The conodonts retrieved from this sample where generally poorly preserved fragments of simple cone elements, mostly of the cusp. They have been assigned to *Colaptoconus* sp. and *Parapanderodus* sp.

The *Colaptoconus* specimens have quadrate symmetry typical of *C. quadraplicatus*, a form that ranges throughout the Early Ordovician (Stairsian-Blackhillsian) and closely similar forms extend into the earliest Middle Ordovician.

Parapanderodus specimens are striated and show narrow posterior grooves indicative of species such as *P. gracilis, P. striatus and P. arcuatus*. These species range from Early Ordovician (Ibexian, Stairsian) to early Middle Ordovician (Whiterockian)

Based on the conodont assemblage, the sample could be of Early Ordovician (Ibexian, Stairsian) through early Middle Ordovician (Whiterockian).

SRM05-774 (GSC loc. C-450625)

This sample was collected from an outcrop of a small structural slice of platform carbonate within the Spruce Brook Ultramafic Belt Imbricate Zone.

This sample yielded two conodont fragments, one of which was of indeterminate species and the other was assigned to *Glyptoconus* sp. This specimen is classified as an *a* element after the terminology of Ji and Barns (1994) with pronounced inner anterolateral groove and a sharply rounded innner carina. These characteristics are indicative of *G. triplicatus*, but is more squat than typical representatives of that species. The sample is though to most likely be of Early Ordovician (Ibexian, Stairsian or younger) age, however and early Middle Ordovician age is possible.

SRM04-324 (GSC loc. C-450627)

This is a sample from a lens of dark grey limestone pebble to cobble conglomerate in black and brown, locally calcarious shale occurring on the eastern edge of the SB3 thrust slice.

The sample yielded two distinctly different sets of fragmentary conodont specimens, one tentitivly assigned to *Rossodus* and *Teridontus* and the second assigned to *Parapanderodus*. The first set are earliest Ordovician (Ibexian; Skullrockian) and the second set are Early Ordovician (Ibexian; Tulean to Blackshillsian) in age.

The mixed biostratagraphic origin of this sample is a result of the detrital nature of the specimen (Laboratory contamination was ruled out).

