STRATIGRAPHY, PETROGRAPHY, STRUCTURAL GEOLOGY, AND GEOCHEMISTRY OF THE HUMBER ARM ALLOCHTHON, NORTH ARM, BAY OF ISLANDS – SOUTH ARM, BONNE BAY, NEWFOUNDLAND

by

© Michael Kelly

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Abstract

The Humber Arm Allochthon in Western Newfoundland has long been recognized as a region where an ancient hydrocarbon system is thought to have developed. Nevertheless, and in spite of the many oil seeps along the western Newfoundland coast, no significant commercial discoveries have been made in this fold and thrust belt. The complex structural geology and stratigraphy may hinder any development of successful exploration plays. Recent mapping in other parts of the allochthon may be pointing towards other interpretations of the strata as possible targets for unconventional source rock reservoirs. To address at least part of this hypothesis, higher resolution mapping of parts of the Humber Arm Allochthon on and north of Bay of Islands is used as an indicator for another direction in exploring the petroleum system that developed across this area. In exploring the rocks north of the Bay of Islands new data will offer a better pattern for the distribution of the muddy, deep marine (source rock) strata in western Newfoundland.

The Blow Me Down Brook formation is the most expansive sedimentary unit in the map area. Regionally, this tightly cemented low grade metamorphic rock structurally overlies organic rich and petroliferous strata of the Cooks Brook, Middle Arm Point, and Lower Head formations. The overlying ophiolitic rocks are separated from the Blow Me Down Brook formation by a dismembered unit of Lower Head formation containing exotic clasts and herein considered mélange. Petrographic and geochemical analyses of the sandstone blocks in the mélange indicate both the Blow Me Down Brook and Lower Head formation lithologies dominate the mélange sandstones.

Significant differences in geochemistry indicate a more complicated pattern for origins and transport for volcanic strata that lies adjacent to and sometimes interbedded with. Mapping indicates identifiable deep marine outer shelf and slope strata are significantly folded before or during emplacement of the ophiolite suites. In this setting, tightly cemented Blow Me Down Brook formation sandstones may become the seal laying upon folded and fractured, muddy source rock reservoirs.

Acknowledgements

For this, I must first thank my parents, for without their support and encouragement I would have never been able to get through this project. My supervisors Dr. Elliott Burden and Dr. Joe MacQuaker offered guidance, advice, experience, and patience. They provided me with a tremendous opportunity for growth and development. Financial assistance was provided from Dr. Burden's Petroleum Exploration Enhancement Programme grant from the Government of Newfoundland and Labrador.

All my field assistants through the two summer mapping campaigns played an integral role in this project. For Jill Evans, Chris Corcoran, Mark Cooper, and Matt Scott, the days were long, the terrain treacherous. Their hard work, perseverance, and attitudes made many of the hardest times enjoyable. Some special thanks must be extended to a supporting cast of Memorial University faculty for their help. One special call out must go to Dr. George Jenner who went above and beyond when, on a personal camping trip he joined us for a day in the field. Dr. Toby Rivers, Dr. Graham Lane and Dr. Greg Dunning were particularly helpful with discussions, and suggestions on petrography and geochemistry.

During the first summer mapping, our camp was in the Trout River Camp site in Gros Morne National Park. The hospitality of the park staff deserves special mention, especially Kris Oravec for her constant help and insights into the regional geology, and to Cyril Abbott's accurate weather forecasts that kept us prepared.

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Chapter 1

Introduction

1.0 – Introduction

Hydrocarbon exploration in western Newfoundland has shown that the Cambro-Ordovician sedimentary rocks show potential as hydrocarbon sources and reservoirs. Natural oil and gas seeps and shows in boreholes have been reported for 200 years (Fleming, 1970; Government of Newfoundland and Labrador 1982; 1989). However, the stratigraphy, structural elements, and structural evolution that are key components of the hydrocarbon system on the west coast remain poorly understood.

Adjacent to, and beneath, siliciclastic strata of the Humber Arm Allochthon is one of the most prospective areas for the discovery of hydrocarbons in western Newfoundland. To the west of Corner Brook, and northward to Portland Creek, oil seeps have been recorded in coastal outcrops and at least one family of source rocks have been identified (Fowler et al., 1995). Recent drilling on the west coast has however highlighted the lack of understanding in the region's complex geology. This lack of understanding is a fundamental weakness developing successful of exploration strategies.

In recent years, targeted programs and sometimes site-specific studies (e.g. Gillis, 2006; Buchanan, 2004; van Staal et al., 1998; Waldron and van Staal, 2001; Waldron et al., 2002) are successfully teasing additional knowledge of the plate tectonic assembly of this area and its mineral and hydrocarbon potential (e.g. Cooper et al., 2001; Swinden and Dunsworth, 1995; van Staal, 2007).

As regional features are examined more closely, the study of the stratigraphy and structural character of the allochthonous sedimentary strata show western Newfoundland as a complex, polydeformed region characterized by several episodes of deformation (Waldron and Palmer, 2000; Waldron et al., 2002; Buchanan, 2004). This complexity often means that progressive and new insights into the local stratigraphy (e.g. Botsford, 1987; Quinn, 1992, 1995; Waldron and Palmer, 2000; Gillis, 2006) are not always easy to test, and not necessarily generally applied throughout the region. Given that many recent studies are focused upon the Bay of Islands region of western Newfoundland (Calon et al., 2000; Waldron, 2002; Buchanan, 2004; Gillis, 2006), the physical, sedimentary and structural characteristics of other regions of western Newfoundland are, likewise, equally important to our developing a better understand of the geology. Nowhere in this complex region can one easily separate local and regional events and processes. The structure, provenance and history of suturing offer important regional considerations that impact sediment composition, the movement of fluids, and the generation and distribution of hydrocarbons and mineral resources.

The igneous and sedimentary rocks of the Canadian Appalachians are recognized for a wide range of mineral deposit types, volcanogenic sulphide, gold, chromite, PGE, and industrial minerals (van Staal, 2007). The western Newfoundland Appalachians specifically have several MVT deposits located on Newfoundland's Northern Peninsula (Williams, 1995; van Staal, 2007). These same sedimentary strata also have hydrocarbon potential for both conventional and unconventional resources (Weaver and Macko, 1988; Fowler et al., 1995).

One of the most prospective areas for the discovery of hydrocarbons in western Newfoundland lies adjacent to, and beneath, strata of the Humber Arm Allochthon (Cooper et al., 2001; Weaver and Macko, 1988). Oil seeps, first reported in coastal areas nearly 200 years ago (Fowler et al., 1995), extend from the Port au Port Peninsula northward to Portland Creek. Regionally, at least one family of source rocks has been identified (Weaver and Macko, 1988; Fowler et al., 1995). Despite these positive showings, wells drilled in the region have produced very little in the way of results (Hicks, 2006). Exploration efforts may have been hampered by our limited understanding of this complicated stratigraphy, structure and diagenesis.

For reservoirs, traps, and seals, our basic lack of understanding is a fundamental weakness in developing successful exploration strategies in these rocks. It is clear that more detailed analyses are required to better appreciate the complex geology of western Newfoundland and therein improve statistical risk/odds for finding a commercial hydrocarbon resource.

This study focuses on siliciclastic and calcareous successions of the Humber Arm Allochthon and is developed as an effort to resolve additional details of the regional stratigraphy and structure. In this area, physical examination of strata remains an important process for learning. Offshore seismic data is very low quality, meaning physical measurement and analysis of adjacent onshore structures is an important step towards recognizing and characterizing correlative structures and strata in deeply buried reservoirs.

1.1 – <u>Purpose and Objectives</u>

For nearly 200 years petroleum exploration on the west coast of Newfoundland has provided evidence of an active hydrocarbon system in the region. Source rocks as well as potential reservoirs are identified in western Newfoundland (Weaver and Macko, 1988; Fowler, 1995; Williams et al., 1998). However, very little is known about the continuity of these rocks beneath the ophiolite and north of the Bay of Islands. This has important ramifications for determining the extent and distribution of any petroleum system that might exist along this coast. This is a significant exploration problem that can only be addressed by careful mapping and analysis of samples. An examination of the successions surrounding and underlying the ophiolitic massifs between the Bay of Islands and Bonne Bay is beneficial in understanding north-south stratigraphic continuity in the external Humber Zone.

To the north of the study area, between Parsons Pond and St. Paul's Inlet oil seeps have been observed since 1812 (Fleming, 1970; Government of Newfoundland and Labrador, 1989).

Both oil and natural gas occur in many of the boreholes in this region. Within the last 30 years studies have identified potential source rocks (Weaver and Macko, 1988; Fowler et al., 1995) and have determined the burial history and thermal maturation of the strata in the region (Nowlan and Barnes, 1987; Williams et al., 1988). Despite drilling and research, there have been no significant discoveries of hydrocarbons on the west coast. A major obstacle confronting any search for hydrocarbons is the complex structural geology of the region. There is an incomplete understanding of the geographic distribution of the strata, and particularly source and reservoir rock (Nowlan and Barnes, 1987; Burden pers. comm.).

The aim of this thesis is to improve our understanding of the stratigraphic and structural character of strata adjacent to the upper structural slices of the allochthon between North Arm of the Bay of Islands and South Arm of Bonne Bay. A detailed analysis will determine structural and stratigraphic relationships, and geochemistry of the various units within the study area. The analysis could indicate how the petroleum system south of the Bay of Islands extends northward towards Parson's Pond.

To achieve this aim, structural data, sandstone, mudstone and igneous rock samples will be collected throughout the study area (Figure 1.1). In particular, the inland areas that flank the upper allochthonous slices have hardly been studied in any detail. Mapping of these isolated areas should offer new insight into the distribution of the strata in the allochthon. A more detailed examination of generally inaccessible coastal sections may improve our understanding of the distribution of strata across this region. Within this study, special attention will be given to the extensive bodies of rock historically mapped as *mélange*. By attempting to delineate and to resolve certain patterns of sedimentological and geochemical characteristics it may be possible to correlate some *mélange* with other named strata of the allochthon.

Indeed, several geologic issues still exist despite many previous studies of the allochthon. The regional distribution of strata within the allochthon are not entirely resolved. In particular, there are extensive belts of apparently chaotic rocks that lie adjacent to and between structural slices of the allochthon. Early work differentiated belts of mélange along the eastern flanks of the ophiolitic massifs north and south of the Bay of Islands (Godfrey 1982). That distribution pattern was changed in later regional maps (Williams and Cawood, 1989), where the Blow Me Down Brook formation and its equivalents are directly juxtaposed with ophiolitic rocks at the eastern flanks of the North Arm and Table Mountain massifs. Williams and Cawood (1989) also classified broad belts of chaotic rock as *mélange* throughout the allochthon. This interpretation has been challenged in the southern Bay of Islands (Buchanan, 2004; Calon et al., 2002; Burden et al., 2006). The broad belts of mélange have been divided into imbricate slices of several lithostratigraphic units of the Humber Arm Allochthon. The confusion and recent reassessment relating to chaotic strata south of the Bay of Islands gives good reason to study the strata north of the Bay of Islands and South of Bonne Bay.

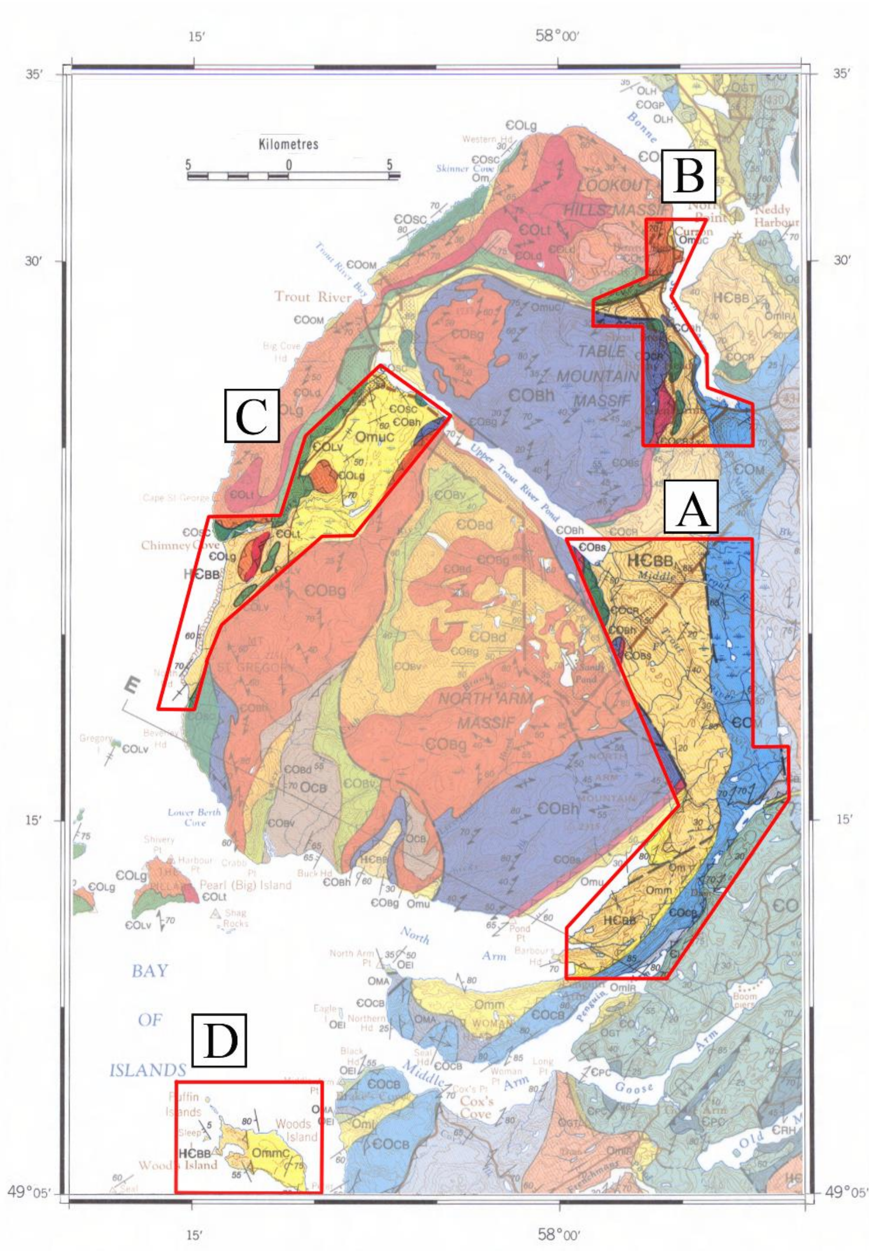


Figure 1.1: Regional geology north of the Bay of Islands (from Williams and Cawood, 1989). Areas studied are within the labeled boxes. A: North Arm-Trout River Pond, B: South Arm of Bonne Bay, C: Chimney Cove, and D: Woods Island. Map scale 1:250 000.

Aside from *mélange*, the stratigraphic distribution of siliciclastic, and volcanic lithologies will be examined. Petrography and geochemistry will be applied to siliciclastic and igneous rocks to correctly determine their stratigraphic context. An improved stratigraphy will provide better insight into possibilities for hydrocarbon exploration in the region.

1.2 – The Study Area – Geography and Access

A regional mapping exercise is the basis for the study reported herein. Some lithologies exposed in this area are equivalent to source rocks and coastal exposures seeping oil into the Gulf of St. Lawrence and to the north at Parsons Pond. The presence of these rocks suggests some strata beneath the igneous allochthon south of Bonne Bay may yet have some prospectivity for hydrocarbon occurrence.

Specifically, the largest part of the study area is located between the North Arm of Bay of Islands and the South Arm of Bonne Bay (A in Figure 1.1) (NTS sheets: 12 G/01, 12G/08, 12 G/09, 12 H/5, 12 H/4). Due to the remoteness of the area, mapping proceeded in steps across sub-regions. In spite of best efforts some parts of this region remained inaccessible within the time frame of this study. The longest continuous mapped part of the region runs along the eastern flank of the North Arm Massif from the North Arm of the Bay of Islands to Trout River Pond (Figure 1.1). North of that region is the South Arm of Bonne Bay region (B in Figure 1.1), a smaller more accessible area was mapped from Glenburnie to Curzon Village. In the west a valley was mapped from the shores of Trout River Small Pond to the southern tip of the Chimney Cove coastline (Figure 1.1, C). Finally, this study also includes data from Woods Island, which was examined as a connecting point linking the north and south shores of the Bay of Islands (Figure 1.1, D). In total, these localities cover an area approximately 300 km^2.

Inasmuch as earlier studies focused upon coastal exposures, the majority of the work effort for this compilation was done inland, away from areas that have been visited by others and where topographic relief, bogs and forests present a challenge for describing and interpreting complex tectonic structures. That said, some coastal exposures do provide opportunities to extend local structural and stratigraphic data inland onto bog and forest covered outcrops. In contrast to coastal exposures, the inland terrain contains highly varied topographic relief and presenting hundreds of metres of elevation change across traverses. For some of these traverses, this means we can resolve structures in greater detail and suggest improvements for drawing boundaries for thrusts and strata.

Access to field camps and the beginning of many traverses was by 4WD vehicle on old and abandoned logging roads and by boat along isolated stretches of coastline and on large islands. Some longer traverses and overnight “fly” camps were also conducted as treks far away from old roads and coastal landings.

The large hills, dense forests, and extensive boggy lowlands make a harsh terrain for locating and mapping strata. The vegetation on the higher ground is very thick old growth and second growth boreal forest with no shortage of slippery, moss-covered deadfall. On the top of the sedimentary rock plateaus the vegetation may open into stunted spruce and fir trees, tuckamore and shrubs. In contrast, the lowland areas are flat and boggy wetlands, generally difficult to cross and with few or no outcrops. Along the coastline and on beaches away from the large sea cliffs, the terrain is passable but chaotic. Slippery, wave-rounded cobbles and boulders form the beaches.

General access to the southern portion of the study area (region A) comes from an extensive network of used and abandoned logging roads joining the North Shore Highway northeast of

Corner Brook. Goose Arm Road, the main logging road from the highway, provides 2WD and 4WD access to the southern part of the study area and onward to the boundary of Gros Morne National Park (Figure 1.1). Other smaller logging roads provide particularly good access to the North Arm-Kennedy Lake area.

The South Arm of Bonne Bay (region B, Figure 1.1) can be accessed from the Bonne Bay Road off Route 430. Isolated coastal areas, such as Woods Island and the Chimney Cove-North Head coastline (C and D) were visited by boat. A strong surge can make coastal landings and extractions difficult and calm weather is required. In addition, and for a specific part of map region A, the eastern end of Trout River Pond was also accessed by boat. The beach in that locality provides an exceptional location to set up a camp and landing is a not normally an issue on the relatively calm pond. At least part of the eastern flank of the North Arm Massif (area A) is far from any shoreline landings, logging roads or trails. It is only accessible by heavy slogging on animal trails or with a helicopter.

Beyond the coasts, outcrop over much of the study area is sparse and oftentimes difficult to see through the thick cover of vegetation. On the highland plateaus the best exposures lie on the tops of ridges and on cliffs on the sides of steep hills. Elsewhere, the network of woods roads in the backcountry, and municipal roads in the Bonne Bay area, provide excellent road cuts to examine. Outcrops are generally abundant and well exposed in rivers and streams. Along some rivers there are rocky waterfalls from ten to a hundred metres high. Overall, the best exposures are found along the coast where sea cliffs that range in height from around 2 m to perhaps as many as 100 m present continuous, well-exposed sections.

1.3 – Previous Work in Western Newfoundland

1.3.1 – Early Work (1860-1960)

Geologic exploration has been ongoing in western Newfoundland since before the mid- 19th century. Some of the earliest work, and namely reconnaissance surveys by Alexander Murray and J.P. Howley, led to the first regional geology maps of Newfoundland (Williams, 1995). During this time and without the benefit of proper biostratigraphy, the sedimentary successions of Newfoundland were thought to be Silurian age.

During the early 20th century Schuchert and Dunbar (1934) measured stratigraphy, and collected fossils from the strata of western Newfoundland. They made significant progress in establishing a stratigraphic framework for the region. Mudstone, carbonate, and sandstone successions were paleontologically grouped into seven series. Fossil assemblages provided depositional ages that align with current models. Graptolites collected near Curling confirmed the maximum age of their “Humber Arm Series” as Middle Ordovician. Schuchert and Dunbar (1934) described the western Newfoundland geology as a geosynclinal trough. Without today’s concepts of tectonism and orogenesis, they interpreted the igneous rocks of western Newfoundland as Middle Ordovician intrusions.

In 1936 the term Bay of Islands Igneous Complex was introduced by Cooper to describe the igneous rocks in the region of the Bay of Islands. Cooper (1936) and later Smith (1958) recognized that these rocks were thrust over the sedimentary rocks. However, both interpreted the igneous rocks of the complex to have originally been generated from intrusive activity and later transported by high angle reverse faulting.

Through the late 1940's until the early 1960's studies in western Newfoundland focused on understanding the stratigraphy. The efforts by Troelson (1947), Walthier (1949), Weitz (1953), and Lilly (1963) produced local successions that were not entirely correlative across the region. By that time the depositional ages for the strata were better controlled with new paleontological data. For example, Kindle and Whittington (1958) collected trilobite and graptolite assemblages and determined deposition of the Cow Head Group ranged from the Late Cambrian to Middle Ordovician (Williams, 1995).

1.3.2 – Work in the Era of Plate Tectonic Theory (1960's-present)

In the early sixties the long-standing ideas on the evolution of the Humber Arm Series were being challenged. Rodgers and Neale (1963) argued that the sedimentary successions of the deep-water facies, as well as the igneous rocks of the Bay of Islands Igneous Complex were transported as allochthonous terrains. The view was in opposition to the contemporary idea that the successions were deposited conformably on the platform.

By the mid to late 1960's new, revolutionary ideas were being applied in the field of Earth Science, and consequentially to our understanding of western Newfoundland geology. Theories of ocean cycles (Wilson, 1966) and plate tectonics (Dewey, 1969) were directly tied to the geologic history of western Newfoundland (Dewey and Bird, 1971). The plate tectonics paradigm encouraged revised modeling for the regional history of stratigraphy and orogenesis. The geosyncline model (Cooper, 1936; Smith, 1958) was replaced with a more dynamic tectonic model. This new understanding of the strata and structure of western Newfoundland led to a significantly revised interpretation of the origins for the Bay of Islands Igneous Complex. Stevens (1970) and Dewey and Bird (1971) determined the igneous complex was in fact a fragment of oceanic lithosphere. With a new model to test, the stratigraphy of the entire region was open for re-examination. In 1970 Stevens published a revised stratigraphy for the allochthonous sedimentary rocks of Humber Arm. He divided the strata into five formations and united under the title Curling Group. The formations, Summerside, Irishtown, Cooks Brook, Middle Arm Point, and Blow Me Down Brook, are named after locations where the rock suites were first described. The term Humber Arm Supergroup was used to encompass all of the transported igneous and sedimentary tectonic slices of the Humber Arm Allochthon.

In recent years, studies of the Humber Arm Allochthon have refined the biostratigraphic framework. With trilobite and graptolite assemblages as markers, Botsford (1988) further divided the stratigraphy of the Curling and Northern Head groups. His revised stratigraphy constrained the Summerside and Irishtown Formations to the early Cambrian and grouped the Cook's Brook and Middle Arm Point formations within the Northern Head Group.

Quinn's (1985) petrographic study concluded the Blow Me Down Brook formation and its equivalents were continentally derived and not Ordovician flysch as previously suspected. The discovery of the Early Cambrian trace fossil *Oldhamia* in the Blow Me Down Brook formation, confirmed the unit is indeed a much older succession and not Ordovician strata (Lindholm and Casey, 1989). Quinn (1992) later studied successions of Ordovician flysch deposited across the allochthon. Given the results of her petrographic and geochemical analyses she was able to divide the flysch and separate Goose Tickle Group rocks from the Lower Head formation. Another flysch, the Eagle Island formation was correlated with the Arenig Lower Head formation.

Within the last ten years, efforts to better understand the geology of the allochthon have continued. In an attempt to define type sections for the Blow Me Down Brook formation and the Curling Group Waldron and Palmer (2000) measured several stratigraphic sections in the Bay of

Islands. However, given the pervasive deformation of the rocks, as well as a lack of exposure, type sections could not be defined. Elsewhere in the area, Burden et al. (2001), Calon et al. (2002), and Buchanan (2004) have shown that extensive belts of chaotic sedimentary rocks loosely interpreted to be *mélange* (Williams and Cawood, 1989) apparently have an internal stratigraphy and can be differentiated in the western part of the allochthon. Expanding upon this idea, Buchanan (2004) completed an extensive survey along a portion of the southern shore of the Bay of Islands. In addition to providing a detailed analysis of the structural architecture Buchanan also differentiated extensive exposures of the *mélange*. He determined the "Companion Mélange" (Williams and Cawood, 1989) near Frenchman's Cove and Woods Island was a fault-bounded array of dismembered varieties of Irishtown Formation, Northern Head Group, and Eagle Island Formation. In 2006, Gillis reported an informal stratigraphy for the Blow Me Down Brook formation. That stratigraphy was based on a detailed study involving the measurement of many stratigraphic sections throughout the western part of the allochthon. Gillis (2006) interpreted the Blow Me Down Brook formation strata as submarine fan deposits with a continental provenance.

Chapter 2

Background Material – Geology and Geochemistry

2.1– Regional Geologic Setting– The Appalachian-Caledonian Orogen

The Appalachian Orogen, along North America's eastern seaboard, is a 3000 km long belt of Paleozoic deformation linked with the mountain chains of northern Europe and Greenland (Williams, 1984, 1995). In eastern Canada, the Appalachians extend from the Maritimes and Quebec's Gaspe region, across the Gulf of St Lawrence and onto the island of Newfoundland (Figure 2.1). With an extensive glacially carved and irregular coastline, Newfoundland offers many of the best exposures of the Paleozoic strata seen in eastern North America (Williams, 1995). The western portion of the island delineates the deformed structural front of the Appalachian Orogeny with the essentially flat-lying Paleozoic carbonate platform (Williams, 1995). Farther east, distinctive, structurally complex, sedimentary, igneous and metamorphic terranes track the history of the assembly of this mountain system. Now, with more than a century of research reported, the rocks of western Newfoundland have contributed significantly to our collective understanding of orogenesis and plate tectonic theory (e.g. Stevens, 1965; Williams 1975, 1995).

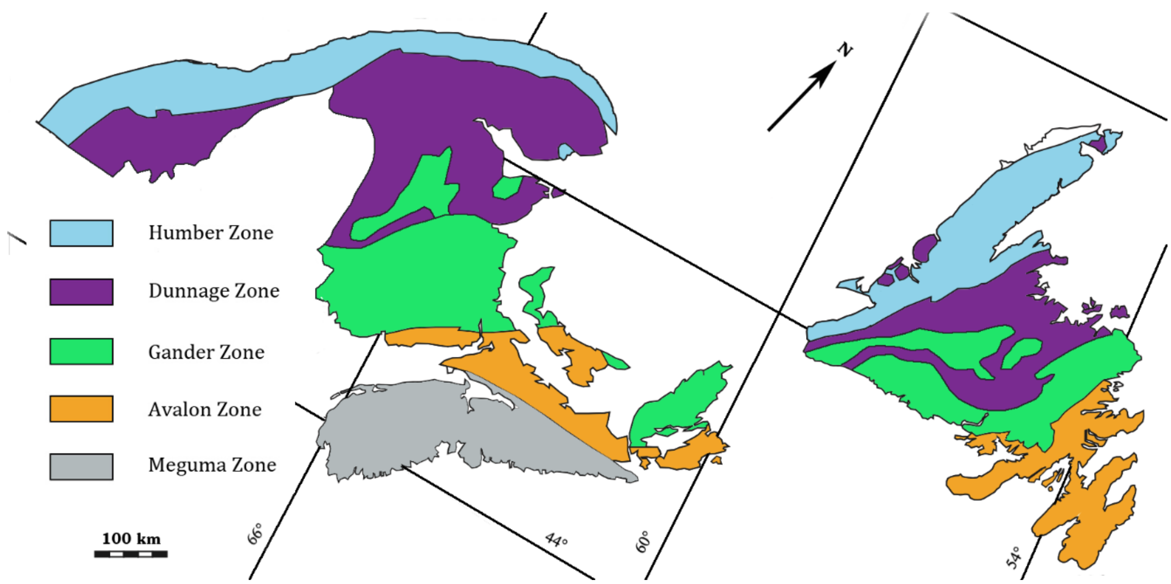


Figure 2.1: Simplified tectonostratigraphic divisions of the eastern Canadian Appalachians (after Williams, 1995 and van Staal, 2007).

According to plate tectonic models, between the Cambrian and the Permian periods, two large paleocontinents, Laurentia and Gondwana collided with each other in complex collision involving multiple ribbon-shaped terranes (van Staal, 2007). The union between the two paleocontinents resulted in the closing of the contemporary Iapetus Ocean and created the supercontinent Pangea, the suture between them is an extensive orogenic belt, termed the Appalachian-Caledonian Orogeny (Dewey, 1969; Williams, 1995). It spans modern day North America, Greenland, Western Europe, and northwest Africa (Williams, 1984; Williams, 1995). Specifically, the modern mountain belt in North America is termed the Appalachian Mountains. The European counterpart is the Caledonian Mountains. The Appalachian and Caledonian orogens, once continuous, became separated by the opening of the Atlantic Ocean in the Mesozoic (Wilson, 1966).

The geologic history of the Appalachian orogen begins in the late Precambrian with the breakup of a paleocontinental landmass and the birth of the Iapetus Ocean (Wilson, 1966; Stukas and Reynolds, 1974). The rift basins created accommodation space for the accumulation of continental derived siliciclastic sediment, coincident with the formation of rift-related volcanic rocks (Williams, 1995). Following this break up, new paleocontinents, principally Laurentia and Gondwana drifted away from each other, divided by the Iapetus Ocean (Wilson, 1966; Cawood et al., 2001). During the Cambrian, the southern margin of Laurentia developed as a passive margin upon which a thick carbonate succession formed a broad platform (Knight et al., 1995). At the onset of Appalachian orogenesis in the early Ordovician, the passive margin transitioned to an active margin (Church and Stevens, 1971; van Staal, 2007).

The Appalachian Orogeny was complex. It involved multiple collisions and spanned the Ordovician, Silurian, Devonian, and Carboniferous periods (van Staal, 2007). Contemporaneous orogenic events can be correlated in North America (Appalachian) and Western Europe (Caledonian). In North America the individual orogenic events of the Appalachians are termed the Taconic Orogeny (500-450 Ma), the Penobscot Orogeny (ca. 490-481 Ma), the Salinic Orogeny (445-425 Ma), the Acadian Orogeny (423-385 Ma), the Neoacadian Orogeny (366-350 Ma), Late Pennsylvanian Orogeny (300-290 Ma), and the Alleghenian Orogeny (280-260 Ma) (Robinson et al., 1998; van Staal, 2007).

The geologic result of Appalachian orogenisis in eastern Canada is the juxtaposition of 5 distinct tectonostratigraphic terranes born of continental margins, island arcs, oceanic floor and ribbon shaped micro-continents (Figure 2.1; Williams 1979, 1995; van Staal, 2007). They are named the Humber Zone, Dunnage Zone, Gander Zone, Avalon Zone, and the Meguma zone (Williams, 1995; Figure 2.1). The Humber Zone is the westernmost tectonostratigraphic terrane in the eastern Canadian Appalachians. Allochthonous successions within the zone are the subject of the research presented herein.

2.2 – The Appalachian Orogen in Newfoundland

On the eastern Canadian island of Newfoundland, the Appalachian Orogeny is expressed as 4 distinct tectonostratigraphic terranes separated by tectonic boundaries (Williams, 1995; Figure 2.1). They include the all the terranes delineated in the eastern Canadian Appalachians with the exception of the Meguma Zone (Figure 2.2).

2.2.1 – The Humber Zone

The westernmost tectonic division of the Appalachian Orogen in Newfoundland is termed the Humber Zone. The western structural boundary is the Appalachian structural front. The eastern boundary is a steep structural belt, delineated by ophiolites, called the Baie Verte-Brompton Line (Williams and St. Julien, 1982; Williams, 1995; van Staal, 2007).

Geologically, the zone consists of Late Precambrian-Ordovician siliciclastic and calcareous sedimentary rocks deposited on a Grenville basement (Williams, 1995; Erdmer and Williams, 1995; van Staal, 2007). It preserves the development and transition of a passive margin to active margin and foreland basin. The passive margin is the product of a Neoproterozoic phase of rifting that opened the Iapetus Ocean (Williams, 1979; Williams and Hiscott, 1987; Lindholm and Casey, 1989; van Staal, 2007). The passive margin sedimentary successions of the Humber Zone are deposited on a crystalline basement complex. As the Taconic Orogeny occurred, the margin was converted to an active setting and by the mid Ordovician it transitioned into a foreland basin. The orogeny emplaced an imbricate stack of Neoproterozoic rift-related volcanic rocks, late Precambrian-early Ordovician siliciclastic and calcareous continental shelf, slope, and related sedimentary successions (Knight et al., 1995), and late Cambrian island arc related mafic and ultramafic rocks onto the continental margin (Williams, 1995; van Staal, 2007). The ophiolite complexes of the allochthon represent ocean floor in a suprasubduction zone and are related to the adjacent Dunnage Zone (Waldron and Stockmal 1994; Williams, 1995).

The Humber Zone is further subdivided into the Humber Zone External and Humber Zone Internal based on metamorphic grade and varying intensities of deformation (Figure 2.2; Williams, 1995). The Humber Zone Internal is the inboard division of the Humber Zone, east of its boundary, the Cabot Fault. The rocks of the internal zone are equivalent to the strata of the Humber Zone External. However, unlike the rocks of the Humber Zone External they are intensely deformed and metamorphosed (Hibbard et al., 1995). The Humber Zone External is the outboard division of the Humber Zone, west of the Cabot Fault (Figure 2.2). It hosts mildly deformed strata of an ancient passive margin and Taconic allochthons. This study focuses on an external Humber Zone allochthon termed the Humber Arm Allochthon.

2.2.2 – The Dunnage Zone

Immediately east of the Humber Zone lies the Dunnage Zone. It represents Cambro-Ordovician arc terranes related to several subduction zones that formed in the Iapetus Ocean (van Staal et al., 1998; van Staal, 2007). It is comprised of arc volcanics and basin margin sediments that overlie an oceanic crust (Williams, 1979; Williams et al., 1988; Cawood et al., 1988). The zone has been further divided into two subzones termed the Notre Dame and Exploits subzones. The classification is based on contrasting paleomagnetic data, fossil content, and other geology (Williams et al., 1988, 1995; van Staal, 2007). The subdivisions divide two accreted terranes of different affinities. The Notre Dame subzone was formed in the Laurentian realm and the Exploits subzone was formed in the Gondwanan realm (van Staal, 2007).

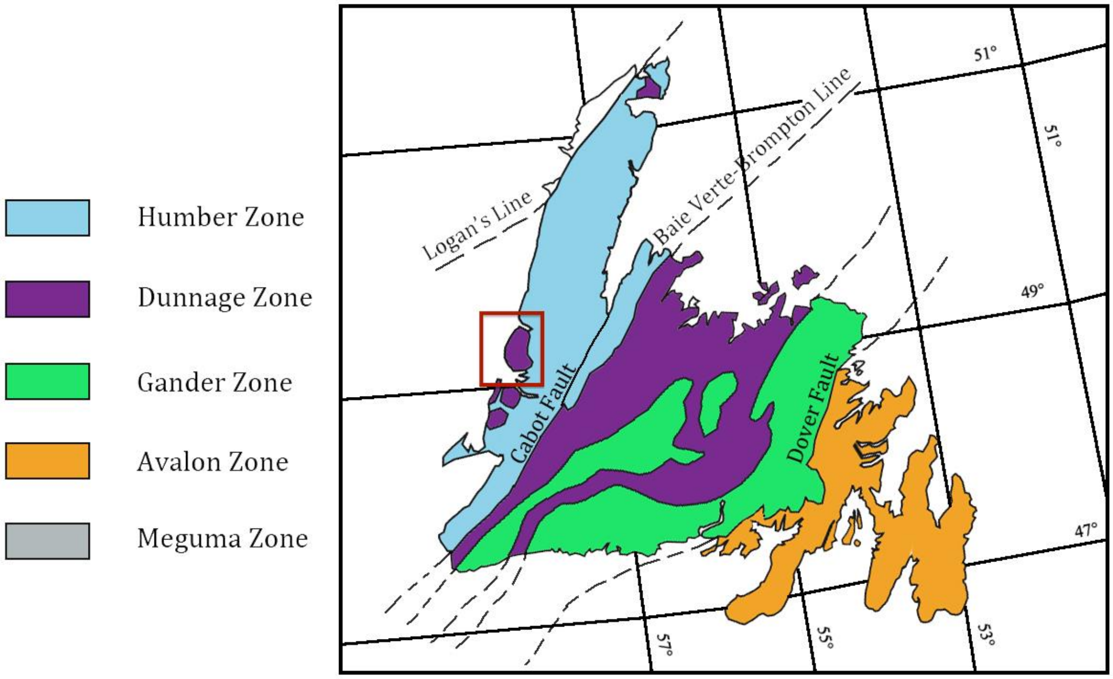


Figure 2.2: Simplified tectonostratigraphic divisions of Newfoundland. The Cabot Fault divides the External and Internal subzones. Note the Dunnage Zone rocks (ophiolite complexes) at the western margin of the Humber Zone. The study area is highlighted in red (after Williams 1995 and van Staal, 2007).

2.2.3 – The Gander Zone

East of the Dunnage Zone, Lower Cambrian to Lower Ordovician polydeformed and metamorphosed arenites, siltstones, and/or mudstone, deposited on Neoproterozoic crystalline basement, form the geology of the Gander Zone (Williams, 1995; van Staal, 2007). This represents the distal region of a passive margin. Isotopic and geological evidence suggest the Gander Zone represents a tectonic block correlating with the Peri-Gondwanan realm (van Staal et al., 1996; van Staal, 2007).

2.2.4 – The Avalon Zone

The Avalon Zone is the easternmost tectonostratigraphic division of the Appalachian orogeny in Newfoundland. It is separated from the Dunnage Zone by the Dover-Hermitage Bay-Caledonia fault system (van Staal, 2007). The zone is composed of a Neoproterozoic belt of volcanic and sedimentary sequences with associated plutonic rocks and an overlying Cambro-Ordovician siliciclastic platform succession (Williams, 1995; Landing 1996; van Staal, 2007). The zone originated in an arc setting but shows a lengthy history of deformation, including Precambrian mountain building (Williams, 1995). As with the Gander Zone, the Avalon Zone is a peri-Gondwanan terrane (van Staal, 1996; van Staal et. al., 1998).

2.3 - Stratigraphy of the Cambro-Ordovician Autochthonous Strata

The autochthonous strata are composed of sedimentary rocks deposited on the Laurentian margin. The strata are proximal, shallow-water equivalents of the successions making up the Humber Arm Allochthon. The autochthon is not a focus of this research. The following description is provided for regional context.

2.3.1 – Labrador Group

The Labrador Group is the oldest succession of autochthonous sedimentary rocks, ranging in age from the Late Precambrian to the Middle Cambrian (Figure 2.3). These strata were deposited on the Grenvillian basement during rifting and in the early stages of opening of the Iapetus Ocean (Hiscott et al., 1984). The group is divided into the Bateau, Lighthouse Cove, Bradore, Forteau and Hawke Bay formations (Williams et al., 1995). The Bateau, Lighthouse Cove and Bradore formations consist of quartzite, rift-related mafic volcanic rocks, and red arkosic sandstone. The late Lower Cambrian Forteau and Hawke Bay formations are composed of limestone, siltstone, mudstone, and sandstone.

2.3.2 – Port au Port Group

The dominantly calcareous strata of the Port au Port Group record the development of a continental shelf and, during the Mid to the Late Cambrian, and its transition to a broad low-energy marine environment (Stenzel et al., 1989). The group is subdivided into three formations, respectively called, March Point, Petite Jardin, and Berry Head formations. Lithologically the group mostly consists of limestone, dolostone and mudstone (Chow and James, 1987).

2.3.3 – St. George Group

Conformably overlying the Port au Port Group is the St. George Group (Figure 2.1), a body of shallow marine carbonate strata deposited on Laurentia's shelf during the mid-Early Ordovician to Middle Ordovician. The contemporary continental shelf was a wide, low-energy, passive margin (Stenzel et al., 1989). This group is divided into the Watts Bight, Boat Harbour, Catoche and Aguathuna formations (James et al., 1989). Lithologies for the St. George Group are mostly shallow marine limestone and dolostone. The upper boundary of the group is a regional unconformity, a consequence of uplift and sub-areal exposure on the shelf. This unconformity is interpreted to represent the development of a peripheral bulge from outboard loading by Taconic allochthons to the east (Knight et al., 1991).

2.3.4 – Table Head Group

The Table Head Group unconformably overlies the St. George Group. These Middle Ordovician strata record events marking the onset of the destruction of the carbonate platform along the Laurentian margin (Stenzel et al., 1989). The Group consists of the Table Point Formation, the Table Cove Formation and the Cape Cormorant Formation. Strata are dominantly formed as successions of massive, fossiliferous limestone, muddy limestone and calcareous mudstone, and mudstone with interbedded carbonate conglomerate.

2.3.5 – Goose Tickle Group

The Goose Tickle group is a Middle Ordovician syn-tectonic flysch. It was deposited as low energy turbidites in a deep, anoxic basin (Quinn, 1992). This group, the uppermost unit of lower Paleozoic autochthonous strata, is overlain by the tectonically emplaced Humber Arm Allochthon (Figure 2.4). Rocks are subdivided into the Mainland and American Tickle formations. The American Tickle is comprised of black mudstone and minor silt laminae. The Mainland Formation contains black mudstone as well as thinly interbedded black mudstone and green silt, with thin-bedded green sandstone (Quinn, 1992).

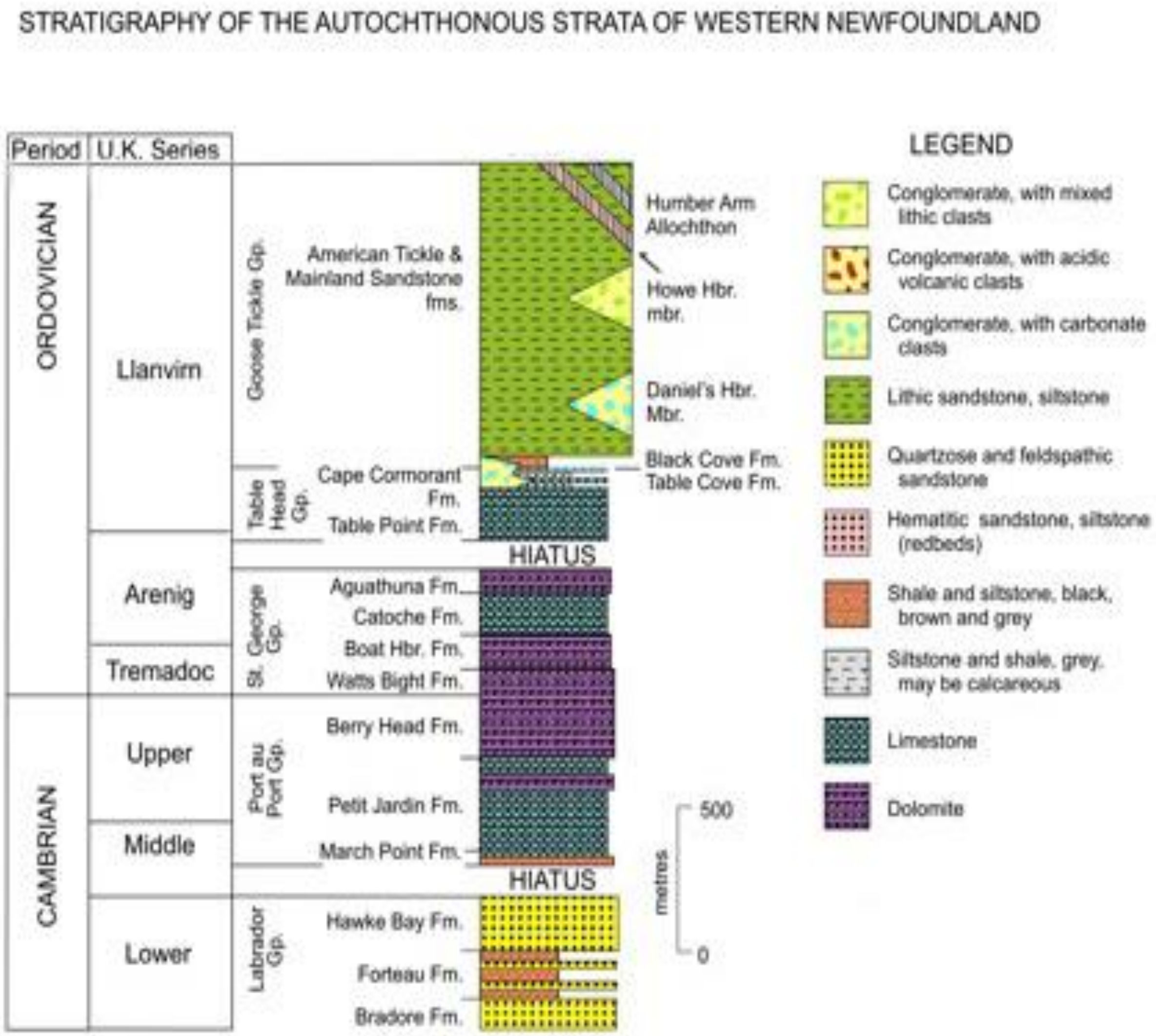


Figure 2.3: Stratigraphy of the early Paleozoic autochthonous strata underlying the Humber Arm Allochthon (Courtesy of Burden, E.; after Cooper et al., 2001)

2.4 – Transported Strata of the Humber Arm Allochthon

A fundamental part of this research concerns the transported strata of the Humber Arm Allochthon that are lying upon the autochthonous successions. A key part of this study is the sedimentary strata of the lower and intermediate thrust sheets and namely the Curling Group, Northern Head Group, Lower Head Formation and Blow Me Down Brook formation. The allochthon covers an area of about 200 X 50 km, and is estimated to be around 1000-1500 m thick (Williams, 1975). The three major thrust sheets of the allochthon were emplaced during the Taconic Orogeny, between 495 and 450 ma. The stacking order of these imbricate slices consists of consecutively older and farther-transported sheets thrust upon younger, less-travelled slices (Figure 2.4).

