Reservoir Quality, Diagenetic History and Provenance of the Late Triassic Sandstones of the Wolfville Formation, Cambridge Cove, Bay of Fundy, Nova Scotia.

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Submitted as a Research Project

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ABSTRACT

The Wolfville Formation, which is overlain by the Blomidon Formation, has limited exposed area relative to its wide subsurface extension beneath the Bay of Fundy, where it is underlain by the Horton Bluff Formation in the Minas Basin area, and by Meguma and/or Avalon Zones in the southwestern parts of the Bay of Fundy. The sandstones of the Triassic Wolfville Formation at Cambridge Cove exposed at the southern coast of the Bay of Fundy were investigated petrographically. The study included grain size analysis, diagenesis, porosity, and heavy mineral analysis and reservoir characteristics depending on these properties. These fluvial sandstones are calcite cement- supported feldspathic litharenites to lithic felsarenites. They consist of cement (dominated by calcite and minor iron oxide and clays) (36.4%), quartz (31.5%), lithics (13.0%), feldspars (9.9%), heavy minerals (0.9%), mica & chlorite (0.5%) and the rest is pore spaces. The average ratio of plagioclase/alkali feldspars is 10.8%. The sandstones have a recycled orogenic provenance derived from metasedimentary and granitic rocks postdating the collision type setting and during the early stages of rifting. Their heavy minerals consist of iron oxides (75.9%), garnet (13.6%), apatite (3.3%), chlorite (3.3%), zircon (1.4%), tourmaline (1.3%), biotite (1%) and few others. The main sources of these sediments are the Paleozoic rocks which are now underlying the Wolfville Formation. The probable source of arenaceous rocks (siltstone, sandstone, chert and quartz) and metasediments (slates, schists, and quartzites) are Meguma Supergroup, Horton Group, Windsor Group, Torbrook, Canso and Kentville formations, that of granitoids, quartz and feldspars is dominantly South Mountain Batholith (SMB), while those of limestone are Windsor Group and Canso (Mabou) Formation. The provenance of opaques (Fe and Fe-Ti oxides) are possibly the SMB and iron formations of Torbrook Formation, while the main source of the garnets are the Meguma Group and SMB, and those of the zircon-tourmaline-rutile (ZTR), apatite and micas are mostly the SMB with minor contributions from the other formations. The Meguma, Horton and Windsor Groups and SMB, which were and still are the dominant rock units in the area, are the main source of the Wolfville Formation sediments. Minor contribution from the Appalachian Mountain exposures to the north of the Bay of Fundy in New Brunswick can not be excluded but the absence of volcanics in the studied sediments minimizes that possibility. The Wolfville sandstones have a porosity ranging from 2.6 to 16.6% (6% on average) which gives it the potential to be a moderate to good reservoir rocks for hydrocarbons, especially where it overlies the potential source rocks such as the organic-rich shales of Horton Bluff Formation, or other younger shales within the Mesozoic rocks in the subsurface section beneath the Bay of Fundy.

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TABLE OF ABBREVIATIONS AND SYMBOLS

Qt = Total quartzose grains

Qm= Monocrystalline quartz (>62.5µm) + polycrystalline quartz (>62.5µm) as quartzite

Qp = Polycrystalline quartz (< 62.5µm) as chert

F = Total feldspar grains

P = Plagioclase grains

K = K-feldspar grains

Lm = Metamorphic rock grains (slates, phyllite and schist)

Ls = Sedimentary rock grains (siltstones)

Lv = Volcanic rock grains

Lsm = Sedimentary and metasedimentary rock grains (slates, phyllite, schist & siltstones)

Lvm = Volcanic and metavolcanic rock grains

Ca = Calcarenite rock fragment (detrital limestone) (not included in L)

Rm = metamorphic rock grains (slate, phyllite, schist and quartzite)

Rg = Magmatic rock grains (granitoid)

Rs = Sedimentary rock grains (siltstone, sandstone and limestone)

pe = Perthite feldspar

st = Siltstone

sl = Slate

q = Quartz

mg = Micrographic granite

c = Calcite

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I would like to thank Dr.Grant Wach and Dr.Yawooz Kettanah for proposing the research project and continuous scientific guidance and financial support during the project. I am also thankful to Dr. Patrick Ryall who was teaching the research project course for his guidance to improve the project and reading the chapters throughout the fall and winter terms. I would like to thank Gordon Brown for preparing the thin and polished thin sections for petrographic study, and Debra Wheeler for preparing the heavy liquid used to separate the heavy minerals.

CHAPTER 1

INTRODUCTION

1.1 Opening Statement

The Bay of Fundy forms an important part of the geological history of eastern Canada being formed during early rifting of Pangaea during Early Mesozoic time. It was formed within a wide valley along the Avalon/Meguma suture line which is the extension of Cobequid-Chedabucto fault system. Mesozoic sediments were deposited during various stages of rifting and the early development of the Bay of Fundy. They are exposed along the beaches of the Minas Basin which forms part of the northeastern Bay of Fundy (Fig.1.1 and 1.2). The stratigraphic section of the Mesozoic Formations is shown in Fig.1.3. The exposed portion of Mesozoic strata is relatively small in comparison to its wide extension beneath the Bay of Fundy. Petroleum companies became interested in synrift sediments and explored in the Bay of Fundy during 1968-1983. Seismic exploration was conducted and two exploration wells were drilled in the southwestern part of the Bay of Fundy (Wade et al., 1996).

This project describes the lower part of the Triassic Wolfville Formation which is the first synrift formation deposited during the early stages of the opening of the Bay of Fundy. These sediments were deposited under fluvial, alluvial and aeolian conditions (Klein, 1962, Fensome et al., 2006). It is exposed on both sides of Minas Basin; the study is on the Cambridge Cove located along its southern coast (Fig.1.1). The aim of the project is to study the petrography of Wolfville sandstone beds, their heavy mineral content and use the data to determine the tectonic provenance. The study also includes the porosity and diagenesis of the sandstones which are important properties to assess the reservoir characteristics and significance of these Triassic deposits as possible petroleum reservoirs.