SRM05-878A (GSC loc. C-450624): Barren of conodonts

SRM05-771 (GSC loc. C-450626): Barren of conodonts

SRM05-483B (GSC loc. C-450628): Barren of conodonts

SRM05-082 (GSC loc. C-450629): Barren of conodonts

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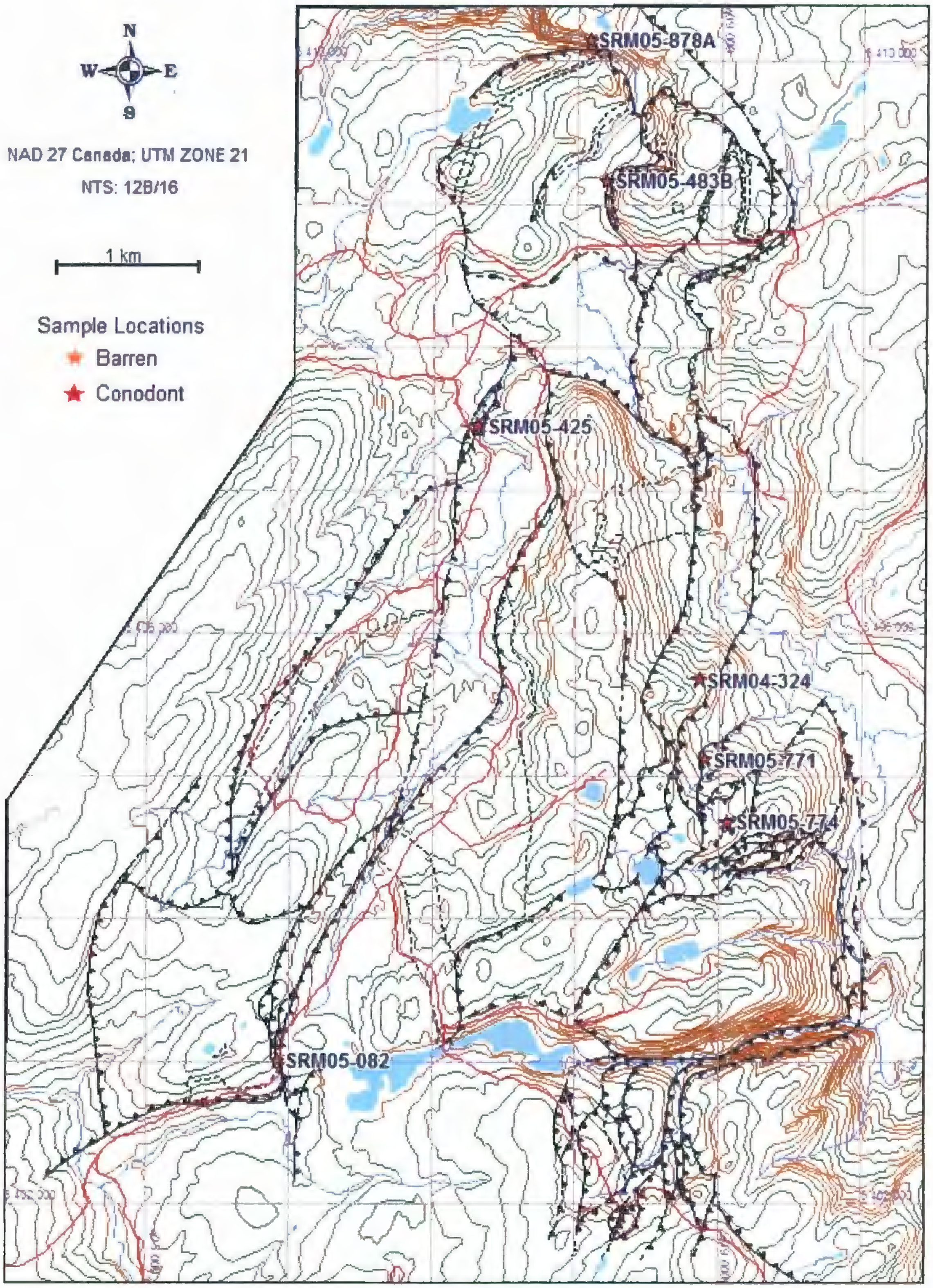
Ji, Z. and Barnes, C.R. 1994. Lower Ordovician conodonts of the St.George Group. Port of Port Peninsula, western Newfoundland, Canada, Palaeontographica Canadiana, no. 11 pp. 149.

Table 1: Conodont Samples SRM 2005								
SampleNo	Station	utmzone	Easting	Northing	Location	Lithology	Assumed Age	Conodont Age
SRM05-425	srm05-425	21	407,310	5,407,457	SB2 north	Catoche Fm.	Cassinan	Ibexian (Stairsian to Blackhillsian)
SRM05-878A	srm05-878	21	408,085	5,410,152	SB4 north	American Tickle Fm.	Llanvirn	unknown
SRM05-774	srm05-774	21	409,057	5,404,688	SBUBIZ	Aguathuna Fm.	Llanvirn	Ibexian, possibly Skullrockian
SRM05-771	srm05-771	21	408,903	5,405,123	SBUBIZ	Table Cove Fm.	Llanvirn	barren
SRM04-324	sm4b-324	21	408,863	5,405,687	SB3east	American Tickle Fm.	Llanvirn	Ibexian
SRM05-483B	srm05-483	21	408,205	5,409,171	SB4b	Costa Bay M.	Cassinan	barren
SRM05-082	srm05-082	21	405,917	5,403,006	SBCFZ	Table Point Fm.	Llanvirn	barren