The allochthonous slices are reportedly separated from one another by extensively developed zones of broken and deformed strata labeled broadly as mélange (Williams and Cawood, 1989). These mélange is a chaotic unit consisting of a combination of greywacke, quartzite, chert, and limestone blocks in a black, green, and red mudstone matrix (Williams, 1995).

Allochthonous lithologic units distributed between the Bay of Islands and Bonne Bay have previously been classified under the name Bonne Bay Group (Nyman et al., 1984; Quinn, 1985; Williams and Cawood, 1989). Botsford's (1988) classification scheme for the Curling Group and Northern Head Group has not been applied to the Bonne Bay Group. There are however not enough significant differences between the Bay of Islands lithostratigraphic units and their Bonne Bay Group equivalents to warrant a different nomenclature. Initially distinguishing characteristics of the Cooks Brook Formation such as carbonate conglomerate were thought to be lacking north of the Bay Islands (Quinn, 1985). However relatable carbonate conglomerates are exposed in the southern regions of the map area. To simplify the stratigraphy on a regional scale the term Bonne Bay Group and its associated subdivisions need not be used.

The following sections offer an introduction to the lithologic units that are the subject of this regional study. Their introduction gives context to the regional stratigraphic framework.

2.4.1 – Blow Me Down Brook formation

The siliciclastic Late Precambrian to Early Cambrian Blow Me Down Brook formation is one of the oldest units of the allochthon. These rocks are a component of the intermediate thrust slice of the allochthon, and structurally wedged between an underlying slice of Curling and Northern Head group strata and overlying imbricate slices of igneous mafic and ultramafic rocks of the Little Port and Bay of Islands complexes (Figure 2.4). Both the base and top of the formation are truncated. The sedimentary strata were previously thought to be Ordovician flysch (Stevens, 1970). However petrographic work determined a continental provenance for the sandstone (Quinn, 1985; Gillis, 2006). In addition, occurrences of the trace fossil *Oldhamia* (Lindholm and Casey, 1989) place these rocks in the Early Cambrian, and well before the onset of Taconic orogenesis. The formation consists of thick-bedded, greyish-green, coarse-grained, massive, arkosic sandstone with intervals of black, green, and red mudstone. The cyclical nature of the strata indicates these rocks were deposited by turbidity currents and may be part of a submarine fan 400-600 m thick (Gillis, 2006; Buchanan 2004)). It is suggested the Blow Me Down Brook formation correlates laterally to the allochthonous Curling Group (Lavoie et al. 2003; Gillis, 2006). Regionally, the formation is a distal succession equivalent in age to the Bradore Formation of the autochthonous Labrador Group.

2.4.2 – Curling Group

The Curling Group, consisting of the Summerside and Irishtown Formations, is stratigraphically the lowest major interval in the Humber Arm Allochthon. The Late Precambrian to Early Cambrian Summerside Formation was deposited during the early stages of rifting and opening of the Iapetus Ocean (Williams, 1975). It is a succession of maroon and grey-green mudstone that is interbedded with very fine to coarse-grained, grey-green, quartz-rich arkosic sandstone beds of varying thickness (Waldron and Palmer, 2000). The sandstone can be parallel laminated, ripple cross laminated, tabular cross bedded, trough cross bedded, and also have fluid escape structures. The mudstone may also laminated with parallel and cross lamina. The base of the formation has not yet been recorded, but it has an estimated thickness of 1000 m (Waldron et al., 1988). According to Waldron and Palmer (2000), the upper part of the Summerside, where Stevens (1965, 1970) and Williams (1975) placed their Summerside-Irishtown contact tends to be on a gradation between grey-green slate and black, graphitic slate. Waldron and Palmer (2000) suggest this boundary is problematic for correlations and suggest a slightly higher position where the base of the Irishtown formation is "the first occurrence of medium sandstone beds (10 to 30 cm thick)".

The other major division of the Curling Group is the Early Cambrian Irishtown Formation (Stevens, 1965). In general, the formation is a thick succession of grey, graphitic, pyritiferous mudstone and interbeds of quartzose sandstone, sometimes thick-bedded and polymictic conglomerate. Intervals of conglomerate contain clasts of granitic rocks, likely originating from the Grenville basement, and as sedimentary clasts originating from platform rocks of the Labrador Group. An assemblage of reworked fossils (zombies) including trilobites, salterellids, and archaeocyathans collected from carbonate clasts indicate the Irishtown Formation is no older than late Early to Middle Cambrian (Walthier, 1949; McKillop, 1963; Stevens, 1965; James and Stevens, 1982).

2.4.3 – Northern Head Group

The Middle Cambrian to the Middle Ordovician Northern Head Group, a term informally defined by Botsford (1988) and discussed in Waldron and Palmer (2000), conformably overlies the Curling Group (Figure 2.4). It is further divided into the Cooks Brook, and Middle Arm Point formations (Botsford, 1988), thick stratigraphic intervals that approximate the lithologic subdivisions of the Green Point Formation of the Cow Head Group. In general, the Northern Head Group is predominantly calcareous and dolomitic successions that are for the most part formed in deep water and deposited down slope from the carbonate platform of the Laurentian continental margin.

The Cooks Brook Formation is dominated by ribbon limestone interbedded with grey to black mudstone and thick intraformational carbonate conglomerate. Middle Cambrian trilobite assemblages confirm the maximum age for deposition upon the Irishtown Formation (Cawood et al., 1988). In the field, and at its type locality in the Bay of Islands, Cooks Brook Formation is estimated to have a thickness of 350 m, however the lack of a fully exposed section casts some uncertainty on this estimate. The boundary between the Irishtown and Cooks Brook formations is the first bed of calcarenite limestone above the grey and black mudstone of the Irishtown Formation (Botsford, 1988).

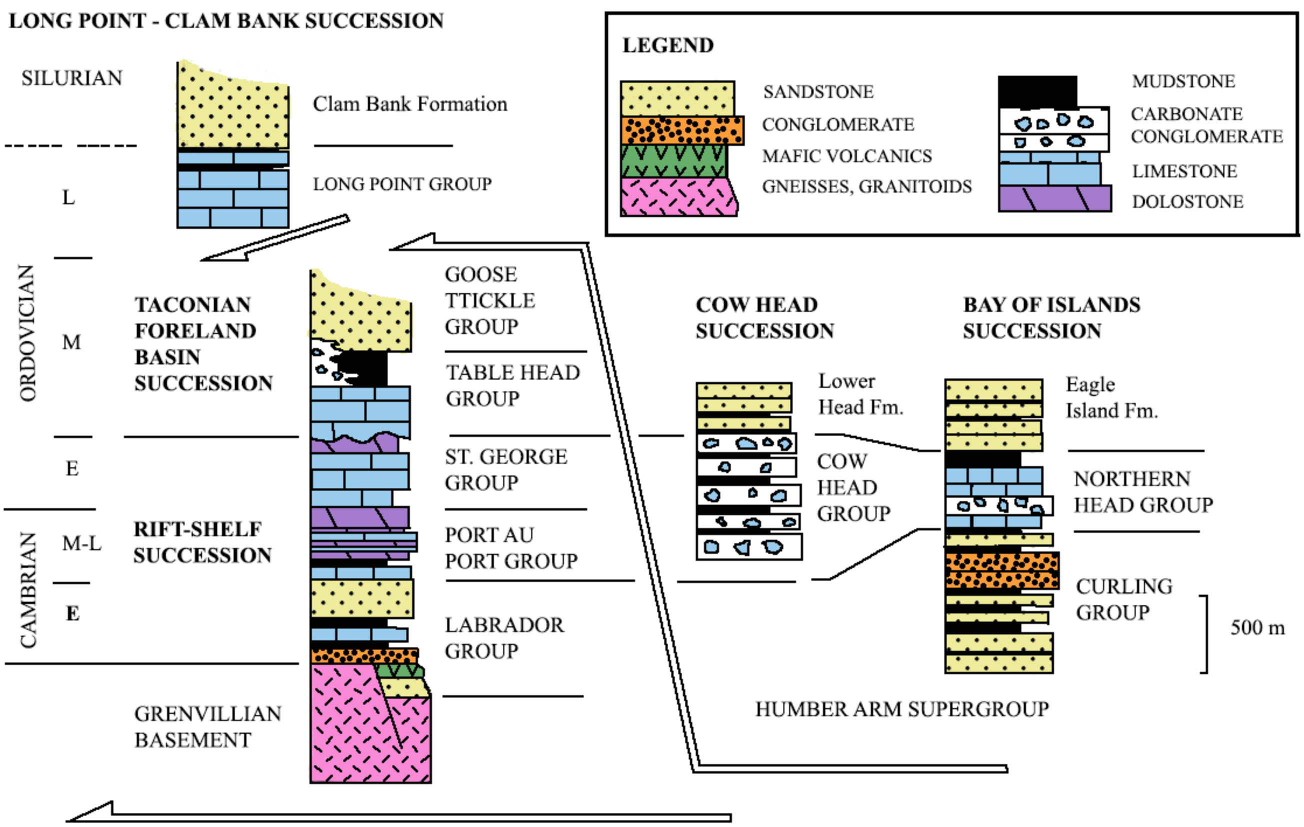


Figure 2.4: Stratigraphy and assembly of the Humber Arm Allochthon (after Waldron and Stockmal, 1994).

The Middle Arm Point Formation, a 120 m thick interval of silty dolostone, grainstone, siliceous green mudstone with interbedded silty dolomite and a distinctive red, black, and green mudstone at the top, conformably overlies the Cooks Brook Formation (Botsford, 1988). The graptolite assemblages collected from the unit indicate an age range from Late Tremadoc to Early Floian (Botsford, 1988). The basal contact of the Middle Arm Point formation is at a distinctive yellow-weathering interval of silty dolostone, 10-15 m thick (Stevens, 1965) and informally called the Woman Cove member. The upper boundary of the Middle Arm Point Formation and transition to the Lower Head Formation is placed at the base of the first bedded sandstone.

2.4.4 - Lower Head Formation

The Lower Head Formation is a middle Ordovician syntectonic flysch deposited over the Middle Arm Point Formation (Botsford, 1988; Figure 2.4). It is dominantly composed of thick-bedded sandstone with interbedded grey, black and red mudstone. Its northern correlative, the Lower Head Formation contains thin to medium beds of dolomitic siltstone and chaotic pebbly mudstone (Quinn, 1992). The formation is age equivalent to the autochthonous Goose Tickle and Table Head Groups.

In earlier studies of Humber Arm strata, the term Eagle Island formation was used to describe the Ordovician flysch (e.g. Botsford, 1988; Williams and Cawood, 1989; Cawood and Botsford, 1991). However, Quinn (1992) later concluded that the lithologic differences between the ‘Eagle Island formation’ and the Lower Head Formation were not great enough to merit a separate nomenclature for the units. The term ‘Eagle Island formation’ is therefore not used in this compilation.

2.4.5 - Igneous Rocks of the Humber Arm Allochthon

2.4.5.1 – Skinner Cove Formation/Crouchers formation

From tectonostratigraphic assembly, the 550 Ma Skinner Cove Formation (McCausland, 1995) sits within an intermediate thrust slice of the allochthon (Williams, 1975; Williams and Cawood, 1989). Lithologies of the formation include well-bedded pillow basalt, volcanoclastic rocks, and trachyte within the uppermost section. The alkaline basaltic rocks and pyroclastic rocks of the formation have been interpreted as deposits from mature oceanic volcano and have a thickness of 800 m (Baker, 1978; McCausland, 1998). A varied group of mafic volcanic rocks in the allochthon have been correlated with the Skinner Cove Formation, including the Fox Island River Formation south of the Bay of Islands and the Crouchers formation in the South Arm area (Schillereff, 1980; Williams and Cawood, 1989). Units classified as Crouchers formation are exposed as kilometer-scale wedges of rock sandwiched between the ophiolitic complexes and the Blow Me Down Brook formation (Quinn, 1985; Williams and Cawood, 1989).

Quinn (1985) questioned the correlation of Skinner Cove Formation and Crouchers formation based on a petrographic analysis of Crouchers formation rocks at the South Arm of Bonne Bay. More recently Langille (2009) determined the thick slices of mafic volcanics equivalent to Skinner Cove Formation and flanking the ophiolitic complexes south of the Bay of Islands were deposited in several tectonic settings including mid-ocean ridge, oceanic island, and arc-related basalts. The classification of the mafic volcanic rocks skirting the ophiolite as Skinner Cove equivalent is suspect. It is further examined herein through a geochemical analysis.

2.4.5.2 - Little Port and Bay of Islands Complexes

The Little Port and Bay of Islands complexes together form the highest structural slice of the Humber Arm Allochthon (Williams, 1995). The 505 Ma Little Port Complex underlies the 484 Ma Bay of Islands Complex (Jenner et al., 1991). Both suites are associated with subduction zone magmatic regimes. The Little Port Complex is an assemblage of pillow basalt, volcanic breccia, gabbro, mafic dykes, and trondhjemite associated with an island arc. The pillow basalt, gabbro, mafic dykes, ultramafic rocks, and amphibolite of the Bay of Islands Complex are the remnants of a suprasubduction zone ophiolite (Jenner et al., 1991).

2.5 – Mélange: Concepts and Terminology

2.5.1 – Definition of Mélange

According to Sengör (2003) chaotic strata with a block-in-matrix texture have been observed in the geologic record since 1825 (Festa et al., 2010). Some of the earliest descriptions of mélange come from the Nagelfuh conglomerates of the Alps (Studer, 1825, 1834). The term *wildflysch* was used to describe chaotic rocks with exotic blocks in a finer grained matrix. The *wildflysch* was interpreted to be a result of brecciation during gravity flow. The term *mélange,* French for mixture, was introduced by Greenly in 1919 (Raymond, 1984). The term was adopted in reference to the tectonically deformed strata of the Gwna Group in Anglesey, Wales. The chaotic unit was considered a result of tectonic processes rather than sedimentary processes.

With further research the term mélange was used to describe lithologies with a chaotic, block-in-matrix fabric, regardless of how they formed. Hsu (1968) described the process of mélange formation broadly as one of “fragmenting and mixing” (Raymond, 1984). In an attempt to offer some clarity for the definition of the term, Hsu argued its usage be restricted to tectonically deformed strata. The term “broken formation” was also introduced to describe chaotically deformed bodies with a block-in-matrix fabric that lacked exotic blocks. A further point to refining the meaning for mélange comes from the introduction of the term *olistostrome* as a name applied to a body of chaotic rock formed through sedimentary processes, such as gravity flows (Florres, 1955; Hsu, 1968). This name specifically highlights origin as an important factor in the classification of one or another type of a chaotic rock unit. Mélange is, after all, a product of the various sedimentary, magmatic and metamorphic processes of the tectonic setting in which this rock formed (Festa et al., 2010).

Several geologic processes can be responsible for fragmenting and mixing a stratigraphic succession. Sedimentary, tectonic and diapiric processes have all been attributed to the formation of mélange (Raymond, 1984). The three processes may act individually to create olistostromes, broken formation and mélange, or may also act together to produce a polygenetic mélange (Raymond, 1984). To further clarify the criteria and definition of mélange, particularly in contrast to related chaotic units, Raymond (1984) proposed that mélange is one end member in a continuum of deformation while a well-bedded, intact formation is the other end member. The formation can break-up and deform along a path that leads to “broken formation”, “dismembered formation” and finally, with the addition of exotic lithologies, mélange (Figure 2.5). Those exotic lithologies can only come together when very different (exotic) thrusts or terranes are in juxtaposition. It is the mixing of two formations that creates a proper mélange (end-member IV of Figure 2.5) out of dismembered formation (stage III of Figure 2.5)

Raymond (1984) proposes a concise and detailed definition of mélange. The term encompasses a mappable body of rock, characterized by a lack of internal continuity of contacts, the inclusion of fragments and blocks of all sizes, with compositions that are both exotic and native, and in a finer-grained matrix. This definition is adopted for this study and applied to some of the strata of the west-central Humber Arm Allochthon. Similar lithologies lacking an exotic block component are considered broken formation or dismembered formation, depending on the degree of deformation.

2.5.2 – Environments of Mélange Formation

The conditions for mélange formation can occur within a range of tectonically juxtaposed environments and settings. Mélanges have been reported on rifted margins, continental slopes, in zones of strike-slip faulting, subduction zones, zones of tectonic collision, and zones of nappe emplacement (Festa et al., 2010). The detailed classification scheme proposed by Festa et al. (2010) highlights the multitude of genetic processes and tectonic settings in which mélange is generated (Figure 2.6). Since there are only three genetic processes that result in mélange (gravitational, tectonic and diapiric), there are more than five geodynamic environments identified by Festa et al. (2010) (Figure 2.6). Gravity, for example, may produce mélange in a number of specific settings across intracontinental sites through extensional and passive margins, and into subduction zones.

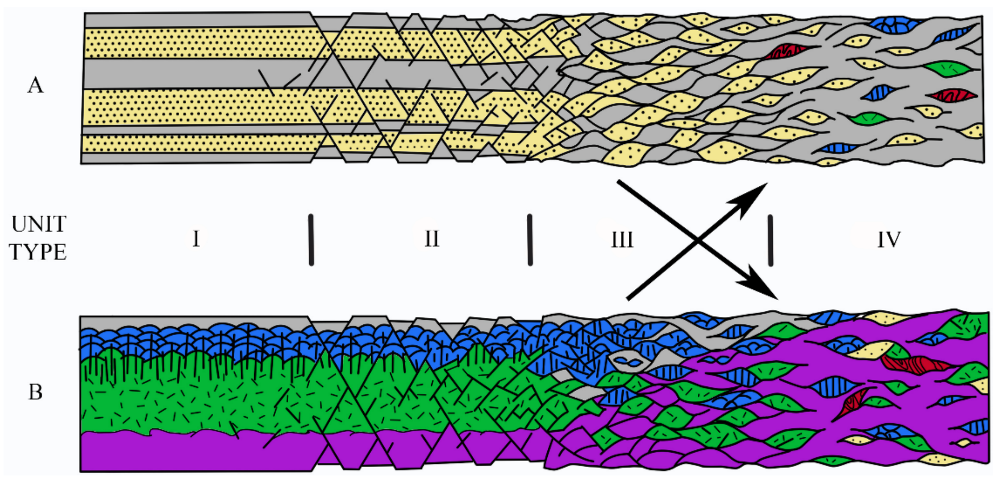


Figure 2.5: A schematic representation of a continuum of deformation in A) a sedimentary formation, and B) an ophiolite complex. I= formation, II= broken formation, III= dismembered formation, IV= mélange. Note the mixing of units A and B to form mélange as the end-member at stage 4 (after Raymond, 1984).

From their comprehensive analysis of global mélanges Festa et al. (2010) concluded that the majority of mélanges were originally deposited as gravity flows, or olistostromes, overprinted by later tectonic events that further fragmented and mixed the strata. Most mélanges found around the world can therefore be called polygenetic. Olistostromes deposited at the front of a subduction zone, accretionary wedge or advancing nappe, for example will become incorporated underneath the overriding body over time. The resulting highly deformed and sheared rock is structurally emplaced as a basal mélange but nevertheless had its origins as a gravity flow deposit.

In light of this, it is clear that understanding the regional geologic history is a key component to the study of any given mélange. The Humber Arm Allochthon is assembled from strata that were deposited in a number of different geodynamic settings such as extensional tectonic, passive margin, and collisional tectonic environments. It stands to reason that different mélange types must be considered when compiling and analyzing the Humber Arm Allochthon.

2.6 – Humber Arm Allochthon Mélange

As models for Newfoundland's Appalachian allochthons evolved so too did models for mélange development and diagnosis. Early on, these beds that separated major thrust slices were interpreted as fault zone breccia (Schuchert and Dunbar, 1934; Walthier, 1949). This clearly points to tectonism as a defining characteristic for these rocks. Later, Bruckner (1966) suggested submarine debris flows were responsible for these chaotic rocks.

Types of mélange	Geodynamic environments	Processes	Products	Minor related products
Related to:				
1. Extensional tectonics	Rifting	Gravitational	Mass-transport deposits (megabreccias, breccias, olistoliths, olistolith fields or swarm, debris avalanches, and flows, etc.)	Fault zones along normal fault?
2. Passive margins	Passive margins (after rifting)	Gravitational	Poorly sorted olistostromes (soft sediment deform.; progressive deformation from slumping to debris flows, to complete strata disruprion); slides	In-situ fluidification; mud diapirs?
3. Strike-slip tectonics	Different types of collision	Tectonic	Broken formations; mélanges (exotic blocks were commonly recicled from other previously formed mélanges)	Olistostromes s.l.; mud diapirs s.l.
4. Subduction				
a. Mass-transport deposits at the wedge front	Subduction (at the front of the wedge)	Gravitational	Olistostromes and mass-transport deposits (debris flows and avalances, slumps, slides, etc.)	Mud diapirs and mud volcanoes, serpentinite diapirs
b. Broken fms. and tectonic mélanges	Subduction (at the base of the wedge)	Tectonic	Broken formations; mélanges? (exotic blocks were commonly recycled from other previously formed mélanges)	
5. Collision	Different types of collision	Tectonic and gravitational	Broken formations; mélanges? (exotic blocks were commonly recycled from other previously formed mélanges)	Olistostromes s.l.; diapirs s.l.
6. Intracontinental deformation				
a. Sub-nappe				Mud diapirs and mud volcanoes
a1. Precursory olistostromes	At the base or front of intracontinental thrust sheets or nappes	Gravitational	Olistostromes and mass-transport deposits (debris flows and avalanches, slumps, slides, etc.)	
a2. Olistostromal carpet		Gravitational and tectonic	Mélanges (exotic blocks were commonly recycled from other previously formed sedimentary mélanges), broken formations	
a3. Tectonic mélanges		Tectonic, gravitational		
b. Intra-nappe				
b1. Sedimentary	Within intracontinental thrust sheets or nappes	Gravitational	Olistostromes and mass-transport deposits (debris flows and avalanches, slumps, slides, etc.)	Mud diapirs and mud volcanoes
b2. Tectonic and/or tectono-sedim.		Tectonic, gravitational	Broken formations; mélanges? (exotic blocks were commonly recycled from other previously formed sedimentary mélanges)	
c. Epi-nappe				
c1. Sedimentary	A top of intracontinental thrust sheets or nappes	Gravitational	Olistostromes and mass-transport deposits (debris flows and avalanches, slumps, slides, etc.)	
c2. Tectono-sedim.	(e.g. piggy back, top thrust basins)	Tectonic, gravitational	Broken formation, mélanges	
c3. Diapiric		Diapiric	Mud diapirs and mud volcanoes	

Figure 2.6: Types of mélange, their geodynamic environments, processes and products (from Festa et al., 2010).

By the 1970's and as more detailed mapping and measurements were being collected, tectonic processes emerged as the favoured mechanism for mélange development (Malpas and Stevens, 1977; Godfrey, 1982). Buchanan (2004) attributed tectonic processes to the development of mélange at the eastern tip of Woods Island. Also in more recent times there has been a shift in the classification of the chaotic deformed strata historically termed "mélange"

Within the Humber Arm Allochthon, particularly around the Bay of Islands it has been concluded that chaotic bodies of deformed strata represent, for the most part "broken formation", rather than mélange based on the lack of an exotic block component (Waldron, 1985; Buchanan, 2004). Waldron and Palmer (2000) were able to separate mappable units of distinct Humber Arm Supergroup lithologies from belts of mélange based on the amount of disruption to the stratigraphy. Five stages of stratigraphic disruption are recorded in the mélange Humber Arm Allochthon. Their "Index of Disruption" is similar to Raymond's (1984) generalized continuum of deformation (Figure 2.5). Buchanan (2004) used details of the structure, stratigraphy, and palynology to separate the "Companion Mélange" in the Bay of Islands into various fault-bound and broken up sections of Irishtown, Cooks Brook, Middle Arm Point, and Lower Head formations. Waldron and Palmer (2000) and Buchanan (2004) concluded that true mélange is basically confined to relatively narrow zones at the base of the ophiolite massifs, and where exotic blocks are found mixed with other broken strata.

In this thesis a similar classification scheme will be applied to outcrop in the field. Raymond's (1984) definition of mélange will be adhered to. For chaotically deformed strata to be termed mélange a variety of exotic blocks will have to be present. Deformed and intensely dismembered strata that do not contain exotic blocks are termed dismembered formation.

2.7 – Geochemistry: Chromium and Nickel as Indicators of Ultramafic Source Rocks in Sedimentary Rocks of the Humber Arm Allochthon

Ultramafic rocks associated with an ophiolite complex, similar to that of western Newfoundland, have distinct Cr and Ni signatures. Cr and Ni occur in greater abundance in ultramafic rocks than any other common rock-types found at the surface (Goles, 1967). Obducted ultramafic rocks shed detritus rich in Cr and Ni into sedimentary basins. Indeed, relatively high abundances of Cr and Ni within Ordovician flysch of the northern Appalachians and Humber Arm Allochthon have been attributed to the presence of ultramafic sources in several studies (Hiscott, 1984; Botsford, 1988; Quinn; 1992; Garver et al., 1996).

In the Canadian Appalachians, Hiscott (1984) reports typical Cr concentrations of 300-900 ppm in Middle Ordovician flysch. In the Humber Arm Allochthon, the American Tickle Formation, Mainland Formation, and Lower Head formation contain sediment shed from uplifted ophiolitic rocks (Quinn, 1992; Botsford, 1988). Here, Cr concentrations in sandstone average 430 ppm, and range from 48-1440 ppm. In the American Tickle Formation, they average 456 ppm with a range of 79-1030 ppm. For the Mainland Formation, they average 331 ppm, and typically occur between 153-1100 ppm. Finally, in the Lower Head Formation (Quinn, 1992), Cr concentrations for the mudstone of the Lower Head Formation average 60 ppm, and typically vary between 12-209 ppm (Botsford, 1988). The large disparity between Cr concentrations in sandstone and mudstone is a result of grain size effect. The coarser grained sandstones tend to contain detrital chromite grains that increase the concentration of Cr (Garver et. al., 1996).

Within the Ordovician flysch of the allochthon, Cr occurs in detrital grains of chromite in sandstones and absorbed ions within clay minerals (Quinn, 1992). However, relatively high concentrations of Cr are not restricted to the relatively young flysch. Botsford (1988) reported relatively high concentrations of Cr in mudstone of the Irishtown Formation in the Bay of Islands. Clearly the concentration of Cr alone cannot be relied upon to determine whether or not there was sedimentary input from ultramafic rocks. Cr may be enriched in sedimentary rocks by input from volcanism as well as ultramafic uplift (Garver et al., 1996). The concentration of Ni can be used in conjunction with the concentration of Cr in geochemical provenance studies since Ni is also in high abundance in ultramafic rocks. A further extended discussion is included in section 3.1.3.1.

The depositional environments for the older Cambrian sandstones of the Irishtown and Blow Me Down Brook formations and the younger Ordovician sandstone of the Lower Head Formation are well constrained. The former two are related to passive margin sedimentation while the latter is related to an active margin featuring ophiolite obduction. Given different settings, abundances of Cr and Ni in these different sandstone and mudstone deposits should provide distinguishing characteristics for confidently separating discrete samples, i.e. blocks within mélange. This has implications for the stratigraphic and structural assembly of rocks within the allochthon.

Chapter 3

Methods

3.1 – General Methodology

To resolve general and specific questions regarding the distribution of strata, structures and mélange, field studies descriptions, measurements, and sample collections were obtained over a period of four months during the summers of 2010 and 2011. Quantitatively the results for this fieldwork were captured in multiple structural measurements from 640 stations spanning an area of land approaching 300 km^2. Overall, 124 samples were collected from lithologies that reflect all of the rocks of the Humber Arm Allochthon, including ultramafic and mafic igneous rocks, and siliciclastic and calcareous sedimentary rocks. A selection of these samples was analyzed for petrography and geochemistry. In total, 34 sandstone samples were analyzed petrographically. Geochemical analyses were completed on 19 igneous rock samples, 24 sandstone samples, and 38 mudstone samples (Figure 3.1). Samples of fossils were collected from several localities throughout the region. Paleontological identification of *Oldhamia* was provided by Dr. Elliott Burden of Memorial University and identification of graptolites was provided by Dr. Henry Williams, currently at Suncor.

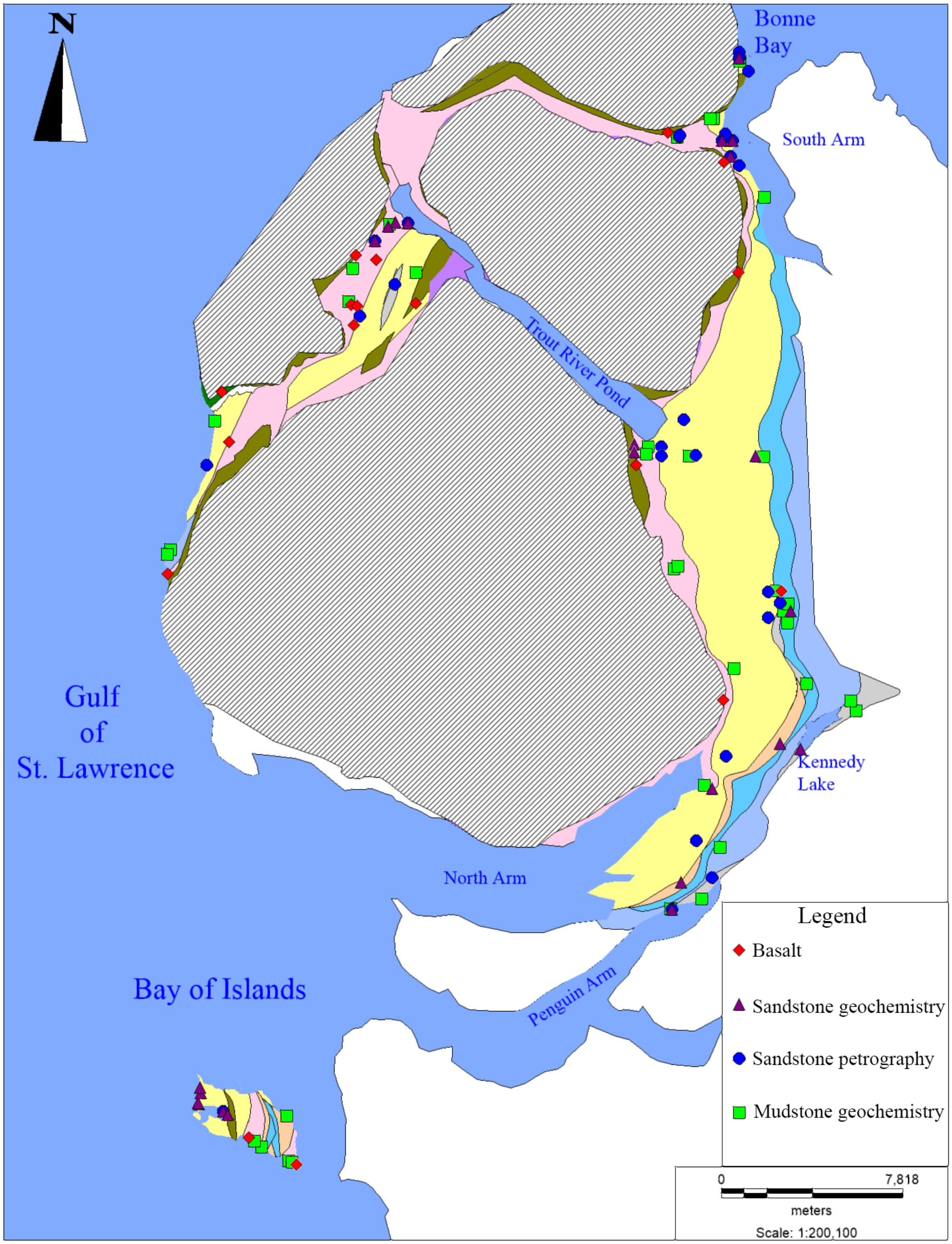


Figure 3.1: Map of sample locations. See Map sheets for lithology legend.

3.1.1 – Field Mapping

The initial preparation for mapping in the field involved studying stereoscopic aerial photographs of the region as well as examining the older regional geologic maps (Williams, 1973; Williams and Cawood, 1989; Godfrey, 1982; Nyman et al., 1984; Quinn, 1985). Larger outcrops were easily seen on these photos and allowed for traverses to be planned. Traverses originating from resource roads provided very good coverage for some of the study area. Other traverses were planned along rivers and coastal sections where a greater proportion of bedrock is exposed. All measurements were taken with a Silva compass and recorded in the field notebooks using the right-hand rule format. Station locations were recorded with a hand-held GPS receiver that was generally accurate to about 10 m. The UTM coordinates were measured with reference to the NAD27, Zone 21 datum. Station locations are compiled in Appendix B.

3.1.2 – Sample Analysis Petrography

A petrographic study is crucial toward differentiating siliciclastic strata. Due to their generally similar macroscopic characteristics, sandstone of the Blow Me Down Brook formation and the Lower Head Formation can be difficult to differentiate in the field. Determining the true nature of all of the sandstone units has important implications for stratigraphic and structural distribution patterns within the Humber Arm Allochthon. Furthermore, these distinctions can be used to determine the origin of sandstone blocks in dismembered formation and mélange.

Of the 34 petrographic samples, 18 are Blow Me Down Brook formation sandstones, 4 are Irishtown Formation sandstones, and 12 are sandstones samples collected from the mélange and dismembered formation. Sandstones selected for petrography were generally chosen based on their proximity to major contacts. Any samples that were collected from outcrops of questionable affinity were also analyzed. Sandstone samples collected from the mélange and dismembered formation were taken from broken up blocks. Several other petrographic analyses have been completed on sandstones of the Humber Arm Allochthon, and particularly the Blow Me Down Brook formation (e.g. Quinn, 1985; Gillis, 2006). Comparisons between the petrography of sandstones collected for this research and those reported in previous studies is a key aid for identifying and classifying the strata. The Gazzi-Dickinson method (Appendix A) for petrographic analysis was used in both earlier studies. For consistency, this method is also applied here; the data are available in Appendix C, and discussed in Chapter 5. Quinn (1985, 1992) and Gillis (2006) covered the application of the technique on sandstone of the Humber Arm Allochthon.

3.1.3 – Sample Analysis – Geochemistry

Geochemical analyses of the samples were obtained by X-ray fluorescence and Inductively Coupled Plasma Mass Spectrometry. Lithologies analyzed include sandstone, mudstone, and basalt. For the sandstone and mudstone, a geochemical analysis may provide a means for differentiating the sedimentary units of the allochthon. For the mélange an analysis of both the mudstone matrix and sandstone blocks will provide insight into the origin of the chaotic unit.

Results of the study are compared to results of previous geochemical analyses of related allochthonous rocks by Botsford (1988), Quinn (1992), for sedimentary rocks and Baker (1978) and Jenner et al. (1991) for igneous rocks. Analytical methods are described in Appendix A.

3.1.3.1 – Sedimentary Rock Geochemistry

Major and trace element geochemistry is used in conjunction with petrography to classify sandstone and mudstone in the allochthon. A total of 24 sandstone samples were analyzed for major and trace element geochemistry. They were collected from the Blow Me Down Brook, Irishtown and Lower Head formations, and from blocks of sandstone in the mélange. The relationships among the major and trace elements in the sandstones provide information on the provenance of the strata. The geochemical data is compiled in Appendix D (sandstone) and E(mudstone).

Roser and Korsch (1986) developed discrimination diagrams that differentiated three tectonic settings: Island Arc, Active Continental Margin, and Passive Margin. These settings are identified from the ratio of K_2O/Na_2O against SiO_2 (wt.%). The fields that divide the diagram show both K_2O/Na_2O and SiO_2 (wt.%) increase in passing from an island arc setting to an active margin setting to a passive margin setting. Bhatia (1983) generated discrimination diagrams capable of distinguishing between four tectonic settings: Passive Margin (PM), Active Continental Margin (ACM), Continental Island Arc (CIA), and Oceanic Island Arc (OIA). Bhatia found tectonic settings can be distinguished from the amount of Al_2O_3/SiO_2, and TiO_2 individually plotted against (Fe_2O_3+MgO). For trace element geochemistry, the goal is to obtain concentrations of Cr, Ni, Y, V. Cr and Ni concentrations are also the reason for analyzing mudstone samples for trace element geochemistry. The 38 mudstone samples that were analyzed for trace element geochemistry were selected from the Blow Me Down Brook, Irishtown, Cooks Brook, Middle Arm Point, Lower Head formations as well as the matrix of the mélange and dismembered formation.

Garver et al. (1996) proposed three criteria for distinguishing ultramafic input from volcanic input in mudstone using the relationship between Cr and Ni.

(1) For mudstone Cr concentrations are greater than 150 ppm and Ni is greater than 100 ppm.

(2) For multi-sample suites, a strong correlation between Cr and Ni (a correlation coefficient, r >0.90) can be a criterion for identifying ultramafic sources from trace element chemistry.

(3) A Cr/Ni ratio can be applied to determine sedimentary provenance. Cr/Ni ratios of approximately 1.4-1.6 for mudstone are indicative of ultramafic input. Higher Cr/Ni ratios may be attributed to volcanic detritus rather than an obducted ultramafic source. Sandstones may have Cr/Ni ratios greater than 3.0 signifying greater proportions of Cr than Ni. This disparity is essentially caused by a grain size effect. Sandstones frequently contain detrital chromite grains (Garver et al., 1996), as is the case for the Ordovician strata of the western Newfoundland Appalachians (Hiscott, 1984; Quinn, 1992).

McLennan et al. (1993) produced a Cr/V vs. Y/Ni plot to visually represent ophiolitic source material in sediment. An ophiolitic source terrain contributes significant Cr and Ni to detrital sandstones. V is also considered a proxy for other ferromagnesian elements, and Y represents heavy REE. The ratio of Cr/V is an index of enrichment of Cr over other ferromagnesian elements. The Y/Ni ratio represents the general enrichment of ferromagnesian elements, monitored by the Ni content, against changes in the heavy REE content generally associated with felsic source rocks. Sandstones with ultramafic sources have high Cr/V ratios and low Y/Ni values.

3.1.3.2 – Volcanic Rock Geochemistry

The origins for the volcanic rocks that flank the ophiolitic complexes have been a subject of debate. A large subset of thick basalt slices underlying the ophiolite complexes surrounding the Bay of Islands were originally correlated (Williams and Cawood, 1989). Recently, Langille (2009) demonstrated the volcanic slices south of the bay have contrasting geochemistry and formed in differing tectonic settings. Quinn (1985) noted petrographic distinctions between the volcanic slices north of the bay and suggested the various volcanic units do not correlate. A geochemical study of the variety of basalts sampled for this study should provide a better understanding of the igneous complexes in the allochthon and may ultimately contribute to our better understanding mineral, and hydrocarbon exploration in this area.

The 19 samples of mafic volcanics examined in this study come from basalts carrying different stratigraphic names. Nine samples were collected from units classified as Crouchers formation (Williams and Cawood, 1989), a rock unit exposed along the flanks of ophiolitic massifs south of Trout River Small Pond, at South Arm, and at Chimney Cove. Six samples were collected from blocks in mélange at Woods Island and Chimney Cove. One sample was collected from an anomalous block of volcaniclastic material at the top of a section Blow Me Down Brook formation along the banks of Middle Trout River. Another single sample was collected from the Skinner Cove Formation (Williams, 1973; Williams and Cawood, 1989) at Chimney Cove. Analytical results for trace element geochemistry are plotted on the classification diagram of Winchester and Floyd (1977). This diagram compares the ratio of Zr/Ti to the ratio of Nb/Y to classify volcanic rocks. Results are compared against data published in Baker (1978), and Jenner et al. (1991). All of the geochemical data for basalts and volcaniclastics is listed in Appendix F.

3.2 – Data Management and Analysis

All of the field records were entered into composite Microsoft Excel spreadsheets. Waypoint and structural data were input into MapInfo to create regional geology maps. Topographic base maps were obtained from the online NRCan Geogratis Portal at www.nrcan.ca. In addition to Excel and MapInfo, other software packages were used to produce maps and stereonets for structural data. The program GEOMapSymbol, a free-to-students software package specifically produced as an add-on for MapInfo, was used to synthesize structural measurements and symbols on the map. Georient, another software package free to students, was used to plot structural measurements on lower hemisphere projection equal-area stereonets. The software was created by Dr. Rod Holcombe, adjunct professor of structural geology, at Queensland University and available for download from his website.

Chapter 4

Lithostratigraphy of the Sedimentary and Igneous Strata of the Humber Arm Allochthon in the Bay of Islands-Bonne Bay Area

4.1 – Introduction

The map area contains 9 rock units representing all strata of the Humber Arm Allochthon and the three major Taconic thrusts exposed in this region. Sedimentary rock assemblages include siliciclastic sandstone, mudstone, and calcarenite of the Blow Me Down Brook, Irishtown, Cooks Brook, Middle Arm Point, and the Lower Head formations. Igneous and volcaniclastic rocks of various origins belong to the Skinner Cove Formation, the Little Port Complex, and the Bay of Islands Complex. The sedimentary strata measured and presented herein include many previously unknown outcrops. Collectively these rocks provide additional data and therein new constraints on the stratigraphic framework of the region.

Relatively narrow belts of deformed strata identified as mélange are exposed at the base of the ophiolitic massifs. The belts separate the ophiolitic rocks from the underlying Blow Me Down Brook formation. These belts of deformed strata host blocks of sandstone, calcarenite, and a variety of igneous lithologies. The sedimentary characteristics of this mélange indicate it may be primarily derived from dismembered Lower Head Formation strata.

4.2– The Blow Me Down Brook formation

4.2.1 – Geographic and Stratigraphic Distribution

The siliciclastic strata of the Blow Me Down Brook formation form the most aerially extensive lithology in this map area. In the Eastern Flank region (Map Sheet 1), a long narrow belt of this rock extends northward from the North Arm of the Bay of Islands, along the eastern flank of the North Arm Massif, and into the South Arm of Bonne Bay. Elsewhere, broad belts of these rocks are also exposed in the Chimney Cove region west of North Arm Massif (Map Sheet 2), and on the western half of Woods Island in the Bay of Islands (Map Sheet 3). Regionally, the formation structurally overlies younger Northern Head Group strata and is in turn overlain by the highest thrust sheet of the Humber Arm Allochthon, the Bay of Islands Complex. Both upper and lower contacts are tectonic in nature. The thickness of the Blow Me Down Brook formation was not determined in this study; however, it has been estimated to be around 400 m thick (Gillis and Burden, 2006).

4.2.2 – Lithologic Characteristics

The Blow Me Down Brook formation consists of greyish-green and dark greyish-green, thick to very thick-bedded coarse-grained subarkosic sandstone, interbedded with greyish red, medium dark grey, and light greyish-green mudstone and siltstone. Beds of siltstone, very fine- and fine-grained sandstone tend to be thin (3-10 cm), and with individual beds on the centimeter scale. In addition, there are minor massive, quartzose, pebble conglomerates. A particularly notable example is exposed along Woods Island's western shoreline and has a thickness of 20 m. This interval may be related to another thinner quartz pebble conglomerate exposed north of Fox

Island River along Newfoundland's western coastline, and south of the mouth of the Bay of Islands (Gillis, 2006).

Throughout the study area, greyish-green and, less frequently, red mudstone is interstratified with the sandstone beds. Successions of mudstone can be several metres thick (Figure 4.2); however, individual beds within a succession are generally thin. Another variety of the banded mudstone occurs with dark grey and light greenish-grey beds.

Relatively few sedimentary structures are preserved in what are apparently predominantly massive sandstones of the Blow Me Down Brook formation. Scoured surfaces at the base of the coarser-grained beds represent the most abundant sedimentary structure. Normally graded beds are sometimes preserved. Asymmetric and parallel planar ripples sometimes delineate laminae, particularly in the fine-grained beds. At coastal exposures on Woods Island dish structures and fluid escape pipes are relatively common.

4.2.4 – Contacts

Regionally the Blow Me Down Brook formation overlies younger strata of the Northern Head Group and underlies a relatively thin veneer of chaotically deformed siliciclastic strata (section 4.8). This mélange and dismembered formation separates the Blow Me Down Brook formation from the younger mafic volcanics and plutonic rocks of the ophiolite complexes.

Within this study area the lower contact was examined at two localities, Birchy Head in the South Arm of Bonne Bay (Map sheet 3) and along Middle Trout River (Map sheet 1). At Birchy Head the contact is well exposed and overturned. Strata of the Middle Arm Point Formation are in direct contact with sandstone of the Blow Me Down Brook formation.

Figure 4.1: A typical medium- to thick-bedded coarse-grained quartzose sandstone of the Blow Me Down Brook formation, station 11MK-317. Geologist for scale. B). Thick-bedded sandstone successions across a 20 m field of view, South Arm.

There is a well-developed foliation and isoclinal folding in the adjacent Middle Arm Point Formation, a feature suggesting the contact is structural and overturned. At Middle Trout River the contact is eroded and covered by overburden over a narrow zone around 1.5 m thick. There is some dismemberment in the underlying Cooks Brook Formation.

4.2.5 – Paleontology of the Blow Me Down Brook formation

The Lower to Middle Cambrian trace fossil *Oldhamia* sp. occurs in mudstone horizons of the Blow Me Down Brook formation at several localities in western Newfoundland (Lindholm and Casey 1989, 1990; Buchanan, 2004; Gillis and Burden 2006).

In this study area *Oldhamia* sp. traces occur in beds of mudstone the Blow Me Down Brook formation at several localities. Two new locations are identified in the vicinity of the North Arm Massif and along the Chimney Cove coastline. One, near the eastern flank of North Arm Massif is found in light greyish-green silty mudstone outcropping along the river banks that parallel the edge of the massif (Map sheet 1) (EB11-180 and EB11-293). Farther west, in the low cliffs at Chimney Cove (Map Sheet 2) *Oldhamia* sp. traces are scattered on bedding planes in a succession of black, rusty-weathering mudstone (Figure 4.2; MK11-536 and EB11-347).