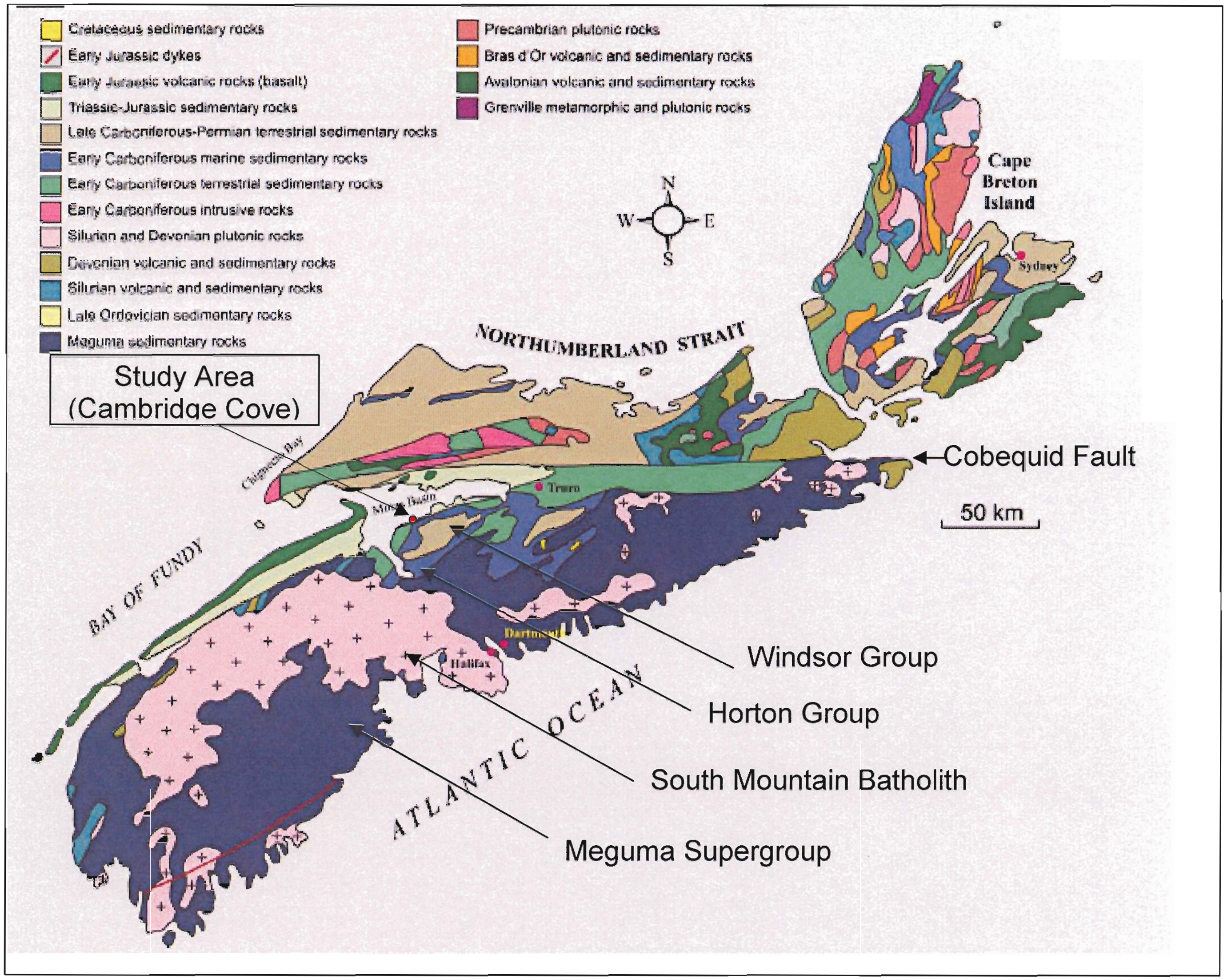


Fig. 1.1: Geology of Maritimes (Fensome and Williams, 2001) showing the location of Cambridge Cove Area.