Appendix 2

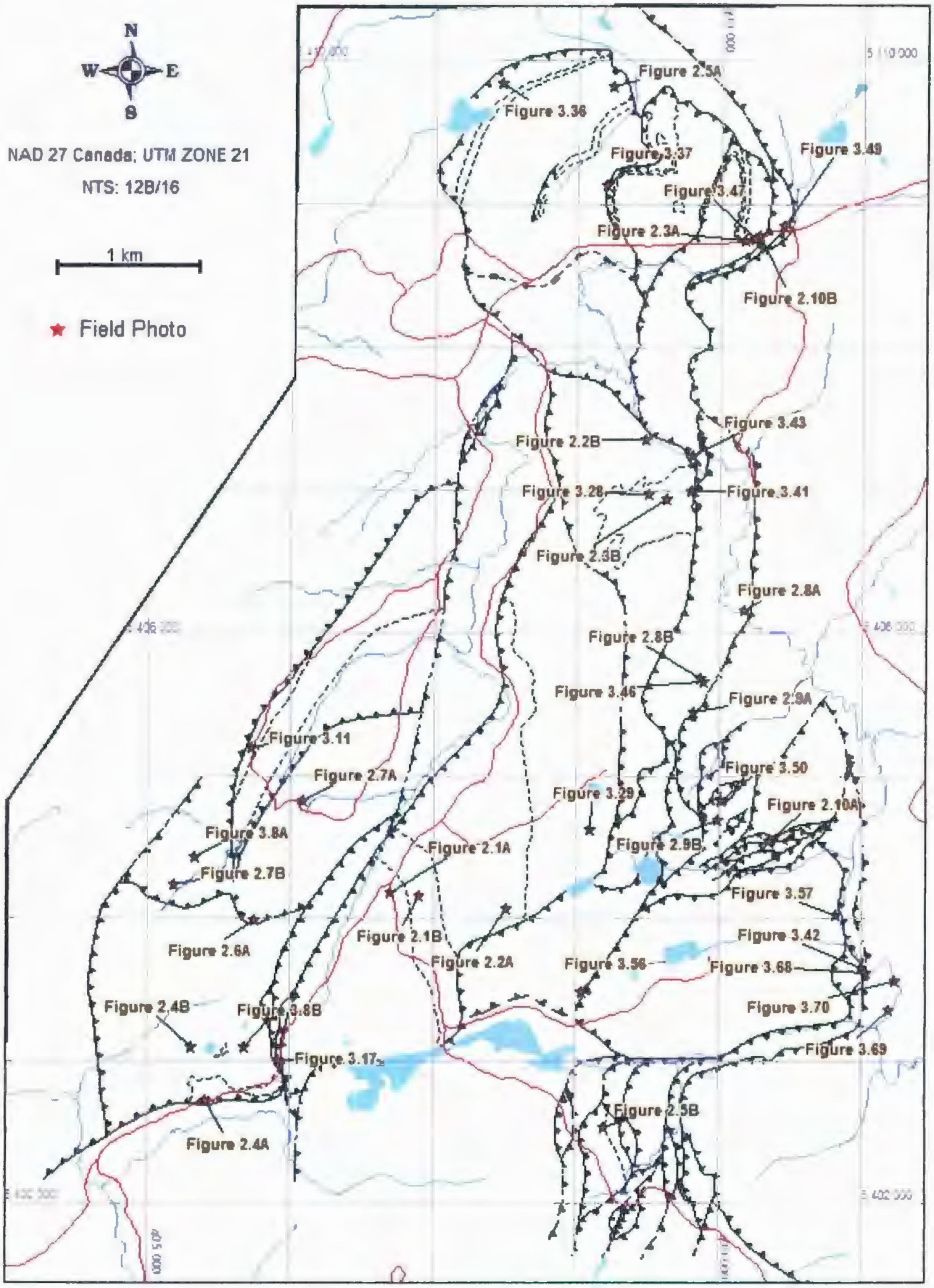
Map 1: Locations of samples for conodont analysis; Spruce Brook map area, Western Newfoundland.

Appendix 3: Location of Field Photographs

Locations of field photographs are listed in Tables 1 and 2 and are shown on Map 1. Photos are listed by figure number as presented in the text. Tables 1 and 2 include UTM coordinates (NAD27, Zone 21) for field stations corresponding to individual figures.