Figure 4.2: Fossiliferous dark grey mudstone succession of the Blow Me Down Brook formation exposed at Chimney Cove. Abundant trace fossils of the genus *Oldhamia* sp. occur at this locality. Brittle faults (330/55) are highlighted by dashed lines. Station 11MK-537. Field of view is 10 m.

4.3 – The Irishtown Formation

4.3.1 – Geographic and Stratigraphic Distribution

The quartz-rich siliciclastic strata of the Irishtown Formation form a less commonly identified part of the stratigraphy of this region. Farther east, these rocks are otherwise well exposed beyond the limits of this study's area (see Nyman et al., 1984; Quinn, 1985; Williams and Cawood, 1989).

For this work, the best exposures of Irishtown strata are found along the northern coast of Penguin Arm, in the Bay of Islands (Map Sheet 1). Here, these rocks extend northeast and beyond the southern shore of Kennedy Lake (Map Sheet 1) as a narrow discontinuous belt of white quartzite and black mudstone laying beneath the Cooks Brook Formation. Another smaller belt of Irishtown Formation occurs in the same general area, northwest of Kennedy Lake, and as an imbricate slice laying beneath the Blow Me Down Brook formation and other, otherwise deformed and broken, Middle Arm Point strata.

In the valley west of North Arm Massif and northeast of Chimney Cove (Map Sheet 2) several isolated, aligned, east-dipping outcrops of white quartzarenite are exposed. They are interpreted as a broken slice of Irishtown Formation strata inserted into the Blow Me Down Brook formation.

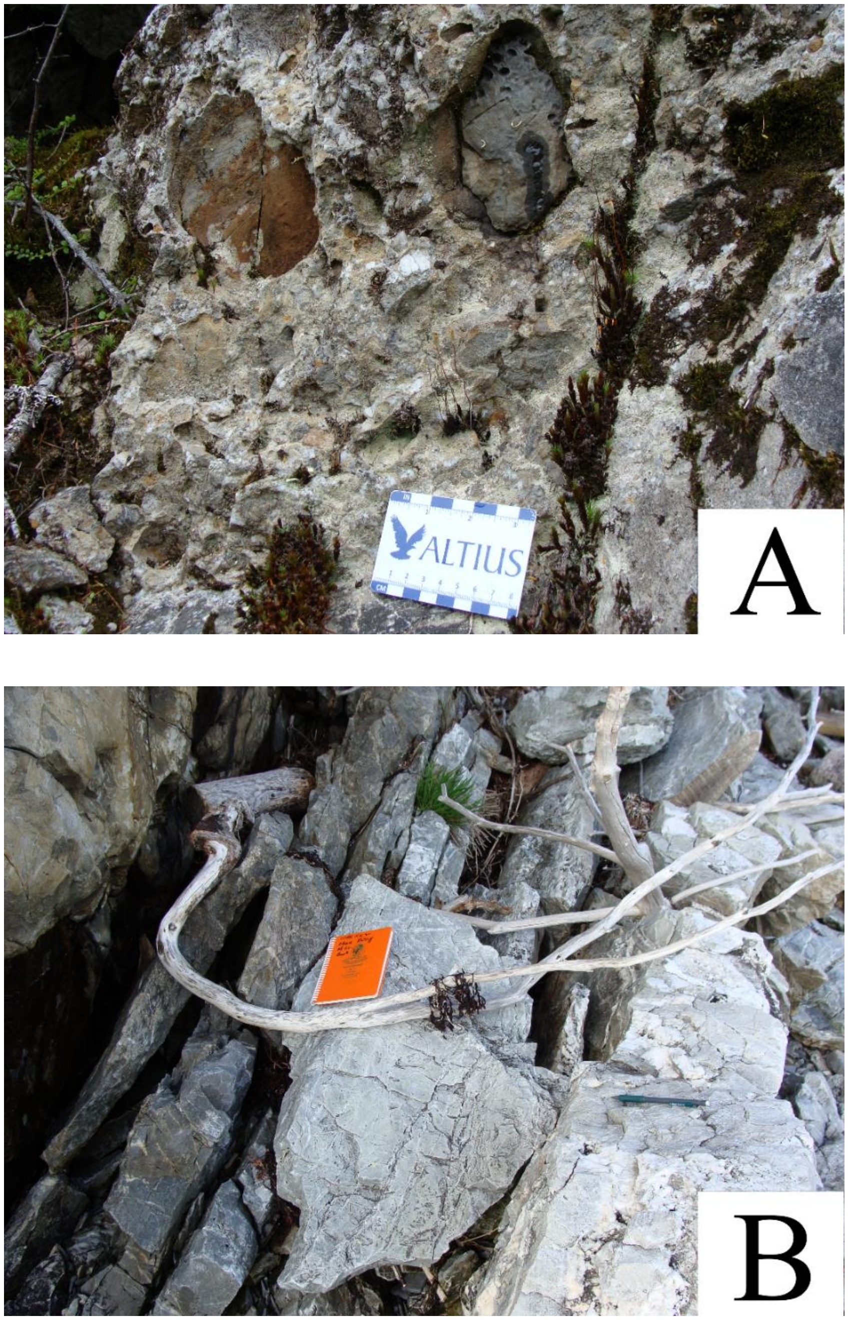


Figure 4.3: A) Boulder conglomerate in the Irishtown Formation near Kennedy Lake (station 11MK-388). 8.5 cm card for scale. B) Medium- and thick-bedded quartzose sandstone of the Irishtown Formation on the Penguin Arm coastline (station 11MK-242). Notebook for scale with pencil pointing north.

4.3.2 – Lithologic Characteristics

The Irishtown Formation is characterized by a distinct assemblage of thick-bedded, coarse-grained to very coarse-grained, massive quartzarenite and black micaceous mudstone. The quartzarenite is generally white on the weathered surface. Texturally the sandstone is massive, with some grading identified at a locality at Penguin Arm. Elsewhere, an outcrop of massive, polymictic boulder conglomerate occurs near Kennedy Lake (Figure 4.3; Map Sheet 1). This conglomerate lies on a thick bed of massive coarse-grained quartzose sandstone. It hosts centimeter-scale clasts of grey carbonate and quartz pebbles within a quartzose very coarse-grained sandstone matrix. Beds of this conglomerate are around 50 cm thick. The limestone clasts notably contain small shell fragments. Locally, the dark grey micaceous mudstone of the formation has rusty stains on exposed and weathered surfaces.

4.3.3 – Contacts

The upper contact between the Irishtown and overlying Cook's Brook Formation is poorly exposed along the northern shoreline of Penguin Arm. A greyish-green quartzose pebbly sandstone is separated from massive, planar-laminated, Cooks Brook Formation limestone by a light grey, fissile mudstone.

<u>4.4 – The Cooks Brook Formation</u>

4.4.1 – Geographic and Stratigraphic Distribution

The Cambro-Ordovician, carbonate-rich Cooks Brook Formation is the second most extensive unit in this region. North of the Bay of Islands the formation is outcropping along a narrow north-south trending belt from the shore of Middle Arm (Penguin Arm) of the Bay of Islands to the coast of South Arm in Bonne Bay (Map Sheet 1; Map Sheet 2). It is also exposed along the western shore of the Gulf of St. Lawrence at Shoal Cove (Map Sheet 2). The formation is stratigraphically below the Middle Arm Point Formation and above the Irishtown Formation.

4.4.2 – Lithologic Characteristics

Several lithologies and successions are found in the Cooks Brook Formation. One of the more common successions is interbeds of massive, medium and dark grey to very dark grey mudstone with thinly interbedded, light grey, calcareous siltstone to fine-grained calcarenite. A similar, less common succession is dark grey and light green banded mudstone with interbedded thin to medium light grey calcareous siltstone to fine-grained calcarenite. Massive, very thick-bedded, light grey coarse-grained calcarenite is locally exposed near North Arm. The least common rock is a thick-bedded, monomictic, and massive, carbonate-clast, conglomerate located near Kennedy Lake and along the northern shoreline of Penguin Arm (Map Sheet 1).

4.4.2.1- Dark Grey Mudstone-Carbonate Successions

Successions of dark grey mudstone with interbedded very thin to thin beds of light-grey calcarenite (Figure 4.5) are exposed from North Arm of the Bay of Islands, as far north as South Arm. The grain size of the calcarenite ranges from silt to sand size particles. Individual calcarenite beds are mostly discontinuous and pinch out relatively quickly. Internally, they can be massive or parallel- and wavy-laminated. Some beds carry current ripples on or about the upper surface. Other beds may be somewhat silicified. Across these intervals, the mudstone-carbonate ratio is variable between about 10-50% carbonate sand and silt beds.

4.4.2.2 – Dark Grey and Green Mudstone Successions

Exceptionally well-exposed sections of successive black and green mudstone and thinly interbedded, very-fine to fine-grained calcarenite, and calcareous siltstone are found along the coast at the southern end of Chimney Cove (Figure 4.4). The thickness of the dark grey and green banding in this mudstone is generally several cm to 20 cm. Carbonate beds are light grey, and they too range in thickness from several cm to around 20 cm. Calcarenite beds are laminated with parallel-wavy laminae. A less common unit is thin-bedded (3-10 cm), laminated, tan-weathering calcareous siltstone interbedded with the dark grey and green mudstone.

The banded mudstone at Chimney Cove hosts fossils, contains pyrite nodules up to 15 cm diameter, and has oil seeps. Graptolites (discussed in section 4.4.3) are densely scattered across many bedding surfaces of these carbonate beds. Droplets of degraded, heavy petroleum are frequently seen in tight fractures and joints of these Cooks Brook mudstone rocks (Figure 4.7). Offshore, an oily sheen on the surface of the water may indicate an active hydrocarbon seep from Cooks Brook mudstone at the southern end of the Chimney Cove shore.

Figure 4.4: Successions of mudstone and thin-bedded calcarenite on the Chimney Cove coast, Map Sheet 2, station 11MK-557. Hammer for scale.

4.4.2.3 – Massive, Coarse-Grained Calcarenite and Conglomerate

Beds of very thick-bedded, coarse-grained, light grey calcarenite are exposed in the North Arm-Kennedy Lake region (Map Sheet 1). The thickest bed containing this lithology is around 5 m thick (Figure 4.5). Weak laminae are difficult to discern but do occur in the very thick calcarenite beds. The laminae delineate smaller scale bedding in an otherwise massive lithology. Discrete breccia layers with centimeter-scale clasts of calcarenite and micrite are distributed within the massive units. The thick beds of calcarenite are bound by successions of light grey, thin-bedded, very fine to fine-grained calcarenite and calcareous siltstone, interbedded with dark grey mudstone.

Carbonate clast, monomictic conglomerates are also exposed near Kennedy Lake and the northern shoreline of Penguin Arm. Along a logging road proximal to, and paralleling, the southern shoreline of Kennedy Lake there lies a massive very thick-bedded steeply-dipping cobble conglomerate. The approximate thickness of this conglomerate is 15 m. The bed is sharply overlying a thick mudstone succession. The clasts within the conglomerate are up to 15 cm and are prominently elongate and sub-angular (Figure 4.5) calcarenite. At Penguin Arm a similar 1 m thick carbonate clast conglomerate is at the base of a very thick-bedded massive to planar laminated limestone.

4.4.3 – Paleontology

Within the entire map region there is but one locality identified with fossiliferous Cooks Brook Formation strata. Located at Chimney Cove (Map Sheet 2), the overturned outcrop contains dense groupings of black dendroid graptolites on bedding planes of light grey, calcareous siltstone and very-fine calcarenite. The fossils are pendent-shaped with relatively straight theca (Figure 4.6). They have been tentatively identified as *Rhabdinopora* sp. (pers. comm. Williams, 2016). It is the only genus of graptolite on these bedding planes.

4.5 – The Middle Arm Point Formation

4.5.1 – Geographic and Stratigraphic Distribution

Early-Middle Ordovician Middle Arm Point Formation is mostly exposed between North Arm of the Bay of Islands and South Arm of Bonne Bay. The outcrops east of the North Arm Massif (Sheet 1) and Table Mountain Massif (Sheet 3) trend along a narrow belt no more than 300m wide. The lower contact with the Cooks Brook Formation is apparently conformable. The upper contact is a structural contact with Blow Me Down Brook strata. On some of these upper contacts, there are beds that may be described as Lower Head Formation, broken formation and mélange. Farther south on Woods Island in the Bay of Islands (Map Sheet 3) the Middle Arm Point Formation appears as narrow belts of deformed rock.

4.5.2 – Lithologic Characteristics

Middle Arm Point is dark grey mudstone with thinly interbedded dolomitic siltstone and very fine-grained sandstone. The thin beds of dolomitic siltstone are generally laminated with either wavy-parallel laminae and less often planar parallel laminae. They are mostly discontinuous and lens shaped (Figure 4.7). The dolomitic beds are a yellowish-brown to tan colour on the weathered surfaces. Fresh surfaces are generally light grey. The best-exposed sections, as seen in this study, are found along the northern and southern coastlines of the eastern end of Woods Island.

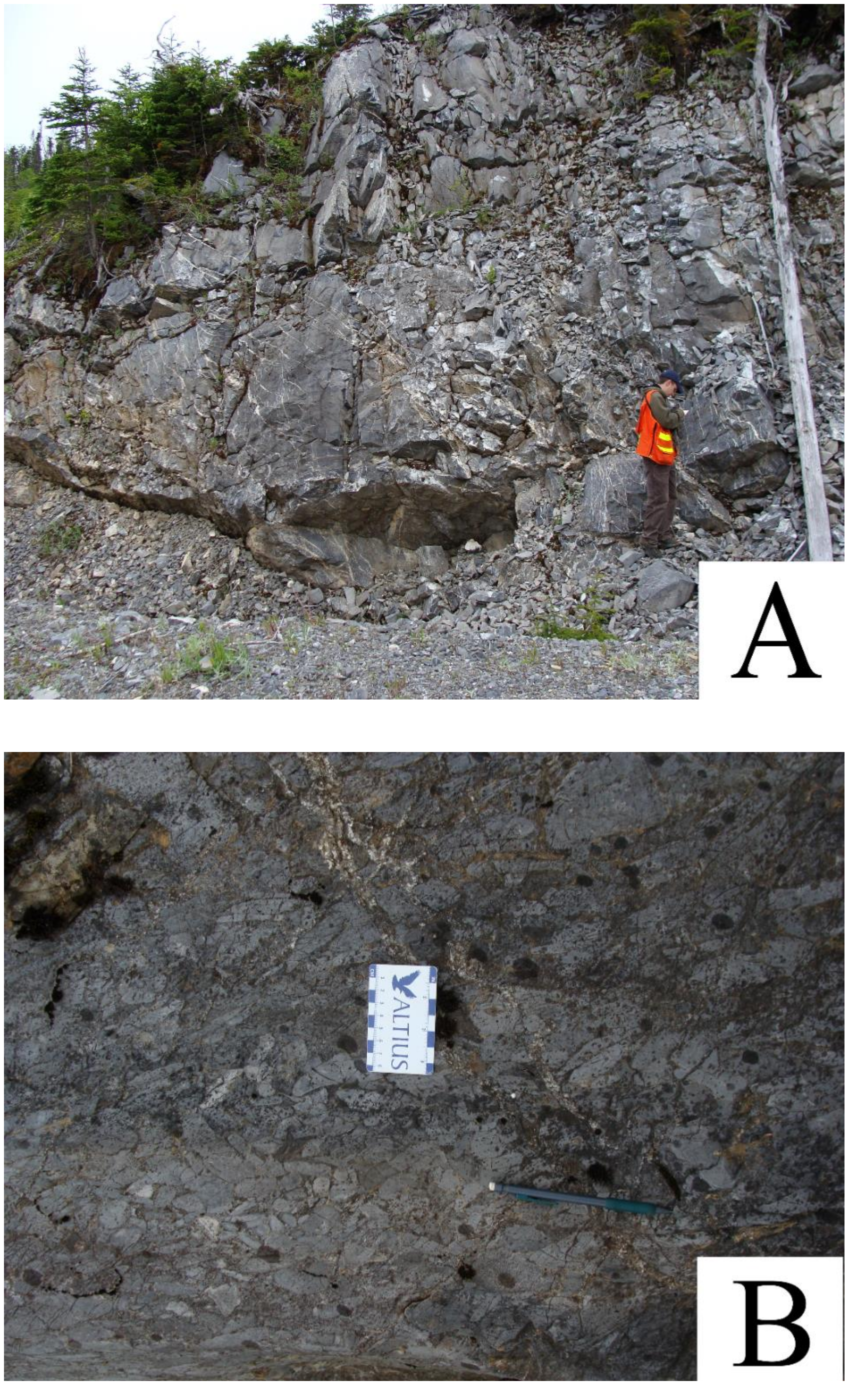


Figure 4.5: A) Very thick, massive, medium to coarse-grained calcarenite, Station 11MK-210. Geologist for scale. B) Carbonate clast conglomerate at Kennedy Lake. Pencil points north, station 11MK-379. 8.5 cm card for scale

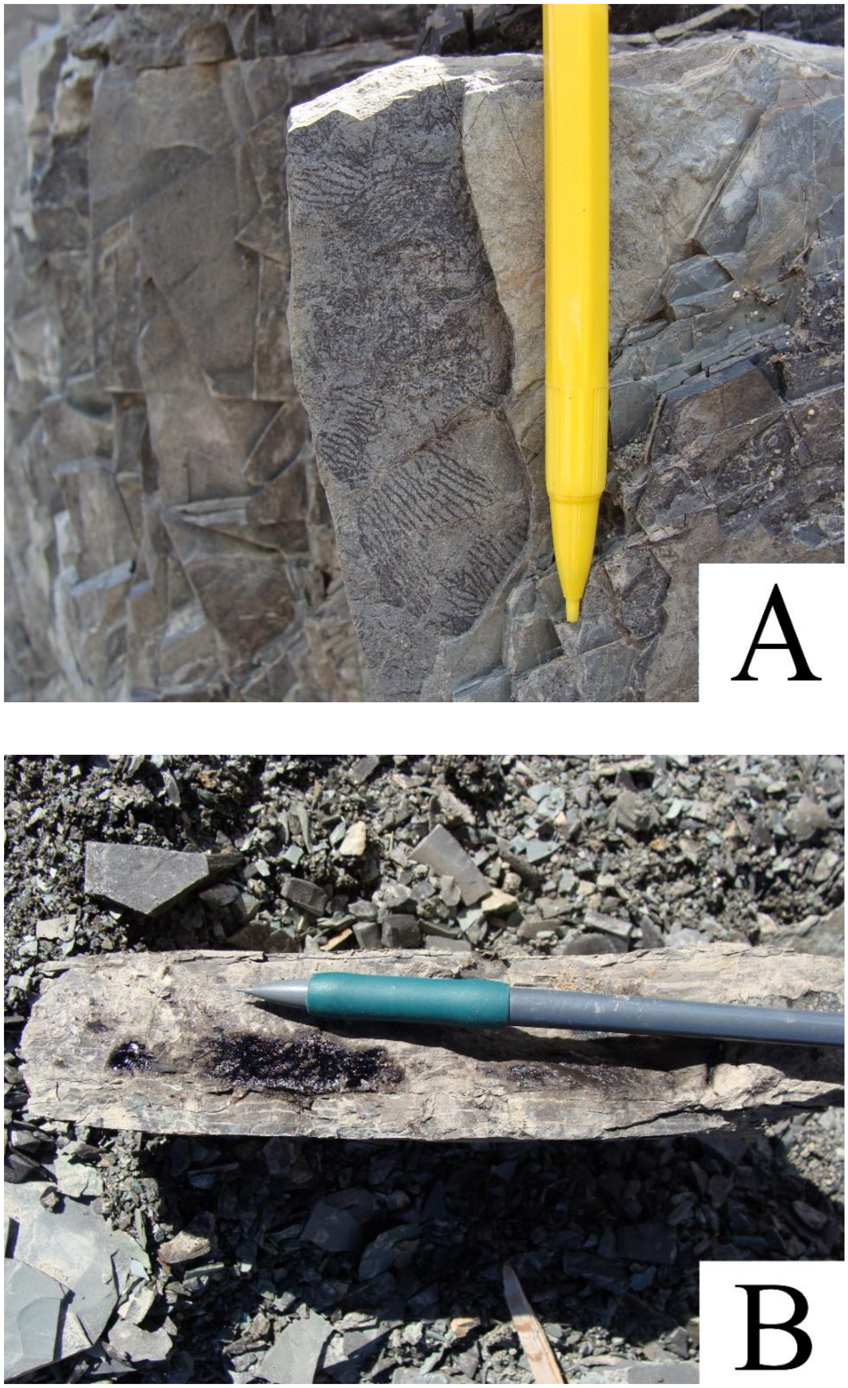


Figure 4.6: A) A dendroid graptolite assemblage densely distributed on a bedding surface of very fine-grained calcarenite. B) A small patch of oil on a fracture face of calcareous siltstone at Chimney Cove. Station 11MK-555.

Fault-bound, slices of dark grey to black, green, and red banded mudstone with thin to medium beds of interbedded tan weathering dolomitic siltstone to fine-grained calcarenite are exposed along these shores (Figure 4.7). Here, bands of black and green mudstone are generally around 10-30 cm thick. The interbedded parallel-wavy laminated carbonate beds range from several cm to around 40 cm, with grain size being generally larger in the thicker beds.

4.6 – The Lower Head Formation

4.6.1 – Geographic and Stratigraphic Distribution

Isolated sandstone outcrops, exposed near Kennedy Lake, extend along a trend to the southwest, and toward North Arm of the Bay of Islands (Map Sheet 1). In the southern Bay of Islands, Lower Head Formation strata are exposed in narrow imbricate slices along the northern and southern coastlines of the eastern part of Woods Island (Map Sheet 3). Regionally the formation may be seen as laying structurally beneath the older Blow Me Down Brook formation. Neither the upper nor the lower contacts for the Lower Head Formation are exposed.

4.6.2 – Lithologic Characteristics

The strata assigned to the Lower Head Formation are dominated by medium- to thick-bedded quartzose sandstone interbedded with dark grey mudstone, and sometimes interlaminated dark grey and greyish green mudstone. Sandstone beds are generally massive and laminated at their tops. They are mostly dark grey or dark greenish-grey and weather to a grey to buff colour. Where full sections are exposed at Woods Island, upward fining, upward thinning successions of the sandstone are interbedded with dark grey mudstone. Sandstone of the Lower Head Formation is characteristically similar to sandstone of the Blow Me Down Brook formation.

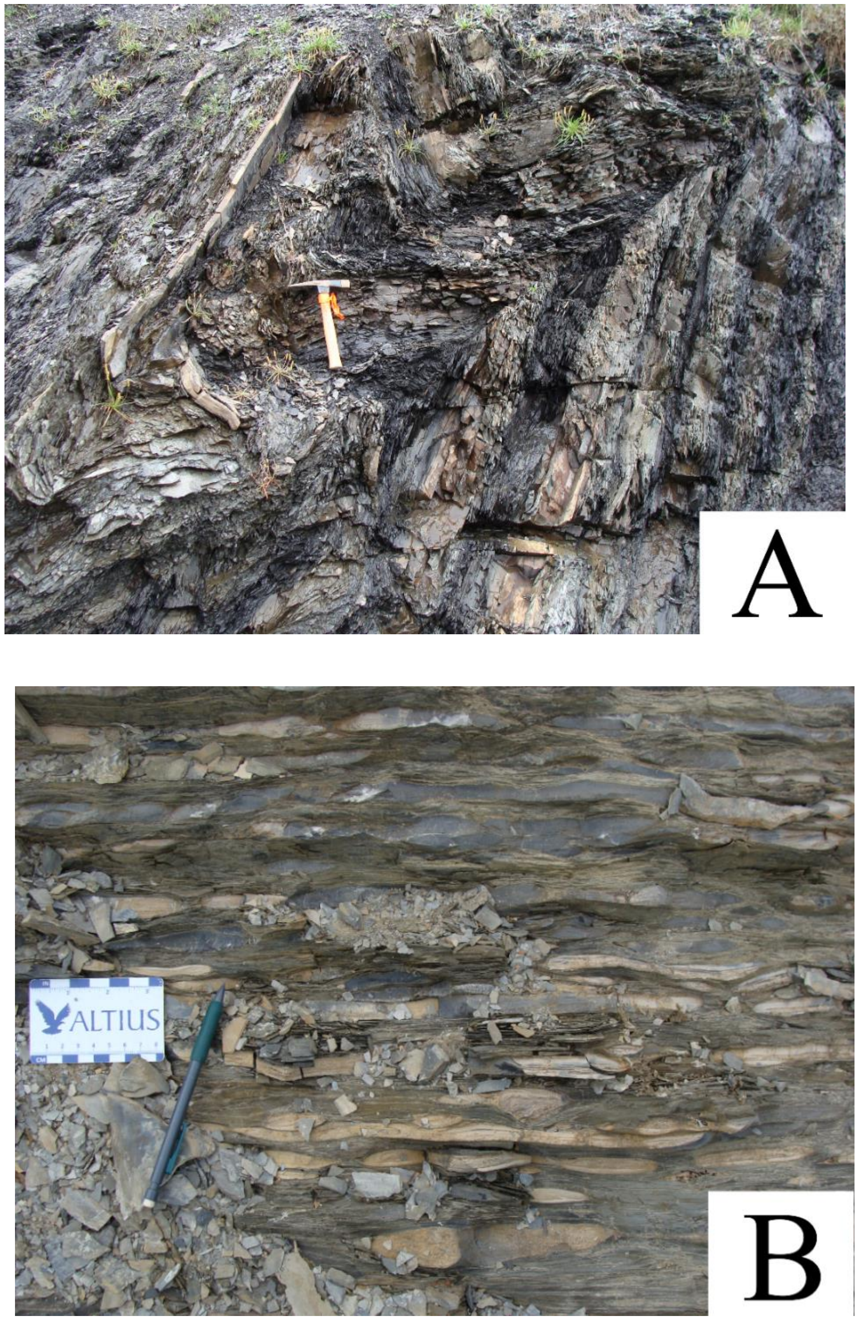


Figure 4.7: Middle Arm Point Formation lithologies. A) folded, black, green and red banded mudstone with thin dolomitic siltstone beds, station 11MK-422. Southeast Woods Island, with hammer for scale. B) Discontinuous laminated thin bedded dolomitic siltstone with interbedded dark grey mudstone between North Arm and Trout River Pond, station 11MK-208. 8.5 cm card for scale, pencil points north.

In the field the units have a comparable composition and colour. Traits that distinguish the Lower Head and Blow Me Down Brook formations include the friable nature of bed tops, basal cobble conglomerates, and generally low sandstone to mudstone ratio in the Lower Head Formation are characteristics not common in the similar Blow Me Down Brook formation.

4.7 – Igneous Rocks of the Humber Arm Allochthon

Mafic volcanic, volcaniclastic, and mafic and ultramafic plutonic rocks outcrop throughout the map region, and generally accounting for topographic relief on a scale of 10 to 300 m above nearby sedimentary terrain. The igneous rocks occurring in the area include mafic volcaniclastics, pillow basalt, breccia, basalt flows and dikes, gabbro, and variably serpentinized peridotite. The plutonic rocks, such as gabbro and peridotite are parts of the Bay of Islands and Little Port Complexes. They are outside the scope of this study and are not discussed here. The current lithostratigraphic nomenclature for the mafic volcanics (e.g. Williams and Cawood, 1989) is viewed as a more complicated matter and one that is tentatively reassessed in a geochemical study (Chapter 7). A reclassification of the volcanic lithologies is presented in Chapter 8.

4.7.1 – Geographic and Stratigraphic Distribution

Igneous rocks are identified in the entire study region. A cluster of three volcanoclastic outcrops is exposed along the banks of Trout River along the eastern flank of the North Arm Massif (stations 11MK-622, and 623). This grouping is interstratified with sandstone and mudstone successions of the Blow Me Down Brook formation. Volcaniclastics also flank the eastern side of the coastal highlands at Chimney Cove.

Pillow basalt and massive basalt flank the North Arm Massif south of Trout River Pond (Map Sheet 1), and the Table Mountain Massif in South Arm (Map Sheet 3). In the former region, and including Chimney Cove, discrete, tectonic slices of basalt separate mélange and dismembered formation from the Blow Me Down Brook formation. To the north in Bonne Bay several other tectonic slices of basalt are exposed in the same stratigraphic configuration, and separated from the Blow Me Down Brook formation by thin sheets of mélange and dismembered formation. Basalt is also exposed at Woods Island (Map Sheet 3). There, a north-south oriented sliver bisects the island and is structurally flanked by Blow Me Down Brook sandstone to the west and fault-bound panels of Blow Me Down Brook, Middle Arm Point, Lower Head Formation and mélange to the east.

Intrusive igneous rocks are not a principal component of this thesis study, but are generally exposed higher on the flanks of the massifs in the map area. Gabbro and peridotite are exposed at the western margin of the North Arm-Trout River Pond map area (Map Sheet 1) and form the North Arm Massif. They are also exposed at the northern and eastern margin of Chimney Cove (Map Sheet 2), and at the western and northern margins of South Arm (Map Sheet 3) where they form the Table Mountain Massif and the Lookout Hills Massif, respectively. These lithologies form the core of the regional highlands along this part of the western coast of Newfoundland. Here, plutonic rocks form the highest structural slice of the Humber Arm Allochthon (Williams 1973). For these lithologies, the focus of research was at their boundaries with the aim of better understand the relationship between the mafic rocks and the underlying sedimentary strata.

4.7.2 – Lithologic Characteristics of the Mafic Volcaniclastics

Mafic volcaniclastic rocks, such as agglomerate and ignimbrite (Figure 4.8) are exposed along the banks of Trout River (stations 11MK-622, and 623). The principal inclusion in the agglomerate is red weathering elongate, and round mafic bombs. The fragment size is highly variable and monomictic. The matrix of the rock is that of a very fine-grained, highly vesicular, green tuff. A parallel fabric is defined by the orientation of the long axes of the clasts.

Another prominent outcrop at this locality is a very thick, normally graded ignimbrite (Figure 4.9). Clasts in the ignimbrite are on the cm-scale and generally have a lenzoid shape, particularly near the base of the outcrop (Figure 4.8, B). Both the size and shape of the clasts is dependent on their distance from the base. Higher in this section, the clasts become smaller and more spherical in shape. The matrix is characteristically similar to the matrix of the nearby agglomerate to the south. It is a variably green vesicular tuff.

The volcaniclastic belt flanking the western highland at Chimney Cove (Map sheet 2) is a different rock suite from the volcaniclastics at Trout River. Here, a black cobble conglomerate, is comprised of a very fine-grained dark grey matrix with rounded cobbles of dark grey basalt interbedded with a carbonate clast breccia. The dark grey, very fine-grained matrix for the breccia hosts centimetre-scale, angular clasts of light grey carbonate (Figure 4.9).

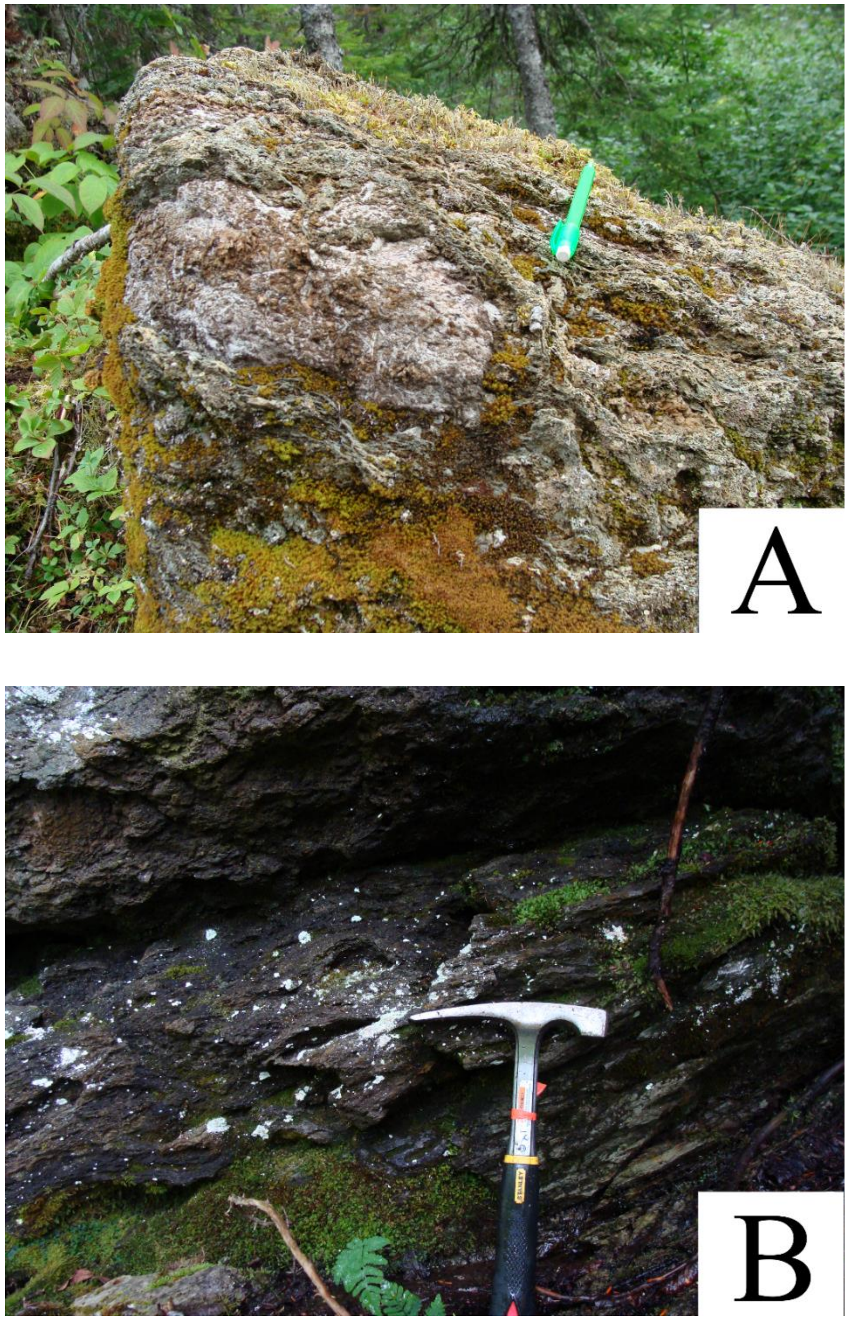


Figure 4.8: Volcaniclastic lithologies. A) Green mafic agglomerate with pencil pointing north, station 11MK-622. B) Texture of mafic ignimbrite on northern shore of Trout River, station 11MK-623.

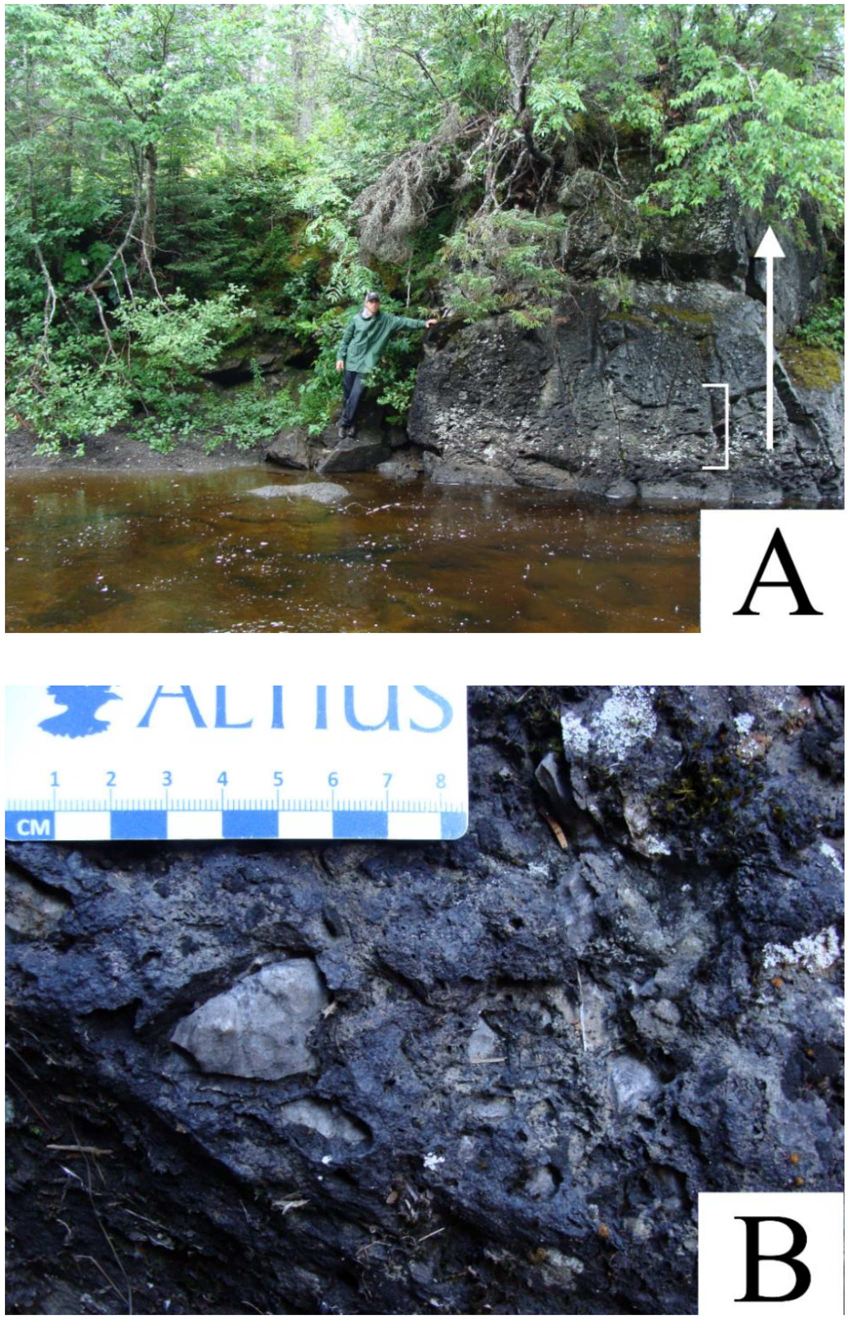


Figure 4.9: A) Outcrop of graded ignimbrite on the northern shore of Trout River. White arrow shows grading. Note flattened clast layer in the bracket. Station 11MK-623. Geologist for scale. B) Carbonate clast breccia exposed at the western margin of the Chimney Cove map region (10MK-152).

4.7.3 – Lithologic Characteristics of the Pillow Basalt and Massive Basalt

Red and less commonly purple pillow basalt and massive basalt are generally interlayered with one another (Figure 4.10). The basalt is generally green on fresh surfaces. Pillows range in size from approximately 50 cm to 1 m diameter. Veins and patches of white calcite mineralization are common within the mafic volcanic lithologies of this unit. Rarely, mafic dikes up to 1 m cross cut the mafic volcanic rocks. One of the better examples of a crosscutting dike is exposed at the southern end of Chimney Cove (Map Sheet 2).

4.8 – Mélange and Dismembered Formation

Pervasively deformed strata are poorly exposed along the flanks of ophiolitic massifs. These rocks separate the intermediate allochthonous slice from the highest structural assemblage of the allochthon. The strata are differentiated into broken formation or mélange based on the identification of easily definable exotic blocks in the latter. Given the close geographic and stratigraphic association of these beds, they are described together in this section.

4.8.1 – Geographic and Stratigraphic Distribution

Relatively narrow bands of mélange and dismembered formation are closely associated in the map region. They are exposed along the eastern flank of the North Arm Massif (Map Sheet 1), the eastern flank of the Table Mountain Massif at South Arm (Map Sheet 3), on the east and west margins of the valley in the northeast of Chimney Cove, (Map Sheet 2) and on the eastern end of Woods Island (Map Sheet 3).

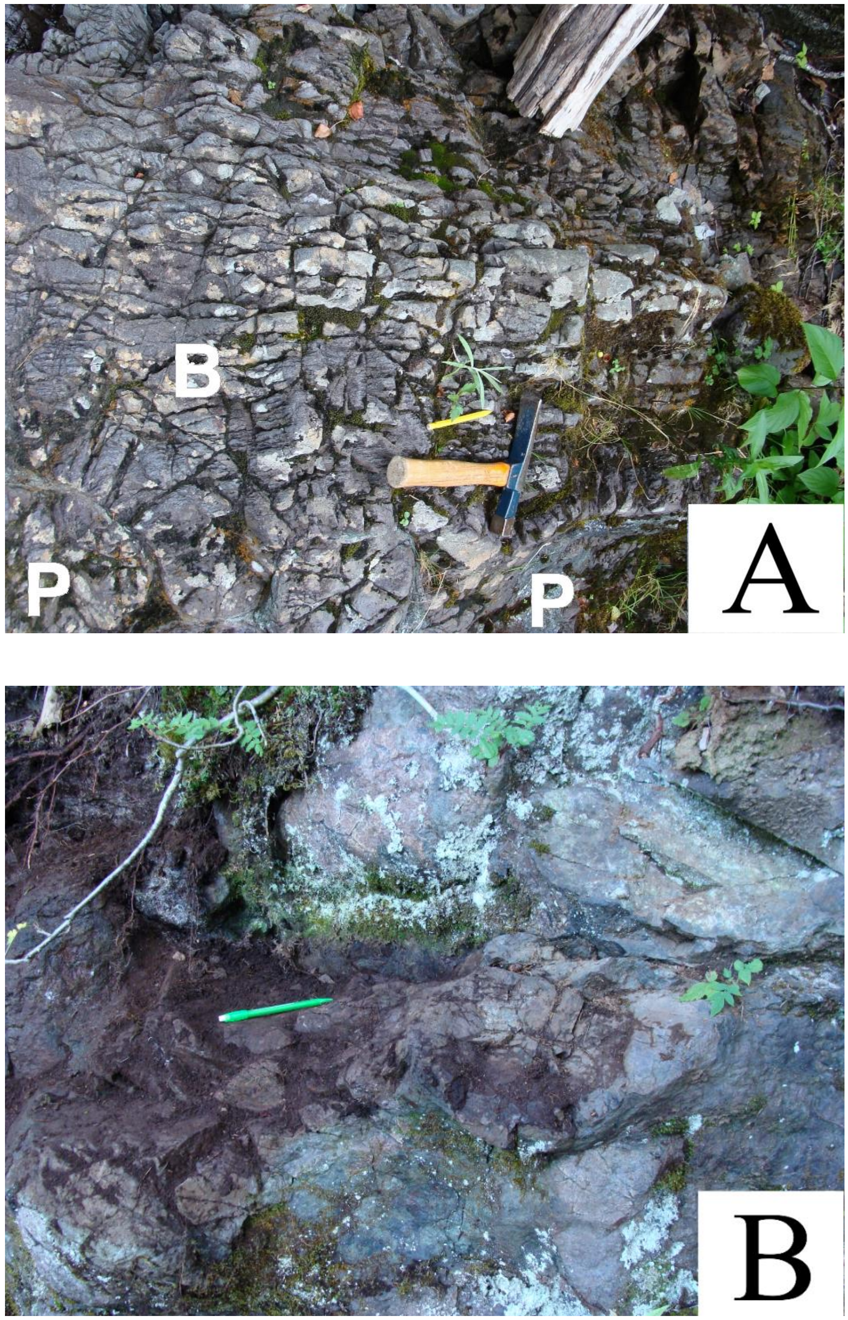


Figure 4.10: Mafic volcanic rocks. A) Massive (B) and pillow basalt (P) south of Trout River Pond, station 11MK-528. Note the hammer for scale. B) Red pillow basalt at South Arm, station 11MK-640. Note the pencil for scale.

Throughout the mapped area, upper and lower mélange contacts are not well exposed; hence, total thicknesses cannot be measured. Stratigraphically the mélange and dismembered formation underlies the Bay of Islands and Little Port complexes (Williams and Cawood, 1989) and it overlies the Blow Me Down Brook formation. On eastern Woods Island this tectonostratigraphy is broken by additional late faulting.

4.8.2 – Lithologic Characteristics

The mélange and dismembered formation that skirts the massifs is generally comparable at all of the field localities, and particularly in the composition of the matrix material and its underlying structure. The matrix is a phacoidally cleaved siliciclastic mudstone. It is predominantly dark grey in colour, though some matrix may have dismembered horizons of green mudstone, with smaller amounts of red mudstone (Figure 4.11). These lenses are mostly seen on a centimeter scale. At Woods Island, where there are excellent exposures of mélange and intercalated dismembered formation along the coastline, successions of thin- to thick-bedded, medium- to coarse-grained, quartzose sandstone are exposed (Figure 4.13). Several of the steeply dipping sandstone beds contained within mélange along the southern and northern shorelines of eastern Woods Island have basal conglomerates. These cobble conglomerates are monomictic with sub-angular to sub-round clasts of sandstone that are very similar in composition to the host sandstone.

A pebble-matrix mudstone is exposed at one locality in the northeastern Chimney Cove mélange, near Trout River Small Pond. Pyrite nodules up to 3 cm diameter are also hosted in this dark Chimney Cove mudstone matrix. In total, the mélange mudstones are by and large characteristically identical at every locality. Nevertheless, there is a variety of lithologies represented in the inclusions, or blocks.