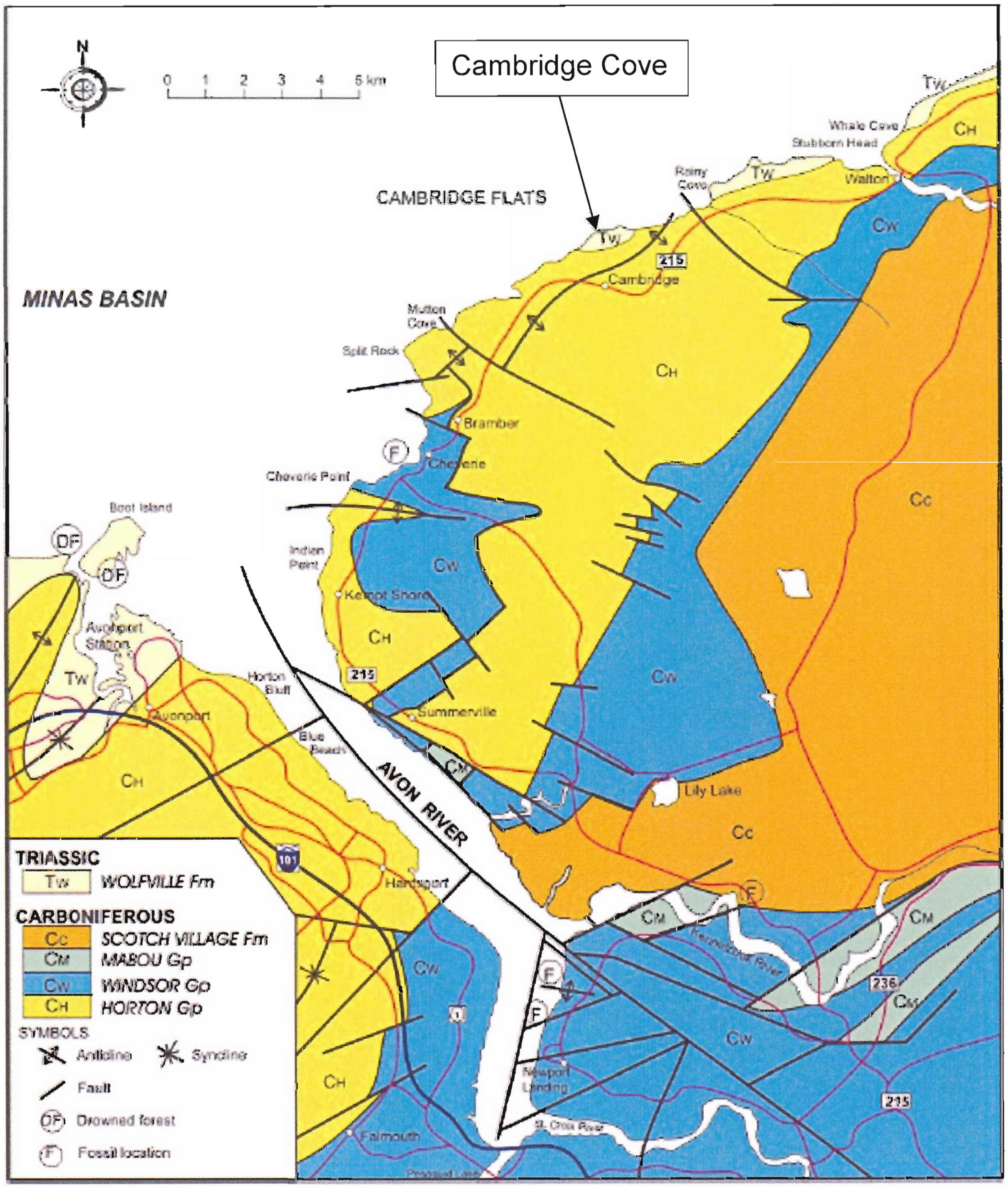
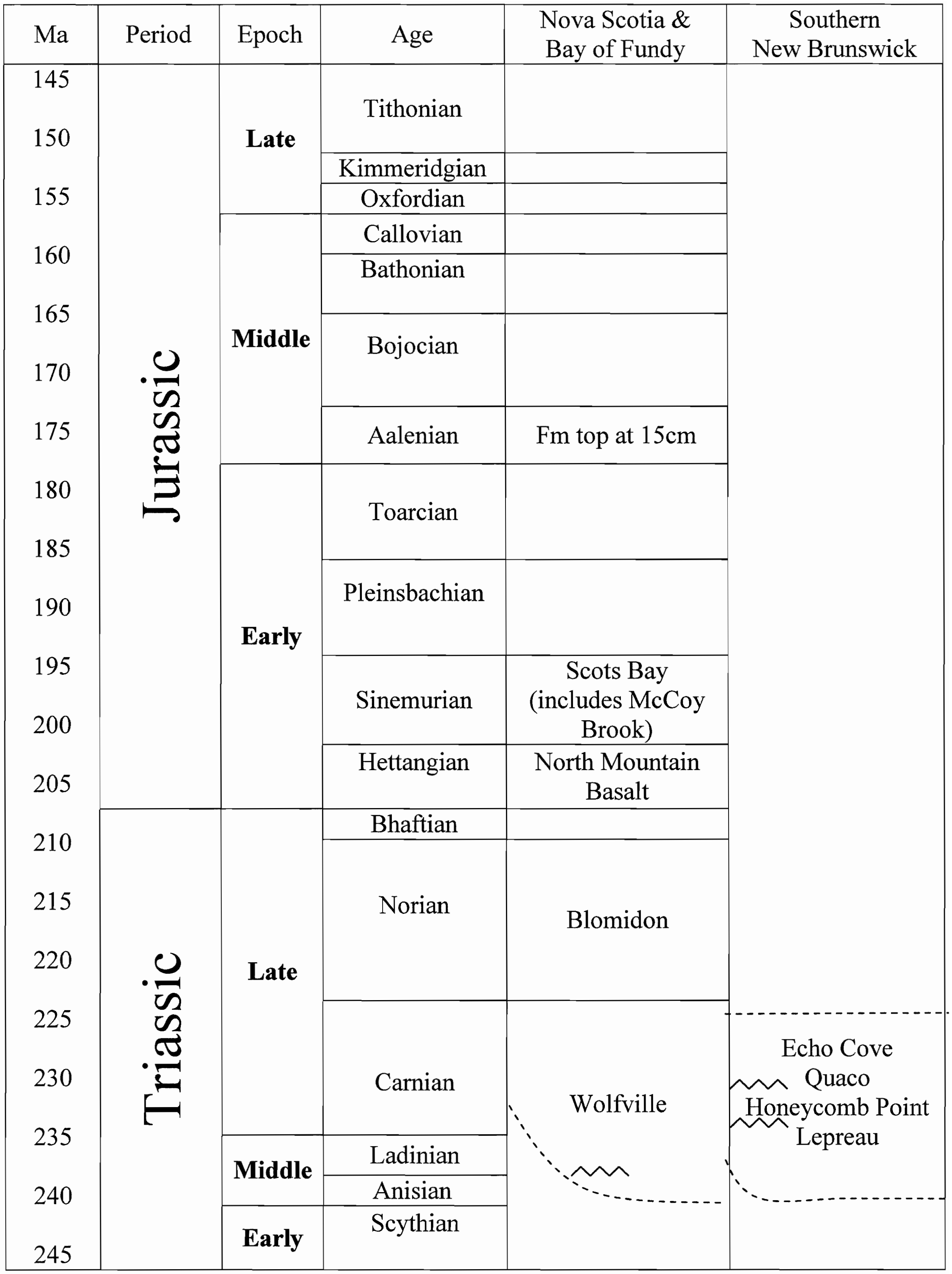


Fig. 1.2: Geologic map of the area around Cambridge Cove (Courtesy R. Raeside, 2004; taken from Fensome et al, 2006)