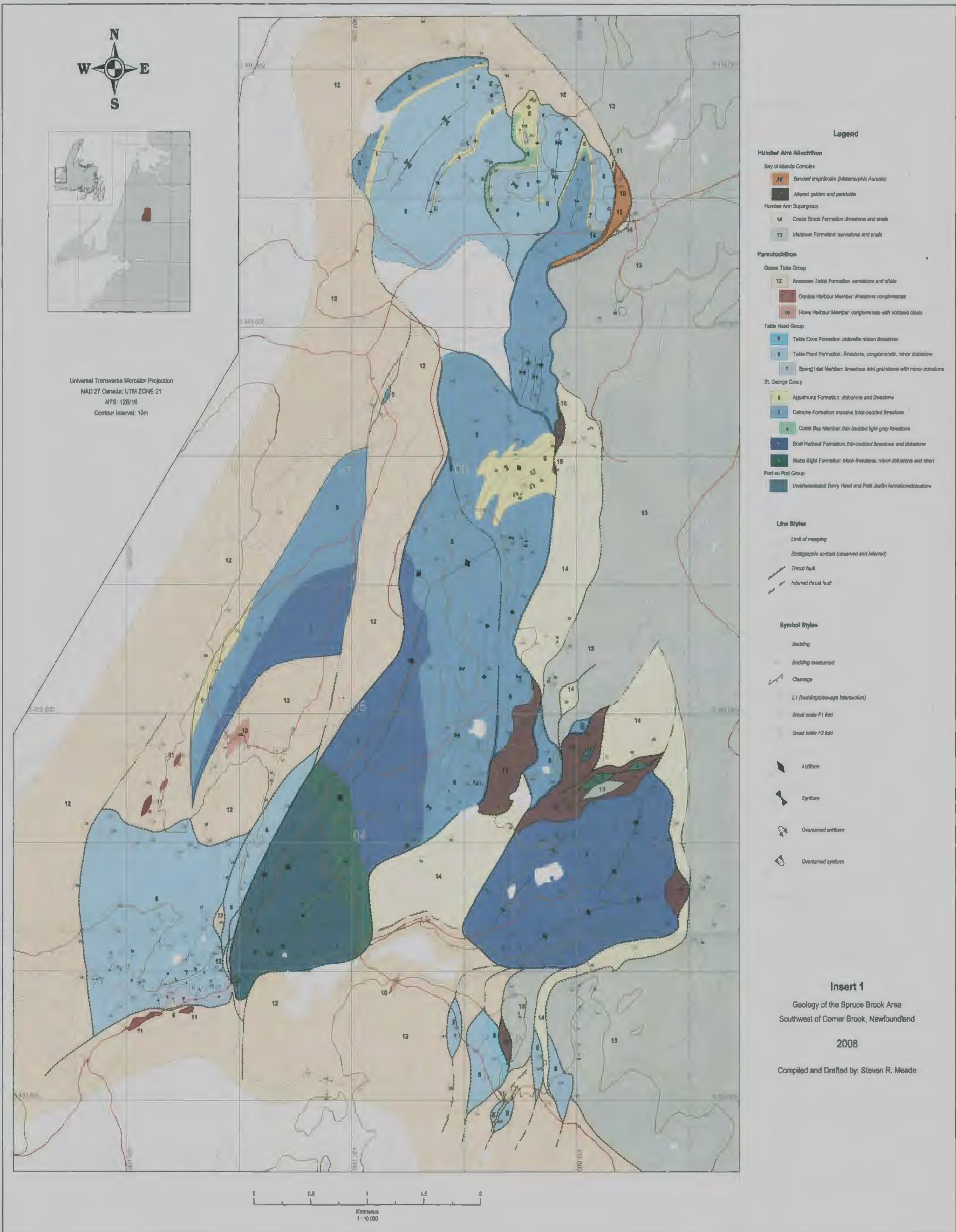
Table 1: Location of Field Photographs					
FIGURE	STATION	DATUM	UTMZONE	EASTING	NORTHING
Figure 2.1A	srm05-068	NAD27	21	406,701	5,404,188
Figure 2.1B	srm05-072	NAD27	21	406,904	5,404,161
Figure 2.2A	sm4b-253	NAD27	21	407,511	5,404,074
Figure 2.2B	sm4b-371	NAD27	21	408,487	5,407,362
Figure 2.3A	srm05-690	NAD27	21	409,172	5,408,753
Figure 2.3B	sm4b-337	NAD27	21	408,629	5,406,942
Figure 2.4A	srm05-099	NAD27	21	405,408	5,402,732
Figure 2.4B	srm05-189	NAD27	21	405,306	5,403,098
Figure 2.5A	sm4b-358	NAD27	21	408,242	5,409,822
Figure 2.5B	sm4e-1246	NAD27	21	408,199	5,402,532
Figure 2.6A	srm05-316	NAD27	21	405,750	5,403,991
Figure 2.6B	srm05-270	NAD27	21	409,542	5,400,914
Figure 2.7A	srm05-347	NAD27	21	406,088	5,404,833
Figure 2.7B	sm4e-1016	NAD27	21	405,180	5,404,244
Figure 2.8A	sm4b-381	NAD27	21	409,176	5,406,160
Figure 2.8B	sm4b-324	NAD27	21	408,863	5,405,687
Figure 2.9A	sm4b-330	NAD27	21	408,823	5,405,451
Figure 2.9B	sm4e-944	NAD27	21	408,987	5,404,696
Figure 2.10A	sm4c-431	NAD27	21	409,350	5,404,545
Figure 2.10B	srm05-019	NAD27	21	409,269	5,408,781