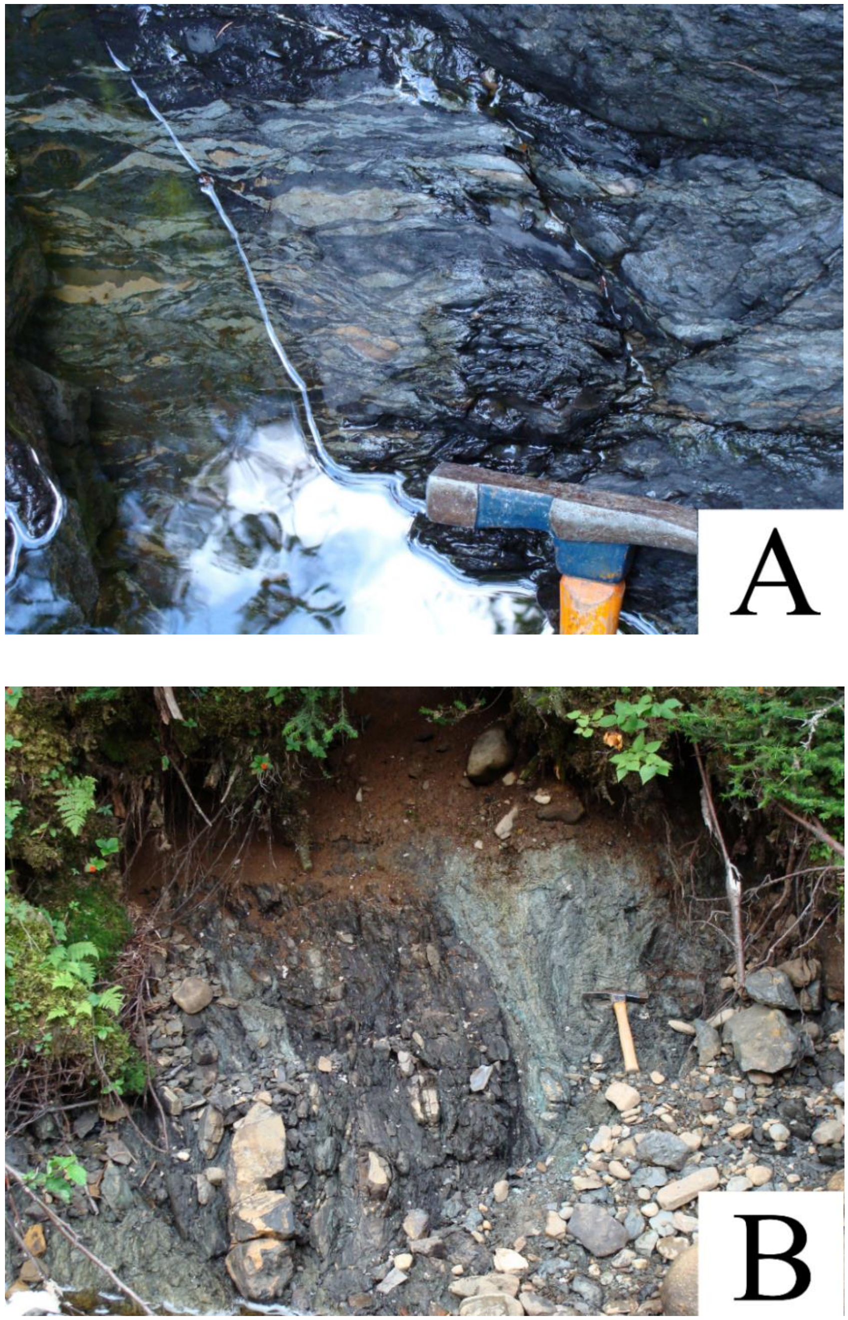


Figure 4.11: General characteristics of the matrix of mélange. A) cm-scale boudinage in fractured mudstones (North Arm Massif mélange, station 11MK-519). B) Broken pieces of laminated dolomitic siltstone in a dark grey and greyish-green matrix (Chimney Cove, station MK-594). Hammer for scale.

4.8.3 Classification of Large Blocks in Broken Formation and Mélange

Blocks in the dismembered formation and mélange are generally on the scale of 1-2 m. Sedimentary rock lithologies account for the range of block types in the dismembered formation. Mélange contains both sedimentary and igneous rocks. The sedimentary blocks include interbedded thin to medium bedded dolomitic siltstone and dark grey mudstone, and grayish-green quartzarenite. Carbonate blocks are divided into two groups; blocks that are successions of carbonate and mudstone, and blocks that are individually broken beds of carbonate beds. The igneous blocks include pillow basalt, mafic agglomerate, gabbro, and listwanite - a carbonate altered ultramafic rock.

4.8.3.1 – Bedded Carbonate and Mudstone

Bedded carbonate and mudstone blocks are metre-scale blocks of bedded successions of dolomitic siltstone and dark grey or light grey siliciclastic mudstone (Figure 4.12). They are the least abundant blocky component of the mélange and dismembered formation. The blocks are occasionally exposed in the deformed mudstone matrix and outcrop in streams along the eastern flanks of the massifs in the North Arm-Trout River Pond area (Map Sheet 1) and in the north of the Chimney Cove area (Map Sheet 2). The blocks are dolomitic beds with associated thin to medium bedded mudstones. The dolomitic beds are wavy laminated and trough cross-laminated rocks, light grey on fresh surfaces and weather to a tan or a light yellow colour. Their interbedded mudstones can be light grey to dark grey in colour.

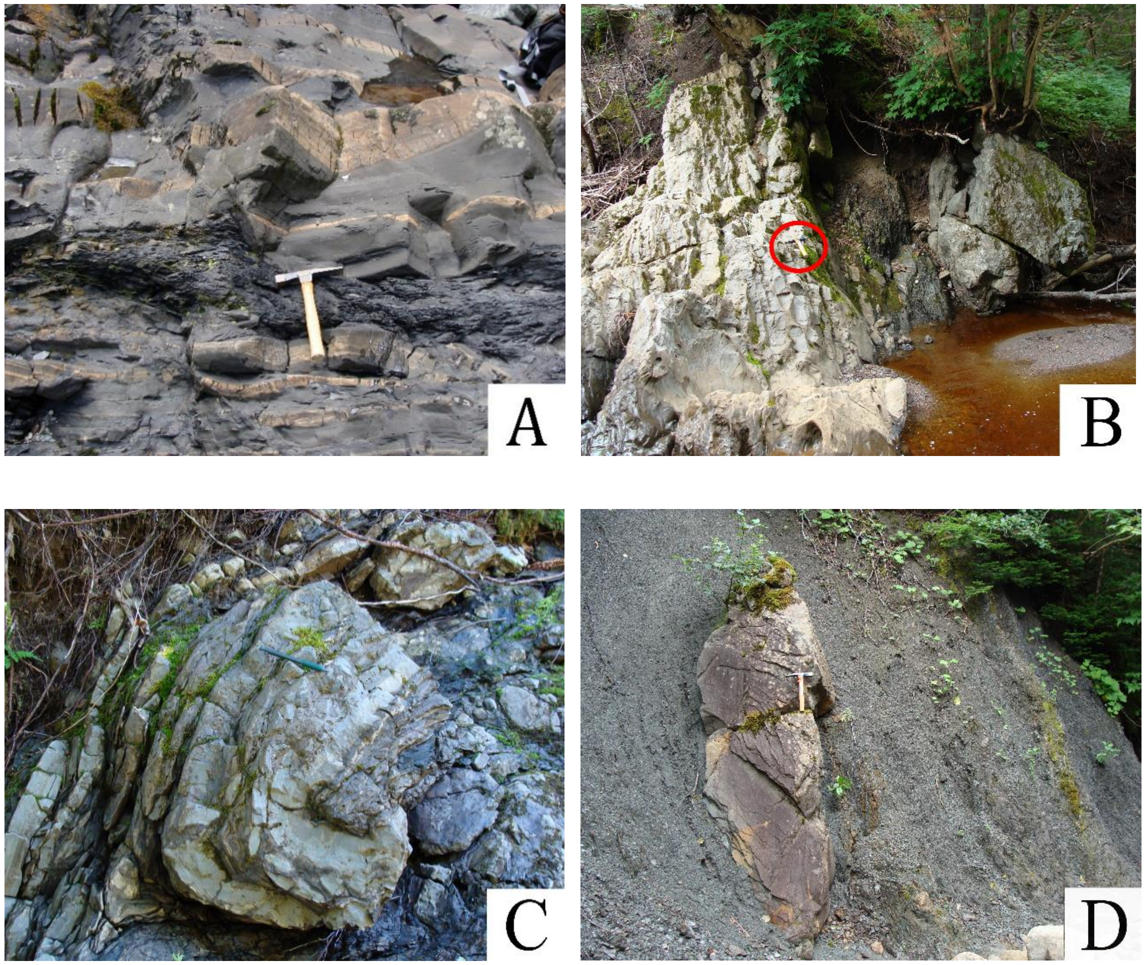


Figure 4.12: A), and B) Bedded carbonate and mudstone blocks of interbedded dolomitic siltstone and mudstone successions. The hammer for scale in B is highlighted by the red circle. Note (in A) the mudstone injection at the hammer. C) Dolomitic siltstone block rootless fold hinge in dismembered dolomitic siltstone bed, with pencil for scale. D) Quartzose sandstone. A - eastern flank of the North Arm Massif, B, C, and D - Northeast Chimney Cove. Stations 11MK-519, 10MK-125, 10MK-125, and 11MK-411 respectively.

In overall appearance, these blocks of broken carbonate-mudstone successions are conspicuously less deformed than the surrounding host matrix. This characteristic is most clearly seen by the lack of any pervasive deformation in the mudstone interbeds in the blocks (Figure 4.12, A and B). The blocks may also hold an odd array of mudstone dikes that simply crosscut the exotic blocks (Figure 4.12).

4.8.3.2 – Dolomitic Siltstone Blocks

Dismembered tan to yellow-weathering dolomitic siltstone beds are often associated with deformed muddy matrix materials (Figure 4.11, B). These pieces are the most numerous fragments in the mélange and are widely distributed throughout the map region. The broken dolomitic siltstone blocks are virtually indistinguishable from the dolomitic siltstone in the larger bedded carbonate and mudstone blocks. Unlike the larger bedded blocks there are no interbedded mudstone and dismembered carbonate beds. The dolomitic siltstone blocks are likely the residue from single beds that have been completely dismembered. This style of block tends to be small in size and normally no more than 20 cm thick. A large number of these dolomitic blocks are laminated. For the most part they are parallel laminated, and less frequently the blocks may be trough cross-laminated. A very minor subset of these blocks host pyrobitumen in fractures.

4.8.3.3 – Medium to Coarse-Grained Sandstone Blocks

Siliciclastic blocks in the mélange and dismembered formation (Figure 4.13) are relatively common. They are distributed throughout the mélange and dismembered formation at all localities. However, they are disproportionately common on the east end of Woods Island (Map Sheet 3). At a few localities these siliciclastics contain rounded, equant grains of black mudstone.

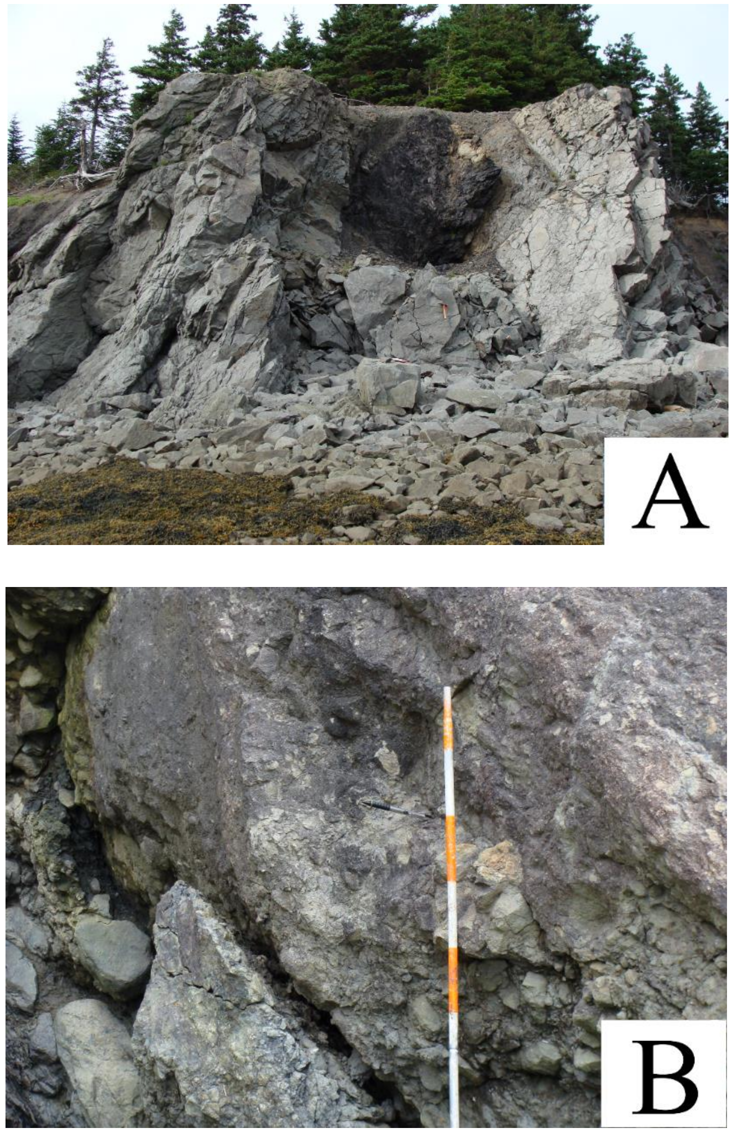
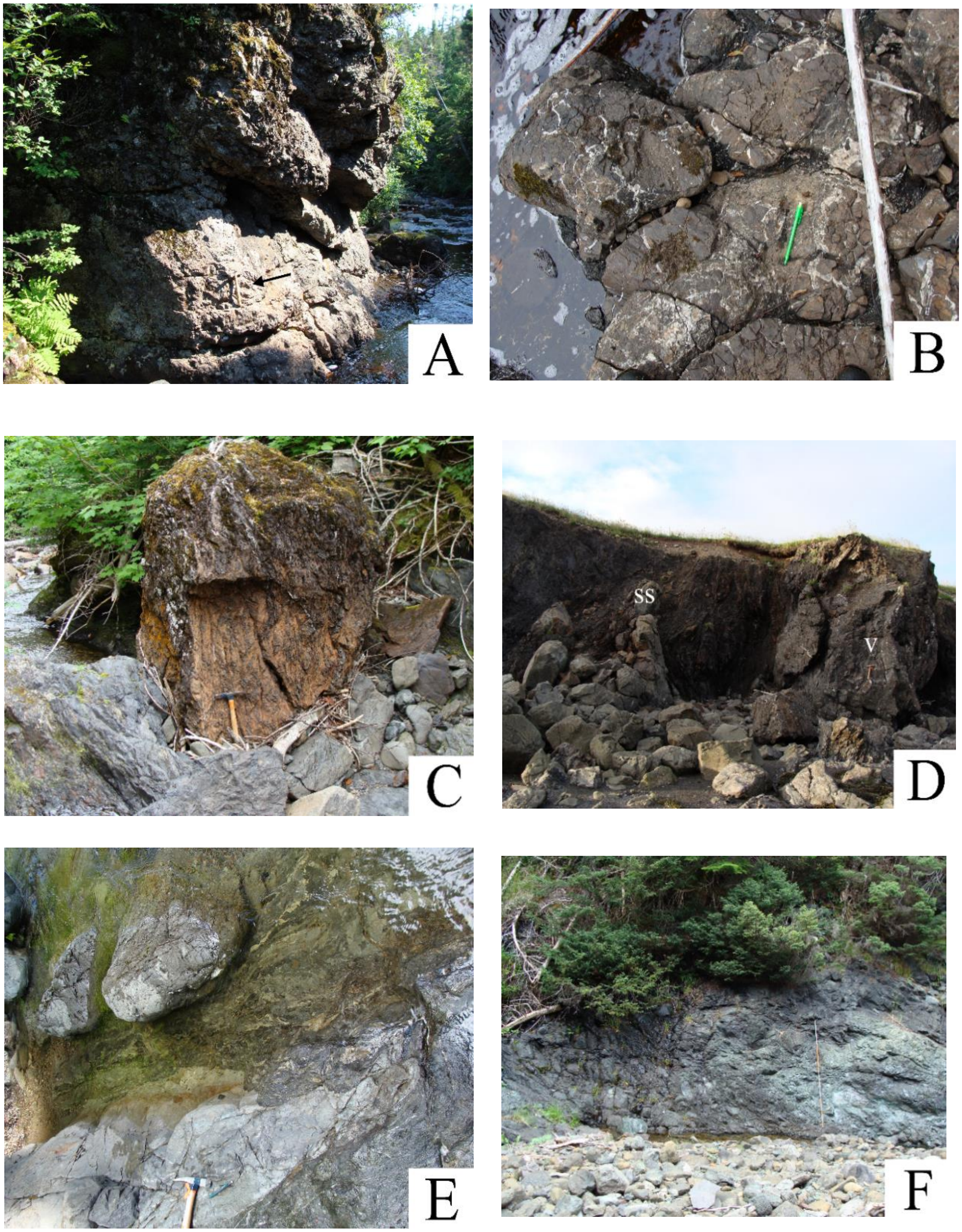


Figure 4.13: Sandstone blocks. A) Steeply west dipping thick-bedded quartzose sandstone in mélange at Woods Island (11MK-414; hammer in the centre of photo). B) Basal conglomerate in sandstone in mélange (11MK-410; 10 cm divisions on rod).

From petrography (Chapter 5) and geochemistry (Chapter 7), these blocks are typically medium to coarse-grained, grey and greenish-grey massive sandstone from both Blow Me Down Brook and Lower Head formations. The sandstone blocks are up to 1.5 m thick and predominantly massive, poorly sorted, quartzose sandstone that may thin and fine upward.

4.8.3.4 – Igneous Blocks

The variety of igneous blocks includes basalt and pillow basalt, listwanite, mafic agglomerate, gabbro, and serpentinite. The blocks of basalt may be on the order of up to 6 metres in thickness and may extend over an indeterminate but likely small surface area. For pillow basalt, the predominantly green pillows and larger pillow fragments may be up to 1 m in size. Some other mafic rocks are brecciated and contain calcite veins, vesicles and other unspecified void space (Figure 4.14). Blocks of yellow-weathering listwanite can range in size from several cm to 1.5 m. These distinctive rocks are exposed in mélange in the North Arm-Trout River Pond area and in the Chimney Cove area. Large mafic volcaniclastic blocks up to 4 m tall are exposed as blocks and small elevated mossy knobs near the eastern shore of Woods Island. The blocks are composed of centimeter-scale, rounded clasts of vesicular basalt and gabbro with minor intercalated black mudstone in a fine-grained mafic matrix (Figure 4.14, D). At South Arm, a similar suite of mélange and dismembered formation in Winterhouse Brook contains blocks of gabbro at least 5 m thick. Not too far away at Shoal Brook mélange contains a large block of blue serpentinite.


A
B
ss
v
C
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F

Figure 4.14: Varieties of igneous blocks. A) and B) Pillow basalt in northern Chimney Cove. The black arrow in A) points to the hammer used for scale C) Listwanite near Trout River Big Pond, D) Mafic volcaniclastic (v) in Woods Island mélange. The hammer used for scale is under the (v), E) Gabbro in South Arm mélange, F) Serpentinite in South Arm mélange with a 2 m pole for scale. Stations 11MK-586, 11MK-594, 11MK-525, 11MK-436, 10MK-104, and 10MK-069 respectively.

Chapter 5

Sandstone Petrography of the Blow Me Down Brook formation, Irishtown Formation, and Mélange and Dismembered Formation Sandstone Blocks

5.1 – Introduction

In an effort to classify the sandstone of the area, samples of the Blow Me Down Brook formation, and Irishtown Formation were analyzed petrographically and compared with petrographic analyses of sandstone blocks from mélange and dismembered formation. Their respective framework grains, texture and compositions are described, also their compositions are quantified, and summaries of analyses are plotted on ternary diagrams.

5.2 – Framework Grains, General Textures, and Modal Percentages of the Blow Me Down Brook formation

5.2.1 – Framework Grains

Quartz is the most abundant detrital grain in samples collected from the Blow Me Down Brook formation. Quartz grains are both monocrystalline and polycrystalline. They may be angular to rounded and highly variable in size. Here, quartz displays both undulose and straight extinction. A small subset of the quartz grains contains needle-like inclusions that could not be identified. Polycrystalline quartz grains are generally larger than the mean grain size. The predominantly sub-angular to sub-rounded grains are variably composed of clusters of 2 to 30 small grains and with most commonly containing 5 or less small grains. The boundaries between small grains in a cluster are most often seen as irregular, and sutured (Figure 5.1).

Grains of potassium feldspar (orthoclase) are commonly larger than the overall mean grain size for the sample and tend to be sub angular in shape. They are colourless in plane-polarized light but sericitic alteration tends to give the feldspar a cloudy appearance. Detrital orthoclase grains may either display indistinct tartan plaid twins or are have no twinning (Figure 5.3).

Plagioclase grains are generally smaller than the mean grain size and are sub-angular to angular. The crystals are commonly twinned according to the Albite Law (Figure 5.3). Grains are colourless in plane-polarized light and present a cloudy texture from sericitization. In addition, they are commonly altered, either partially or completely, to calcite. Minor amounts of chlorite within the plagioclase grains indicate incipient chloritization of the feldspar or its weathering products.

There are several types of rock fragments identified as detrital grains in this formation. They include mudstone, sandstone and plutonic rock clasts. Though distinctive in appearance, mudstone fragments are sparsely distributed within the sandstone samples. The fragments are generally elongate, rounded and brown in colour. They consist of brown and highly birefringent clay minerals that are too fine to classify. The sandstone fragments are composed of angular to sub-angular quartz and feldspar grains surrounded by a clay matrix. They too are proportionally rare, and perhaps because the similarities between the grains and the host sandstone hinders any definitive interpretation. Felsic plutonic rock fragments consist of intergrown quartz and feldspar crystals (Figure 5.3). They are generally sub-round and round. They are more often larger than the mean grain size and less commonly, equivalent to the mean grain size.

Several varieties of accessory minerals also occur in the Blow Me Down Brook formation sandstone. These include minor quantities of mica, chlorite, and zircon. For mica, biotite and muscovite are both observed in these sandstones. The tabular mica grains are generally angular and smaller than the mean grain size. In one sample the biotite grains were laying on the bedding plane. Chlorite, another minor component, is found within the matrix of the sandstone samples (Figure 5.2) and also as detrital grains. Detrital zircon is a rare accessory mineral in these sandstone samples. The grains are angular and sub-angular and commonly below the mean grain size. These high relief grains are colourless in plane-polarized light and have high order interference colours under cross-nicols (Figure 5.2).

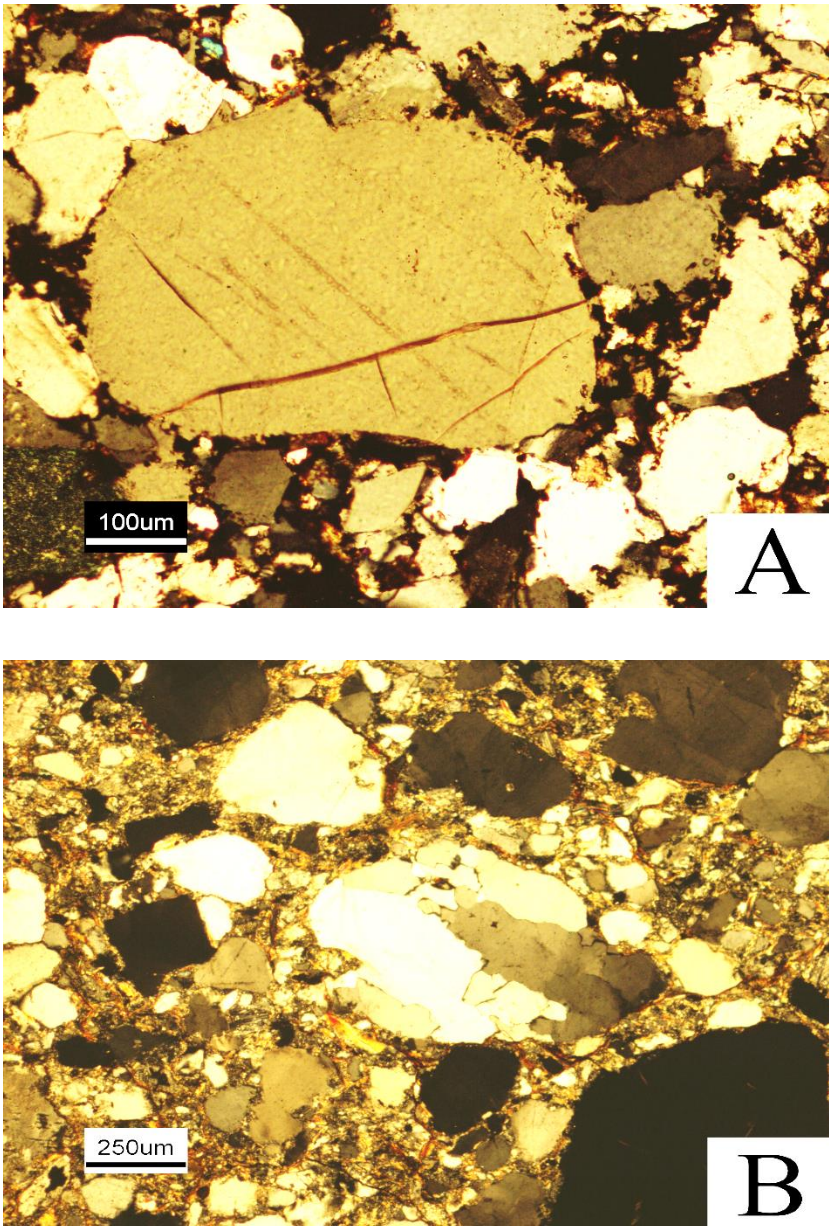

Figure 5.1: A) Quartz grain with pitted and embayed grain boundaries from a sample collected from the Blow Me Down Brook formation. Sample MK-223 under cross-nicols. B) Example of polycrystalline quartz grain of the Blow Me Down Brook formation with irregular to sutured sub-grain boundaries. Sample MK-300, cross-nicols.

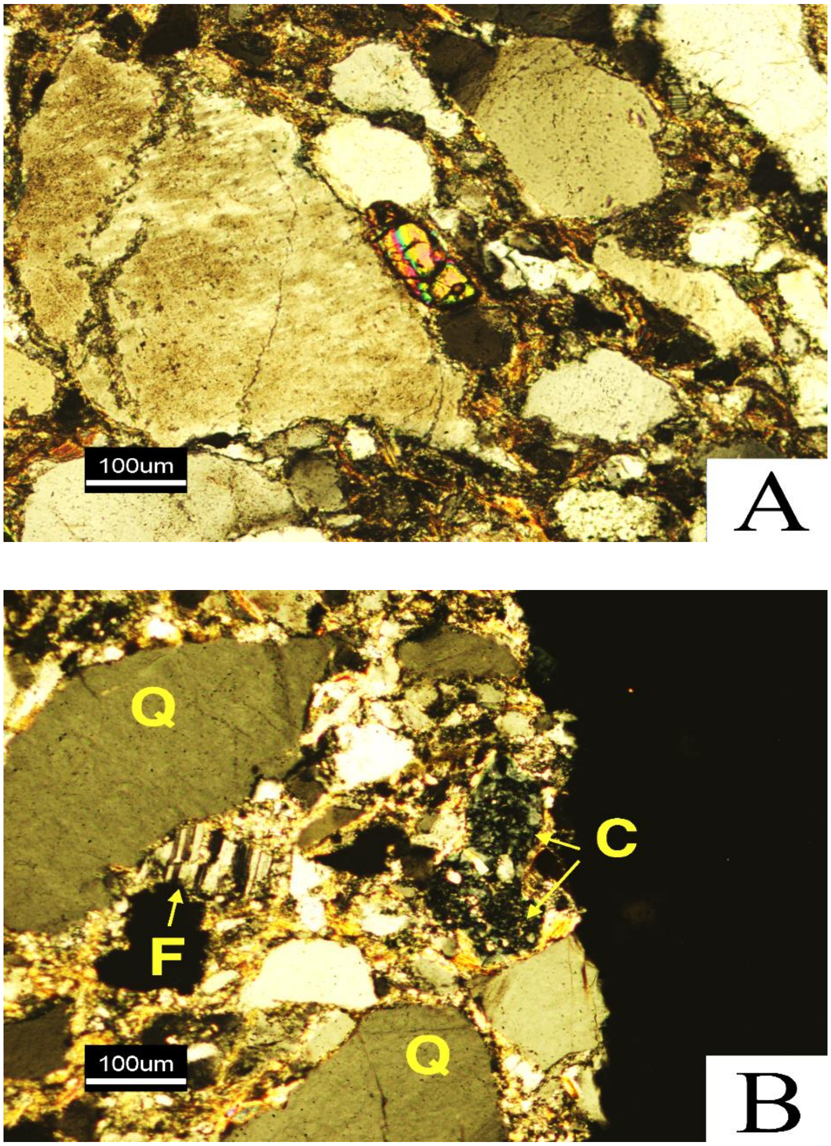

Figure 5.2: A) Untwinned feldspar grain (largest grain in photo) in the Blow Me Down Brook formation, with sericite alteration. Note highly birefringent zircon at the center of image. Sample MK 76-4. B) Small, unaltered, plagioclase (left of centre) in the Blow Me Down Brook formation. Sample MK-300. Q = quartz, F = plagioclase, C = chlorite.

5.2.2 – General Texture of the Blow Me Down Brook formation in Thin Section

The Blow Me Down Brook formation sandstone can be characterized as a poorly to moderately sorted, fine to pebbly sandstone, with round to angular grains (Figure 5.4).

The roundness of the individual grains is dependent upon the size and composition of the grains. Larger quartz grains are generally round, whereas large feldspar grains are sub-round and sub-angular. The relationship between rounding and grain size is most pronounced in both monocrystalline and polycrystalline quartz grains. For feldspar, the grains are less resilient and tend to show sericite alteration, with some chloritization and frequently significant replacement by calcite.

The poorly sorted sandstone tends to be matrix supported, whereas the better sorted sandstones are grain supported. In grain support, the grain-to-grain contacts are prominently planar; in other samples irregular, and pitted contacts are also seen as indications of compression with pressure solution. Where matrix supported, the grains also show signs of compression. Grain edges are pitted, embayed, and indistinct from dissolution of the grain. The degree to which grain edges are dissolved varies among samples, however it is generally uniform within any individual sample.

For matrix supported rocks, the matrix accounts for 10-37% of the sandstone and is a brown colour in plane polarized light. Under high magnification, it is thought to be composed of highly birefringent clay minerals with a minor component of chlorite. Calcite sometimes occurs as a fracture filling cement and also as a replacement product from feldspar. The abundance of matrix and late calcite cement significantly reduces the porosity of the Blow Me Down Brook sandstones examined in this study area.

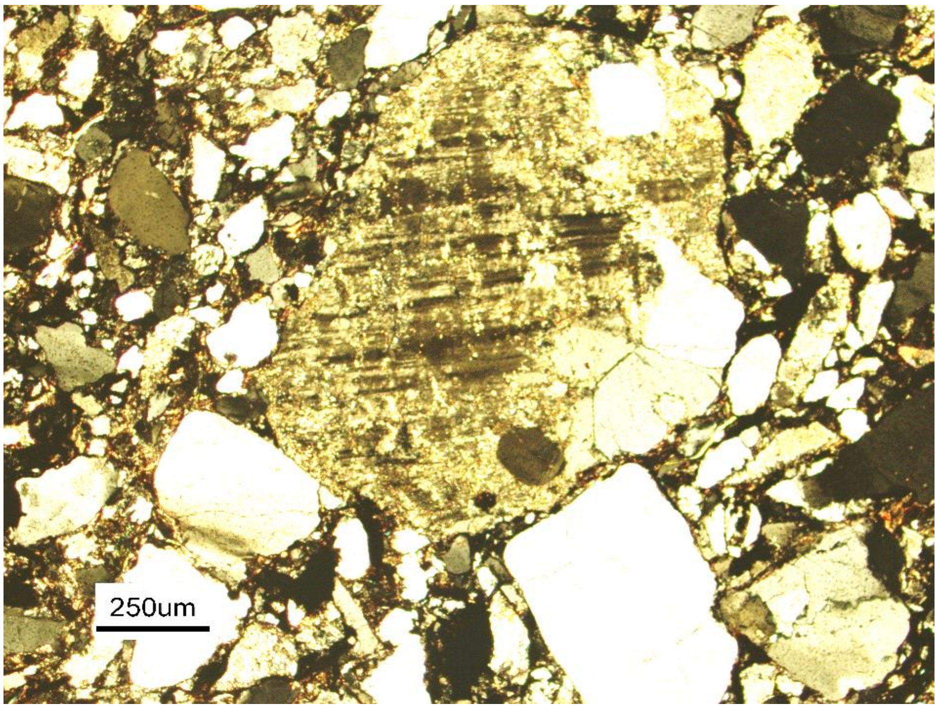

Figure 5.3: Felsic rock fragment. Sample MK-154.

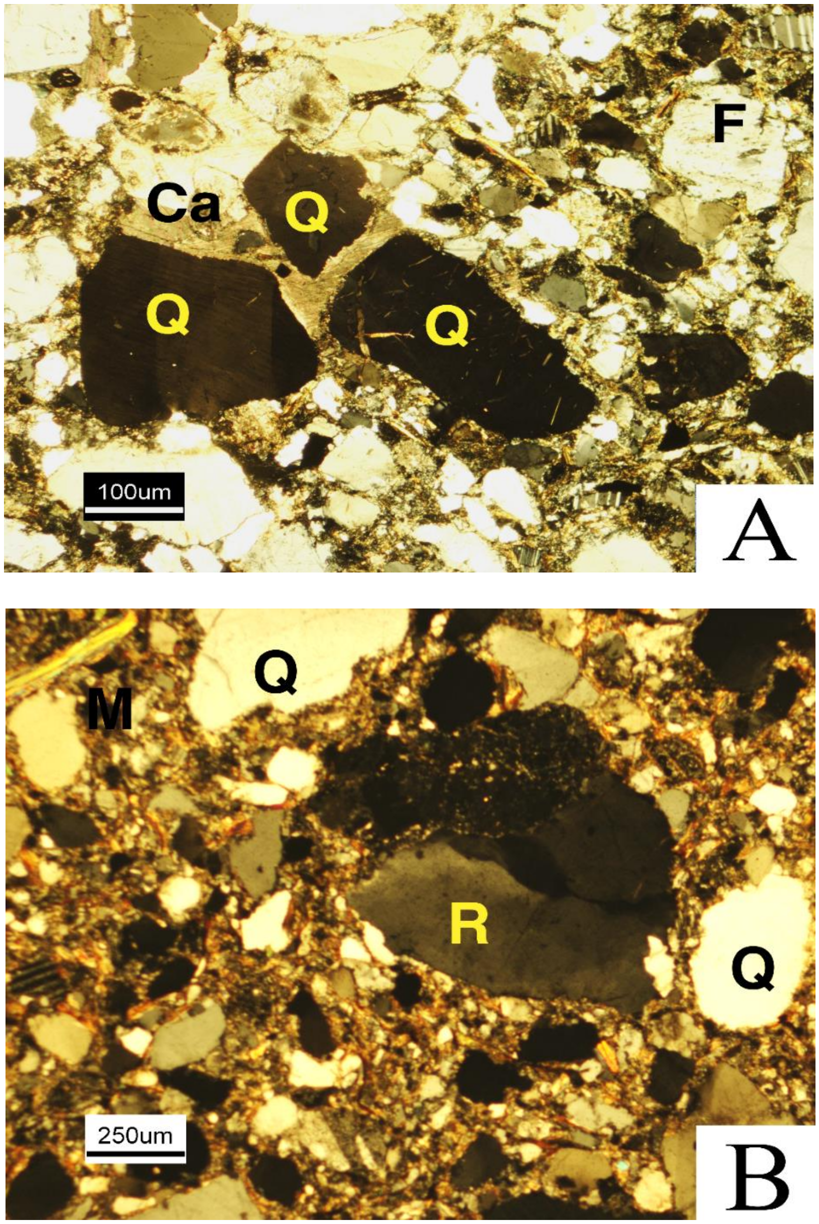

Figure 5.4: Typical texture and composition of the Blow Me Down Brook formation sandstone under cross-nicols. A) Mostly sub-angular to sub-rounded grains, poorly sorted, within a clay-chlorite matrix. Note the minor calcite cement (Ca) between monocrystalline quartz grains (Q) in the top photo. Sample MK-76-2. B) Plutonic rock fragment (R). Sample MK-300. Q = quartz, F = feldspar.

In outcrop mapping, many stations are modest in size, rarely showing any form of bedding, and appearing massive. In other areas, grading and distinctive bedding is identified, but overall this is not a frequently observed feature. For some samples in the field and in the lab, biotite grains provide a faint indication of bedding.

5.2.3 – Modal Percentages for the Blow Me Down Brook formation

Blow Me Down Brook formation petrography indicates a quartzo-feldspathic composition for sandstones (Figure 5.5), with samples distributed in the subarkosic arenite and quartz arenite fields. Total quartz grains range from 59-97% of the total composition of the sandstone, with an average of 82%. It's worth noting that the lower bounding sample, in the arkosic arenite field, is an anomalous red sandstone (sample MK154), compositionally distinct from the rest of the Blow Me Down Brook samples. Discounting the anomalous sample with 59% total quartz boosts the quartz range to 72-97% and with an average of 84% total quartz for the unit.

The proportion of feldspar grains in the sandstone ranges from 2% to 36%. The average modal percent is 14%. The least common fragments, the lithic fragments, range between 1% and 9% with a mean of 4% for these coarse Blow Me Down Brook siliciclastics.

5.3 – Framework Grains, General Textures, and Modal Percentages for Irishtown Formation Sandstone

5.3.1 – Framework Grains

Quartz, feldspar, and sedimentary rock fragments are all part of the Irishtown Formation sandstone. This also includes both monocrystalline and polycrystalline quartz grains in the sediment detritus.

Grains of monocrystalline quartz are the most abundant sand grain in Irishtown Formation (Figure 5.6). They are sub-round and round and variable in size. Contacts are generally concave-convex, and some contacts have overgrowths of silica (Figure 5.6). They dominantly display undulose extinction. A minor subset of the quartz grains contains needle-like inclusions that indiscernible. The grains also have very thin rims composed of an opaque material that is likely oxide minerals.

Polycrystalline quartz grains are made up of amalgamations of 2-12 quartz grains. For the most part they are made up of 3 or less irregularly sutured grains.

The grains of potassium feldspar are dominantly sub-angular to sub-round and smaller than the mean grain size. The potassium feldspar detritus is dominantly untwinned. Plagioclase grains are similarly small and sub-angular. They are distinguished by Albite twinning.

The lithic fragment component of the Irishtown Formation is entirely sedimentary rock fragments, and mostly silty mudstone clasts. They are commonly smaller than the mean the grain size, and sometimes around the average grain size. They are brown in both plane-polarized light and with the cross-nicols inserted. Silt sized, round, silica and carbonate grains lie in the clay matrix of the mudstone (Figure 5.7).

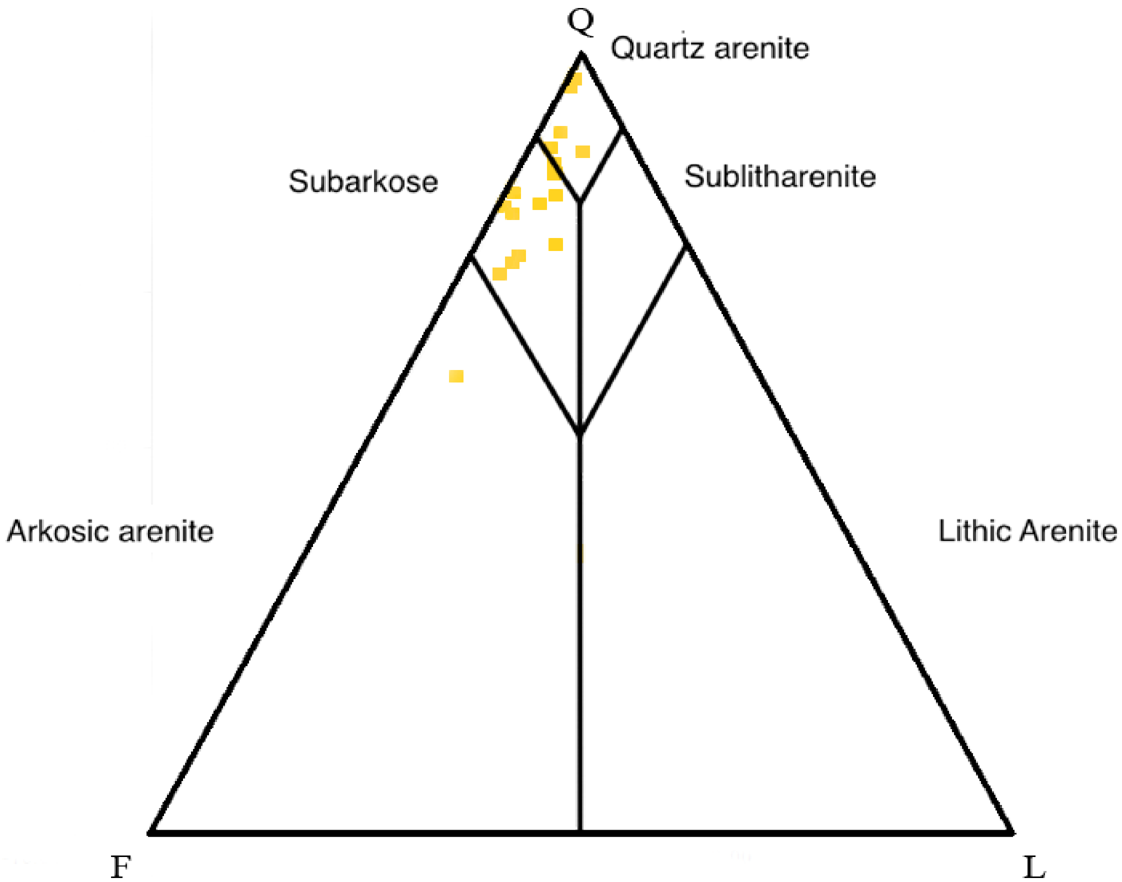

Figure 5.5: Sandstone classification diagram for the Blow Me Down Brook sandstone from all regions studied. Q = total quartz, F = total feldspar, L = lithic fragments. Diagram after Pettijohn (1975).

There are a few types of accessory grain types sparsely distributed throughout the Irishtown Formation sandstone samples. These include biotite, zircon, and opaque minerals. Their size is generally much smaller than the average grain size and they make up a fraction of the sandstone's overall composition.

5.3.2 – General Texture of the Irishtown Formation in Thin Section

The sandstones of the Irishtown Formation are well sorted, tightly packed, and massive (Figure 5.6). They are dominantly composed of, monomineralic sub-round to round quartz grains. Contacts between grains may be concave or pitted. Overgrowths of silica also occur at the edges of some of the monocrystalline quartz grains.

Matrix distributed in relatively small spaces between the sand grains is rare in the sandstone samples examined here. It is thought to be composed of clay minerals that are too fine to discern, and with a light brown colour in plane-polarized light. Calcite also fills other small pore space not otherwise occupied by the matrix material.

5.3.3 – Modal Percentages for the Irishtown Formation

This formation's sandstone is quartz rich (Figure 5.8). With 4 samples analyzed, the lowest proportion of quartz grains was 95% with an average quartz composition of 97.5%. Feldspar composition lies between 0 and 4% and is on average of 1.75% of the grains counted. Lithic fragments account for up to 1% of the grains and average 0.5% across the four Irishtown samples Angular to rounded quartz grains in the sandstone blocks and beds make up the greatest proportion of framework grains. They are dominantly monocrystalline grains, with lesser numbers of polycrystalline grains.

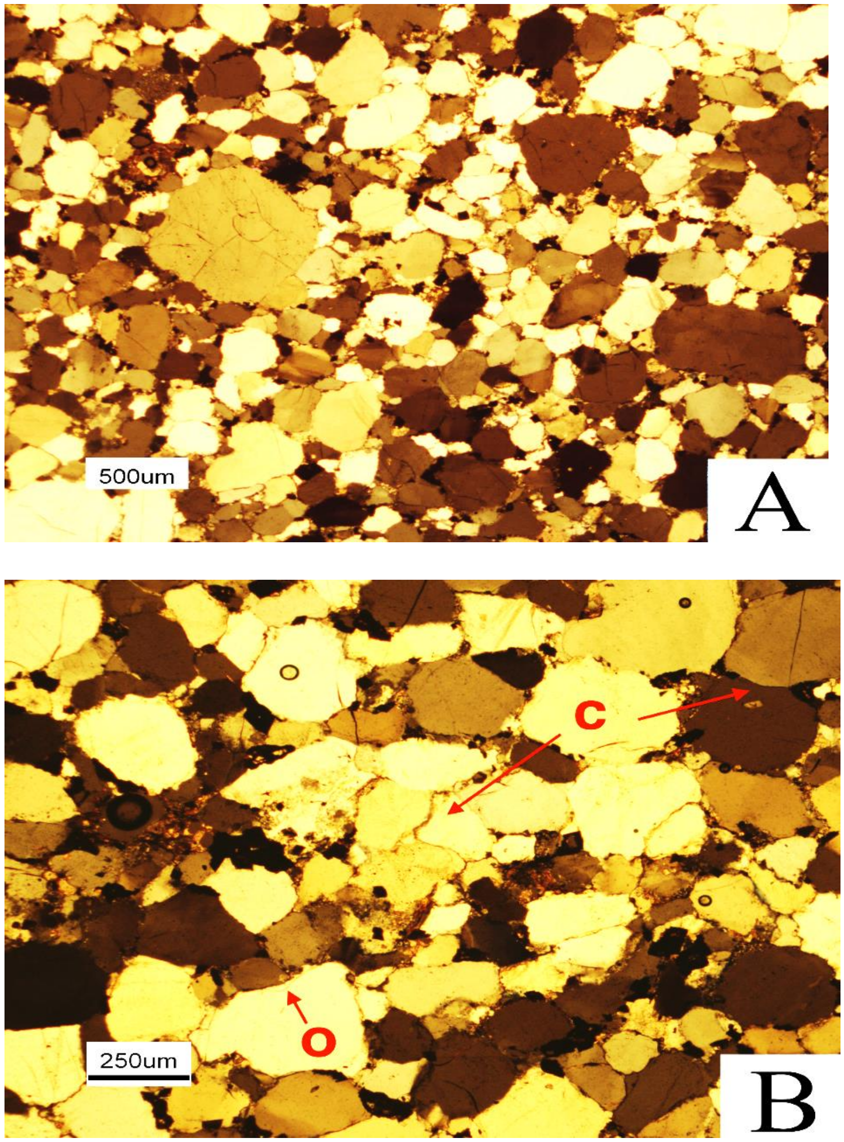

Figure 5.6: Photomicrograph of Irishtown Formation sandstone. A) General texture of the sandstone. B) Concave-convex grain boundaries (C), and quartz overgrowths (O). Sample MK-237.