1.2 Regional Geologic Setting

The Bay of Fundy area is part of the northern Appalachian Mountains which was divided by Williams (1979) on the basis of tectonism, metamorphism, plutonism, metallogenesis and stratigraphy into five "lithotectonic zones". These zones are from south to north: Meguma, Avalon, Miramichi (Gander), Dunnage and Humber (Fig. 1.4). The Meguma zone forms the southern part of Nova Scotia and the adjacent continental shelf which consist of thick turbiditic sediments of Cambrian-Ordovician Meguma Supergroup, Silurian metasediments and volcanics of White Rock, Kentville and New Canaan Formations, and Early Devonian Torbrook Formation. The Meguma Supergroup consists of sand-dominated, metamorphosed turbidites of the Goldenville Formation and overlying silt/shale-dominated metamorphosed turbidites of the Halifax Formation. The South Mountain Batholith has intruded the older formations (Fig.1.1). The Avalon zone occupies southern New Brunswick and northern Nova Scotia and comprises late Precambrian and early Paleozoic mafic volcanics and continental metasediments intruded by granites (Rast et al., 1976; Keppie, 1979). The Bay of Fundy forms a half graben at the boundary of Meguma and Avalon zones (Wade et al., 1996). Both zones were affected by many tectonic events including the Acadian Orogeny during mid-Paleozoic which deformed and metamorphosed these rocks. The Mesozoic formations are underlain beneath the Bay of Fundy by Carboniferous formations in the northeastern parts of the bay and by Meguma and/or Avalon zone rocks towards the southwestern parts as indicated from the seismic profiles and sections studied by Wade et al. (1996) (Fig. 1.5 to 1.7). The Horton Group in the Minas Basin covers a large area and rests unconformably on lower Paleozoic rocks of Meguma Supergroup and is conformably to unconformably overlain by Windsor Group of Early Carboniferous age (Fig.1.1). The Mesozoic formations in these sections are from older to younger: Wolfville, Blomidon, North Mountain Basalt, Scots Bay / McCoy Brook Formations (Fig. 1.3). The Wolfville Formation (Fig.1.1) is exposed on both coasts of the Minas Basin and Cobequid Bay and also in the Annapolis Valley (Keppie, 1979). It unconformably overlies Carboniferous and older Paleozoic sedimentary / metasedimentary or granites, sandstones, conglomerate



Ma	Period	Epoch	Age	Nova Scotia & Bay of Fundy	Southern New Brunswick
145 150	Jurassic	**Late**	Tithonian		
			Kimmeridgian		
155			Oxfordian		
		Middle	Callovian		
160			Bathonian		
165 170			Bojocian		
175			Aalenian	Fm top at 15cm	
180 185		**Early**	Toarcian		
190			Pleinsbachian		
195 200			Sinemurian	Scots Bay (includes McCoy Brook)	
205			Hettangian	North Mountain Basalt	
	Triassic	**Late**	Bhaftian		
210 215 220			Norian	Blomidon	
225 230 235			Carnian	Wolfville	Echo Cove Quaco Honeycomb Point Lepreau
		Middle	Ladinian		
240			Anisian		
245		**Early**	Scythian		

Fig.1.3: Simplified stratigraphic section of the Mesozoic Formations of the Bay of Fundy area (redrawn from Wade et al., 1996).

and minor siltstones and shale. They were deposited in continental environments by fluvial (braided rivers) and aeolian processes under semi-arid conditions (Klein, 1962, Hubert and Forlenza, 1988, Wade et al., 1996). The red brown colour of these sediments indicates that they were deposited subaerially in an oxidizing environment. The Wolfville Formation around the Bay of Fundy is overlain by Blomidon Formation which is in turn overlain by North Mountain Basalt and finally the Scotts Bay Formation.

The Blomidon Formation is well exposed at Cape Blomidon on the western shore of Minas Basin where it reaches a thickness of ~315m bounded by the North Mountain Basalt and the Wolfville Formation (Klein, 1962). It represents the first Formation deposited under lacustrine environment which took place during the rifting process and indicates the end of the rift basin during the Late Triassic and the beginning of aquatic sedimentation stage (Wade et al., 1996). It also conformably overlies Wolfville Formation beneath the Bay of Fundy. It has a thickness of 1157 m at Chinampas N-39 well and 690 m at Cape Spencer No.1 well (Wade et al., 1996) (Fig. 1.5). It consists of repeated cycles of sheet flood/sand flat, playa mud flat and playa lake deposits (Mertz and Hubert,1989), which means, it consist of alternating sandstones, siltstones and shale.

The North Mountain Basalt overlies the Blomidon formation and consists of columnar and amygdaloidal basalts. It is of early Jurassic age and was formed subaerially as successive basalt flows. It forms the prominent North Mountain bounding the Annapolis and Cornwallis valleys and also was penetrated by Chinampas N-39 and Cape Spencer No.1 wells where it has thickness 333 m and 187 m (Wade et al., 1996).

The Scots Bay and McCoy Brook formations are stratigraphic equivalents, unconformably overlying the North Mountain Basalt (Tanner, 1990). The Scots Bay formation consists of interbedded limestone, silty and cherty sandstone and shale deposited mostly in lacustrine environments; its thickness in the type sections is about 8 m. The McCoy Brook Formation consists of terrestrial sediments (breccia, sandstone and mudstone), lacustrine sandstone and shale and aeolian dunes which were deposited on the North Mountain Basalt (Tanner, 1990). In the subsurface beneath the Bay of Fundy, McCoy Brook-like sediments were penetrated by Chinampas N-39 (357 m thick) and

Cape Spencer No.1 (169 m thick) wells and the thickness of Wolfville Formation increases to >3 kms further to the southwest in the Bay of Fundy (Wade et al., 1996) (Fig. 1.5).