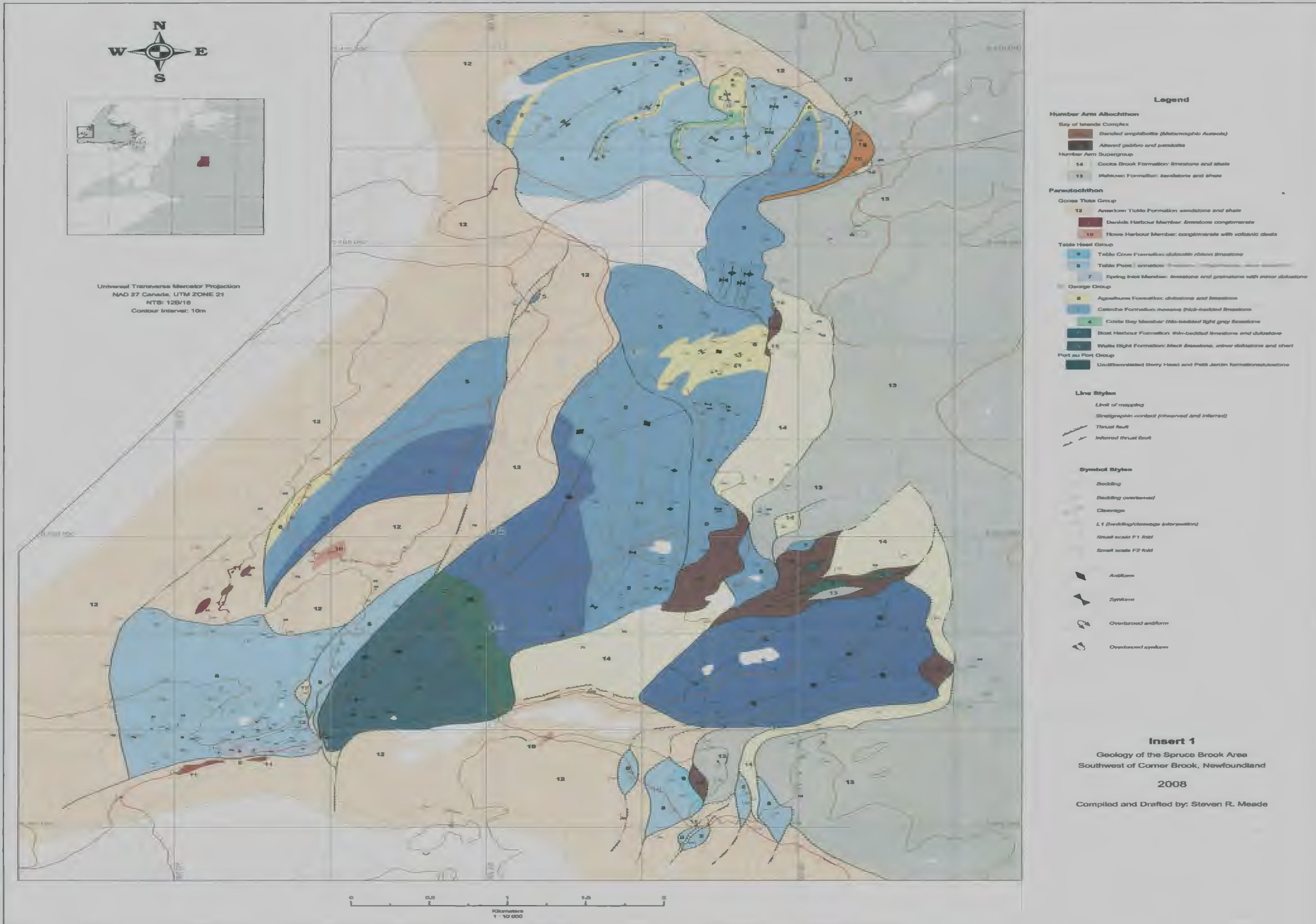
Table 2: Location of Field Photographs					
FIGURE	STATION	DATUM	UTMZONE	EASTING	NORTHING
Figure 3.8A	sm4b-394	NAD27	21	405,329	5,404,436
Figure 3.8B	srm05-089	NAD27	21	405,677	5,403,100
Figure 3.11	srm05-375	NAD27	21	405,722	5,405,198
Figure 3.17	srm05-082	NAD27	21	405,917	5,403,006
Figure 3.28	sm4b-348	NAD27	21	408,507	5,406,974
Figure 3.29	sm4b-267	NAD27	21	408,100	5,404,621
Figure 3.36	srm05-448	NAD27	21	407,462	5,409,847
Figure 3.37	srm05-484	NAD27	21	408,199	5,409,134
Figure 3.41	sm4b-342	NAD27	21	408,800	5,407,002
Figure 3.42	sm4c-464	NAD27	21	410,000	5,403,659
Figure 3.43	sm4b-376	NAD27	21	408,810	5,407,249
Figure 3.46	sm4b-325	NAD27	21	408,891	5,405,668
Figure 3.47	srm05-692	NAD27	21	409,242	5,408,762
Figure 3.49	sm4a-011	NAD27	21	409,443	5,408,847
Figure 3.50	sm4e-1068	NAD27	21	409,019	5,404,835
Figure 3.56	sm4e-907	NAD27	21	408,047	5,403,479
Figure 3.57	sm4c-460	NAD27	21	409,816	5,404,030
Figure 3.68	sm4c-476	NAD27	21	410,033	5,403,618
Figure 3.69	sm4c-489	NAD27	21	410,190	5,403,364
Figure 3.70	sm4c-485	NAD27	21	410,235	5,403,567