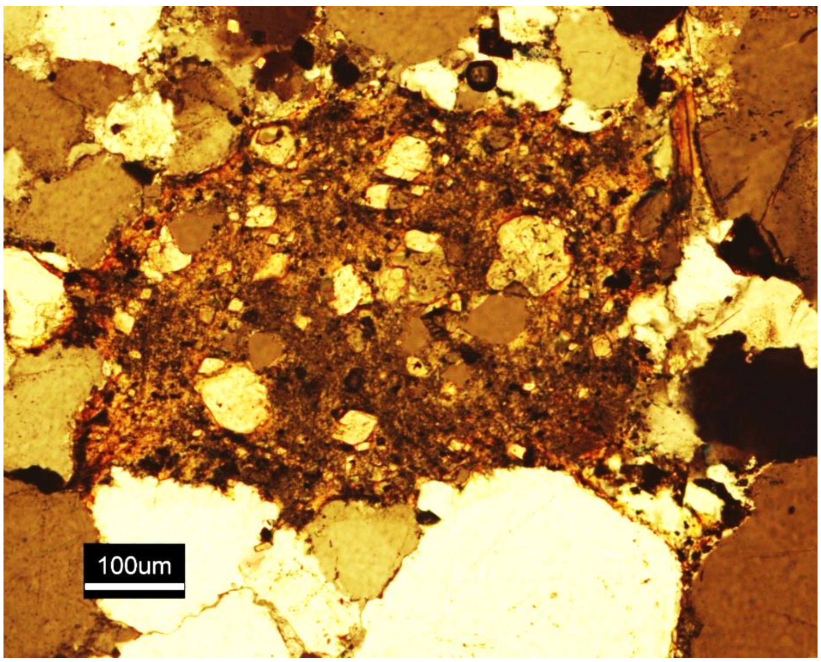

Figure 5.7: Silty mudstone lithic fragment with quartz and calcite detritus. Sample MK-237.

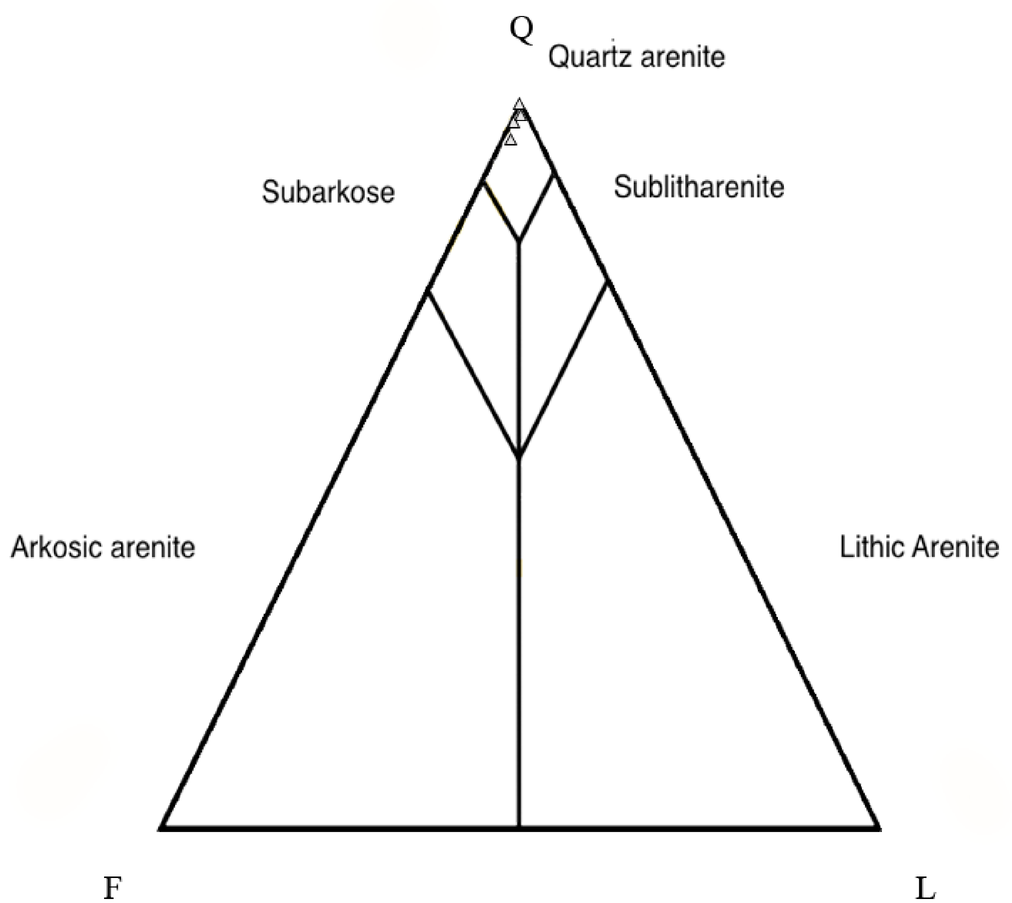

Figure 5.8: Figure 5.8: Sandstone classification diagram for the Irishtown sandstone from all regions studied. Q = total quartz, F = total feldspar, L = lithic fragments. Diagram after Pettijohn (1975).

5.4 – Framework Grains, General Textures, and Modal Percentages of Mélange and Dismembered Formation Sandstone Blocks

5.4.1 – Framework Grains

Monocrystalline quartz grains show considerable variation in their size and generally account for the majority of grains that are larger than the mean grain size (Figure 5.9). Polycrystalline quartz grains are sub-angular to sub-round and all are generally larger than the mean grain size. Smaller varieties are rare. Commonly the polycrystalline grains are assemblies of 5 or less small grains irregularly sutured together.

Potassium feldspar detritus is generally sub-angular, and almost always larger than the mean grain size. The grains are colourless in plane-polarized light and have a distinct cloudy texture due to sericite alteration. Some feldspar grains display tartan plaid twinning and others are not twinned (Figure 5.9).

Detrital plagioclase grains are predominantly sub-angular to angular and generally below the size of the average grains. They have both Carlsbad and polysynthetic twins, sometimes in the same grain. Sericite alteration commonly creates a cloudy texture on their surface and there is often incipient calcite and chlorite alteration of the grains.

Mudstone, sandstone and plutonic rock fragments make up the lithic grain assemblage of the framework grains in the mélange and dismembered formation sandstone. Distinctive mudstone fragments are sparsely distributed within the sandstone. These fragments are generally elongate, rounded and brown in colour. They consist of brown and highly birefringent clay minerals that are too fine to classify. The sandstone fragments are composed of angular to sub-angular quartz and feldspar grains surrounded by a clay matrix. They are proportionally rare,

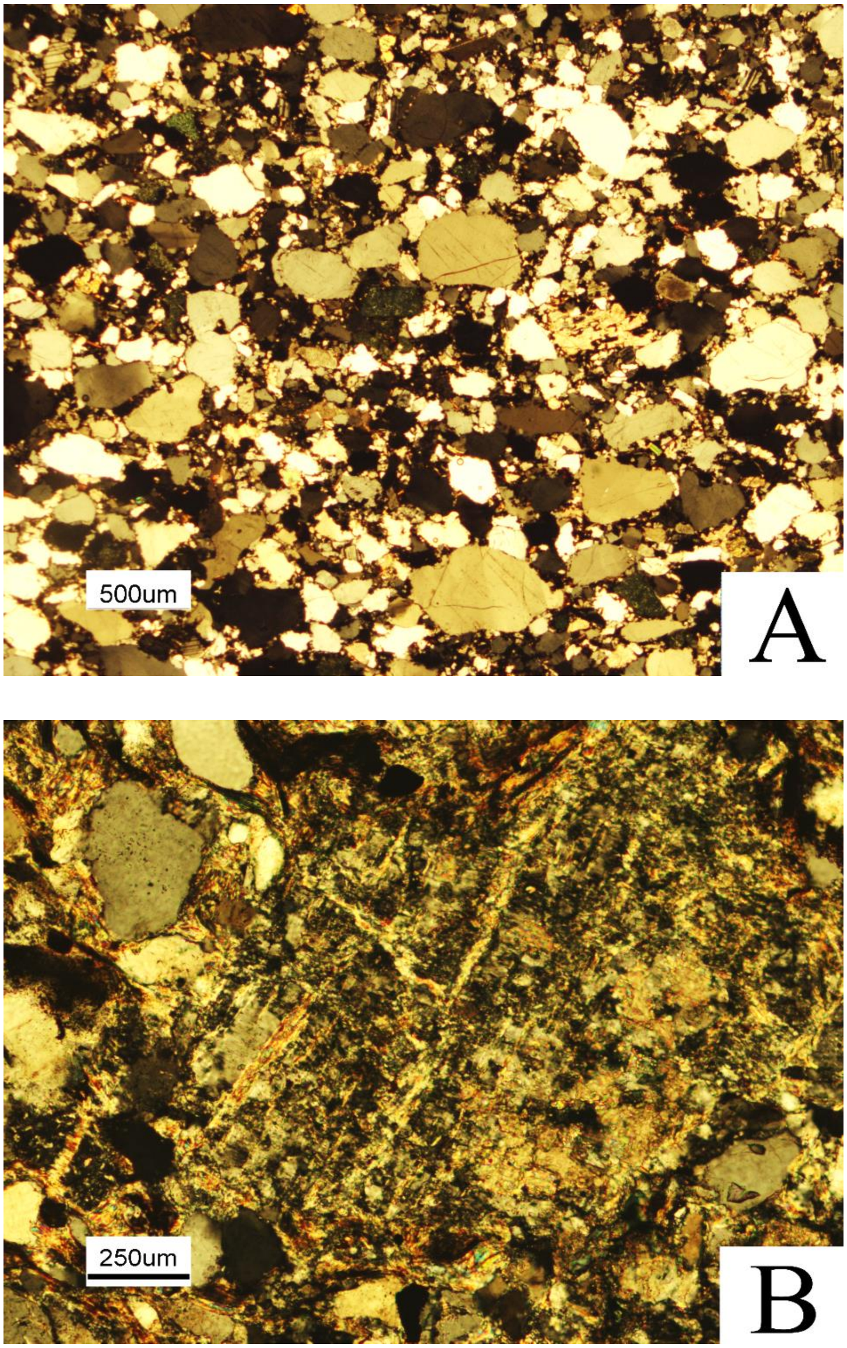

Figure 5.9: A) Quartzose grain-supported sandstone collected from mélange (MK-572). B) Tartan plaid twinned, and calcite altered potassium feldspar grain (MK-532-2).

and perhaps because similarities among rock fragments the grains in the hosting sandstone hinders their interpretation. Where identified, felsic plutonic rock fragments consist of quartz and feldspar crystals intergrown together (Figure 5.10). The fragments are generally sub-round and round in shape. In total, these small composite clasts often above the mean grain size for the sediment and less commonly identified as equivalent to the mean grain size.

Accessory mineral assemblages found in the mélange sandstone include mica, chlorite, and zircon. Biotite and muscovite are common tabular grains, angular in shape and smaller than the mean grain size. In one sample biotite grains appear relatively long and aligned on the bedding plane. Chlorite, another minor component occurs within the matrix of the sandstone samples and also as detrital grains. Detrital zircon is a rare component of the sandstone samples. These grains are angular and sub-angular and commonly below the mean grain size. The high relief grains are colourless in plane-polarized light and have high order interference colours under cross-nicols (Figure 5.10).

5.4.2 - General Textures in Thin Section

Sandstone samples were collected from blocks in mélange and dismembered formation at localities at the base of the North Arm Massif, at South Arm, along the southwestern shore of Trout River Small Pond and from Woods Island. These sandstones are predominantly quartzose, poorly sorted, and matrix supported (Figure 5.9).

Quartz grains are sub-angular to rounded and generally with moderate sphericity. Quartz grains may account for the largest clasts in the sandstone. Feldspars are generally sericitized, and with a cloudy texture. These samples rarely show any bedding or lamination. Sometimes, imbrication of tabular grains (e.g. feldspar), is apparent. Grain boundaries are generally pitted and embayed. In some samples quartz overgrowths are identified at quartz grain margins. Elsewhere in a sample, the edges of grains may be diffuse and apparently gradational.

The matrix in mélange sandstone samples accounts for 20% of the composition of this rock. In composition, matrix is seen as brown, very fine-grained minerals under plane-polarized light, and with high birefringence under cross-polars. Grain-size precludes any accurate determination for the mineralogy; however, it is likely a mix of biotite, chlorite and other clay minerals. Calcite is a minor component often associated with secondary quartz and filling of small fractures and veins. Calcite is also present as an alteration mineral within feldspar grains.

5.4.3 – Modal Percentages of the Mélange and Dismembered Formation Sandstone Blocks

Sandstone blocks collected from the deformed strata has a quartzo-feldspathic composition (Figure 5.11). On the classification diagram the samples dominantly fall in the subarkose sandstone field with outliers in the quartz arenite and arkosic arenite fields. Quartz grains, of both monocrystalline and polycrystalline varieties account for an average of 78% of total framework grains. The range of total quartz grains is 65-90%. Grains of feldspar have a modal percentage in the range of 4%-30% and a mean of 19%. For other framework grains, the lithic fragment component ranges from 0%-12% with an average of 5%.

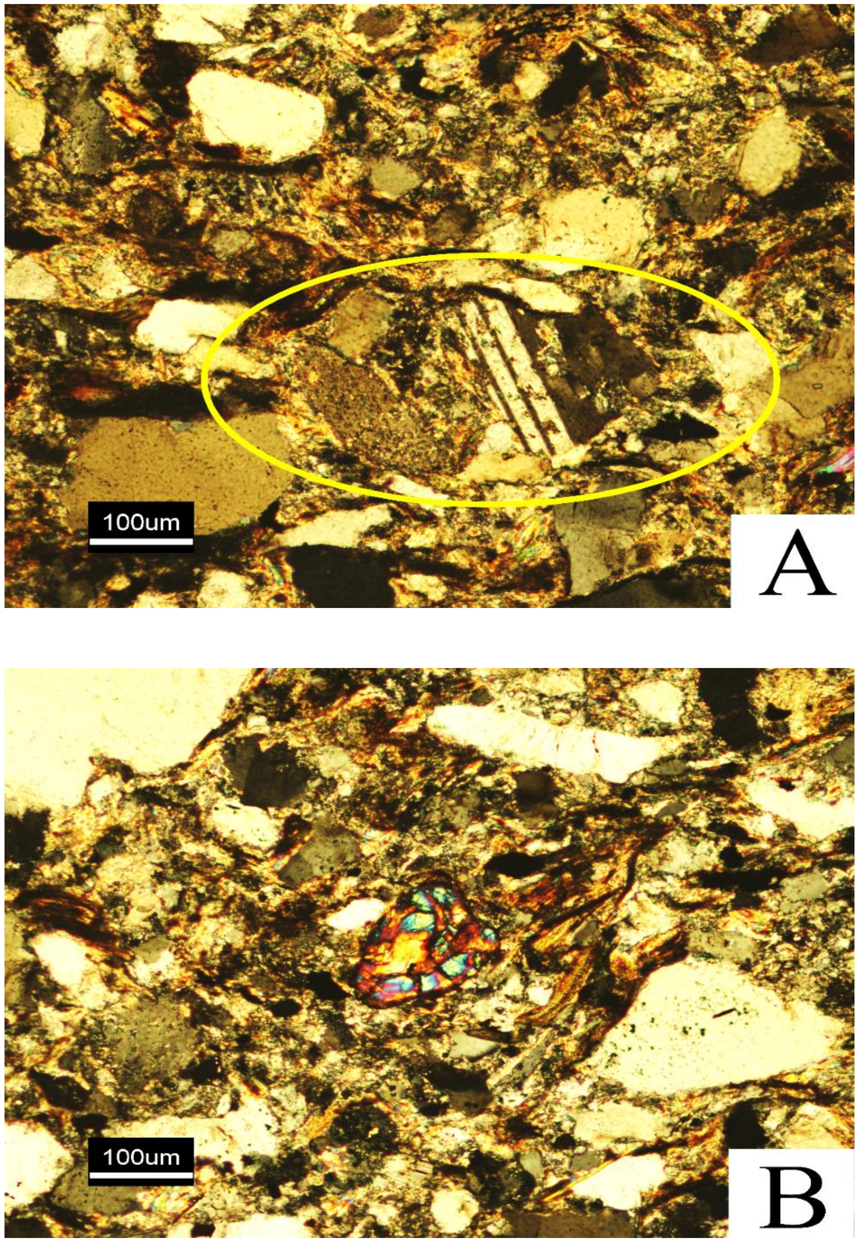

Figure 5.10: Mélange sandstone. A) Plutonic rock fragment with twinned plagioclase and quartz crystals highlighted by the yellow circle. B) Zircon detritus in a mélange sandstone block. Both photos from MK-532-2.

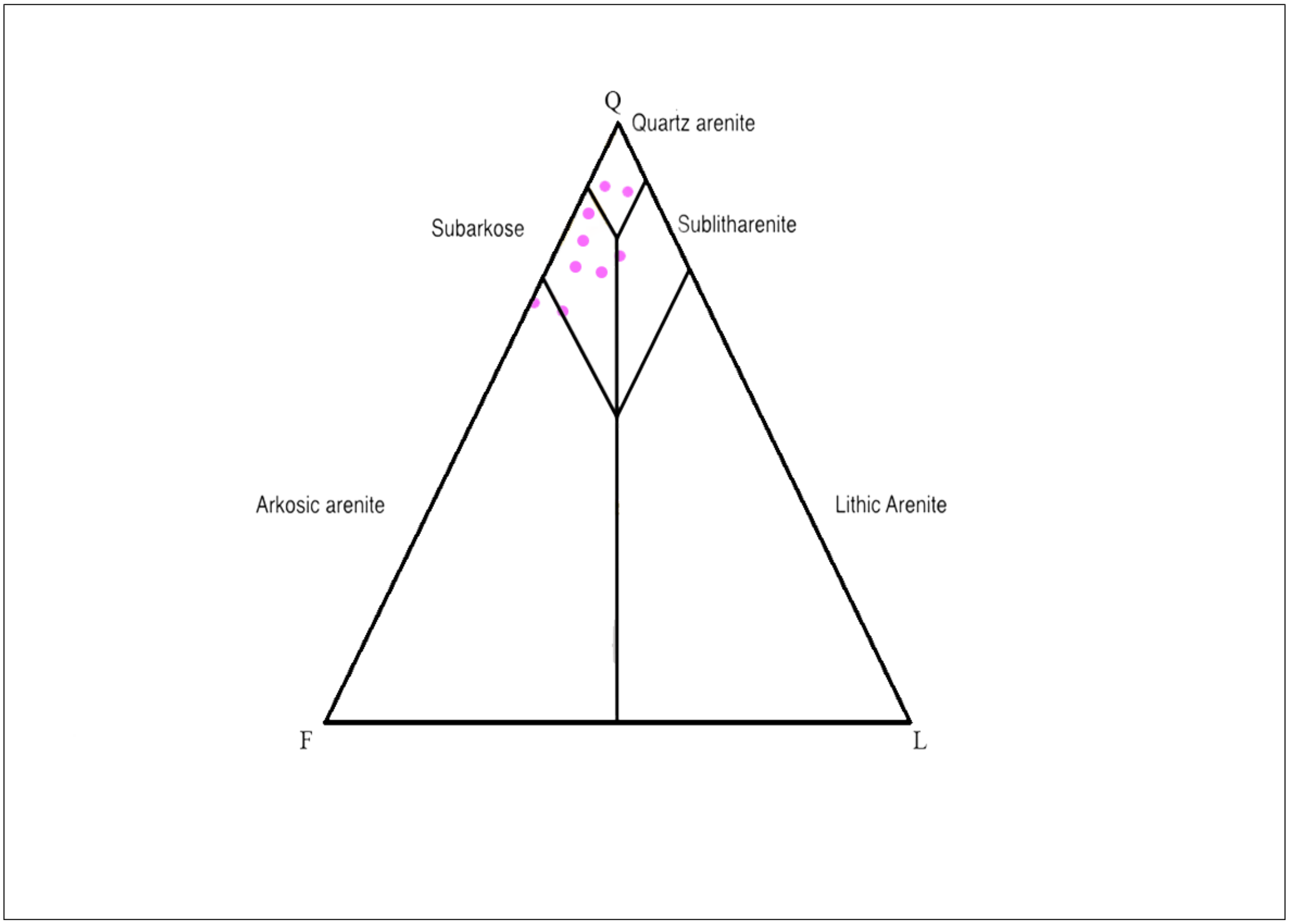

Figure 5.11: Sandstone classification diagram for sandstone blocks in mélange at the base of ophiolitic massifs. Q = total quartz, F = total feldspar, L = lithic fragments. Diagram after Pettijohn (1975).

Chapter 6

Structural Geology of the Map Area

6.1 – Introduction

The study of structures and their relationships in the map area is relatively difficult given the dense vegetation cover. Relative timing relationships are sparse. However, one phase of soft sediment deformation, and three phases of structural deformation overprint the regional strata occupying the lower and intermediate major thrust slices. The first two phases are represented by thrusting, folding, and cleavage development. The latest episode of deformation is characterized by an array of high-angle, brittle faults that overprints all slices. The multiple generations of structures are best exposed overprinting the thin-bedded successions of Northern Head Group strata occupying the lower tectonic slice.

The deformation is stylistically different in the lower and intermediate slices, and mélange. The lower thrust slice is dominated by outcrop-scale, tight, parasitic folds overprinting isoclinal folds. In contrast the upper slice is predominantly overprinted by broad, open folds. Both slices are penetrated by an axial planar cleavage. Deformation in the mélange is characterized by an intense phacoidal cleavage, intense dismemberment of bedding, and rootless fold hinges.

6.2 – Deformation of the Lowest Major Thrust Slice

6.2.1 – Initial Dismemberment

Weak bedding and soft sediment separation is the earliest outcrop-scale structure in the doloarenite- and calcarenite-mudstone successions of the Middle Arm Point and Cooks Brook formations. The amount of separation between the bedding fragments is variable but most are generally on the scale of several centimeters. The fragments are generally angular with little to no flattening (Figure 6.1 A, and 6.2 B) and dominantly parallel to bedding. There is a wide range of sizes amongst dismembered bed fragments - from several centimetres to decimetres. The size of fragments correlates with the thickness of the bed from which they originated. The carbonate beds have not been dismembered at all localities. Intact bedding predominates in the units.

6.2.2 – F_1 Folding

Tight to isoclinal F_1 folds overprint Cooks Brook and Middle Arm Point strata where the units are best exposed between at North Arm, South Arm, and southern Chimney Cove (Figure 6.1 A, and 6.2). F_1 fold hinges culminate in the limbs of later F_2 folds. F_1 fold axes are generally sub-parallel to F_2 fold axes. An axial planar S_1 cleavage is not developed with the F_1 fold system in the lowermost thrust slice.

6.2.2 – F_2 Folds and S_2 Axial Planar Cleavage

Minor asymmetric F_2 fold trains overprint strata in the Cooks Brook and Middle Arm Point formations. The folds are dominantly upright to steeply inclined, and gently plunging to sub-horizontal. Orientations of axial planes and fold axes vary slightly across the region, but dominantly trend to the northeast-southwest.

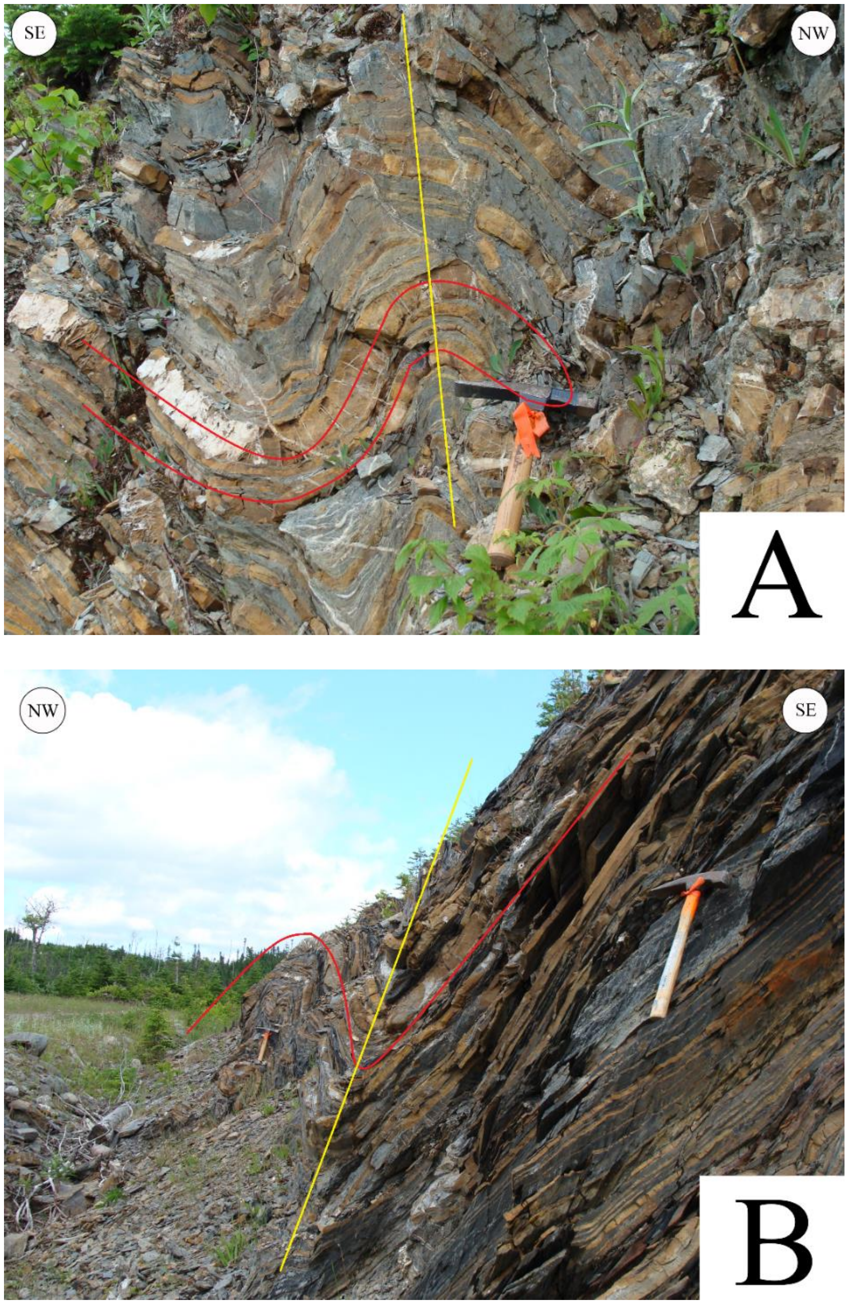

Figure 6.1: Two examples of southeast verging F_2 minor folds with northwest dipping, steeply inclined axial planes and sub-horizontal fold axes near Kennedy Lake. Top: station 11MK-331, bottom: station 11MK-328 with two hammers highlighting the offset between the foreground and background. Note the Z-asymmetry and S_2 axial planar cleavage at the right margin. S_0 in red, F_2 axial trace in yellow. Hammer for scale.

Figure 6.2: A: Isoclinal F_1 folds and close F_2 synform with a steeply inclined, northwest dipping axial surface, in the Cook's Brook Formation at the south end of Chimney Cove. S_0 in red, F_2 axial trace in yellow. Station 11MK-559. Hammer for scale.

The one exception to the northeast-southwest trend is the belt of strata between Kennedy Lake and Trout River Pond along the eastern flank of the North Arm Massif. There the axial features uniformly trend north-south. Fold symmetry is also locally dependent. Near North Arm folds are asymmetric (Figure 6.1) and at Chimney Cove they are more symmetric, as well as tighter (Figure 6.2). A slaty axial planar S_2 cleavage is associated with the minor macroscopic folds overprints the strata (Figure 6.1, B).

6.3 – Deformation Overprinting the Intermediate Major Thrust Slice

6.3.1 – Folds and Axial Planar Cleavage

The Blow Me Down Brook formation is dominated by thick and massive, well cemented, sandstone beds that are not overprinted by minor folds. Proper differentiation of fold generations is hampered by the lack of minor folds throughout most of the map region. The majority of folding can only be appreciated on a macroscopic scale. For example, a large and distinctive asymmetric anticline culminates along the western coast of Woods Island (Figure 6.3, A). The eastern backlimb of this structure extends approximately 1.75 km. At the mesoscopic scale, common, open, upright, gently plunging synforms spanning several metres (Figure 6.3, B) are on the hinges of larger regional structures that are apparent in cross-section (Map sheet 3). Fold axes and axial surfaces have a northeast-southwest trend throughout most of the map region. The exception is between Kennedy Lake and Trout River Pond (Map sheet 1), where the axial features trend north-south.

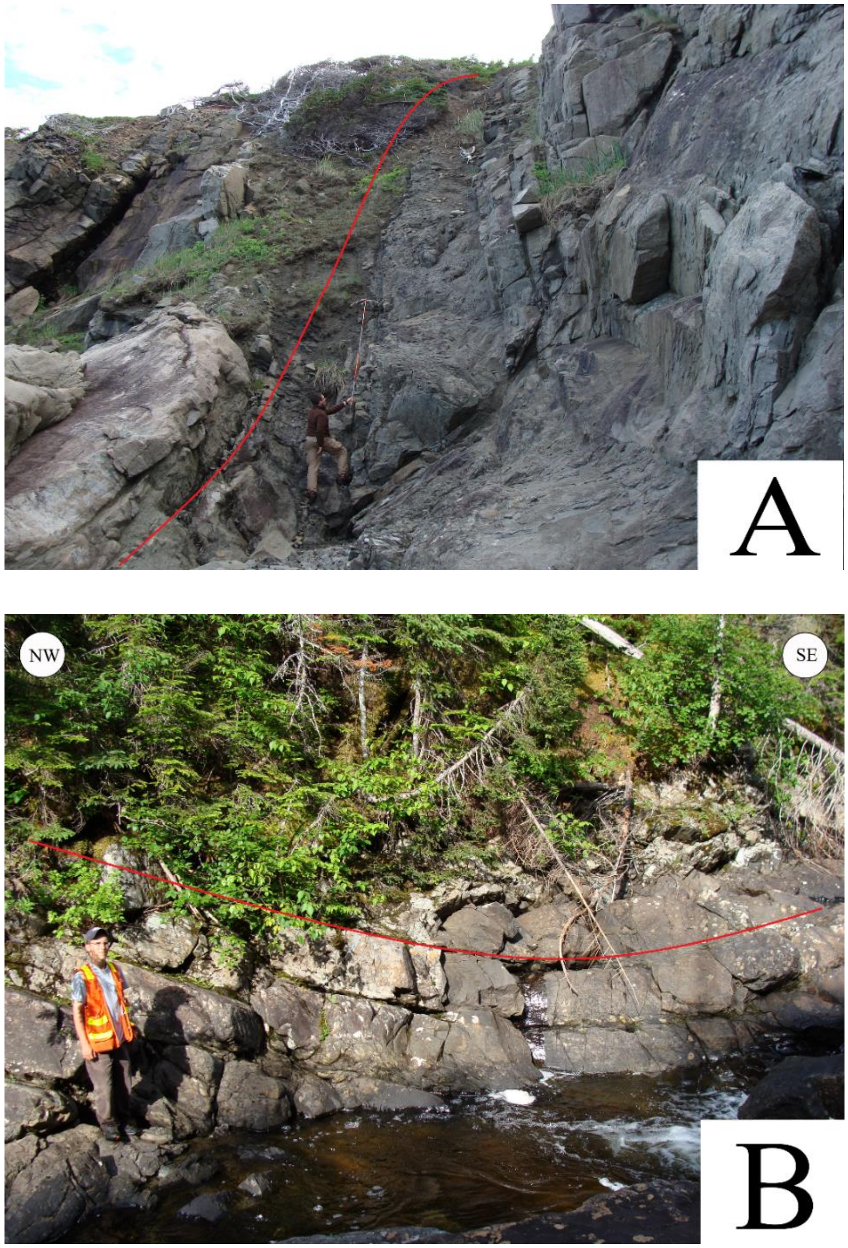

Figure 6.3: Macroscopic folds in the Blow Me Down Brook formation. A) Steeply dipping western forelimb of a regional-scale asymmetric anticline on Woods Island (MC-63). B) An open, gentle synform overprinting Blow Me Down Brook formation strata (11MK-317). Geologists for scale.

Overall, The Blow Me Down Brook formation has a distinct structural style across the entire map area. There are broad areas of uniform dipping beds with abrupt changes in orientation, suggesting a kink-style fold architecture. A moderately developed, axial planar cleavage is associated with the regional fold system that overprints the Blow Me Down Brook formation. The cleavage may be scaly or slaty in the mudstone, whereas, fracture cleavage is sometimes developed in the sandstone.

6.4 – Deformation in the Mélange and Dismembered Formation

6.4.1 – Bedding Dismemberment and Folding in the Carbonate-Mudstone Blocks

Blocks of carbonate-mudstone successions (Figure 4.15 A, B, and C) preserve early, weak dismemberment of bedding into centimetre-scale fragments. Separation of fragments along the bedding plane is on the order of centimetres to decimetres. Bed fragments are generally not rotated from the bedding plane orientation. There is no foliation associated with the fragmented bedding.

The lack of F_2 deformation is common, however not consistent to all blocks of carbonate-mudstone successions. The calcareous strata of the blocks in Figure 4.15 A, and B, are not folded. The block in 4.15 C is a rootless F_2 fold with an isoclinal F_1 fold cresting in its upper limb

Figure 6.4: Rotated equant bed fragments in the pervasively cleaved matrix of the mélange at Woods Island (11MK-408).

6.4.2 – Matrix and Bedding Dismemberment and Phacoidal Cleavage

The mélange and dismembered formation have unique structural characteristics distinct from those of the underlying thrust slices. A penetrative, anastomosing, phacoidal cleavage overprints the broken-up strata. Cleavage surfaces on phacoids tend to be polished. The matrix of the strata is significantly flattened and dismembered. The banded mudstone is extended into lens shaped boudins with up to several centimetres of separation along the bedding plane (Figure 4.13, A). Dolomitic siltstone strata are also dismembered (Figure 6.4). The siltstone blocks are angular in contrast to the lens-shaped boudins of the matrix. Separation of the siltstone can be up to several metres. The long axis of longer blocks is oriented parallel to the cleavage.

Locally relatively smaller and equant fragments are rotated from their original orientation, such as at station 11MK-408 (Figure 6.4). Across the region the phacoidal cleavage has a northeast-southwest orientation, with the one major exception being the entire area between Kennedy Lake and Trout River Pond (Map sheet 1). In that region the phacoidal cleavage is almost consistently north-south oriented.

6.4.3 – F_2 Folds

The cleavage in the mélange and dismembered formation is a first generation fabric that is overprinted by folding on several scales. At the centimetre scale the cleavage is overprinted by isoclinal folds (Figure 6.5). At the mesoscopic level, close, moderately inclined asymmetric antiforms are superposed on the cleavage. Near Trout River Little Pond (Map sheet 2) the anastomosing cleavage is truncated by a fault surface with culminations of F_2 antiforms in the hanging wall (Figure 6.6). F_2 folding is also expressed at Woods Island where second generation antiforms overprints the phacoidal cleavage and refolds F_1 isoclinal folds and the S_1 fabric.

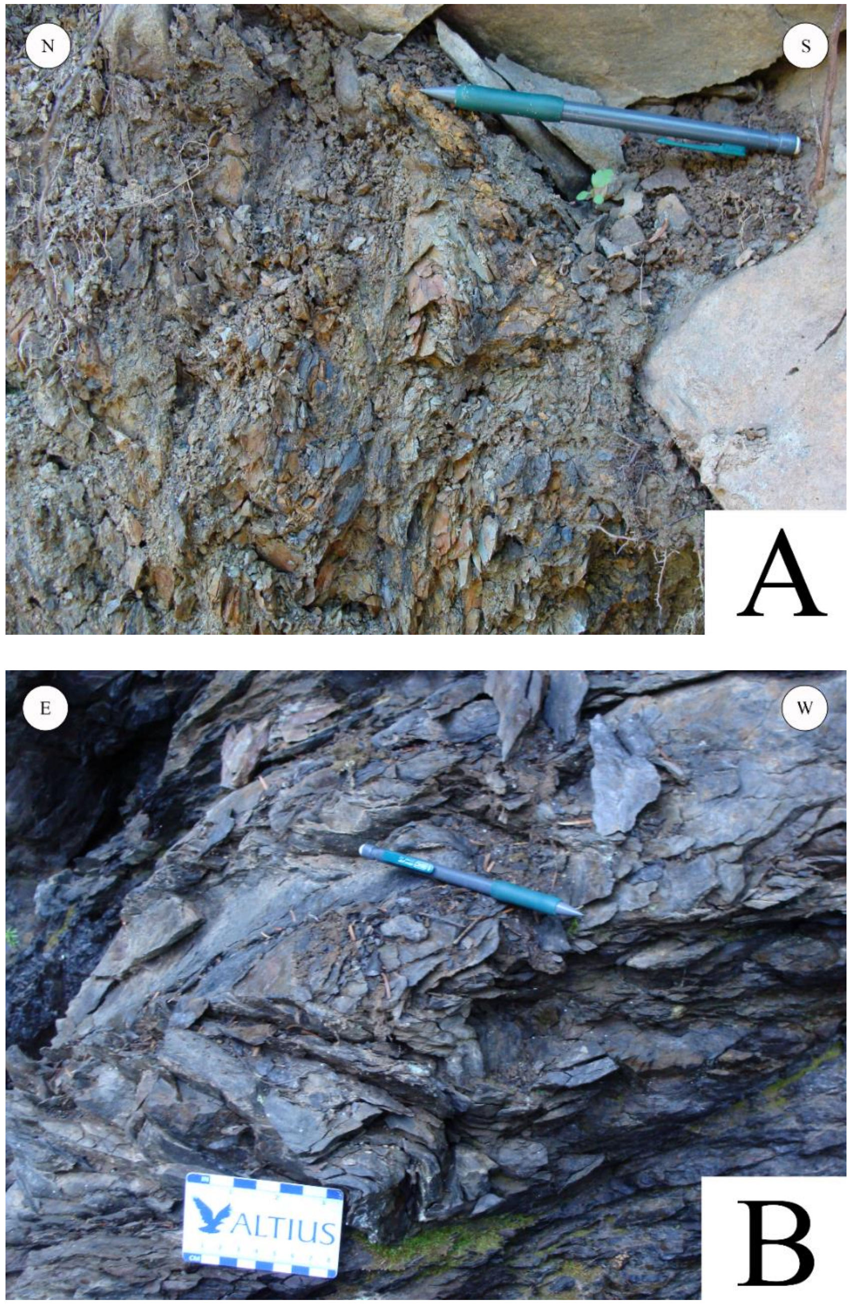

Figure 6.5: Varying orientations of cm-scale folds overprinting phacoidal cleavage in mélange matrix adjacent to Trout River Little Pond (Map sheet 2). A) Upright, steeply plunging close cm-scale folds, station 10MK-138. Pencil for scale. B) Recumbent, gently plunging folds, station 10MK-134. 8.5 cm card for scale.

Figure 6.6: Refolded F_1 fold in mélange at Chimney Cove (Map sheet 2). The F1 fold hinges in the southeast. S_0 is highlighted in red. The F_2 fold axial trace is shown in yellow, and the fault surface is blue. Station 10MK-124. Hammer is 90 cm long.

6.4.4 – F_2 Fold Vergence on Woods Island

There is a clear and pronounced change in F_2 fold vergence along the southeast coastline of Woods Island. Figure 6.7 is a collection of photographs taken at varying scales and representing a northwest to southeast traverse along the southeastern shore of Woods Island. The diagram emphasizes the change in fold vergence from the northwest to the southeast. Photo A is from the westernmost locality at station 11MK-412. Forelimb and backlimb orientations of an east-verging antiform overprinting mélange are 147/56 and 149/64, respectively.

Photo B was taken at station 11MK-422. Two measurements of the long limb of the F_2 asymmetric fold give orientations of 184/62 and 187/60. Photo C is from 11MK-428 to the southeast. The sub-vertical bedding is oriented 048/80. The final photo from station 11MK-431 where the eastern limb of a close F_2 antiform is oriented 030/45.

The mosaic highlights the shift in vergence of the fold structures from east-verging in the west (Figure 6.7, A and B) to west-verging in the east (Figure 6.7, D). The figure also demonstrates the contrasting deformation styles across the coastline. There is phacoidal cleavage and pervasive dismemberment in the mélange (Figure 6.7, A). In contrast, strata of the Middle Arm Point Formation (Figure 6.7, B, C, and D) are not severely dismembered.

6.6 – High Angle Faults

Arrays of steeply dipping, northeast-southwest trending faults dissect the strata across the region. The brittle structures also separate the mélange from the adjacent volcanic and volcanogenic strata of the Little Port Complex at South Arm and Chimney Cove. The faults dip between 70° and 90°. Stepped grooves along the eastern face of the North Arm Massif are evidence of high angle, brittle faulting. Slickenfibre surfaces several centimetres thick are common although they are often considerably eroded on exposed surfaces. They are generally growths of white quartz in the Blow Me Down Brook formation or white calcite in the Middle Arm Point and Cooks Brook formations. The sense of displacement on the faults is difficult to measure in most cases because multiple generations of slickenfibre growths and grooves are often preserved and overprinting one another. Where slip can be measured, the directions are variable across localities and dominantly oblique. A lack of discernible marker beds hinders the measurement of displacement.

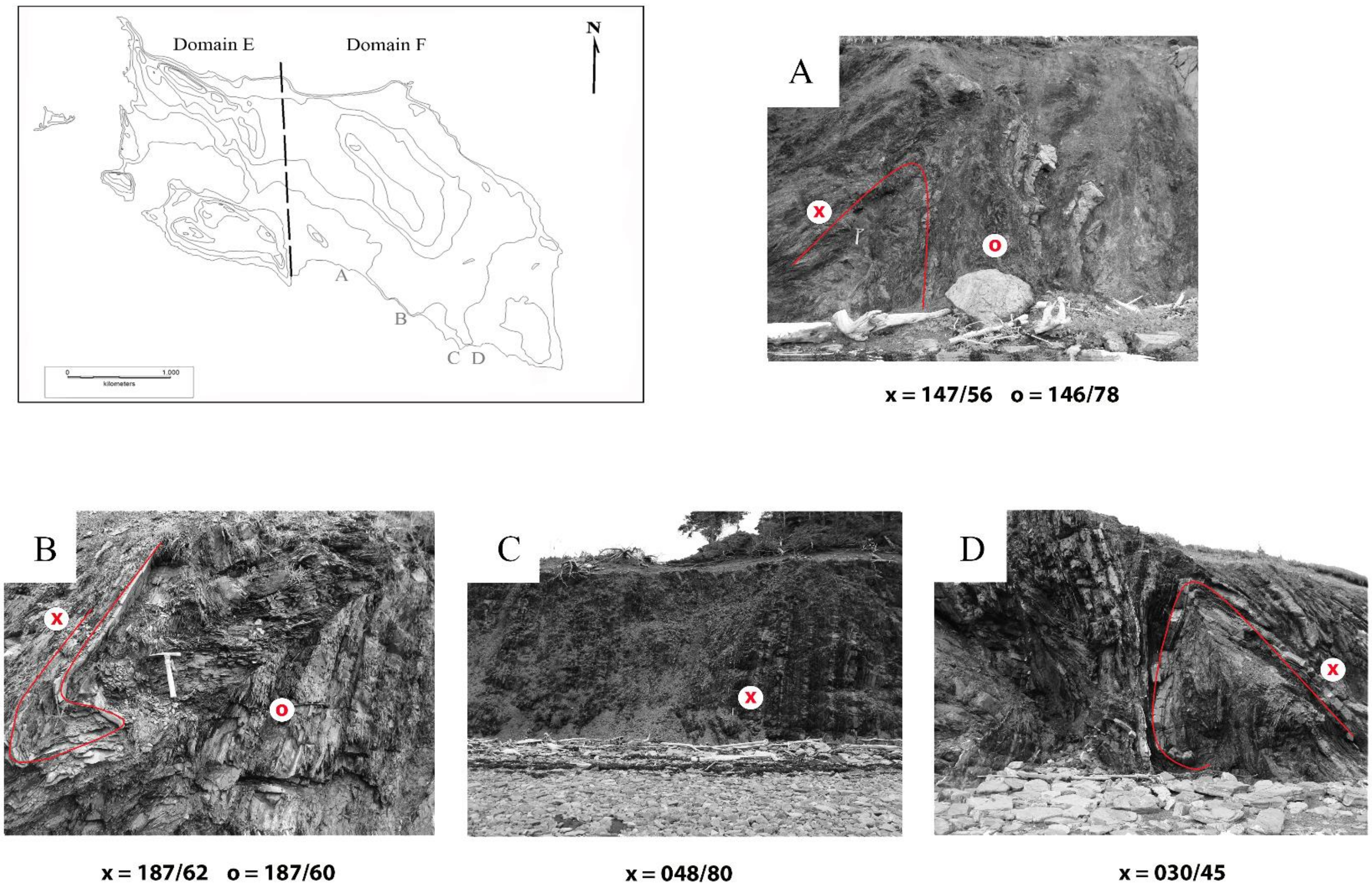

Figure 6.7: Photograph mosaic cross-section from west to east along the southern shore of Woods Island. Inset map gives localities for mélange (A) and Middle Arm Point Formation (B, C, D) strata. Bedding is indicated by red lines. Note F_2 folds in A, B, and D. Bedding orientation is denoted in the right-hand rule format below each photo. There is a change in fold vergence from west to east. A and D have a 5 m field of view, B has a hammer for scale, C has a 10 m field of view.