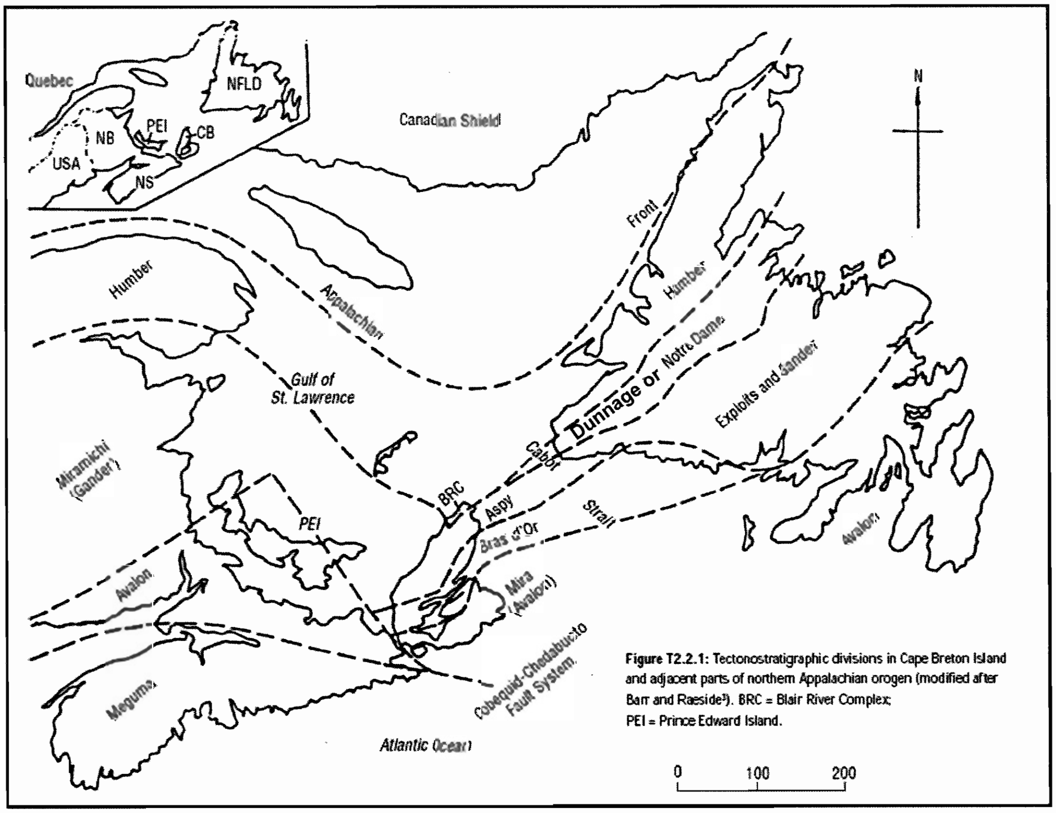


Figure T2.2.1: Tectonostratigraphic divisions in Cape Breton Island and adjacent parts of northern Appalachian orogen (modified after Barr and Raeside[3]). BRC = Blair River Complex; PEI = Prince Edward Island.

Fig. 1.4: Lithotectonic zones of northern Appalachians originally outlined by Williams (1979) and later modified by Barr and Raeside (1989), (from Simmons, et al., 1984).