Appendix 3

Map 1: Locations of field photographs;
Spruce Brook map area, Western Newfoundland.


N
W
E
S
Universal Transverse Mercator Projection
NAD 27 Canada; UTM ZONE 21
NTS: 12B/16
Contour Interval: 10m
Legend
Humber Arm Allochthon
Bay of Islands Complex
16 Banded amphibolite (Metamorphic Aureole)
Altered gabbro and peridotite
Humber Arm Supergroup
14 Cooks Brook Formation: limestone and shale
13 Irishtown Formation: sandstone and shale
Parautochthon
Goose Tickle Group
12 American Tickle Formation: sandstone and shale
11 Daniels Harbour Member: limestone conglomerate
10 Howe Harbour Member: conglomerate with volcanic clasts
Table Head Group
9 Table Cove Formation: dolomitic ribbon limestone
8 Table Point Formation: limestone, conglomerate, minor dolostone
7 Spring Inlet Member: limestone and grainstone with minor dolostone
St. George Group
6 Aguathuna Formation: dolostone and limestone
5 Catoche Formation: massive thick-bedded limestone
4 Costa Bay Member: thin-bedded light grey limestone
Boat Harbour Formation: thin-bedded limestone and dolostone
Watts Bight Formation: black limestone, minor dolostone and chert
Port au Port Group
Undifferentiated Berry Head and Petit Jardin formations: dolostone
Line Styles
Limit of mapping
Stratigraphic contact (observed and inferred)
Thrust fault
Inferred thrust fault
Symbol Styles
Bedding
Bedding overturned
Cleavage
L1 (bedding/cleavage intersection)
Small scale F1 fold
Small scale F2 fold
Antiform
Synform
Overturned antiform
Overturned synform
0
0.5
1
1.5
2
Kilometers
1 : 10 000
Insert 1
Geology of the Spruce Brook Area
Southwest of Corner Brook, Newfoundland
2008
Compiled and Drafted by: Steven R. Meade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Universal Transverse Mercator Projection
NAD 27 Canada, UTM ZONE 21
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L1 (bedding/cleavage intersection)
Small scale F1 fold
Small scale F2 fold
Antiform
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Overturned antiform
Overturned synform
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0
0.5
1
1.5
2
Kilometers
1 : 10 000

Structure of the Spruce Brook Thrust Stack at the base of the Humber Arm Allochthon, Western Newfoundland Appalachians

SRM 2008

Appendix 1: List of Field Stations