When considered in aggregate, several trends in the strike of the fault planes emerge. When plotted on lower hemisphere equal area pi-plots the common trends manifest as clusters of poles to the fault planes (Figure 6.8). The largest group of poles lies in the western and northwestern margins of the plot. Smaller clusters are spread across the eastern and northeastern, and southern and southwestern margins of the plot. The distribution of poles suggests a dominance of north-south and northeast-southwest striking high angle fault planes. The secondary allocations of poles imply two other common fault trends in the region are east-west and northwest-southeast.

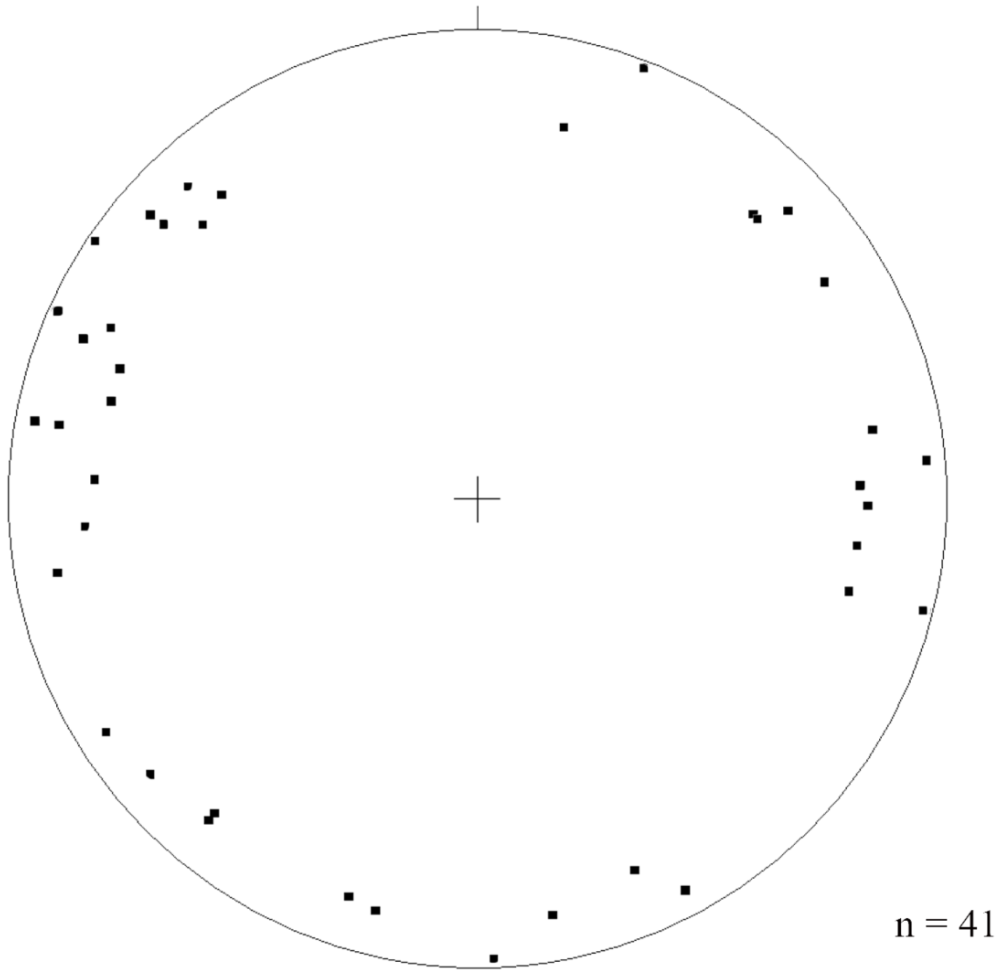

Figure 6.8: Lower hemisphere equal area stereonet for poles to high angle fault planes. The largest cluster of poles is spread across the western and northwestern margin. They represent north-south, and northeast-southwest striking faults. Secondary clusters, in the eastern-northeastern and southern-southwestern margins represent east-west and northeast-southwest striking faults.

Chapter 7

Geochemistry of Sedimentary and Igneous Rocks of the Bay of Islands -Trout River Pond Region

7.1 – Introduction

A geochemical analysis of three lithostratigraphic units from the map area was completed to enhance our understanding of the regional geology, stratigraphy and structural relationships. The rocks analyzed for both major and trace element geochemistry include sandstone, mudstone, basalt and exotic blocks from the mélange, Blow Me Down Brook formation, Irishtown, Cooks Brook, and Lower Head formations and basalt and mafic volcaniclastics from the Little Port Complex (mapped as Crouchers formation by Williams and Cawood, 1989) and Skinner Cove Formation. The completed geochemical data is plotted on a number of different classification diagrams to aid with the interpretation of the depositional setting for the samples.

7.2 – Geochemistry of Sedimentary Rocks

7.2.1 – Major Element Geochemistry for Sandstone from the Blow Me Down Brook formation, Lower Head Formation, and Mélange.

Figure 7.1 is the plot of K_2O/Na_2O vs. SiO_2 for sandstones of the Blow Me Down Brook, and the Lower Head formations and mélange. The fields of Roser and Korsch (1986) represent the chemistry of island arc, active continental margins and passive continental margins sediments. For Blow Me Down Brook samples, the concentration of

SiO_2 has a range of 62.0-97.8 wt.% and averages 75.8 wt.%. The K_2O/Na_2O ratio ranges from 0.36 to 3.72, with an average of 1.69 for 15 samples. The majority of the Blow Me Down Brook formation samples straddle the “Passive margin” and “Active margin” boundary. Outliers that skirt the boundary between “Active margin” and “Passive margin” represent samples MK-71, MK-76-2, and MK-76-3, all from the South Arm area.

In contrast, sandstones identified as belonging to the Lower Head Formation generally have a markedly lower silica content ranging between 34.8 and 77.6 wt.% with an average value of 69.6 wt.%. The K_2O/Na_2O ratios for these Ordovician sandstones are between 0.92 and 2.46, averaging 1.59. On the discrimination diagram of Roser and Korsch (1986) (Figure 7.1), the Lower Head Formation sandstones plot along the boundary between the “Island arc” and “Active margin” fields. One silica rich sample lays on the “Active margin”-“Passive margin” boundary. The point represents E11-368 collected in the eastern flank of the North Arm Massif.

A small set of 5 sandstone samples from blocks and beds in the mélange show a wide range of variation (Figure 7.1). Some of the high silica samples plot on the “Active continental margin”-“Passive margin” boundary and within the “Passive margin” field. One silica-poor sandstone, and namely sample MK-128, from the mélange to the northeast of Chimney Cove is in the “Island arc” field (Map sheet 3).

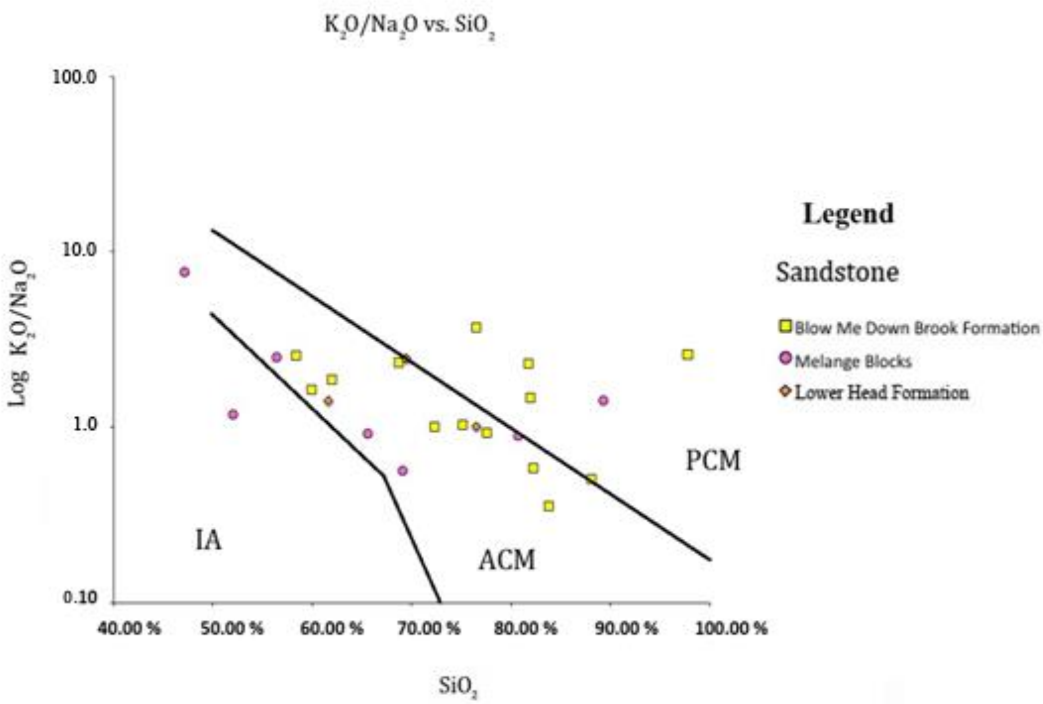

Figure 7.1: Chemistry of sandstone samples of the Blow Me Down Brook formation, Lower Head Formation and mélange plotted on tectonic discrimination diagram of Roser and Korsch (1986). The fields are divided into island arc (IA), active continental margin (ACM), and passive continental margin (PCM).

Sandstone chemistry is also plotted on the (Fe_2O_3+MgO)% vs. Al_2SiO_3/SiO_2 (Figure 7.2) and (Fe_2O_3+MgO)% vs. TiO_2% (Figure 7.3) tectonic discrimination diagrams of Bhatia (1983). For the Blow Me Down Brook formation the sum of the concentrations of Fe_2O_3 and MgO in the sandstones is between 2.41 and 9.70 wt.% with a mean of 5.94 wt.%. The Al_2SiO_3/SiO_2 ratio in the sandstones ranges from 0.004 to 0.36 and average 0.18. TiO_2 concentrations vary from 0.17 to 1.16 wt.% and the average concentration is 0.62%. In Figures 7.2 and 7.3 the majority of data points for the Blow Me Down Brook formation are scattered across the diagrams with many outliers laying outside the discrimination fields identified by Bhatia (1983).

In the Lower Head Formation (Fe_2O_3+MgO) concentrations range from 10.22 to 15.06 wt.% with a mean of 12.64 wt.%. Al_2SiO_3/SiO_2 ratios span from 0.13 to 0.25 with an average ratio of 0.19. Concentrations of TiO_2 are between 0.56 and 1.03 wt.% with an average of 0.72 wt.%. In the (Fe_2O_3+MgO) vs. Al_2SiO_3/SiO_2 discrimination diagram (Figure 7.2), the data for the Lower Head Formation falls on the right-hand side of the diagram owing to the high concentrations of (Fe_2O_3+MgO) and low Al_2SiO_3/SiO_2 ratios. Similarly, the majority of Lower Head Formation data points plot to the right-hand side of the (Fe_2O_3+MgO) vs. TiO_2 diagram (Fig. 7.3).

Data for sandstone blocks in mélange (Figure 7.2 and Figure 7.3) are widely distributed across the diagrams. These sandstones have a broad range in the concentration of (Fe_2O_3+MgO), and namely from 3.31 wt.% to 15.78 wt.%. The Al_2SiO_3/SiO_2 ratios range between 0.08 and 0.34 and the concentration of TiO_2 varies from 0.36 wt.% to 1.35 wt.%.

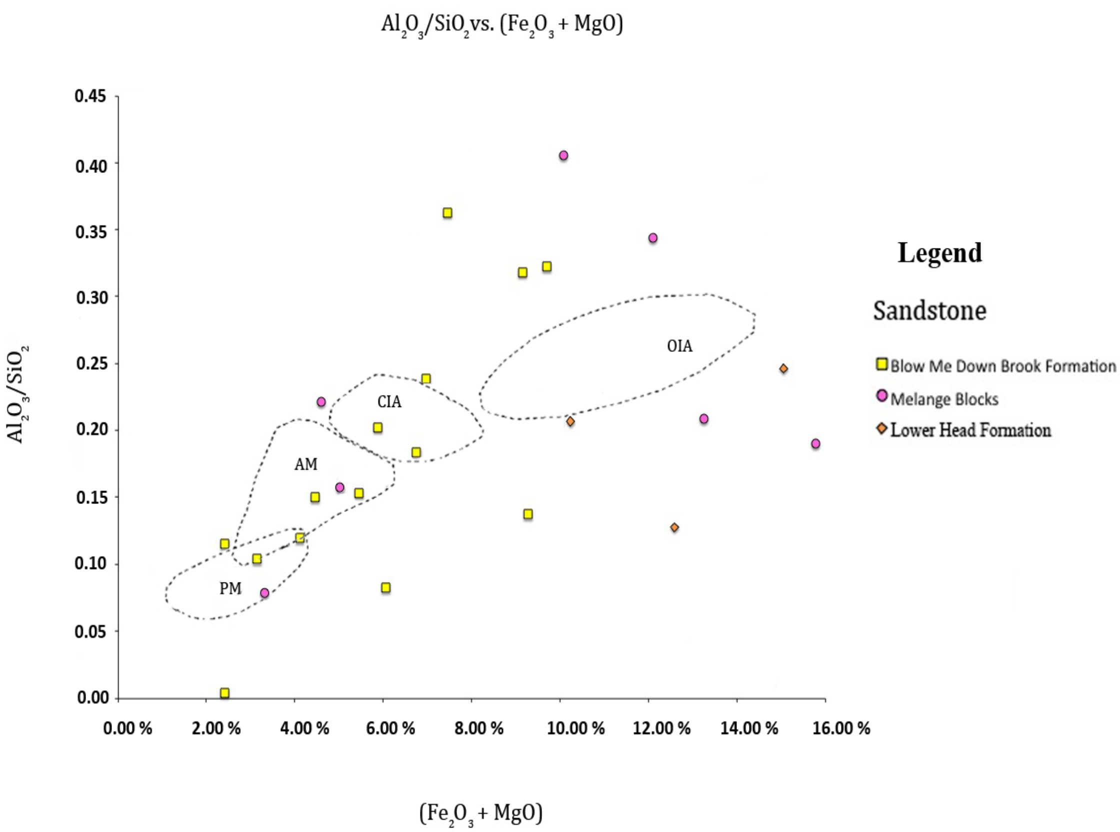

Figure 7.2: Chemistry of sandstone from the Blow Me Down Brook formation, Lower Head Formation and mélange plotted on Al_2O_3/SiO_2 vs. (Fe_2O_3+MgO) discrimination diagram of Bhatia (1983). PM = Passive margin, AM = Active margin, CIA = Continental island arc, OIA = Oceanic island arc.

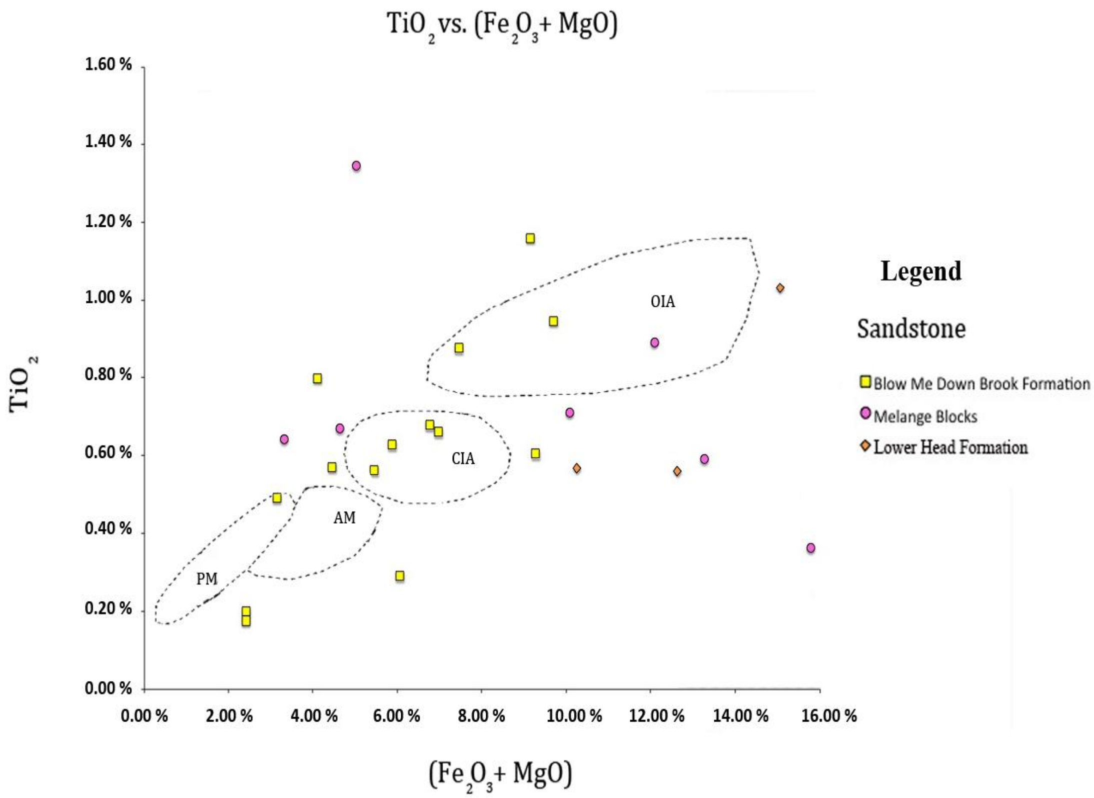

Figure 7.3: Chemistry of sandstone from the Blow Me Down Brook formation, Lower Head Formation and mélange plotted on TiO_2 vs. (Fe_2O_3+MgO) discrimination diagram of Bhatia (1983). PM = Passive margin, AM = Active margin, CIA = Continental island arc, OIA = Oceanic island arc.

7.2.2 – Trace Element Geochemistry of Sandstone of the Blow Me Down Brook, Irishtown, Lower Head Formations and Mélange

7.2.2.1 – Cr and Ni in Sandstones of the Blow Me Down Brook, Irishtown and Lower Head Formations and Mélange

Cr concentrations in sandstones of the Blow Me Down Brook formation range between 13-113 ppm and have a mean value of 59 ppm. Ni concentrations in the formation range between 7-45 ppm with an average of 22 ppm. The Cr/Ni ratios for sandstone is between 2.00 and 6.05. In addition, 2 samples of Irishtown Formation sandstone were analyzed for Cr and Ni. The concentrations of Cr and Ni in E11322 are below the limits of detection. In contrast, in Sample MK-440, the Cr concentration of 609 ppm is much higher than Ni at 12 ppm. The Cr/Ni ratio for this anomalous MK sample is about 50:1. In sandstone of the Lower Head Formation Cr concentrations are between 36 and 642 ppm with an average of 251 ppm. Ni concentrations range from 23-188 ppm with a mean of 59 ppm. Cr/Ni ratios range between 1.24 and 7.20. Sandstone samples recovered from mélange fragments have Cr concentrations between 20 and 65 ppm, with an average Cr concentration of 40 ppm. Ni concentrations for these blocks range from 6-28 ppm with an average of 18 ppm. The spread of Cr/Ni ratios for these sandstone samples is 1.6-3.3.

For the Cr/V vs. Ni/Y plot (McLennan, 1993) for the sandstones (Figure 7.4), the Blow Me Down Brook formation sandstones have Cr/V ratios of 0.46-1.5 and Y/Ni ratios of 0.43-4.8. The ratios average 1.1 and 1.0 respectively. These samples plot in a tightly grouped cluster below a ratio of 1.5 in both Cr/V and Y/Ni (Figure 7.4). Only one

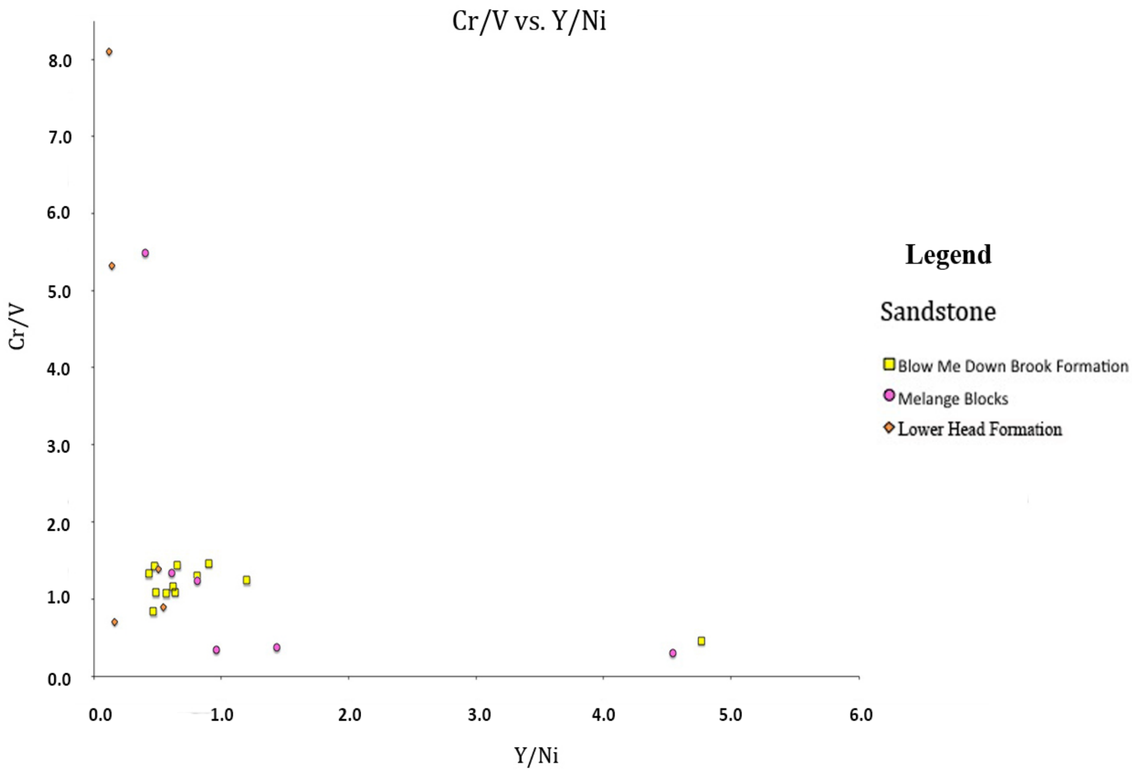

Figure 7.4: Cr/V vs. Y/Ni diagram from McLennan et al. (1993) with data for sandstone of the Blow Me Down Brook formation, Lower Head formation and mélange. Some Lower Head and mélange samples have a tendency towards higher Cr concentrations.

anomalous sample (MK-517) with a relatively high Y/Ni ratio of 4.8 lays outside this cluster.

Samples of the Irishtown Formation do not plot on Figure 7.4. Cr content in E11322 is below the limits of detection. For sample MK-440 with an anomalously high Cr concentration, the Cr/V ratio is 45.9 and Y/Ni is 0.29. The Cr/V ratio is so great relative to the sample suite that plotting it distorts the spacing of the main group of samples along the Cr/V axis.

Sandstones of the Lower Head Formation have Cr/V ratios of 1.4-8.1 and Y/Ni ratios of 0.12-0.51, with respective average values of 4.9 and .25. They are distributed near the Cr/V axis and along its length, with one small anomalous cluster below the Cr/V ratio of 1.5. Sandstone blocks from mélange have Cr/V ratios from 0.34-5.5 and Y/Ni ratios ranging from 0.96-4.5, with averages of 1.4 and 1.3 respectively. The low Cr/V ratios place the samples near the Y/Ni axis (Figure 7.4) and spread along the length of the Y/Ni axis. The sample point with the highest Cr/V ratio is MK-521-3. The sample was collected from the mélange flanking the North Arm Massif at the southern tip of Trout River Pond. The sample with the highest Y/Ni ratio is MK-114-1. It was collected from mélange flanking the Table Mountain Massif at South Arm.

7.2.2.2 – Cr and Ni in Mudstone of the Blow Me Down Brook, Irishtown, Cooks Brook, Middle Arm Point and Lower Head Formations and Mélange

Table 7.1 shows Cr and Ni concentrations and ratios for allochthonous mudstone samples from this study and from Botsford’s (1987) geochemical analysis of 96 mudstone samples. Table 7.2 lists Cr/Ni ratios for each mudstone sample.

Collected mudstone samples				
Cr range (ppm)	Cr Formation Average (ppm)	Ni range (ppm)	Ni Formation Average (ppm)	Cr/Ni range
Blow Me Down Brook formation (8 Analyses)				
76-101	77.7	36-71	48.3	1.05-2.375
Irishtown Formation (4 Analyses)				
61-136	108.3	23-58	41.5	1.98-5.94
Cooks Brook Formation (5 Analyses)				
62-101	83.2	43-60	52.5	1.12-1.93
Middle Arm Point Formation (0 Analyses)				
N/A	N/A	N/A	N/A	N/A
Lower Head Formation (7 Analyses)				
34-125	79	25-51	42.8	1.35-2.56
Mélange (13 Analyses)				
45-92	72.5	33-69	49.9	0.928-2.04
Botsford Geochem				
Blow Me Down Brook formation (0 Analyses)				
N/A	N/A	N/A	N/A	N/A
Irishtown Formation (11 Analyses)				
90-173	122.5	33-53	43.3	2.02-5.09
Cooks Brook Formation (22 Analyses)				
39-122	77.1	12	30.2	1.26-4.87
Middle Arm Point Formation (34 Analyses)				
15-174	62.9	6-124	32.8	0.545-6.00
Lower Head Formation (29 Analyses)				
12-209	60.6	14-132	37.9	0.5-4.13
Mélange (0 Analyses)				
N/A	N/A	N/A	N/A	N/A

Table 7.1: Comparison of Cr and Ni concentrations and Cr/Ni ratios between mudstone samples collected for this study (top) and Botsford's (1988) geochemical results (bottom).

In the eight samples of Blow Me Down Brook formation mudstone analyzed for trace element geochemistry the concentrations of Cr are 76-101 ppm, the average concentration is 78 ppm. Ni concentrations in the mudstone are 36-71 ppm, the mean concentration is 48 ppm. Cr/Ni ratios in the samples range from 1.05-2.375.

In Irishtown Formation mudstone, Cr occurs in concentrations of 61-136 ppm, and Ni occurs in concentrations of 23-57 ppm. The average Cr concentration of Cr is 108 ppm and Ni is 41 ppm. Cr/Ni ratios are spread over a range from 1.98-5.94. Mudstone from the Cooks Brook Formation contains 62.0-101.3 ppm Cr and 43-60 ppm Ni. The mean concentrations of Cr and Ni are 83 and 53 respectively. The ratio of Cr/Ni in this formation is between 1.12 and 1.93. The five Lower Head Formation mudstone samples have a range of Cr values from 34-125 ppm, and Ni concentrations between 25 and 51 ppm. The average concentrations of Cr and Ni are 79 and 43 ppm respectively. Ratios of Cr/Ni in the Lower Head Formation mudstone are between 1.35 and 2.56. Mudstone collected from the matrix of the mélange is 45-92 ppm Cr with a mean of 73 ppm, and 33-69 ppm Ni with a mean of 49 ppm. Cr/Ni ratios are in the range of 0.93-2.04.

7.3 – Geochemistry of Mafic Volcanic Rocks

Nb concentrations in the 19 samples of basalt range between 1.1 and 12.6 ppm. Zr concentrations have a range of 3.6-131.8 ppm (Table 7.3). The basalts have Y concentrations of 2.3-42.2 ppm, and Ti concentrations of 720-10620 ppm.

Sample	Cr/Ni
Blow Me Down Brook formation	
MK100	2.11
MK537-2	1.67
MK-623-5	2.11
E11180	2.04
MK-532	1.23
MK-623-4	1.06
MK-521-2	1.00
MK-629	2.38
Irishtown Formation	
MK474	2.10
MK239-2	2.11
MK392	1.98
MK388	5.94
Cooks Brook Formation	
MK555-2	1.12
MK556	1.42
E11142	1.94
MK-209	1.67
MK-473	1.88
MK-62	1.48
Lower Head Formation	
E11367-2	2.30
MK566	1.74
MK-420	1.49
MK-414	1.35
MK-434	1.73
E11083	1.36
E11060	2.56
Mélange	
E11273	1.50
E11275	1.37
E11230-C	1.28
E11230-B	1.29
MK-161	2.04
E11230-A	1.36
MK-585	1.73
MK-519	1.56
MK-126	0.93
MK-107	1.66
MK-110	1.30
MK-436-2	1.63
MK101	1.46

Table 7.2: Cr/Ni ratios for all allochthonous mudstone samples.

In the classification diagram of Winchester and Floyd (1977) (Figure 7.5) the data for basalts collected in this study (red squares) are widely spread across several basaltic composition fields in the x-axis and a relatively narrow distribution in basalts in the y-axis. In other words, the Nb/Y ratio is variable, whereas the Y/Ti ratio is constant. The majority of data points fall within the “Andesite, Basalt” field, and with a couple of data points straying between “Andesite, Basalt” and “Andesite”.

Three samples plot completely within the “Sub-alkaline basalt” field, and one sample (E11315A), collected from the Chimney Cove area, plots within the “Alkali basalt” field. Samples MK-607 and MK-623-2 are Nb-rich (Table 7.3) and lie in the “Basanite, Nephelinite” region. Sample MK-607 was collected at the mouth of the Gregory River in Chimney Cove. Sample MK-623-2 was collected from the banks of Trout River along the eastern flank of the North Arm Massif (Figures 4.9, 4.10). Data for Skinner Cove Formation (dark grey diamonds), and Little Port Complex (green triangles) are taken from Baker (1978), and data for the Bay of Islands Complex (blue circles) comes from Jenner et al. (1991). Apparently, none of the samples are similar to Bay of Islands basalts.

Sample	Ti (ppm)	Nb (ppm)	Y (ppm)	Zr (ppm)
MK-411	1106.7	2.0	8.9	5.2
MK-436	7478.2	5.7	25.1	72.1
MK-528	9187.5	12.6	21.4	131.8
MK-558D	10614.5	6.6	38.6	113.9
MK-558P	10517.6	7.2	42.2	125.8
MK-640	6835.7	7.0	21.3	92.4
E11-327	700.1	1.1	2.3	3.6
E11-346-2	5843.4	2.2	20.1	59.7
E11-355	7605.7	1.7	8.5	7.2
E11-355-2	6385.8	1.1	25.2	60.6
MK-122	9413.0	9.8	22.3	136.4
MK-586	6878.2	2.2	26.2	89.0
MK-592	11905.6	7.9	36.1	127.4
MK-594	8152.3	3.8	22.5	90.3
MK-607	16964.5	88.7	26.0	269.9
MK-623-2	13748.1	71.3	11.9	172.4
E11-169	5604.9	3.3	18.7	57.8
E11-315A	10820.4	19.7	18.7	131.4
MK-152-2	11041.5	8.3	30.7	160.2

Table 7.3: Basalt samples collected and their respective concentrations of Ti, Nb, Y, and Zr.

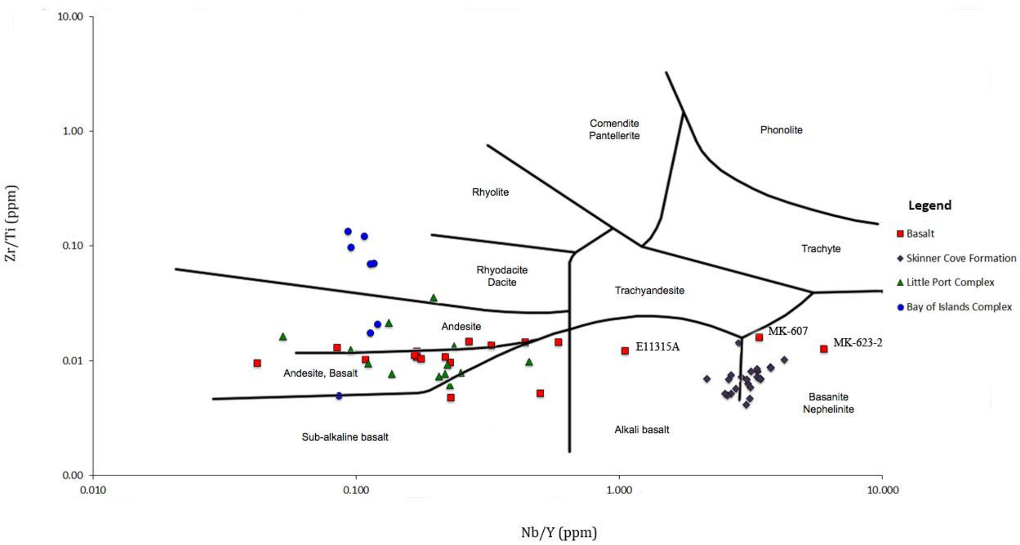

Figure 7.5: Basalt geochemistry plotted on classification diagram of Winchester and Floyd (1977) with basalt samples from this study in red. Skinner Cove Formation and Little Port Complex data from Baker (1978), Bay of Islands Complex data from Jenner et al. (1991). Note labeled samples within Alkali basalt and Basanite-Nepheline fields.

Chapter 8

Discussion

8.1 – Lithostratigraphy and Map Revisions

Differences in distribution patterns add additional detail to the regional map of Williams and Cawood (1989). The distribution of lithostratigraphic units in the region is reinterpreted from the mapping, petrography, and geochemistry completed for this study.

8.1.1 – The Blow Me Down Brook formation

Across the flank of the North Arm Massif and through the South Arm of Bonne Bay (Map sheet 1 and Map sheet 3) the Blow Me Down Brook formation is now seen as a narrower belt of strata. South of Trout River Little Pond and into Chimney Cove, a northeast-southwest belt the Blow Me Down Brook formation has been recognized and added to the map.

Flanking the Blow Me Down Brook formation to the west are slices of dismembered formation and mélange that are structurally wedged between the Blow Me Down Brook formation and adjacent ophiolite complexes. The mélange is discussed in a later section. To the east of the Blow Me Down Brook formation, the Irishtown Formation, Cooks Brook Formation, Middle Arm Point Formation and Lower Head Formation are structurally underlying the Blow Me Down Brook formation

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8.1.1.1 – Sandstone Petrography of the Blow Me Down Brook formation

The modal percentages for the framework grains of the Blow Me Down Brook formation correlate closely with the results of Quinn’s (1985) petrographic analysis from the study area of this thesis. Interestingly Gillis' (2006) study of the Blow Me Down Brook formation from south of the Bay of Islands yielded a slightly different result. The sandstones from Gillis’ study are richer in quartz, and lithic fragments relative to the Blow Me Down Brook sandstone from the map region. While the discrepancy is noteworthy it is not a major difference. Gillis (2006) found that the lower Blow Me Down Brook formation was richer in feldspar. This implies much of what is exposed in the map region is lower Blow Me Down Brook formation.

Blow Me Down Brook formation sandstone from both regions are dominated by quartz, and characteristically equivalent in terms of texture, grain size and shape. Other components, such as accessory minerals are also compositionally comparable. Chlorite, biotite, glauconite, and rare opaque minerals are all accounted for in Blow Me Down Brook formation sandstone both to the north and south of the Bay of Islands.

The petrography also highlighted the sandstone’s lack of porosity. The strata is tightly packed and matrix rich with minor secondary calcite. With respect to hydrocarbon reservoir potential, the porosity of the formation is generally not encouraging. However in a hypothetical reservoir setup the sandstone could act as an impermeable seal.

8.1.1.2- Sandstone and Mudstone Geochemistry of the Blow Me Down Brook formation

Sandstone sedimentology and petrography of the Blow Me Down Brook formation is characteristic of passive margin sedimentation (Quinn 1985; Gillis, 2006). Geochemically, and in terms of SiO_2, K_2O and Na_2O, it has characteristics of both passive and active margin settings (Fig. 7.1). It is likely that several samples have relatively low SiO_2 concentrations because of the grain size effect. Fine- and medium-grained sandstone can potentially register lower silica content than coarser grained rocks. The discrimination plots by Bhatia (1983) in figures 7.2 and 7.3 were ineffective for differentiating depositional tectonic settings. In the diagrams, there is very little or no correlation between the presumed settings for the Blow Me Down Brook formation and the discrimination fields defined by Bhatia.

For the Blow Me Down Brook formation sandstone there is apparently a general enrichment in Fe_2O_3 and MgO relative to the proposed fields of Bhatia (1983). At one level, this could be indicating mafic volcanic input. The enrichment in Ni, evident from the low Y/Ni ratios in the formation (Figure 7.3) may also be suggestive of input from a volcanic source. However, in thin section there are no clearly distinguishable mafic volcanic clasts in the formation. The majority Fe_2O_3 and MgO is likely concentrated in biotite, chlorite and other clay minerals in the matrix of some of the sediments. As expected, results of the analysis of Cr and Ni concentrations are not anomalous in Blow Me Down Brook formation sandstone.

The results of the mudstone geochemical analysis did not yield any unexpected element concentrations for the formation. There were no anomalously high concentrations of Cr or Ni in the mudstone samples.

8.1.2 – The Irishtown Formation

An anomalous wedge of Irishtown Formation underlies the Blow Me Down Brook formation to the north of Kennedy Lake (Map Sheet 1). The distribution and structural position of the Irishtown strata is anomalous as the wedge is overlying the younger Northern Head Group. The physical relationship between this sliver of Irishtown Formation and adjacent units is unknown. Two potential relationships between the sliver and its surrounding strata are proposed. It is either an imbricate thrust slice that has been displaced out of sequence, or it lays in stratigraphic contact with the overlying Blow Me Down Brook formation. The sparsity of exposure hampers the interpretation of this anomalous sliver of Irishtown Formation, and there is no evidence for any stratigraphic contact between the Blow Me Down Brook and Irishtown formations anywhere in the allochthon. The wedge of Irishtown sandstone is likely an imbricate slice thrust between the Blow Me Down Brook formation and Northern Head Group.

Another slice of Irishtown Formation strata has been added to the Chimney Cove area (Map Sheet 2). The slice is inferred from a northeast-southwest trending series of Irishtown outcrop with consistent orientation. However, the sparsity of outcrop prevents an in depth analysis and interpretation on the relationship between the sliver of Irishtown Formation and adjacent Blow Me Down Brook formation.

8.1.2.1 – Sandstone Petrography of the Irishtown Formation

Petrography of Irishtown sandstone samples highlighted the quartz-rich nature of the sandstone. The samples collected from the map area are mature and dominated by quartz. The results of the petrography confirm the results of Quinn’s (1985) petrographic analysis of the formation.

8.1.2.1 – Sandstone and Mudstone Geochemistry of the Irishtown Formation

Sandstones of the Irishtown Formation were not selected for an analysis of major element geochemistry, as they are readily identifiable in the field no matter if they are in stratigraphic context or as dismembered blocks in mélange. However, the results of the trace element geochemistry do show some interesting results. One sandstone sample (MK-440) contains anomalously high Cr (609 ppm). In contrast, the sample contains 12 ppm Ni which is not anomalously high. The Cr in the sample is likely not sourced from an ophiolite since there is no corresponding Ni anomaly. The age and depositional environment of the formation are well constrained (Section 2.4.2) and do not coincide with ophiolite obduction. The anomalous Cr enrichment in the unit is likely the result of input from a volcanic source. It is unclear from this study what, if any source, for the volcanic material may be identified.

The results of the mudstone trace element analysis conform to the results of Botsford’s (1988) geochemical analysis of the Irishtown Formation. There were no anomalously high Cr or Ni concentrations within the mudstone of the unit.

8.1.3 – The Cooks Brook, Middle Arm Point, and Lower Head formations

At the southern end of the Chimney Cove coastline (Map Sheet 2) a narrow belt of Cooks Brook Formation strata has been identified by the current mapping. The exposure was not classified on the Williams and Cawood (1989), nor the Williams (1973) maps.

At the eastern margin of the map area, from North Arm to Trout River Pond (Map Sheet 1) and into South Arm (Map Sheet 3) the strata have previously been recognized as a Cooks Brook Formation equivalent (Quinn, 1985; Williams and Cawood, 1989). Strata of the Middle Arm Point Formation and the Lower Head Formation have been identified within the belt. The units sit in their proper stratigraphic context above the Cooks Brook Formation. For the Middle Arm Point Formation, it is the thin tan-weathering doloarenite beds that differentiate it from the Cooks Brook Formation.

Chromium-bearing sandstone near Kennedy Lake distinguishes the Lower Head Formation from older siliciclastic units. Sandstone outcrops with a lower concentration of quartz, relative to Blow Me Down Brook formation, suggest the Lower Head Formation extends southwest from the Kennedy Lake area.

Strata at the eastern end of Woods Island has been reclassified as repeating fault-bound sections of Middle Arm Point and Lower Head formations. Buchanan (2004) previously reclassified the mélange mapped by Williams and Cawood (1989) on that portion of the island. Herein a slightly different distribution of the strata is presented, and extended onto the northern shore of the island.

In previous maps a belt of mélange separated the Blow Me Down Brook formation from the Cooks Brook Formation in the region (Williams and Cawood, 1989). The mélange has been reinterpreted to coherent lithostratigraphic units because of a lack of evidence for an exchange of material between formations. For example, outcrops of Irishtown Formation sandstone are not clustered with Lower Head Formation sandstone.

8.1.3.1 – Mudstone Geochemistry of the Cooks Brook Formation

The major element geochemical analysis of mudstone collected from the Cooks Brook Formation largely conforms to a similar geochemical analysis of both units done by Botsford (1988). As expected, the formation does not have any anomalously high concentrations of Cr or Ni.

8.1.3.2 – Sandstone and Mudstone Geochemistry of the Lower Head Formation

Geochemically, sandstone of the Lower Head Formation is classified as “Active Continental Margin” according to Roser and Korsch’s (1986) discrimination diagram (Figure 7.1). The geochemical interpretation agrees with Quinn’s (1992) petrographic interpretation of the formation as a flysch deposited in a foreland basin. Although Bhatia’s (1983) discrimination diagram was of no use for reliably determining the tectonic provenance of the sandstone, it does show the contrasting composition between the Lower Head and Blow Me Down Brook formations. The formation contains more total Fe_2O_3 and MgO than the Blow Me Down Brook formation (Figures 7.2 and 7.3). Quinn (1992) noted the increased total Fe_2O_3 and MgO in the Lower Head Formation and attributed it to the presence of volcanic detritus apparent in thin section.

With regards to key trace elements, sandstone of the formation is typically enriched in Cr, though not in every sample collected. Only a single sample contains an anomalously high Cr/V ratio, enough to suggest an ophiolitic source of detritus according to McLennan’s (1993) Cr/V vs Y/Ni diagram (Figure 7.4). However in the diagram most of the samples from the Lower Head Formation lie in a cluster with samples of the Blow Me Down Brook formation. The common grouping of samples from both formations suggests McLennan's (1993) Cr/V vs Y/Ni diagram is not entirely effective differentiating sandstone of the Lower Head and Blow Me Down Brook formations.

The Lower Head Formation is recognized as containing ultramafic detritus in sandstone (Botsford, 1987; Quinn, 1992). However, there is no clear evidence for ultramafic detritus in mudstone from the formation in the map area. Furthermore the results of the mudstones analyzed herein are in general agreement with Botsford's (1988) results. This might indicate that Cr and Ni in the allochthon are contained in coarse grained minerals and preferentially deposited with sandstone rather than absorbed into clays and subsequently deposited in mudstone.

8.1.4 – Mafic Volcanic Rocks

Skinner Cove Formation

From the Winchester and Floyd's classification diagram (Figure 7.5) two samples of mafic volcanics (MK-623-2 and MK-607) are clearly related to the Skinner Cove Formation. Another sample, E11315A, plots within the Alkali basalt field but it is not otherwise close to the Skinner Cove Formation data described by Baker (1978).

The geographic distribution for sample MK-623-2 is anomalous in that it does not come from mafic volcanics flanking the Blow Me Down Brook formation but rather it was collected from mafic volcanics exposed within the Blow Me Down Brook formation. The volcanic rocks along Middle Trout River are proximal to the Blow Me Down Brook-Middle Arm Point Formation tectonic contact but do not appear related to the fault according to the configuration of the strata. There is not enough observable data to confidently characterize the relationship between the blocks of Skinner Cove volcanics and the Blow Me Down Brook formation at the Trout River locality. The exposures that yielded samples MK-607 and E11315A are not in a similar stratigraphic position.

Both MK-607 and E11315A were collected at Chimney Cove, and between 12 and 20 km south of the coastal type section for the Skinner Cove Formation at Skinner Cove. The geochemistry for sample MK-607 suggests it is the same composition as the Skinner Cove Formation; in contrast, the geochemical character for sample E11315A is not as clear. Both collection localities are classified as Skinner Cove Formation but additional work is necessary on the basalts from Chimney Cove.

Crouchers formation

Geochemical analyses for 16 mafic volcanic samples from rock previously classified as Crouchers formation (Williams and Cawood, 1989) confirms Quinn's (1985) interpretation that Crouchers formation rocks are not equivalent to the Skinner Cove formation. In the classification diagram of Winchester and Floyd (Figure 7.5) Crouchers formation samples dominantly fall within the Andesite-Basalt field and the Sub-alkaline Basalt field. The cluster of data points has a loose correlation to basalt of the Little Port Complex in the plot. The Crouchers formation is herein considered an equivalent to the Little Port volcanics.

8.1.5 – Mélange and Dismembered Formation

Belts of mélange have been added to the map and skirting the eastern boundary of the Bay of Islands Complex from North Arm to the South Arm of Bonne Bay, and the western margin of the North Arm Massif. The additional belts of mélange in the region were recognized by Godfrey (1982) early on, however they were omitted from recent maps (e.g. Nyman et al., 1985; Williams and Cawood, 1989). The material directly underlying the volcanic and ophiolitic massifs fit the criteria for mélange and dismembered formation, and is therefore classified as such.

On Woods Island (Map Sheet 3) the distribution of the stratigraphy has recently been updated (Buchanan, 2004). However igneous blocks within dismembered strata east of the volcanic slice (Station MK-410) were missed during the 2004 mapping campaign, and the strata was consequently misinterpreted. The revised stratigraphy for the eastern half of the island consists of two slices of mélange flanking the Lower Head and Middle Arm Point formations. The repetition of stratigraphy in the map (Map Sheet 3) suggests the strata on the eastern end of Woods Island are folded.