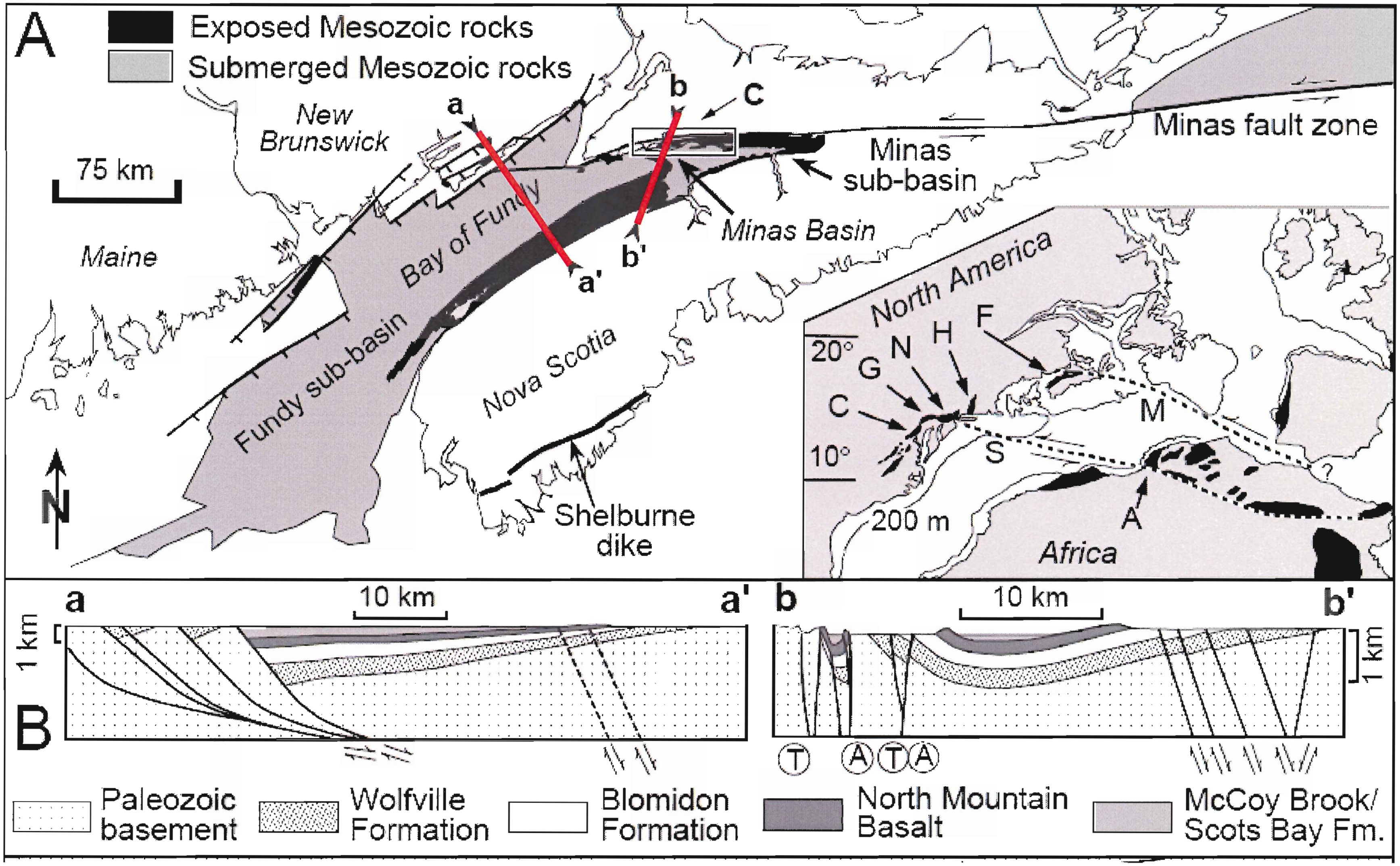


Fig. 1.5: Map of Fundy basin and a cross section through the Minas Basin showing the stratigraphy of Mesozoic formations beneath the basin and onshore (from Olsen and Schlische, 1990).

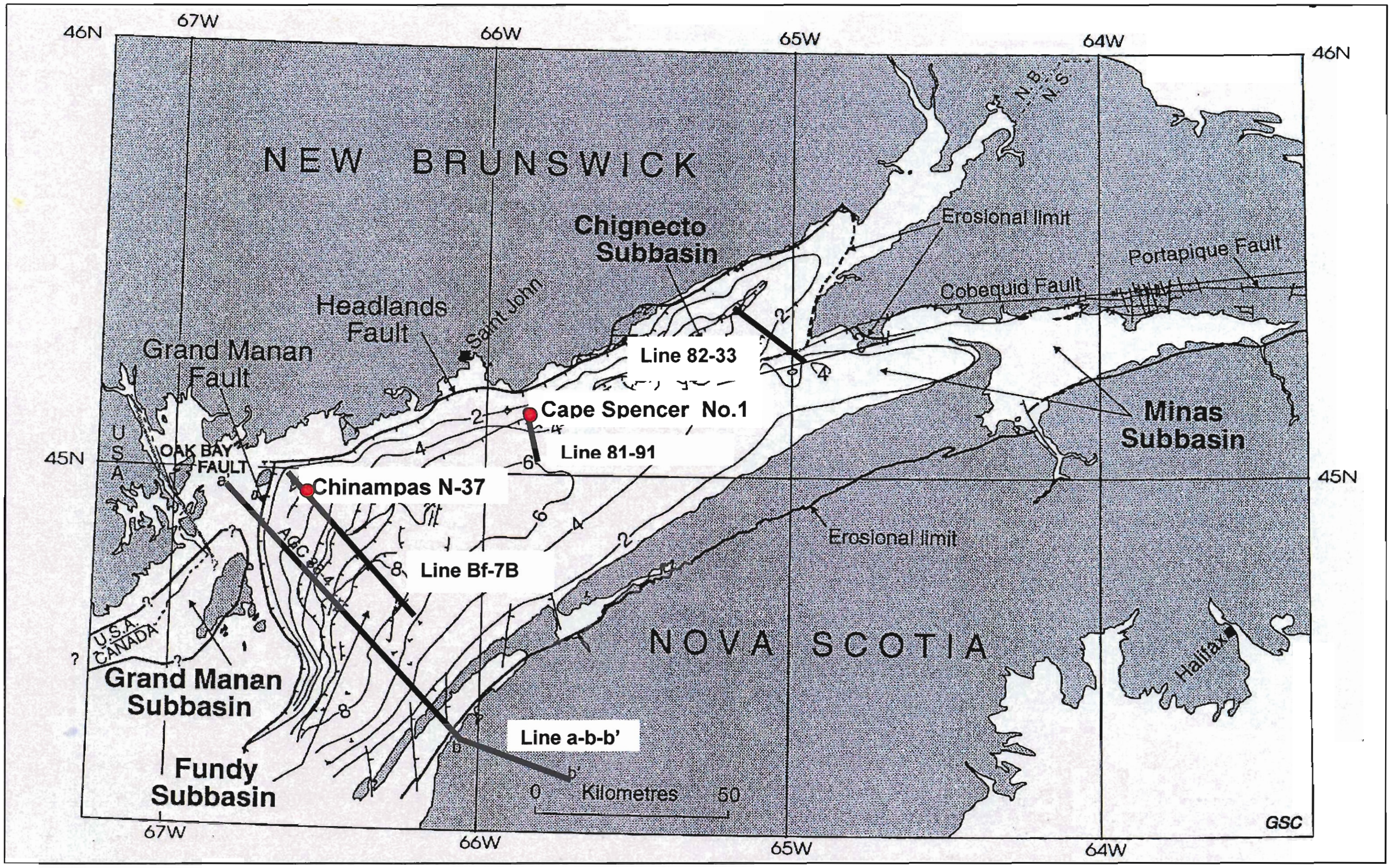


Fig. 1.6: Map of the Bay of Fundy showing its tectonic elements and the location of the two drilled petroleum exploration wells and stratigraphic sections based on seismic traverses (from Wade et al., 1996). The cross sections are shown in Fig.1.7. Contours are subsea depth to the base of Mesozoic strata (from Wade et al., 1996).