8.1.5.1 –Sandstone petrography of the mélange and dismembered formation

From sandstone petrography, the origin of many of the sandstone blocks in the mélange may be derived. The thin section analysis reveals that many sandstone blocks from the mélange are texturally and compositionally comparable to sandstone of the Blow Me Down Brook formation. The lack of mafic lithic fragments in the mélange blocks indicates they are not derived from ophiolitic material. However, for other sandstone blocks the geochemistry indicates a more a complicated story.

8.1.5.2 – Sandstone and Mudstone Geochemistry of the Mélange and Dismembered Formation

Geochemically, the sandstone blocks in the mélange have similarities to both the Blow Me Down Brook and Lower Head formations. The classification diagrams used are not particularly useful in determining the tectonic provenance of mélange sandstone blocks. However, Bhatia's (1983) discrimination diagrams (Figures 7.2 and 7.3) allow for the discrimination of sandstone samples based on Fe_2O_3 + MgO content. The Blow Me Down Brook formation has been shown to be poor in Fe_2O_3 + MgO, and the Lower Head Formation has been shown to be rich in Fe_2O_3 + MgO. On this basis mélange sandstone blocks can be separated into two populations. The population with lower Fe_2O_3 + MgO correlates to the Blow Me Down Brook formation while population with increased Fe_2O_3 + MgO correlates to the Lower Head Formation.

In McLennan's (1993) Cr/V vs. Y/Ni diagram (Figure 7.4) the majority of mélange sandstone samples plot within an indistinct group of Blow Me Down Brook and Lower Head sandstones. The two outliers are each unique in that MK-521-3 represents a sandstone with an ophiolitic source and MK-114-1 represents a sandstone with a continental source. They can be respectively correlated with the Lower Head Formation and the Blow Me Down Brook formation. Other than the two outliers there is no clear differentiation of mélange sandstone blocks into Blow Me Down Brook formation and Lower Head Formation using McLennan's parameters.

Trace element geochemistry of the mudstone matrix of the mélange and dismembered formation reveals that neither Cr nor Ni occur in anomalously high concentrations (Table 7.1). Mudstone samples from every lithostratigraphic unit have similar Cr and Ni concentrations. It is therefore not possible to differentiate them, or compare one individual unit to the mélange using the two trace elements.

8.2 – Structural Considerations

8.2.1 – Regional Structural Geology

The high-angle brittle faults across the region have generally consistent orientations. They are considered to be later structures but timing relationships are not clear. Waldron (1985), Bosworth (1985), and Buchanan (2004) tentatively ascribed high-angle faults in the southern Bay of Islands to Carboniferous deformation. Unfortunately there are no Carboniferous strata exposed in the map region, but a regional northeast-southwest trending strike-slip fault system overprints nearby Carboniferous strata in the Deer Lake and Bay St. George basins (Waldron et al., 1998; Palmer, 2002; Buchanan, 2004). The orientations of the faults in the map area is consistent with Riedel shears, synthetic P, and antithetic X shears generally present in strike slip fault systems. The high-angle fault system in the region is tentatively determined to be Carboniferous.

Sections A-A' and B-B' (Map sheet 3) represent the macroscopic architecture of the southern part of the map area. The regional scale nature of the fold trains is clear. Antiformal culminations at North Arm are of a large enough scale to represent economically important potential reservoirs. The west-verging asymmetric anticline expressed at Woods Island is a similar reservoir-scale macroscopic structure that was originally measured and modeled by Buchanan (2004).

The regional-scale folding in the area suggests the macroscopic structural architecture in the Humber Arm Allochthon is favourable for the development of economic structural hydrocarbon reservoirs. Unfortunately, timing relationships were not evident in most of the outcrop. This hinders a detailed synthesis of the structural geology in the region.

8.2.2- Structural Geology of the Mélange and Dismembered Formation

Structurally the mélange in the region is distinct from the Northern Head Group and Blow Me Down Brook formation. Dismemberment in the Lower Head Formation strata is intense. Bedding separation is on the scale of metres, coloured bands in the mudstone matrix are pinched out to discontinuous lenses. Fragments of bedding are rotated out of their original orientations. In the Northern Head Group there are no pinch and swell structures. The separation of bedding is on the order of centimeters, and there is generally no rotation of bedding fragments. The contrasting structural styles are best exemplified on Woods Island (Figure 6.7). The unique structural geology of the dismembered Lowered Head Formation and mélange can be used to identify the unit it in the map region. It allows for correlation of relatively small outcrops that do not necessarily contain any blocks typical of the unit.

It is evident from structures in the matrix and in dismembered blocks that D_1 initiated broken formation and more chaotic mélange. Progressive dismemberment of the Lower Head Formation generated cleavage and phacoidal cleavage through non-coaxial deformation. This is also an early structure as it is deformed by F_2 folding on Woods Island. Carbonate-mudstone blocks that are not overprinted by F_2 folds or S_2 cleavage would have been incorporated before D_2 affected the host formation. The carbonate-mudstone blocks are from successions of Northern Head Group strata. D_2 folding and axial planar cleavage overprints all strata of the Northern Head Group in the region.

Blocks that lack D_2 structures must have been incorporated into the mélange prior to D_2 deforming the strata regionally.

8.3 – A Protolith for the Mélange and Dismembered Formation

Mélange units across the region are apparently very similar. For example, the dismembered matrix of grey, green, and red mudstone is a common feature at every locality. Dolomitic siltstone blocks are also widespread. In fact, the abundance of common features among all of the mélange localities in this area points toward a single mélange underlying the ophiolitic massifs in the region and generated from a common protolith. Prior to deformation the mélange was most likely banded dark grey, light grey and, greenish grey mudstone with interbedded thin to medium beds of laminated dolomitic siltstone, and medium to thick beds of grey sandstone. Some sandstone beds had conglomeratic bases. The igneous blocks were incorporated into the original formation before or during deformation. It is not clear whether they fell into the mudstone matrix from sedimentary processes or were plucked from an overriding thrust. Nevertheless, the sandstone blocks have distinctive petrographic signatures that allow some progress toward their classification.

The petrography and geochemistry seem to indicate a greater proportion of the sandstone blocks in the mélange are Blow Me Down Brook formation. A more rigorous and focused sample collection will have to be obtained to get a proper understanding of the proportions of Blow Me Down Brook formation siliciclastics to the younger flysch-related sandstone. While many sandstone blocks are interpreted to have originated in the Blow Me Down Brook formation the broader sedimentary characteristics of the mélange and dismembered formation suggest its protolith is not related to the early Cambrian siliciclastics.

Given basic sedimentary characteristics, two potential candidates for the original formation may be considered. The Lower Head Formation, and the Middle Arm Point Formation share several similarities with the mélange. Both formations contain significant quantities of dark grey, green, and red mudstone (Botsford, 1988; Quinn, 1992). In addition, thin bedded dolomitic siltstone is also a component of both, though it is much more common in Middle Arm Point strata. Medium to thick bedded sandstone is a principal lithology for the Lower Head Formation; it does not occur in the Middle Arm Point Formation.

The distinctive pebble mudstone facies in the mélange apparently has a counterpart in the Lower Head Formation. In contrast, a much smaller range of similarities is seen with the Middle Arm Point Formation. Collectively, the stratigraphy, age and common clasts indicate the Lower Head Formation shares more basic characteristics with the mélange and dismembered formation, and is considered the best protolith candidate. By linking these strata, the stratigraphic architecture may be simplified by assigning these rocks to a known lithostratigraphic unit.

Broken Lower Head strata are likely deformed beds and broken beds plucked from the footwall by advancing thrusts. Likely wedged between the hanging wall and footwall blocks, these strata underwent various degrees of pervasive deformation, with fragments of and blocks sheared and incorporated into a generally mixed matrix.

The mélange and its intermediate members in the map area can be modelled by modifying Raymond's (1984) diagram (Figure 8.1). The figure shows the transition of the Lower Head Formation from formation to mélange. The mélange is an end-member in the process and dismembered formation is the final step previous to the end-member.

It is only the presence of exotic material that separates the two in terms of their classification in the field. Observations from the field work in the Humber Arm Allochthon show a continuation of deformation from slightly deformed formation (i.e. Raymond's broken formation) to pervasively deformed formation that has incorporated exotic material (i.e. mélange). The limits of broken formation, dismembered formation and mélange are observable. Each of the transitional phases between formation and mélange represent a change in structural history to a unit with the same genetic history. From a regional stratigraphic standpoint classifying the mélange in context with the stratigraphic framework of the allochthon makes sense.

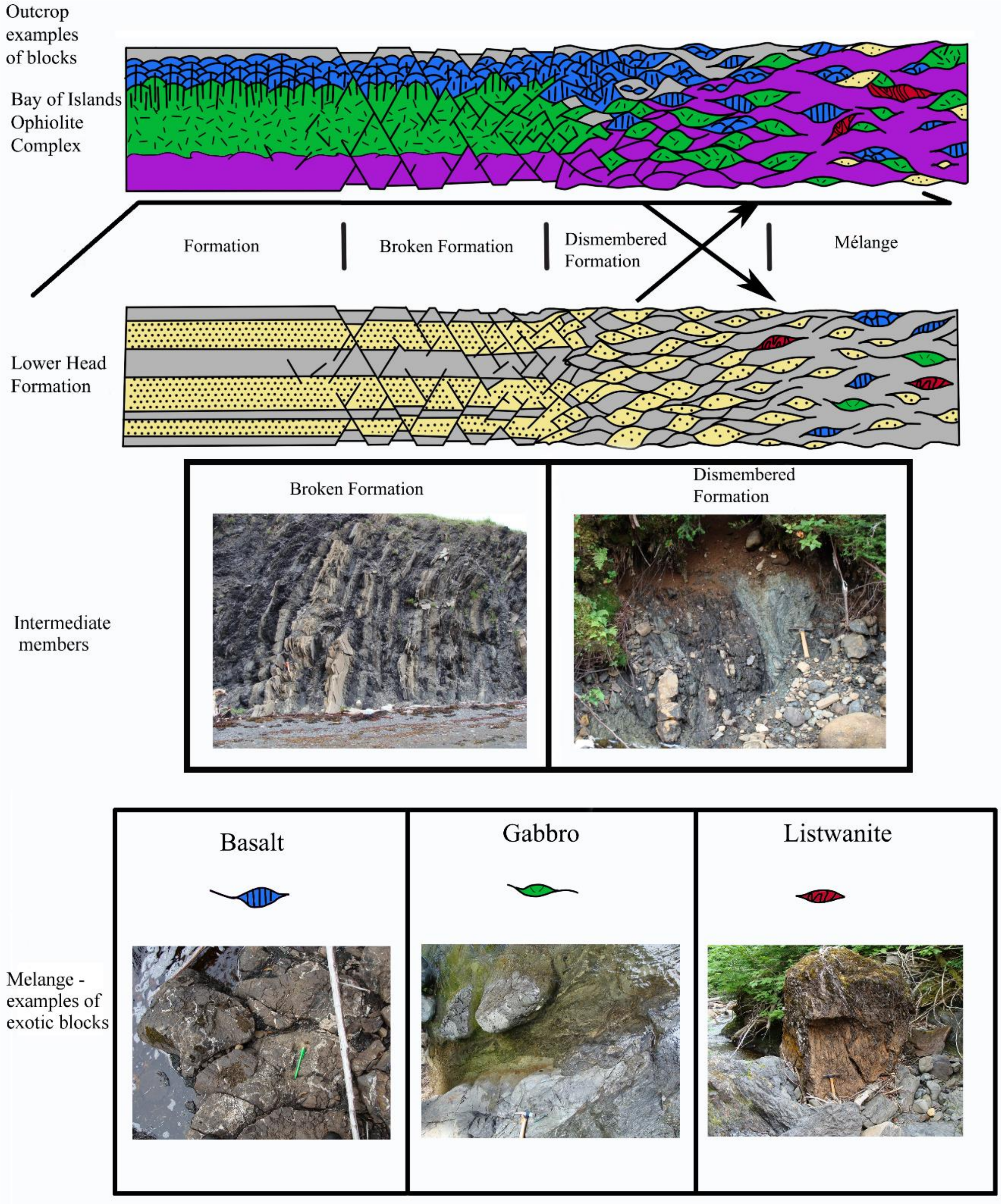
Outcrop examples of blocks
Bay of Islands Ophiolite Complex
Formation
Broken Formation
Dismembered Formation
Mélange
Lower Head Formation
Broken Formation
Dismembered Formation
Intermediate members
Basalt
Gabbro
Listwanite
Melange - examples of exotic blocks

Figure 8.1: Modified version of Raymond's (1984) schematic (Figure 2.3) with outcrop examples of intermediate members and exotic blocks in mélange. Broken formation is from station 11MK-424 (5 m field of view), dismembered formation is from station 11MK-594 (hammer for scale). Basalt is from station 11MK-594 (pencil for scale), gabbro is from station 10MK104 (hammer for scale), and listwanite is from station 11MK-525 (hammer for scale).

8.7 – Hydrocarbon Potential

Oil seeps along the western coastline of Newfoundland are relatively common occurrences in the Cambro-Ordovician strata extending from the Port au Port Peninsula, as far north as Parsons Pond (Fowler et al., 1995). Furthermore, in a comprehensive analysis of potential source rocks and hydrocarbons for western Newfoundland Fowler et al. (1995) indicated the Cooks Brook Formation, is an equivalent for the Green Point Formation in Gros Morne National Park, and it too has some of the necessary characteristics to generate hydrocarbons.

The Green Point Formation has a high organic content, with TOC measuring up to 10.35% and with an HI up to 759 (Fowler et al., 1995). The organic matter in the mudstone of this unit is reported as Type I and II kerogen, and likely of algal origin. Oil samples studied from Port au Port, Green Point, and Parsons Pond all show a strong, positive correlation that indicates the oil samples all share a common source rock, the Green Point Formation (Fowler et al., 1995; Weaver and Macko, 1988). The oil seeping from the Cooks Brook Formation at Chimney Cove is but one more indication of an active petroleum system in or under the Humber Arm Allochthon.

One of the other fundamental contributions to recognizing the region's hydrocarbon potential rests with the identification and mapping of large anticlines in the North Arm region (structural Domain A). Such structures may be viewed as possible analogs for what may lay beneath the surface. The macroscopic west-verging anticline on Woods Island, and initially mapped by Buchanan (2004), and another large hydrocarbon bearing structure mapped by Gillis (2006) at Sluice Brook, indicates this style of folding is a common feature regionally developed across this part of the Humber Arm Allochthon.

From analyses conducted here, the Blow Me Down Brook formation is a tight, matrix-rich sandstone with very little pore space. In addition, the formation structurally overlies Northern Head Group organic rich mudstone, and elsewhere, lenses of Lower Head Formation stratigraphically overly the Northern Head Group. The turbiditic sandstones of the Lower Head Formation may present better reservoirs than the Blow Me Down Brook formation sandstone. The tightly cemented Blow Me Down Brook formation does however provide a potential seal for a structurally trapped hydrocarbon reservoir. Its position over the Northern Head Group is favourable for the development of a cap rock. The Northern Head Group hosts a known hydrocarbon source in the Cooks Brook Formation. With this stratigraphic and structural configuration, one may envision a situation where hydrocarbons generated from the Cooks Brook Formation migrate into regional antiforms capped by the overlying Blow Me Down Brook formation. The oil seeping from rock at Chimney Cove simply confirms that hydrocarbons remain beneath the allochthon and a trapping model with a tight sandstone cap over shattered Cooks Brook mudstone may yet have some merit.

Chapter 9

Conclusions

9.1 – Summary

This mapping project, covering a portion of the Humber Arm Allochthon between the Bay of Islands and the South Arm of Bonne Bay, is focused upon the strata of the lower and intermediate thrust slices of the allochthon. The objective for this work is to clarify some aspects of the stratigraphic assembly in the study area and explore geological matters associated with hydrocarbon exploration in western Newfoundland.

In a geographic context the mapped strata are those skirting and underlying the ophiolitic massifs. They include siliciclastic and calcareous successions of the Blow Me Down Brook formation, Irishtown Formation, Cooks Brook Formation, Middle Arm Point Formation, the Lower Head Formation, and mélange.

The mélange separating the intermediate and highest tectonic sheets have, by their very nature, been a difficult subject to approach. In this matter, Baker (1978) proposed belts of mélange underlying the ophiolitic massifs north and south of the Bay of Islands. Later, Nyman et al., (1984) included some 'chaotic zones' between the Bay of Islands and Trout River Pond as a part of the informally named Winterhouse formation. The regional map of Williams and Cawood, (1989) simply shows mélange as a very broad unit on the eastern end of Woods Island's. Furthermore, and nearby, they did not explicitly define mélange on the eastern flanks of the North Arm Massif and Table

Mountain Massif. More recently, Buchanan (2004) demonstrated that the broad belts of mélange of Williams and Cawood (1989) in the southern Bay of Islands are divisible into imbricate slices of coherent lithostratigraphic units.

To complete the objectives of the project, and namely to better define strata laying below the ophiolite, several geochemical analyses were completed on igneous and sedimentary rock samples around and beneath the North Arm and Table Mountain massifs. For this work, the range of samples collected for petrographic and geochemical analyses apparently show some common characteristics that may prove useful for differentiating broken formation from other more chaotic intervals.

9.2 – Mélange Conclusions

The sedimentary, structural, petrographic, and geochemical characteristics of the strata laying below the ophiolite may be reclassified as mélange and dismembered formation, following Raymond's (1984) classification scheme. The matrix of the chaotic strata is strongly dismembered dark grey, greenish grey, and minor red mudstone. Clasts include several types of fragments of both native (dismembered formation) and exotic (mélange) origin. Fragmented dolomitic siltstone beds and blocks of dolomitic siltstone-mudstone successions are commonly distributed throughout the mélange. They occur with such frequency they are considered a native component of the formation.

Sandstone blocks are not common overall. Given the small sample size, two populations of sandstone blocks have been recovered from the unit. One group has been separated petrographically and identified as Blow Me Down Brook formation. The second group of sandstone samples is distinctly rich in iron oxide and magnesium oxide and correlate with Ordovician flysch. Trace element geochemistry differentiated a single sandstone block based on Cr and Ni content.

The overall sedimentology suggests that chromium bearing sandstones are a native component of the mélange. In contrast the sandstone blocks of the Blow Me Down Brook formation were likely introduced during fragmentation and mixing of the unit and perhaps as sandstone blocks sheared from the hanging wall of a thrust.

Other types of blocks in the exotic assemblage include listwanite, basalt, gabbro, agglomerate, and serpentinite. Generally, these blocks are distributed proximal to nearby sources e.g. the Bay of Islands Complex and Little Port Complex.

The sedimentary characteristics of the mélange are not unique to the allochthon. It is the deformation history that sets the unit apart. The mélange shares a majority of its characteristics with the Lower Head Formation. Dark grey and green mudstone, minor red mudstone, thick sandstone, thin to medium beds of dolomitic siltstone, and pebbly mudstone are all mélange characteristics that are similarly described for the Lower Head Formation and its equivalent Eagle Island Formation (Quinn, 1992; Botsford 1987). The major contrasting characteristic between the mélange and the dismembered Lower Head Formation is the exotic blocks engulfed within the mudstone. Because of the abundant similarities the mélange is herein tentatively classified as Lower Head Formation. The formation was plucked from the hanging wall during initial phases of the assembly of the Humber Arm Allochthon.

Raymond's classification scheme (Figure 2.5) was useful in classifying dismembered formation and mélange in the allochthon. The continuum of deformation, namely between dismembered formation and mélange was observed in the chaotic strata underlying the ophiolitic massifs. Dismembered formation can be distinguished from mélange based on the inclusion of exotic blocks that originated in the ophiolite.

Further work is recommended to confirm the results and classification of the mélange and dismembered formation. A palynologic analysis of the pristine blocks of dolomite-mudstone successions will constrain a minimum age of formation for the unit. A more detailed analysis of sandstone blocks may give greater detail into their origin. Petrography is recommended over geochemistry as it has proven to be a much more rigorous analysis with clearer results.

9.3 – Stratigraphic Conclusions

The lithostratigraphic units of the region have been assigned the classification scheme of their equivalent Bay of Islands units. The reclassification from Quinn's (1985) Bonne Bay Group was done to simplify the stratigraphy across the entire allochthon. The characteristic differences between the strata of Bay of Islands and Bonne Bay are deemed insufficient to warrant separate classification. One of the major implications of the reclassification scheme has been a reinterpretation of the geographic distribution of the lithostratigraphy. There are two major changes to the stratigraphic distribution presented herein. One of the major changes is the reassignment of the informally named McKenzies formation (Quinn, 1985; Williams and Cawood, 1989) into the Cooks Brook Formation, Middle Arm Point Formation, and Lower Head Formation. The second fundamental difference to the stratigraphy rests with changes to the classification and distribution patterns for mélange separating the Blow Me Down Brook formation and ophiolitic complexes.

On the edge of the ophiolite complexes in the map region, a relatively narrow zone of mélange separates the Blow Me Down Brook formation from the igneous strata overlying it. On the eastern side of Woods Island two wedges of mélange bound folded strata of the Middle Arm Point and Lower Head formations.

Finally, mafic volcanic lithologies at the flanks of igneous complexes have been reassigned. The volcanic units were classified as equivalents of the Skinner Cove Formation. An analysis of their geochemical makeup demonstrates they are more closely related the arc-related volcanic rocks of the Little Port Complex. However, the relationship is tentative.

9.4 – Recommendations

Several measures can be taken to improve the regional stratigraphy. It is recommended that future work include appropriate dating for the strata. The mudstone from all of the units in the region, and particularly the Northern Head Group, should be analyzed for appropriate microfossil suites (conodonts, palynomorphs, radiolarians) and where strata allow, radiometric dates. Dating strata will test stratigraphic correlations proposed here and ultimately provide a reliable stratigraphic framework for this region.

The mafic volcanic strata have been loosely correlated with the Little Port Complex. A more rigorous study of samples and localities should be used to develop a clearer picture of their true affinities. The study should include significant radiometric dating to separate the age and origin for the geochemically diverse igneous rocks that are apparently unrelated to otherwise similar looking lithologies in this region.

Finally, an analysis of organic geochemistry on mudstone and oil seeps of the Northern Head Group would add to our knowledge of the petroleum system that lays beneath the Humber Arm Allochthon.

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Appendix A

Petrographic and Geochemical Methods

A.1 - The Gazzi-Dickinson Point Count Method

Petrographic studies of the collected sandstone samples were carried out according to the Gazzi-Dickinson technique. The Gazzi-Dickinson Point Count Method was developed by both Gazzi (1966) and Dickinson (1970). It is a means of calculating modal percentages of framework grain mineralogy in a sandstone. The result of the method is a quantifiable characterization of sandstone that also allows for the interpretation of the provenance of the sandstone. The technique was also used by earlier studies of the allochthon (e.g., Quinn, 1985, 1992; Gillis, 2006), therefore the results for this study are readily comparable to other sandstone petrography, and specifically for the Blow Me Down Brook formation from other localities in the Humber Arm Allochthon.

In practice, the Gazzi-Dickinson technique requires identification and counting of individual grains, larger than 0.0625mm, and with point data collected at regular spaced intervals. To accomplish this, the microscopy thin section is moved a specific distance horizontally across a mechanical stage. After each movement the grain directly below the cross-hair is counted. If pore space or cements are encountered, these too are measured and tabulated in (Appendix B). The framework grains are described as follows:

Stable Quartz – monocrystalline quartz grains and polycrystalline quartz grains. The total component of stable quartz (Q) is the sum of the monocrystalline quartz (Qm) and polycrystalline quartz (Qp) grains.

Feldspar (F) – monocrystalline feldspar grains, of either plagioclase or potassium feldspar.

Unstable Lithic fragments (L) – polycrystalline detrital grains originating from a variety of sources. The fragments can be summarized as volcanic and metavolcanic lithic fragments, sedimentary and meta-sedimentary fragments, and metamorphic rock fragments. The total lithic fragment component (Lt) of the sandstone is the sum of unstable lithic fragments (L) and stable polycrystalline quartz (Qp).

Ternary diagrams for sandstone classification have been developed to graphically represent the modal percentages and classify sandstone (Pettijohn 1975). Together, Pettijohn's (1975) ternary diagram and the Gazzi-Dickinson point count method, offer quantifiable, compositional descriptions for sandstones – information that may assist with genetic interpretation.

B.1 - Geochemistry

Analytical techniques

X-Ray Fluorescence was used to determine major and trace element geochemistry of the sandstone and basalt. Samples were initially broken up into smaller pieces with a rock hammer. The smaller pieces were crushed into a fine powder using the milling machine at Memorial University’s Department of Earth Sciences facility. The crushing equipment was thoroughly cleaned using ethanol and rinsed with distilled water to avoid cross contamination between samples. Silica sand was also run through the crusher to completely remove left over material after a sample was crushed.

The powdered samples were given to Memorial University Department of Earth Sciences Analytical Facilities Coordinator (CREAIT), Pam King for final preparation and analysis. Initially the sample powder is converted into a pressed pellet. 5 g of powder is mixed with 0.7 g of a resin binding agent then pressed at 275.8 MPa for 10 seconds.

Following that the pellet is baked for 15 minutes at a temperature of 200° C. The pressed pellet is analyzed and geochemical results are compiled and distributed.

The trace element analysis of mudstone was done by ICP-MS. For preparation 0.1g of a sample were dissolved in a solution of HF/HNO_3 prior to be being analyzed.

Accuracy and precision

The reliability of geochemical results can be determined using accuracy and precision calculations. Accuracy is a metric of how correct an analysis is. Accepted values from standardized reference material are compared to analytical values for the determination the accuracy of an analysis. Reference material used for XRF analysis are BHVO-1, SY-2, and SY-3. Reference material used for ICP-MS analysis is JGB-2.The equation used to calculate accuracy (ie. relative difference, RD) is:

$$RD = [(X_{lab} – X_{accepted}) / X_{accepted}] * 100$$

In the equation X_{lab} is the experimental result of a concentration of an element for the reference material and $X_{accepted}$ is the accepted concentration of an element in the reference material.

Precision is a metric for the repeatability of analytical results. It is calculated from the difference between duplicated analyses of the same sample. It was calculated for ICP-MS analyses of mudstones for trace element geochemistry. Precision can be calculated as the relative standard deviation, or RSD. The formula for RSD is as follows:

$$RSD = [(X_1 – X_2) / (X_1 + X_2)] * 100$$

In the above formula for RSD, X_1 represents the original analysis and X_2 is the duplicate analysis. Duplicate analyses were done for samples E12058-1 and E12209-3. The samples are mudstones collected for another study. They were analyzed with the mudstones collected for this research. Although they are not part of this work, they are reflective of the repeatability of the analytical run that contained mudstones analyzed herein.

Both accuracy and precision can be classified as excellent, very good, good, and poor based on their calculated results (Jenner, 1996). A calculated result of 0-3% represents an excellent accuracy or precision, a result of 3-7% represents a very good accuracy or precision, a result of 7-10% represents a good accuracy or precision, and a poor accuracy is reflected by results >10%.

Major element accuracy

Accuracy for major elements is generally very good to excellent for all standards. SY-2 has poor accuracy for MgO, BHVO-1 has poor accuracy for P_2O_5, and both SY-2 and SY-3 have poor accuracies for TiO_2.

Trace element accuracy

For trace elements the accuracy was generally poor for JGB-2. Cu had a good accuracy, Cr, Co, La, and Ce had very good accuracies, and Er had an excellent accuracy.

Trace element precision

The precision of the results for the trace element analysis is good to excellent for sample E12209-3. Only Zn and Mo have poor precision. For sample E12058-1 all trace elements have a poor precision.

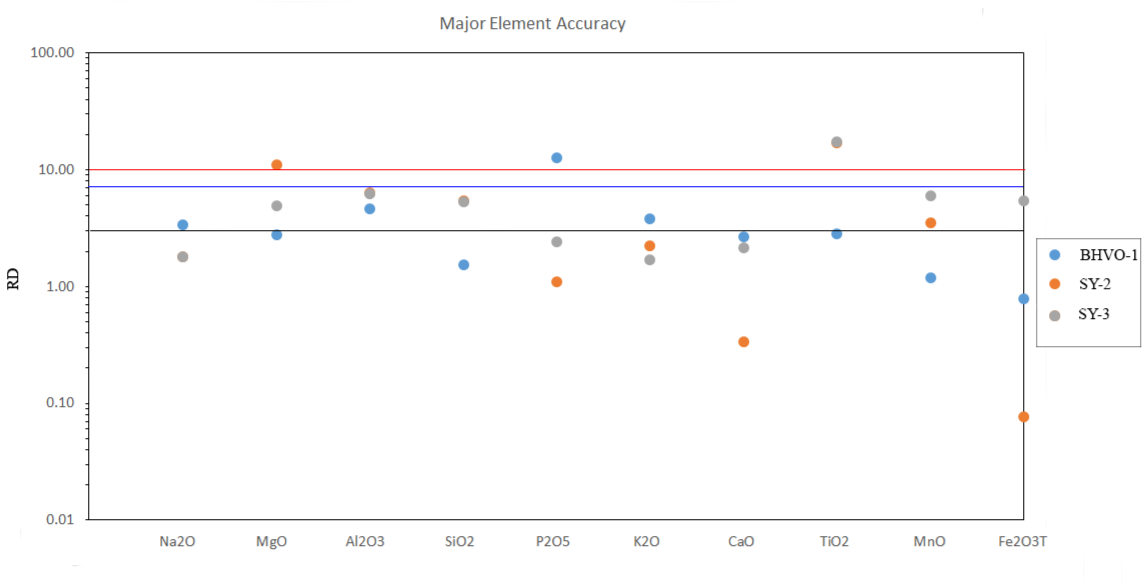

Figure A.1: Major element accuracy of sandstone and mafic volcanic sample runs for standards BHVO-1, SY-2, and SY-3.

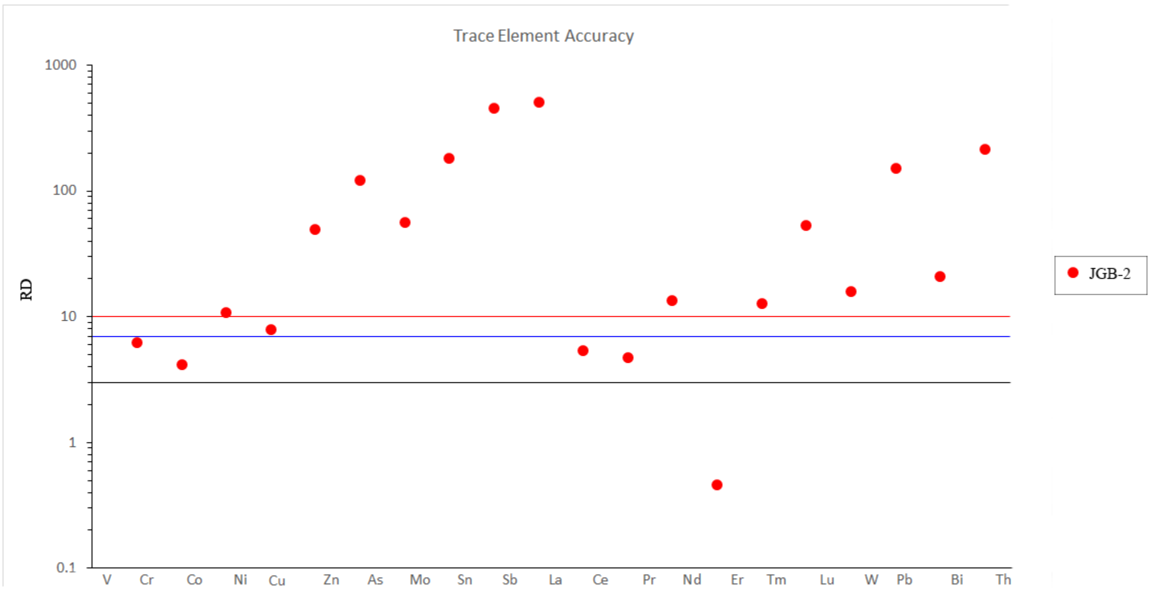

Figure A.2: Trace element accuracy of mudstone sample run for standard JGB-2.

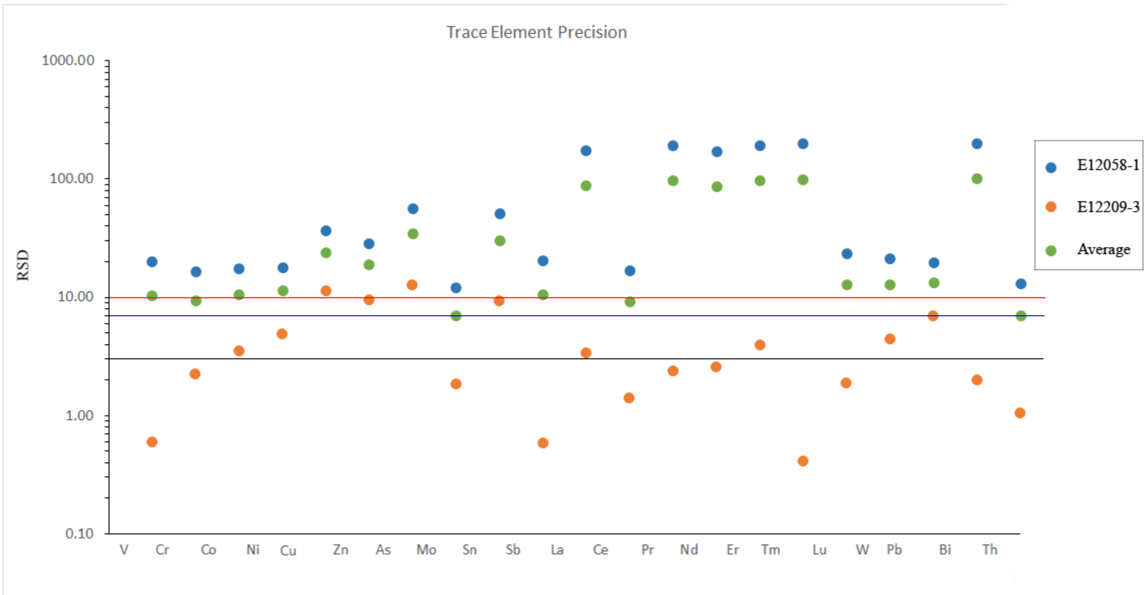

Figure A.3: Trace element precision of mudstone sample run for duplicate samples E12058-1 and E12209-3. Note samples are not for this study but were part of the sample run.

Appendix B

Station Locations

Station	Northing	Easting	Station	Northing	Easting	Station	Northing	Easting
10MK054	435011	5475870	**10MK100**	432294	5481788	**10MK146**	417590	5476286
10MK055	434968	5475919	**10MK101**	432146	5481783	**10MK147**	417500	5476218
10MK056	434468	5476861	**10MK102**	432076	5481759	**10MK148**	417440	5476144
10MK057	434352	5477181	**10MK103**	431966	5481690	**10MK149**	417389	5476066
10MK058	434321	5477407	**10MK104**	431932	5481623	**10MK150**	417307	5475980
10MK059	434301	5477517	**10MK105**	433411	5484629	**10MK151**	417144	5475952
10MK060	434438	5477814	**10MK106**	433413	5484349	**10MK152**	416989	5475950
10MK061	434454	5478000	**10MK107**	433419	5484234	**10MK153**	432909	5481029
10MK062	434487	5478439	**10MK108**	433802	5483829	**10MK154**	433120	5480861
10MK063	434067	5478983	**10MK109**	433848	5483797	**10MK155**	433427	5479890
10MK064	433861	5479263	**10MK110**	416869	5475377	**10MK156**	434299	5478761
10MK065	433633	5479486	**10MK111**	416602	5475262	**10MK157**	434470	5478524
10MK066	433542	5479592	**10MK112**	433219	5484241	**10MK158**	430580	5481170
10MK067	433483	5479657	**10MK113**	433408	5484400	**10MK159**	430593	5481097
10MK068	433404	5479773	**10MK114**	433041	5480178	**10MK160**	430613	5481058
10MK069	433073	5480236	**10MK115**	433049	5480148	**10MK161**	430761	5481002
10MK070	433023	5480500	**10MK116**	433055	5480101	**10MK162**	430835	5481022
10MK071	433011	5480688	**10MK117**	432674	5480858	**10MK163**	430615	5480973
10MK072	432976	5480814	**10MK118**	432530	5480501	**10MK164**	430724	5480986
10MK073	432904	5480869	**10MK119**	432661	5480181	**10MK165**	430868	5481086
10MK074	432912	5480979	**10MK120**	432676	5480181	**10MK166**	430944	5481067
10MK075	432831	5481105	**10MK121**	432756	5479923	**10MK167**	431081	5481124
10MK076	432798	5481140	**10MK122**	432756	5479923	**10MK168**	431177	5481219
10MK077	432712	5481430	**10MK123**	418761	5477438	**10MK169**	431381	5481315
10MK078	432983	5482330	**10MK124**	418702	5477356	**10MK170**	431511	5481491
10MK079	433110	5482478	**10MK125**	418505	5477333	**10MK171**	431699	5481547
10MK080	433215	5482668	**10MK126**	418447	5477267	**10MK172**	423893	5483567
10MK081	433379	5483164	**10MK127**	418397	5477248	**10MK173**	427645	5481976
10MK082	433405	5483249	**10MK128**	418382	5477193	**10MK174**	427438	5482080
10MK083	433289	5484303	**10MK129**	418397	5477145	**11MK175**	432771	5451803
10MK084	433226	5482762	**10MK130**	418336	5477093	**11MK176**	432710	5452010
10MK085	433151	5482645	**10MK131**	418248	5477020	**11MK177**	432529	5452072
10MK086	433060	5482542	**10MK132**	418119	5477032	**11MK178**	432435	5452106
10MK087	432992	5482464	**10MK133**	418043	5476956	**11MK179**	432361	5452226
10MK088	432668	5482266	**10MK134**	431966	5481690	**11MK180**	432285	5452079
10MK089	433219	5484241	**10MK135**	431940	5481641	**11MK181**	432180	5452135
10MK090	433148	5484236	**10MK136**	431932	5481623	**11MK182**	432009	5452193
10MK091	433124	5484231	**10MK137**	417798	5476495	**11MK183**	431753	5452245
10MK092	432578	5482106	**10MK138**	417806	5476568	**11MK184**	431554	5452223
10MK093	432079	5481904	**10MK139**	417819	5476674	**11MK185**	431370	5452046
10MK094	431784	5481605	**10MK140**	417855	5476715	**11MK186**	431292	5451804
10MK095	432566	5481946	**10MK141**	417866	5476767	**11MK187**	431321	5451712
10MK096	432593	5481947	**10MK142**	417905	5476831	**11MK188**	431563	5451589
10MK097	432474	5481851	**10MK143**	417990	5476923	**11MK189**	431742	5451517
10MK098	432414	5481830	**10MK144**	417658	5476414	**11MK190**	432150	5451782
10MK099	432360	5481823	**10MK145**	417592	5476344	**11MK191**	431166	5449285

Station	Northing	Easting	Station	Northing	Easting	Station	Northing	Easting
11MK192	430835	5448988	**11MK238**	431881	5448475	**11MK284**	433513	5454232
11MK193	430551	5448866	**11MK239**	431783	5443412	**11MK285**	433378	5454054
11MK194	430451	5448794	**11MK240**	431695	5448363	**11MK286**	433243	5454188
11MK195	430359	5448895	**11MK241**	431512	5448299	**11MK287**	433139	5454402
11MK196	430314	5449086	**11MK242**	431667	5448549	**11MK288**	433230	5455067
11MK197	430165	5449361	**11MK243**	431579	5448742	**11MK289**	433361	5455379
11MK198	429956	5449488	**11MK244**	431534	5448840	**11MK290**	433555	5455132
11MK199	429544	5449253	**11MK245**	431353	5448906	**11MK291**	433758	5455442
11MK200	429482	5449285	**11MK246**	433601	5452027	**11MK292**	434338	5455343
11MK201	429303	5449364	**11MK247**	433652	5451345	**11MK293**	434060	5455567
11MK202	429058	5449261	**11MK248**	433680	5451145	**11MK294**	433822	5455789
11MK203	428935	5449252	**11MK249**	433577	5450989	**11MK295**	433771	5455824
11MK204	428795	5449226	**11MK250**	433783	5451122	**11MK296**	433584	5455857
11MK205	428793	5449271	**11MK251**	433544	5450723	**11MK297**	433463	5455698
11MK206	429125	5449314	**11MK252**	433183	5450543	**11MK298**	433285	5455479
11MK207	431931	5449897	**11MK253**	433077	5440496	**11MK299**	432905	5454655
11MK208	432141	5450129	**11MK254**	433982	5451286	**11MK300**	432825	5454517
11MK209	432590	5450610	**11MK255**	434072	5451692	**11MK301**	432661	5454188
11MK210	432678	5450648	**11MK256**	433982	5451809	**11MK302**	432621	5454003
11MK211	432588	5450750	**11MK257**	433924	5452345	**11MK303**	432958	5454027
11MK212	432750	5450794	**11MK258**	434090	5452636	**11MK304**	433183	5454121
11MK213	432808	5450834	**11MK259**	433825	5452798	**11MK305**	433919	5454380
11MK214	433036	5451127	**11MK260**	433959	5453002	**11MK306**	434631	5456330
11MK215	432875	5451559	**11MK261**	433768	5453121	**11MK307**	434552	5456306
11MK216	432359	5450881	**11MK262**	433598	5453196	**11MK308**	434479	5456290
11MK217	432287	5450922	**11MK263**	433286	5453298	**11MK309**	434431	5456264
11MK218	431985	5450851	**11MK264**	433867	5453100	**11MK310**	434396	5456256
11MK219	431910	5450787	**11MK265**	435612	5455104	**11MK311**	434395	5456249
11MK220	431852	5450771	**11MK266**	435588	5455118	**11MK312**	434291	5456184
11MK221	431744	5450769	**11MK267**	435463	5455076	**11MK313**	434160	5456022
11MK222	431672	5450895	**11MK268**	435300	5455063	**11MK314**	433969	5456136
11MK223	431562	5450917	**11MK269**	435152	5455043	**11MK315**	433980	5456149
11MK224	431581	5451077	**11MK270**	435030	5455025	**11MK316**	433940	5456246
11MK225	431765	5451190	**11MK271**	434654	5454765	**11MK317**	433892	5456267
11MK226	431588	5451353	**11MK272**	435389	5455026	**11MK318**	433791	5456395
11MK227	431385	5451528	**11MK273**	434788	5455266	**11MK319**	433754	5456383
11MK228	431304	5451465	**11MK274**	434520	5454898	**11MK320**	434661	5452318
11MK229	431129	5451349	**11MK275**	434454	5454992	**11MK321**	434617	5452381
11MK230	430703	5451809	**11MK276**	434436	5455071	**11MK322**	434506	5452555
11MK231	431253	5451820	**11MK277**	434167	5455092	**11MK323**	434586	5453179
11MK232	433168	5450647	**11MK278**	434250	5454972	**11MK324**	434733	5453471
11MK233	432873	5450314	**11MK279**	434249	5454909	**11MK325**	434735	5453518
11MK234	432702	5450185	**11MK280**	434205	5454705	**11MK326**	434657	5453797
11MK235	432158	5449617	**11MK281**	433973	5454491	**11MK327**	434798	5454186
11MK236	432193	5449415	**11MK282**	433812	5454439	**11MK328**	434884	5454319
11MK237	432236	5449336	**11MK283**	433574	5454375	**11MK329**	435253	5454668

Station	Northing	Easting	Station	Northing	Easting	Station	Northing	Easting
11MK442	434706	5460218	**11MK485**	430300	5464868	**11MK528**	428987	5466971
11MK443	434644	5460439	**11MK486**	430602	5463168	**11MK529**	428588	5466948
11MK444	434269	5460290	**11MK487**	431293	5463139	**11MK530**	431017	5467461
11MK445	433929	5460496	**11MK488**	431289	5463206	**11MK531**	431104	5467387
11MK446	433661	5460619	**11MK489**	431280	5463255	**11MK532**	431221	5467389
11MK447	433342	5461493	**11MK490**	431932	5462818	**11MK533**	431349	5467385
11MK448	433258	5461501	**11MK491**	432518	5462994	**11MK534**	434006	5462894
11MK449	433114	5461561	**11MK492**	432665	5462946	**11MK535**	410930	5469130
11MK450	433064	5461617	**11MK493**	433363	5465656	**11MK536**	410956	5468988
11MK451	432961	5461582	**11MK494**	433996	5465756	**11MK537**	410957	5468870
11MK452	432803	5461691	**11MK495**	433234	5465544	**11MK538**	410959	5468774
11MK453	432783	5461697	**11MK496**	433018	5465433	**11MK539**	410926	5468536
11MK454	433401	5461616	**11MK497**	432981	5465313	**11MK540**	410835	5468025
11MK455	432605	5458545	**11MK498**	432907	5465014	**11MK541**	410813	5467890
11MK456	432531	5458503	**11MK499**	433075	5464628	**11MK542**	410781	5467746
11MK457	432600	5457996	**11MK500**	433255	5464275	**11MK543**	410721	5467406
11MK458	432579	5457915	**11MK501**	433800	5463567	**11MK544**	410606	5466974
11MK459	432416	5457920	**11MK502**	430276	5469221	**11MK545**	410578	5466795
11MK460	432183	5458968	**11MK503**	430276	5469221	**11MK546**	410433	5466360
11MK461	432308	5458993	**11MK504**	430359	5469338	**11MK547**	410336	5466239
11MK462	432363	5458988	**11MK505**	430492	5469485	**11MK548**	410213	5465951
11MK463	435027	5461169	**11MK506**	430476	5468810	**11MK549**	410147	5465799
11MK464	434940	5461201	**11MK507**	430643	5468858	**11MK550**	410065	5465632
11MK465	434349	5451597	**11MK508**	430753	5468894	**11MK551**	409886	5465239
11MK466	434247	5461750	**11MK509**	430950	5468882	**11MK552**	409827	5465118
11MK467	434123	5461926	**11MK510**	431031	5468928	**11MK553**	409746	5464837
11MK468	433565	5462613	**11MK511**	431136	5468958	**11MK554**	409657	5464579
11MK469	433507	5462569	**11MK512**	431364	5469036	**11MK555**	409061	5463353
11MK470	433449	5462290	**11MK513**	431665	5469176	**11MK556**	408936	5463153
11MK471	435142	5461078	**11MK514**	431738	5469205	**11MK557**	408812	5462958
11MK472	435191	5461017	**11MK515**	431811	5469199	**11MK558**	408951	5462299
11MK473	435284	5460740	**11MK516**	430283	5469269	**11MK559**	408789	5462646
11MK474	435469	5460216	**11MK517**	429636	5467782	**11MK560**	410508	5466475
11MK475	433103	5462671	**11MK518**	429557	5467772	**11MK561**	419117	5477476
11MK476	432858	5462771	**11MK519**	429543	5467714	**11MK562**	419488	5476159
11MK477	431784	5462822	**11MK520**	429477	5467641	**11MK563**	419494	5475999
11MK478	430309	5462625	**11MK521**	429468	5467469	**11MK564**	419446	5475660
11MK479	430340	5462418	**11MK522**	429401	5467402	**11MK565**	419421	5475588
11MK480	429881	5463026	**11MK523**	429391	5467279	**11MK566**	419555	5475216
11MK481	430010	5463742	**11MK524**	429306	5467198	**11MK567**	420729	5476650
11MK482	430089	5463826	**11MK525**	429503	5467139	**11MK568**	420851	5476482
11MK483	429880	5464560	**11MK526**	429371	5467139	**11MK569**	421875	5475656
11MK484	429924	5464560	**11MK527**	429128	5467110	**11MK570**	421620	5475781