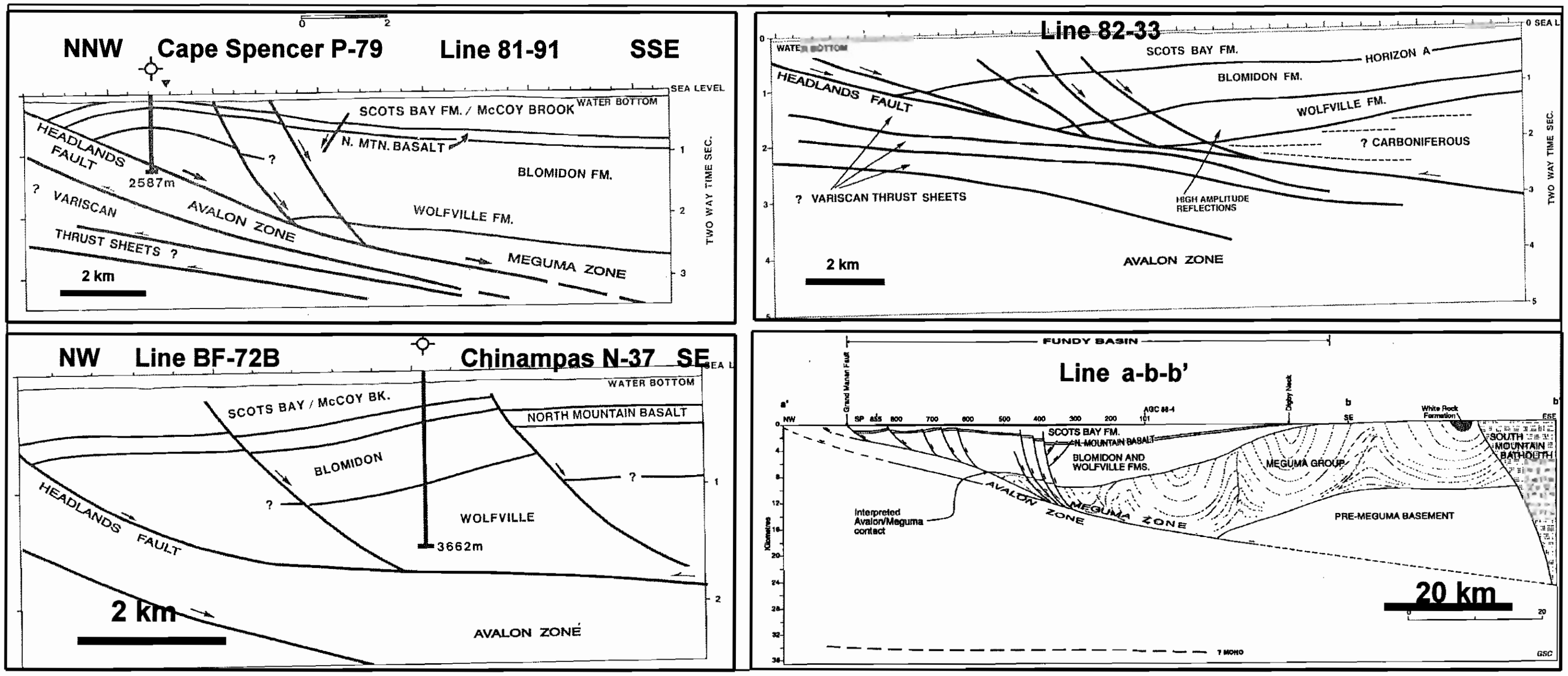


Fig.1.7. The sections show Wolfville formation overlaying Avalon and Meguma Zones (Lines 81-91 and a-b-b'), Carboniferous? and older rocks (Line 82-33), Avalon Zone (Line BF-72B). Cross section lines are indicated Fig. 1.6.

1.3 Previous Work

The Basin where the Mesozoic Formations were deposited started with continental fluvial/aeolian environments, then changed to lacustrine, and ended with marine conditions which are related to the rifting and the formation of the Bay of Fundy. The Wolfville Formation was the first synrift thick sediments deposited mostly by braided rivers and also in parts as alluvial fans and aeolian sands under continental semi-arid oxidizing conditions. The area was studied by many authors including Dawson (1855), Powers (1916), Klein (1962), Keppie (1979), Donohoe and Wallace (1982), Hubert and Forlenza (1988), Baird and Olsen (1983), Olsen and Sues (1986), Olsen (1988), Olsen et al. (1989), Schlische and Olsen (1990), Wade et al.(1996). Dawson (1855) was the first who studied the Acadian Trough and realized that the red beds are younger than Carboniferous and gave them Triassic age based on plant fossils, while Powers (1916) was the first to apply the name "Wolfville" to the basal member of Annapolis Formation (Klein, 1962).

Klein's (1962) work is relevant to this project. However, the methodology used in this study of counting sand grains depends on a more recent classification which can be used to predict the tectonic environment of deposition, and will also include heavy mineral analysis for provenance study, in addition to porosity measurement from thin sections using computer software. Klein (1962) studied Triassic sedimentation, stratigraphy and petrology in detail and introduced the term "Newark", which was first applied to the Maritime Provinces and later changed to Fundy Group, which includes the red beds and interbedded basalts unconformably overlying the Paleozoic rocks of the Maritime Province. He proposed the Wolfville Formation as the name for the lithologically distinct red beds and described its type section along the Minas Basin. He described the Wolfville Formation as stratified coarse to medium-grained clastic rocks, which include conglomerates containing boulder to pebble-size clasts from lower and middle Paleozoic metamorphic rocks, vein quartz, metamorphic quartzite, Mississippian sedimentary rocks, and intraformational siltstone and claystone. The sizes of clasts vary between 2 to 35 cm and consist of lower Paleozoic metamorphic rocks, granite, and rhyolite, which were derived from the Cobequid Mountains and sandstone derived from Pennsylvanian strata. In general the Maritime Basin Triassic sediments consist of interbedded red conglomerate, sandstone, siltstone, and claystone deposited under continental conditions. The Wolfville sandstones are mostly texturally submature and range in grain size from fine to coarse. Klein (1962) counted 300 points on thin sections from various localities of the Wolfville Formation and plotted them according to Krynine's (1948) classification on QMF diagram (Q is detrital quartz, chert and metaquartzite; M is rock fragments excluding metaquartzite and mica; F is feldspar). The results show that most of the samples fall on low-rank greywacke, orthoquartzite, high-rank greywacke and less in arkose fields.

1.4 Outline of the Project and Objectives

The objectives of the study are:

1. Defining the type and properties of the sandstones.
2. Determine the tectonic setting under which the sandstones were deposited,
3. Using the heavy mineral results to find out their provenance.
4. Describing the diagenesis and the porosity of the sandstones and whether they have the characteristics to be reservoir rocks for hydrocarbons.