Station	Northing	Easting	Station	Northing	Easting
11MK571	419180	5477395	**11MK615**	431899	5463331
11MK572	419225	5477340	**11MK616**	434441	5461914
11MK573	419286	5477272	**11MK617**	434572	5461787
11MK574	419350	5477211	**11MK618**	434722	5461682
11MK575	419200	5477364	**11MK619**	434664	5461763
11MK576	417277	5474870	**11MK620**	434217	5462089
11MK577	418436	5473943	**11MK621**	434098	5462204
11MK578	419483	5473835	**11MK622**	434902	5461497
11MK579	418558	5474332	**11MK623**	434910	5461572
11MK580	417990	5474738	**11MK624**	434947	5461582
11MK581	416360	5474070	**11MK625**	434863	5461455
11MK582	416414	5474077	**11MK626**	434857	5461426
11MK583	416514	5474091	**11MK627**	435323	5466949
11MK584	416588	5474055	**11MK628**	434577	5467337
11MK585	416692	5473980	**11MK629**	434453	5467323
11MK586	416794	5473837	**11MK630**	434408	5467315
11MK587	416823	5473755	**11MK631**	434293	5467335
11MK588	417180	5473354	**11MK632**	433838	5467338
11MK589	417017	5473605	**11MK633**	433681	5467285
11MK590	416474	5474159	**11MK634**	434773	5475431
11MK591	416944	5473770	**11MK635**	434584	5475262
11MK592	417048	5473760	**11MK636**	434089	5474608
11MK593	416917	5473069	**11MK637**	433933	5474592
11MK594	416915	5472948	**11MK638**	433733	5474932
11MK595	416891	5472944	**11MK639**	433616	5475052
11MK596	417192	5473338	**11MK640**	433374	5475224
11MK597	419526	5476213			
11MK598	420863	5475028			
11MK599	420680	5474648			
11MK600	420641	5474573			
11MK601	420719	5474654			
11MK602	420852	5474770			
11MK603	421018	5474856			
11MK604	420937	5474892			
11MK605	421103	5475011			
11MK606	421026	5475102			
11MK607	411276	5470113			
11MK608	411630	5469960			
11MK609	412643	5470103			
11MK610	432756	5462559			
11MK611	432709	5462862			
11MK612	432608	5463123			
11MK613	432535	5463123			
11MK614	432330	5463331			

Station	Northing	Easting	Station	Northing	Easting	Station	Northing	Easting
E11001	432966	5451739	**E11039**	431206	5449592	**E11077**	433114	5453476
E11002	432512	5452041	**E11040**	431148	5449574	**E11078**	432987	5453457
E11003	432447	5452311	**E11041**	431054	5449626	**E11079**	432187	5453389
E11004	432426	5452527	**E11042**	430965	5449764	**E11080**	432078	5453692
E11005	432346	5452552	**E11043**	430739	5449715	**E11081**	432087	5453374
E11006	432298	5452701	**E11044**	430614	5449952	**E11082**	432028	5453226
E11007	432288	5452813	**E11045**	430737	5450171	**E11083**	431894	5453279
E11008	432263	5452960	**E11046**	430383	5450128	**E11084**	431800	5453279
E11009	432227	5453090	**E11047**	430329	5450374	**E11085**	436104	5455634
E11010	432231	5453127	**E11048**	430395	5450536	**E11086**	436060	5455739
E11011	432227	5453374	**E11049**	430912	5450783	**E11087**	436015	5455908
E11012	432516	5453244	**E11050**	431026	5450866	**E11088**	435810	5455949
E11013	432692	5453037	**E11051**	431374	5450963	**E11089**	435549	5455978
E11014	432681	5452883	**E11052**	430930	5449114	**E11090**	435507	5456014
E11015	430398	5448784	**E11053**	430832	5448968	**E11091**	435666	5455985
E11016	430093	5448643	**E11054**	430090	5448435	**E11092**	435319	5455805
E11017	429791	5448630	**E11055**	429962	5448280	**E11093**	435139	5455635
E11018	429817	5448645	**E11056**	429929	5447772	**E11094**	435080	5455548
E11019	429722	5448581	**E11057**	430175	5447870	**E11095**	435067	5455476
E11020	429676	5448503	**E11058**	430519	5447958	**E11096**	435029	5455532
E11021	429457	5448387	**E11059**	430443	5448012	**E11097**	435078	5455539
E11022	429306	5448278	**E11060**	430460	5447989	**E11098**	435061	5455648
E11023	429153	5448254	**E11061**	430563	5448051	**E11099**	435142	5456052
E11024	429143	5448378	**E11062**	430594	5448079	**E11100**	435169	5456108
E11025	429108	5448414	**E11063**	430746	5448246	**E11101**	435143	5456149
E11026	429237	5448617	**E11064**	434926	5451861	**E11102**	435078	5456135
E11027	429292	5448685	**E11065**	434850	5451874	**E11103**	435116	5456097
E11028	429389	5448737	**E11066**	434779	5451903	**E11104**	435107	5456068
E11029	429393	5448735	**E11067**	434599	5451611	**E11105**	435055	5456155
E11030	433048	5451817	**E11068**	434588	5451413	**E11106**	435032	5456185
E11031	433152	5451994	**E11069**	434472	5451162	**E11107**	435019	5456261
E11032	433351	5452228	**E11070**	434228	5450598	**E11108**	434984	5456283
E11033	433349	5452354	**E11071**	433823	5450209	**E11109**	434931	5456283
E11034	433391	5452395	**E11072**	433901	5450580	**E11110**	434847	5456248
E11035	433680	5452766	**E11073**	433842	5450615	**E11111**	434547	5456173
E11036	433929	5452753	**E11074**	433291	5453308	**E11112**	434588	5456187
E11037	433988	5452756	**E11075**	433102	5453359	**E11113**	434602	5456183
E11038	431300	5449327	**E11076**	433093	5453431	**E11114**	434634	5456235

Station	Northing	Easting	Station	Northing	Easting	Station	Northing	Easting
E11115	434722	5456369	**E11153**	434162	5457810	**E11191**	439757	5457362
E11116	434627	5456369	**E11154**	433482	5457780	**E11192**	439584	5457471
E11117	434754	5456105	**E11155**	433473	5457919	**E11193**	439111	5457259
E11118	434607	5456337	**E11156**	432945	5457820	**E11194**	437972	5457402
E11119	434574	5456343	**E11157**	433097	5457715	**E11195**	436506	5457127
E11120	434549	5456404	**E11158**	433077	5457637	**E11196**	436542	5457028
E11121	434411	5456605	**E11159**	433200	5457555	**E11197**	436728	5456999
E11122	434300	5456730	**E11160**	433166	5457486	**E11198**	436901	5456952
E11123	434125	5456867	**E11161**	433081	5457399	**E11199**	436966	5456864
E11124	433796	5456946	**E11162**	433129	5457260	**E11200**	437014	5456840
E11125	433766	5456971	**E11163**	433087	5457200	**E11201**	437447	5456777
E11126	433795	5457047	**E11164**	433009	5457153	**E11202**	437118	5456241
E11127	433668	5456841	**E11165**	432982	5457102	**E11203**	437183	5456470
E11128	434612	5456282	**E11166**	432935	5457010	**E11204**	437239	5456539
E11129	434522	5456139	**E11167**	432902	5457010	**E11205**	437679	5457113
E11130	434100	5455908	**E11168**	432737	5456907	**E11206**	437358	5455874
E11131	433571	5455896	**E11169**	432735	5456926	**E11207**	437547	5455954
E11132	433279	5456077	**E11170**	432709	5457068	**E11208**	435388	5455717
E11133	433235	5456181	**E11171**	432620	5456955	**E11209**	435408	5455702
E11134	433063	5456268	**E11172**	432719	5456966	**E11210**	435476	5455538
E11135	432837	5455990	**E11173**	432895	5457323	**E11211**	413169	5438551
E11136	432802	5456110	**E11174**	432925	5457604	**E11212**	413038	5438745
E11137	432773	5456304	**E11175**	432546	5457712	**E11213**	413241	5438871
E11138	433334	5456242	**E11176**	432558	5457780	**E11214**	413412	5439239
E11139	433441	5456306	**E11177**	432634	5457879	**E11215**	423149	5439304
E11140	436003	5457069	**E11178**	433081	5458018	**E11216**	412904	5439335
E11141	436113	5457209	**E11179**	433172	5458197	**E11217**	412984	5439556
E11142	436282	5457619	**E11180**	433180	5458276	**E11218**	412847	5439674
E11143	436766	5457932	**E11181**	433235	5458242	**E11219**	412735	5439739
E11144	434745	5453398	**E11182**	433357	5458221	**E11220**	412282	5439825
E11145	434744	5453371	**E11183**	433571	5458093	**E11221**	412193	5439582
E11146	434619	5453253	**E11184**	433707	5458067	**E11222**	412098	5438950
E11147	436008	5457078	**E11185**	433853	5458043	**E11223**	412074	5438376
E11148	435013	5457623	**E11186**	433846	5458028	**E11224**	413115	5438493
E11149	434906	5457668	**E11187**	434114	5458026	**E11225**	412890	5439070
E11150	435006	5457776	**E11188**	434910	5457660	**E11226**	413485	5438799
E11151	434767	5457772	**E11189**	440196	5457344	**E11227**	413771	5438890
E11152	434544	5457776	**E11190**	439957	5457315	**E11228**	414088	5439072

Station	Northing	Easting	Station	Northing	Easting	Station	Northing	Easting
E11229	414165	5439036	**E11267**	434609	5461330	**E11305**	433196	5464403
E11230	414022	5439144	**E11268**	434534	5461389	**E11306**	433851	5463472
E11231	413904	5439194	**E11269**	434333	5461661	**E11307**	434285	5462014
E11232	413816	5439260	**E11270**	433735	5462579	**E11315**	417884	5475756
E11233	413619	5439372	**E11271**	433968	5462291	**E11316**	417973	5475264
E11234	413459	5439634	**E11272**	431138	5462828	**E11317**	418217	5475132
E11235	413311	5439793	**E11273**	430594	5462545	**E11318**	418631	5474978
E11236	412999	5440177	**E11274**	430630	5462582	**E11319**	418287	5474605
E11237	412859	5440243	**E11275**	430764	5462659	**E11320**	418436	5474510
E11238	412717	5440154	**E11276**	430796	5462658	**E11321**	418653	5474635
E11239	412367	5440104	**E11277**	430832	5462673	**E11322**	418670	5474699
E11240	412011	5440066	**E11278**	429887	5463547	**E11323**	417684	5475662
E11241	411531	5439179	**E11279**	429832	5463746	**E11324**	418794	5474690
E11242	411424	5439816	**E11280**	430045	5463877	**E11325**	418961	5474525
E11243	411146	5440304	**E11281**	429890	5464732	**E11326**	419486	5473829
E11244	411470	5439544	**E11282**	430602	5463167	**E11327**	419565	5473894
E11245	435015	5459940	**E11283**	430675	5463214	**E11328**	419687	5474129
E11246	434880	5459764	**E11284**	430740	5463211	**E11329**	419572	5474099
E11247	435015	5459716	**E11285**	430781	5463235	**E11330**	419654	5474475
E11248	434778	5459822	**E11286**	430855	5463221	**E11331**	419627	5474654
E11249	434651	5459865	**E11287**	430993	5463178	**E11332**	419123	5475011
E11250	434604	5459907	**E11288**	431024	5463190	**E11333**	419036	5475096
E11251	434553	5459849	**E11289**	431315	5463162	**E11334**	419031	5475128
E11252	433487	5459154	**E11290**	431362	5463020	**E11335**	418740	5475121
E11253	433522	5459067	**E11291**	431373	5463043	**E11336**	419537	5474019
E11254	433074	5459566	**E11292**	431365	5463079	**E11337**	419573	5473895
E11255	432973	5459571	**E11293**	431313	5463116	**E11338**	419836	5473832
E11256	433269	5459870	**E11294**	431954	5462778	**E11339**	419763	5473702
E11257	433472	5459553	**E11295**	435051	5459609	**E11340**	420117	5473985
E11258	433616	5459501	**E11296**	435077	5459592	**E11341**	420055	5474406
E11259	433757	5459514	**E11297**	435074	5459584	**E11342**	420078	5474433
E11260	432629	5458465	**E11298**	435060	5459723	**E11343**	419569	5475062
E11261	432592	5458423	**E11299**	434987	5459574	**E11344**	419518	5473619
E11262	432586	5458392	**E11300**	435114	5459461	**E11345**	419467	5473600
E11263	432576	5458348	**E11301**	433725	5465810	**E11346**	430360	5481184
E11264	432254	5458216	**E11302**	434167	5465644	**E11347**	410958	5469021
E11265	432013	5458418	**E11303**	433132	5465509	**E11348**	410963	5468878
E11266	434742	5461262	**E11304**	432897	5465123	**E11349**	410704	5467346

Station	Northing	Easting	Station	Northing	Easting
E11350	410974	5467401	**E11388**	435184	5461682
E11351	410922	5467142	**E11389**	435169	5461609
E11352	411178	5467215	**E11390**	435253	5461786
E11353	411429	5467437	**E11391**	433889	5461939
E11354	411489	5467669	**E11392**	433854	5461655
E11355	411571	5467954	**E11393**	433871	5461603
E11356	411063	5468063	**E11394**	433902	5461577
E11357	435329	5461273	**E11395**	433907	5461765
E11358	435693	5460493	**E11396**	433905	5461808
E11359	435679	5460530	**E11397**	435463	5466666
E11360	435683	5460530	**E11398**	435143	5466743
E11361	435675	5460610	**E11399**	435058	5466752
E11362	435663	5460663	**E11400**	434434	5466813
E11363	435401	5461207	**E11401**	434474	5466575
E11364	435423	5461169	**E11402**	434572	5466697
E11365	435452	5461140	**E11403**	434554	5466733
E11366	435477	5461065	**E11404**	433378	5466338
E11367	435501	5461052	**E11405**	433348	5466208
E11368	435593	5460741	**E11406**	433488	5465954
E11369	435606	5460802	**E11407**	433212	5466218
E11370	435556	5460436	**E11408**	433172	5466553
E11371	435544	5460391	**E11409**	438048	5465701
E11372	435600	5460458	**E11410**	434642	5475318
E11373	435603	5460703	**E11411**	434551	5475200
E11374	435567	5460837	**E11412**	433995	5474622
E11375	435566	5460884	**E11413**	433742	5474929
E11376	435555	5461014	**E11414**	433392	5475206
E11377	434589	5461750			
E11378	434756	5461650			
E11379	434772	5461632			
E11380	434880	5461603			
E11381	434928	5461575			
E11382	434899	5461498			
E11383	435303	5461329			
E11384	435115	5461394			
E11385	435056	5461481			
E11386	434979	5461540			
E11387	434976	5461570			

Station	Northing	Easting	Station	Northing	Easting	Station	Northing	Easting
MC018	410042	5439278	**MC056**	410327	5440015	**MC094**	411076	5440337
MC019	410070	5439244	**MC057**	410380	5440045	**MC095**	411102	5440337
MC020	410034	5439184	**MC058**	410214	5439964	**MC096**	411127	5440320
MC021	410043	5439159	**MC059**	410208	5439938	**MC097**	411184	5440305
MC022	410106	5439107	**MC060**	410214	5439906	**MC098**	411255	5440254
MC023	410130	5439094	**MC061**	410194	5439543	**MC099**	411282	5440238
MC024	410154	5439053	**MC062**	410194	5439567	**MC100**	411257	5438960
MC025	410215	5439004	**MC063**	410215	5439553	**MC101**	411174	5439003
MC026	410191	5439013	**MC064**	410221	5439573	**MC102**	411044	5439062
MC027	410244	5438994	**MC065**	410228	5439586	**MC103**	410796	5439151
MC028	410308	5438935	**MC066**	410225	5439638	**MC104**	410752	5439172
MC029	410336	5430029	**MC067**	410225	5439668	**MC105**	410710	5439167
MC030	410242	5439262	**MC068**	410250	5439709	**MC106**	410667	5439118
MC031	410281	5439349	**MC069**	410238	5439726	**MC107**	410676	5439065
MC032	410389	5439352	**MC070**	410230	5439759	**MC108**	410685	5439017
MC033	410460	5439424	**MC071**	410373	5440130	**MC109**	410669	5438944
MC034	410472	5439457	**MC072**	410351	5440156	**MC110**	410627	5438890
MC035	410487	5439516	**MC073**	410315	5440222	**MC111**	410490	5438828
MC036	410214	5439406	**MC074**	410282	5440233	**MC112**	410425	5438810
MC037	410198	5439461	**MC075**	410270	5440285	**MC113**	410449	5438785
MC038	410208	5439477	**MC076**	410336	5440342	**MC114**	410572	5438670
MC039	411207	5439432	**MC077**	410303	5440360	**MC115**	410627	5438625
MC040	411235	5439416	**MC078**	410319	5440439	**MC116**	410649	5438552
MC041	411286	5439359	**MC079**	410301	5440596	**MC117**	410675	5438516
MC042	411316	5439323	**MC080**	410323	5440658	**MC118**	410764	5438450
MC043	411408	5439130	**MC081**	410334	5440687	**MC119**	410823	5438409
MC044	411430	5439099	**MC082**	410321	5440779	**MC120**	410945	5438367
MC045	410258	5439662	**MC083**	410246	5440879	**MC121**	410919	5438414
MC046	410281	5439637	**MC084**	410270	5440845	**MC122**	411021	5438327
MC047	410262	5439720	**MC085**	410247	5440821	**MC123**	411165	5438314
MC048	410256	5439749	**MC086**	410401	5440637	**MC124**	411265	5438300
MC049	410294	5439756	**MC087**	410429	5440620	**MC125**	411328	5438290
MC050	410292	543977	**MC088**	410449	5440559	**MC126**	411424	5438263
MC051	410294	5439783	**MC089**	410508	5440513	**MC127**	411538	5438247
MC052	410260	5439926	**MC090**	410552	5440498	**MC128**	411629	5438235
MC053	410286	5439875	**MC091**	410897	5440344	**MC129**	411703	5438190
MC054	410325	5439908	**MC092**	411063	5440334	**MC130**	410685	5439715
MC055	410364	5439975	**MC093**	411050	5440307	**MC131**	410842	5439945

Station	Northing	Easting
MC132	410904	5440024
MC133	410985	5440050
MC134	411041	5440121
MC135	411141	5440086
MC136	411145	5439937
MC137	411088	5439684

Appendix C

Point Count Data

Blow Me Down Brook formation

Grain	E1008	MK154	MK138	MK68-2	MK105	MK117	MC42
Qtz (M)	125	87	101	106	160	139	160
QTZ (P)	16	36	9	25	38	28	37
PLAG	19	30	4	6	7	10	4
K-SPAR	9	45	18	32	18	35	17
ROCK FRAG	16	10	0	73	10	12	5
VOLC FRAG	1	1	1	55	0	0	0
SED FRAG	0	1	0	8	0	0	0
MICA	8	8	56	0	13	25	0
OPAQUE	18	26	2	9	2	4	0
MATRIX	60	50	51	0	43	43	9
CEMENT	7	0	39	0	0	0	58
POROSITY	6	6	4	0	9	11	0
CHERT	0	0	0	0	2	0	0
GLAUCONITE	0	0	0	0	0	0	0
CHLORITE	0	0	1	1	1	2	0
Calcite	0	0	0	0	1	0	9
TOTAL COUNT	285	300	286	315	304	309	299
QTZ TOTAL	141	123	110	131	198	167	197
FSPAR TOTA	28	75	22	38	25	45	21
LITHIC TOTAL	17	12	1	9	10	12	5
TOTALS	186	210	133	178	233	224	223
%QTZ	75.8	58.6	82.7	73.6	85.0	74.6	88.3
%FSPAR	15.1	35.7	16.5	21.3	10.7	20.1	9.4
%LITHIC	9.1	5.7	0.8	5.1	4.3	5.4	2.2
Qm	125	87	101	106	160	139	160
F	28	75	22	38	25	45	21
Lt	33	48	10	34	48	40	42
%Qm	67.2	41.4	75.9	59.6	68.7	62.1	71.7
%F	15.1	35.7	16.5	21.3	10.7	20.1	9.4
%Lt	17.7	22.9	7.5	19.1	20.6	17.9	18.8

Grain	MK76-4	MK300	MK223	MK623-3	MK510	MK588	MK76-2
Qtz (M)	145	135	123	176	117	140	96
QTZ (P)	19	19	12	21	9	19	5
PLAG	7	4	13	5	9	10	3
K-SPAR	22	15	31	11	20	26	4
ROCK FRAG	9	8	8	5	1	63	5
VOLC FRAG	0	0	0	0	0	27	0
SED FRAG	0	0	0	0	0		0
MICA	9	22	20	3	2		41
OPAQUE	4	9	5	11	53	4	4
MATRIX	86	98	89	68	76		110
CEMENT	3	0	0	0	0		0
POROSITY	1	2	4	0	0	12	39
CHERT		1	2	5	3		1
GLAUCONITE	0			0	0		0
CHLORITE	2	2	1	0	0		4
Calcite	13	0	0	0	10		0
TOTAL COUNT	320	315	308	305	300	301	312
QTZ TOTAL	164	154	135	197	126	159	101
FSPAR TOTA	29	19	44	16	29	36	7
LITHIC TOTAL	9	8	8	5	1	4	5
TOTALS	202	181	187	218	156	199	113
%QTZ	81.2	85.1	72.2	90.4	80.8	79.9	89.4
%FSPAR	14.4	10.5	23.5	7.3	18.6	18.1	6.2
%LITHIC	4.5	4.4	4.3	2.3	0.6	2.0	4.4
Qm	145	135	123	176	117	140	96
F	29	19	44	16	29	36	7
Lt	28	27	20	26	10	23	10
%Qm	71.8	74.6	65.8	80.7	75.0	70.4	85.0
%F	14.4	10.5	23.5	7.3	18.6	18.1	6.2
%Lt	13.9	14.9	10.7	11.9	6.4	11.6	8.8

Grain	MK544	MK517	MK443	MK624-1	MK624-2	MK624-3
Qtz (M)	178	137	190	131	127	99
QTZ (P)	19	39	22	22	16	7
PLAG	3		9	10	19	10
K-SPAR	20	4	22	31	46	27
ROCK FRAG	8	1	15	9	12	2
VOLC FRAG	0	0	0	0	0	1
SED FRAG	0	0	0	0	0	1
MICA	25	1	5	11	14	36
OPAQUE	4	3	1	16	15	19
MATRIX	32	68	36	53	75	103
CEMENT	0	0		0	0	0
POROSITY	0	0	3	1	0	0
CHERT	0	0			0	0
GLAUCONITE	0	0		0	0	0
CHLORITE	10	44	1	19	0	4
CALCITE	0	20	0	4	0	1
TOTAL COUNT	299	317	304	307	324	310
QTZ TOTAL	197	176	212	153	143	106
FSPAR TOTA	23	4	31	41	65	37
LITHIC TOTAL	8	1	15	9	12	4
TOTALS	228	181	258	203	220	147
%QTZ	86.4	97.2	82.2	75.4	65.0	72.1
%FSPAR	10.1	2.2	12.0	20.2	29.5	25.2
%LITHIC	3.5	0.6	5.8	4.4	5.5	2.7
Qm	178	137	190	131	127	99
F	23	4	31	41	65	37
Lt	27	40	37	31	28	11
%Qm	78.1	75.7	73.6	64.5	57.7	67.3
%F	10.1	2.2	12.0	20.2	29.5	25.2
%Lt	11.8	22.1	14.3	15.3	12.7	7.5

Irishtown Formation

Grain	**MK237**	**E11322**	**E11058**	**MK471**
Qtz (M)	290	257	238	280
QTZ (P)	8	14	23	8
PLAG				1
K-SPAR	2	6		10
ROCK FRAG	2	1		4
VOLC FRAG				
SED FRAG	1			
MICA		3		
OPAQUE		3		
MATRIX	4	10		1
CEMENT				
POROSITY	2			
CHERT	1		3	1
GLAUCONITE				
CHLORITE				
CALCITE			46	
TOTAL COUNT	310	294	310	305
QTZ TOTAL	298	271	261	288
FSPAR TOTA	2	6	0	11
LITHIC TOTAL	3	1	0	4
TOTALS	303	271	261	303
%QTZ	98.3	97.5	100.0	95.0
%FSPAR	0.7	2.2	0.0	3.6
%LITHIC	1.0	0.4	0.0	1.3
Qm	290	257	238	280
F	2	6	0	11
Lt	11	15	23	12
%Qm	95.7	92.4	91.2	92.4
%F	0.7	2.2	0.0	3.6
%Lt	3.6	5.4	8.8	4.0

Mélange sandstone blocks

Grain	MK114-1	MK162	MK113	MK108	MK165-1	MK532-2	MK521-3
Qtz (M)	148	88	134	127	157	92	109
QTZ (P)	55	24	31	35	23	22	31
PLAG	3	11	7	10	0	5	8
K-SPAR	6	36	25	31	6	18	13
ROCK FRAG	2	0	7	9	1	14	3
VOLC FRAG	0	0	0	0	0	0	0
SED FRAG	14	0	0	0	0	0	0
MICA	2	39	37	26	5	25	17
OPAQUE	1	5	1	4	0	15	6
MATRIX	72	89	53	62	98	67	106
CEMENT	0	1	6	1	5	0	0
POROSITY	2	2	3	4	4	1	0
CHERT	0	0	0	0	0	1	0
GLAUCONITE	1	6	0	0	0	0	0
CHLORITE		7	0	2	0	26	8
CALCITE	0	8	0	1	0	13	10
TOTAL COUNT	306	316	304	312	299	299	311
QTZ TOTAL	203	112	165	162	180	114	140
FSPAR TOTA	9	47	32	41	6	23	21
LITHIC TOTAL	16	0	7	9	1	14	3
TOTALS	228	159	204	212	187	151	164
%QTZ	89.0	70.4	80.9	76.4	96.3	75.5	85.4
%FSPAR	3.9	29.6	15.7	19.3	3.2	15.2	12.8
%LITHIC	7.0	0.0	3.4	4.2	0.5	9.3	1.8
Qm	148	88	134	127	157	92	109
F	9	47	32	41	6	23	21
Lt	71	24	38	44	24	36	34
%Qm	64.9	55.3	65.7	59.9	84.0	60.9	66.5
%F	3.9	29.6	15.7	19.3	3.2	15.2	12.8
%Lt	31.1	15.1	18.6	20.8	12.8	23.8	20.7

Grain	MK572	MK521	MK532
Qtz (M)	165	157	106
QTZ (P)	16	3	14
PLAG	8	4	13
K-SPAR	17	9	31
ROCK FRAG	9	4	8
VOLC FRAG	0	0	0
SED FRAG	2	1	2
MICA	4	8	37
OPAQUE	32	11	8
MATRIX	33	119	73
CEMENT	4	0	0
POROSITY	1	0	1
CHERT	1	0	1
GLAUCONITE	6	0	0
CHLORITE	0	0	8
CALCITE	2	2	1
TOTAL COUNT	300	318	303
QTZ TOTAL	181	160	120
FSPAR TOTA	25	13	44
LITHIC TOTAL	11	5	10
TOTALS	217	178	174
%QTZ	83.4	89.9	69.0
%FSPAR	11.5	7.3	25.3
%LITHIC	5.1	2.8	5.7
Qm	165	157	106
F	25	13	44
Lt	27	8	24
%Qm	76.0	88.2	60.9
%F	11.5	7.3	25.3
%Lt	12.4	4.5	13.8

Appendix D

Sandstone geochemistry

Major element geochemistry of Blow Me Down Brook formation sandstone

	SiO2	Al2O3	Fe2O3	MgO	TiO2	Na2O	K2O	MnO
MK-42	88.14%	10.15%	1.59%	0.82%	0.20%	2.42%	1.24%	0.06%
MK-46	81.84%	8.50%	2.14%	1.00%	0.49%	1.05%	2.42%	0.04%
MK-68-2	68.75%	16.41%	4.70%	2.26%	0.66%	1.37%	3.16%	0.06%
MK-71	62.03%	19.74%	6.39%	2.76%	1.16%	1.72%	3.22%	0.12%
MK-76-2	59.93%	21.75%	4.49%	2.96%	0.87%	1.48%	2.40%	0.13%
MK-76-3	58.35%	18.81%	7.21%	2.49%	0.94%	1.15%	2.95%	0.10%
MK-117	82.33%	12.37%	3.10%	1.35%	0.57%	2.68%	1.55%	0.06%
MK-154	72.38%	14.65%	4.35%	1.52%	0.62%	2.55%	2.55%	0.04%
MK-402	82.04%	12.60%	3.81%	1.64%	0.56%	1.31%	1.91%	0.03%
MK-517	76.56%	6.32%	4.42%	1.63%	0.29%	0.18%	0.68%	0.83%
MK-572	83.85%	10.03%	2.55%	1.56%	0.80%	2.44%	0.87%	0.07%
MK-629-2	77.57%	10.66%	6.80%	2.47%	0.60%	1.09%	1.00%	0.12%
E11058	97.82%	0.41%	0.85%	1.56%	0.17%	0.04%	0.10%	0.04%
MK-113	75.16%	13.80%	4.68%	2.08%	0.68%	1.89%	1.94%	0.09%

	CaO	P2O5
MK-42	0.74%	0.03%
MK-46	0.14%	0.04%
MK-68-2	0.14%	0.07%
MK-71	0.77%	0.07%
MK-76-2	0.25%	0.05%
MK-76-3	0.62%	0.09%
MK-117	0.15%	0.05%
MK-154	0.42%	0.06%
MK-402	0.18%	0.06%
MK-517	6.96%	0.14%
MK-572	0.76%	0.08%
MK-629-2	0.75%	0.06%
E11058	3.86%	0.02%
MK-113	1.05%	0.05%

Major element geochemistry of Lower Head Formation sandstone

	SiO2	Al2O3	Fe2O3	MgO	TiO2	Na2O	K2O	MnO
E11368	69.48%	14.39%	6.22%	3.99%	0.56%	0.82%	2.02%	0.03%
E11052	61.65%	15.18%	7.84%	7.22%	1.03%	1.65%	2.32%	0.07%
MK-269-2	76.55%	9.80%	6.45%	6.20%	0.56%	1.09%	1.09%	0.73%

	CaO	P2O5
E11368	2.12%	0.07%
E11052	0.41%	0.13%
MK-269-2	0.63%	0.10%

Major element geochemistry of mélange sandstone blocks

	SiO2	Al2O3	Fe2O3	MgO	TiO2	Na2O	K2O	MnO
MK-114-1	89.27%	7.02%	2.15%	1.16%	0.64%	0.87%	1.23%	0.24%
MK-114-2	80.72%	12.69%	3.13%	1.89%	1.35%	2.14%	1.91%	0.11%
MK-124	47.12%	8.96%	7.05%	8.73%	0.36%	0.26%	1.97%	0.98%
MK-128	52.12%	17.94%	9.45%	2.60%	0.89%	1.33%	1.62%	0.13%
MK-138	69.02%	15.23%	3.17%	1.47%	0.67%	1.47%	0.81%	0.77%
MK-521-3	65.74%	13.78%	9.65%	3.61%	0.59%	1.38%	1.27%	0.14%
E11010	56.17%	22.80%	7.28%	2.80%	0.71%	1.46%	3.63%	0.05%

	CaO	P2O5
MK-114-1	3.10%	0.13%
MK-114-2	1.13%	0.13%
MK-124	17.28%	0.05%
MK-128	1.16%	0.08%
MK-138	5.88%	0.04%
MK-521-3	2.09%	0.06%
E11010	0.24%	0.08%

Trace element Geochemistry of Blow Me Down Brook formation sandstone

	Sc ppm	V ppm	Cr ppm	Ni ppm	Cu ppm	Zn ppm	Ga ppm	As ppm
MK-42	<LD	15	13	<LD	<LD	<LD	6	16
MK-46	<LD	31	45	7	<LD	<LD	<LD	<LD
MK-68-2	<LD	52	56	23	5	13	12	<LD
MK-71	12	79	113	45	14	34	15	<LD
MK-76-2	15	81	107	34	21	45	18	<LD
MK-76-3	17	75	82	26	13	38	18	<LD
MK-113	9	53	77	18	<LD	17	9	<LD
MK-117	<LD	46	60	13	<LD	4	8	<LD
MK-154	10	63	68	21	6	11	10	<LD
MK-402	<LD	37	43	14	4	<LD	8	29
MK-517	8	44	20	10	62	3	6	16
MK-572	<LD	26	33	14	<LD	<LD	<LD	22
MK-629-2	<LD	43	36	29	7	42	5	22
E11058	<LD	8	<LD	<LD	<LD	<LD	<LD	35

	Rb ppm	Sr ppm	Y ppm	Zr ppm	Nb ppm	Ba ppm	Ce ppm	Pb ppm
MK-42	28.2	70.0	6.2	138.5	16.9	252	<LD	8
MK-46	47.8	58.6	6.2	212.1	10.7	464	<LD	14
MK-68-2	71.3	40.7	11.2	321.2	11.9	406	<LD	<LD
MK-71	91.4	73.4	21.3	765.5	23.5	442	118	6
MK-76-2	62.8	88.9	14.6	300.8	14.5	514	117	9
MK-76-3	74.6	90.8	16.9	319.2	16.8	756	95	29
MK-113	42.0	59.9	11.8	296.7	10.1	225	68	<LD
MK-117	41.8	66.9	10.3	315.2	19.1	230	<LD	<LD
MK-154	70.4	93.1	11.7	290.4	18.8	414	64	16
MK-402	54.0	29.7	8.7	333.4	12.9	320	84	11
MK-517	22.4	319.9	48.4	144.9	8.1	5188	44	112
MK-572	20.4	53.2	17.0	503.4	14.6	251	52	16
MK-629-2	30.3	37.9	13.7	331.9	12.7	263	<LD	8
E11058	2.6	30.7	6.2	215.6	4.0	<LD	<LD	<LD

	Th ppm
MK-42	5
MK-46	6
MK-68-2	10
MK-71	18
MK-76-2	9
MK-76-3	6
MK-113	9
MK-117	6
MK-154	9
MK-402	8
MK-517	5
MK-572	9
MK-629-2	4
E11058	<LD

Trace element geochemistry of Lower Head Formation sandstone

	Sc ppm	V ppm	Cr ppm	Ni ppm	Cu ppm	Zn ppm	Ga ppm	As ppm
MK-269-2	8	75	610	132	16	34	9	<LD
E11052	15	120	642	188	20	46	13	<LD
E11368	<LD	54	75	30	7	11	11	20

	Rb ppm	Sr ppm	Y ppm	Zr ppm	Nb ppm	Ba ppm	Ce ppm	Pb ppm
MK-269-2	32.2	43.5	15.7	230.2	11.0	282	<LD	22
E11052	70.3	47.8	24.8	455.9	20.2	398	61	13
E11368	57.1	40.6	15.4	277.8	10.6	389	62	6

	Th ppm
MK-269-2	5
E11052	10
E11368	6

Trace element geochemistry of mélange sandstone blocks

	Sc ppm	V ppm	Cr ppm	Ni ppm	Cu ppm	Zn ppm	Ga ppm	As ppm
MK-114-1	9	68	20	6	91	<LD	<LD	64
MK-114-2	8	88	33	20	64	25	<LD	26
MK-124	22	191	65	28	35	19	11	42
MK-128	13	70	93	25	6	41	12	<LD
MK-138	8	54	67	23	6	29	13	27
MK-521-3	9	51	281	39	10	38	12	<LD
E11010	5	64	57	29	10	29	23	<LD

	Rb ppm	Sr ppm	Y ppm	Zr ppm	Nb ppm	Ba ppm	Ce ppm	Pb ppm
MK-114-1	30.2	54.6	28.0	422.4	12.3	135	48	50
MK-114-2	52.7	61.1	29.4	1144.6	25.7	251	117	34
MK-124	52.7	119.1	26.6	60.0	6.6	237	92	13
MK-128	26.9	57.4	15.3	285.2	15.2	493	86	23
MK-138	21.3	137.6	19.0	252.7	11.0	255	85	8
MK-521-3	33.9	100.2	15.8	234.0	10.6	302	57	23
E11010	98.5	53.8	15.9	196.5	14.7	712	85	16

	Th ppm
MK-114-1	<LD
MK-114-2	12
MK-124	6
MK-128	6
MK-138	6
MK-521-3	8
E11010	7

Appendix E

Mudstone geochemistry

Select trace element geochemistry of Blow Me Down Brook formation mudstone

Sample	V	Cr	Ni	Y
	ppm	ppm	ppm	ppm
MK100	64.8	76.1	36.1	23.8
MK537-2	104.9	100.7	60.4	31.9
MK-623-5	132.0	97.0	46.0	36.0
E11180	104.0	102.0	50.0	28.0
MK-532	80.0	79.0	64.0	30.0
MK-623-4	89.0	75.0	71.0	21.0
MK-521-2	47.0	35.0	35.0	14.0
MK-629	83.0	57.0	24.0	38.0

Select trace element geochemistry of Irishtown Formation mudstone

Sample	V	Cr	Ni	Y
	ppm	ppm	ppm	ppm
MK474	101.9	114.8	54.7	16.0
MK239-2	94.5	121.4	57.7	16.0
MK392	72.6	60.9	30.8	11.3
MK388	110.6	136.3	23.0	10.4

Select trace element geochemistry of Cooks Brook Formation mudstone

Sample	V ppm	Cr ppm	Ni ppm	Y ppm
MK62	90.7	69.7	47.0	9.1
MK555-2	123.5	62.0	55.6	7.5
MK556	220.9	84.6	59.8	12.0
E11142	182.3	101.3	52.3	14.1
MK-209	141.0	87.0	52.0	18.0
MK-473	108.0	81.0	43.0	15.0

Select trace element geochemistry of Lower Head Formation mudstone

Sample	V ppm	Cr ppm	Ni ppm	Y ppm
E11367-2	96.4	113.9	49.5	11.2
MK566	273.4	74.1	42.5	24.0
MK-420	94.0	64.0	43.0	36.0
MK-414	91.0	54.0	40.0	34.0
MK-434	82.0	88.0	51.0	15.0
E11083	44.0	34.0	25.0	13.0
E11060	95.6	125.3	48.9	16.4

Select trace element geochemistry of mélange matrix mudstone

Sample	V ppm	Cr ppm	Ni ppm	Y ppm
E11273	125.7	89.2	59.5	16.4
E11275	102.7	73.1	53.3	31.8
E11230-C	111.0	77.0	60.0	16.0
E11230-B	129.0	66.0	51.0	14.0
MK-161	102.0	110.0	54.0	35.0
E11230-A	83.0	45.0	33.0	28.0
MK-585	288.0	78.0	45.0	21.0
MK-519	176.0	61.0	39.0	17.0
MK-126	339.0	64.0	69.0	19.0
MK-107	75.0	73.0	44.0	23.0
MK-110	169.0	52.0	40.0	65.0
MK-436-2	94.0	62.0	38.0	35.0
MK101	251.9	91.7	62.6	14.8

Appendix F

Mafic Volcanic Geochemistry

Major Element Mafic Volcanic Geochemistry

Sample	Na2O wt%	MgO wt%	Al2O3 wt%	SiO2 wt%	P2O5 wt%	K2O ppm	CaO ppm
MK-411	<LD	8.03%	9.46%	37.53%	0.01%	0.02%	17.37%
MK-436	0.25%	8.07%	8.11%	21.48%	0.12%	0.43%	29.46%
MK-528	3.00%	4.95%	12.38%	45.22%	0.14%	0.96%	13.06%
MK-558D	2.39%	10.06%	10.12%	43.41%	0.11%	0.19%	8.69%
MK-558P	2.54%	10.53%	9.74%	40.05%	0.13%	0.28%	4.88%
MK-640	2.31%	13.29%	13.19%	39.93%	0.09%	0.18%	1.41%
E11327	<LD	4.62%	2.84%	24.39%	0.01%	0.07%	8.77%
E11346-2	3.18%	7.91%	10.38%	37.78%	0.07%	2.17%	6.36%
E11355	1.73%	10.06%	12.89%	40.02%	0.01%	0.91%	2.98%
E11355-2	3.40%	5.18%	11.69%	45.05%	0.08%	2.36%	9.51%
MK-122	2.91%	8.71%	11.42%	37.95%	0.14%	0.28%	7.30%
MK-586	1.12%	22.03%	11.67%	36.83%	0.08%	0.12%	11.58%
MK-592	1.91%	9.49%	10.58%	33.78%	0.15%	0.89%	9.69%
MK-594	3.35%	4.44%	15.66%	48.10%	0.21%	0.01%	39.38%
MK-607	1.55%	16.22%	11.35%	39.50%	0.48%	0.20%	16.14%
MK-623-2	<LD	9.16%	13.94%	42.42%	0.06%	0.05%	10.59%
E11169	3.72%	7.34%	12.62%	45.13%	0.05%	0.19%	5.41%
E11315A	2.48%	8.70%	14.35%	42.60%	0.19%	0.38%	13.37%
MK-152-2	2.17%	10.17%	12.18%	36.73%	0.17%	0.88%	8.87%

Sample	TiO2 wt%	MnO wt%	Fe2O3T wt%
MK-411	0.18%	1.78%	16.10%
MK-436	1.25%	1.50%	15.40%
MK-528	1.53%	0.14%	11.72%
MK-558D	1.77%	0.54%	14.46%
MK-558P	1.75%	0.35%	17.19%
MK-640	1.14%	0.19%	12.85%
E11327	0.12%	1.82%	6.41%
E11346-2	0.97%	0.17%	7.84%
E11355	1.27%	0.16%	13.45%
E11355-2	1.07%	0.21%	14.39%
MK-122	1.57%	0.17%	12.33%
MK-586	1.15%	0.29%	13.00%
MK-592	1.99%	0.50%	20.34%
MK-594	1.36%	0.12%	12.07%
MK-607	2.83%	0.23%	12.81%
MK-623-2	2.29%	0.23%	14.19%
E11169	0.94%	0.18%	11.16%
E11315A	1.81%	0.15%	13.57%
MK-152-2	1.84%	0.56%	12.93%

Trace Element Mafic Volcanic Geochemistry

Sample	Sc ppm	V ppm	Cr ppm	Ni ppm	Cu ppm	Zn ppm	Ga ppm	As ppm
MK-411	28	94	1342	331	85	104	9	<LD
MK-436	60	283	103	44	75	50	11	17
MK-528	30	241	690	215	76	23	14	16
MK-558D	47	504	177	49	268	49	15	20
MK-558P	49	556	73	45	259	54	17	<LD
MK-640	32	200	874	488	85	33	14	<LD
E11327	22	85	3370	1600	24	18	-1	16
E11346-2	41	209	274	63	58	17	11	<LD
E11355	44	769	258	56	96	20	17	<LD
E11355-2	44	359	108	23	41	37	14	<LD
MK-122	34	214	773	357	40	24	12	<LD
MK-586	50	287	438	58	66	31	14	<LD
MK-592	52	553	41	53	178	149	14	18
MK-594	45	183	637	166	23	26	13	<LD
MK-607	21	235	324	81	55	54	14	<LD
MK-623-2	30	75	810	583	19	37	10	<LD
E11169	47	213	742	292	79	22	10	<LD
E11315A	29	279	359	142	13	44	19	<LD
MK-152-2	44	354	221	32	58	39	22	17

Sample	Rb ppm	Sr ppm	Y ppm	Zr ppm	Nb ppm	Ba ppm	Ce ppm
MK-411	<LD	265.7	8.9	5.2	2.0	32	<LD
MK-436	12.3	225.6	25.1	72.1	5.7	130	52
MK-528	15.5	257.5	21.4	131.8	12.6	121	46
MK-558D	2.5	93.0	38.6	113.9	6.6	646	<LD
MK-558P	3.8	142.8	42.2	125.8	7.2	2015	62
MK-640	5.4	317.7	21.3	92.4	7.0	208	<LD
E11327	<LD	203.2	2.3	3.6	1.1	152	<LD
E11346-2	1.8	300.8	20.1	59.7	2.2	567	49
E11355	<LD	186.2	8.5	7.2	1.7	<LD	<LD
E11355-2	3.0	215.5	25.2	60.6	1.1	86	<LD
MK-122	5.7	442.0	22.3	136.4	9.8	98	45
MK-586	5.1	80.6	26.2	89.0	2.2	4346	<LD
MK-592	0.9	126.1	36.1	127.4	7.9	153	<LD
MK-594	61.7	63.7	22.5	90.3	3.8	220	<LD
MK-607	17.1	322.8	26.0	269.9	88.7	1207	155
MK-623-2	69.2	116.8	11.9	172.4	71.3	789	80
E11169	2.4	165.8	18.7	57.8	3.3	59	<LD
E11315A	21.4	364.1	18.7	131.4	19.7	609	<LD
MK-152-2	13.2	300.2	30.7	160.2	8.3	414	47