The start of the study will be making thin section of the rocks, grinding, sieving, heavy mineral separation and preparing thin sections for heavy mineral separates. This will be followed by (1) microscopic examination of the rock and heavy minerals thin sections, (2) using a point counter to count the sand grains and also heavy minerals, (3) taking microscopic images of the thin sections, (4) measuring porosity of the sandstones from images and using Image ProPlus computer software, (5) plotting the data and interpreting the results.

CHAPTER 2

GEOLOGY

2.1 Introduction

Wolfville Formation sandstones, which are exposed on both northern and southern coasts of the Minas Subbasin as part of the red beds, were first recognized and described by Jackson and Alger (1828, 1829a, 1829b) (in Williams, et al., 1985) and subsequently assigned a Triassic age by Dawson (1855) (Williams et al., 1985). Powers (1916) in his regional stratigraphic study used the term Newark Group which included the Lower Wolfville sandstone member, Blomidon shale member, Annapolis Formation, North Mountain Basalt and Upper Scots Bay Formation. Klein (1962) introduced the name Fundy Group instead of the Newark Group and considered the Fundy Group as part of the Newark Supergroup.

2.2 Geology

Two formations are exposed in the Cambridge Cove where the Wolfville Formation is unconformably overlying the Horton Bluff Formation (Figs. 1.1, 1.2, 2.1 and 2.2)

2.2.1. The Horton Bluff Formation

The Horton Bluff Formation has a thickness of 325 m and is disconformably overlain by the Chevrie Formation and together form the Horton Group. It is separated from the older Meguma Group or the South Mountain Batholith by an angular unconformity or fault contact (Williams, 1985). It is of Early Carboniferous age according to the plant fossils which it contains (*Aneimites acadica* and *Lepidodendropsis corrugate).* The Horton Group has been deposited in fluvial-lacustrine environments as alternating grey to black very fine to very coarse grained clastic sediments ranging from shale to conglomerate, and it is commonly of sublitharentic to orthoquartzitic types. In the Cambridge Cove area the Horton Bluff Formation consists of highly deformed alternating very hard brownish gray siltstones and grayish thinly laminated hard shales (Fig.2.2 and Appendix). The siltstones are homogeneous in grain size and the quartz grains are cemented by calcite.

2.2.2 The Wolfville Formation

The Wolfville formation has been studied by many authors since 1828. It was studied in detail as part of the Newark Group by Powers (1916), and as part of the Fundy Group by Klein (1962), and more recently by Wade et al (1996). The thickness of the Lower Triassic Wolfville formation, which is the oldest formation in the Fundy Group, varies in outcrop from 60 m to 833 m (Williams, et al. 1985). It is exposed on both sides of Minas Subbasin. The Fundy Group, from oldest to youngest consists of Wolfville, Blomidon, North Mountain Basalt, and Scots Bay/ McCoy Brook Formations (Fig.1.3) underlying the Fundy Subbasin (Fig.1.5). The thickness of the Wolfville Formation beneath the Bay of Fundy increases toward the southwest from 1308 m in the Irving Cape Spencer No.1 well to >1718 m in the Mobil Gulf Chinampas N-37 well, and is believed to increase to >3000 m east of Grand Manan Island (Wade et al, 1996).

The Wolfville Formation overlies various rock units depending on the location, including the Avalon Zone, the Meguma Zone (Meguma Group, Cambrian to Ordovician), the Kentville (Silurian) and Torbrook formations (Early Devonian), the South Mountain Batholith (Lower Devonian) and Horton and Windsor groups (Lower Carboniferous) and Canso (Mabou) Group (Upper Carboniferous). It is conformably overlain by the Upper Triassic Blomidon Formation or the North Mountain Basalt (Williams et al, 1985).

The Wolfville Formation is well exposed in the southern coast of Minas Basin where it unconformably overlies the Horton Bluff Formation. The angular unconformity between the two formations is sharp and very distinct in Cambridge Cove (Figs. 2.1 and 2.2), Rainy Cove and Clemment Cove. The studied area of Cambridge Cove is characterized by a sharp angular unconformity between the oppositely dipping deformed beds of the Horton Bluff Formation and the gently dipping strata of the Wolfville Formation. The Wolfville Formation beds are parallel to the angular unconformity surface separating it from the underlying Horton Bluff formation; both strike 84° to 90° and dip 20°ENE to 20°N and have been dissected by a number of normal faults trending ~220° and dipping ~70° to 90°NW and NE (Fig.2.3). Both have a maximum exposure thickness of 17 m where the Horton Bluff formation is exposed at the bottom of the vertical cliff (Fig. 2.1). The Wolfville Formation consists of thickly bedded sandstone, pebbly sandstone and conglomerate separated by thin reddish brown silty shales. They are red to brown in colour, poorly sorted sediments and show large scale sedimentary structures such as trough cross bedding and smaller scale structures such as current ripples and imbricated clasts indicating their deposition by rivers under continental oxidizing conditions.

2.3 Methodology:

Eleven samples were taken from the exposed sandstones of Wolfville Formation in Cambridge Cove during the 2005 and 2006 field seasons to the area (Fig.2.1 to 2.3). Thin sections were prepared from these samples using blue epoxy to harden the rock and to show the pore spaces clearly during microscopic studies. Part of each sample was disaggregated using a porcelain mortar and pestle. The disaggregated samples were sieved using standard sieves of <1, 2, 3, 4, and >4Φ sizes (>500, 250, 125, 62.5, and <62.5 μm); each size fraction was accurately weighed using a digital balance. The <4 to >2Φ (62.5 to 250 μm) sizes were mixed and used for heavy mineral separation from each sandstone sample. Na-polytungastate heavy liquid diluted to 2.89 specific gravity was used together with separating funnels and other required glassware to separate the heavy minerals. Thin sections were prepared from the separated heavy minerals for the provenance microscopic study. A Olympus BX51 polarizing research microscope provided with advanced digital camera (Olympus DP71) and Image Pro-Plus software capable of measuring the area of pore spaces was used to study the rock and heavy mineral thin sections

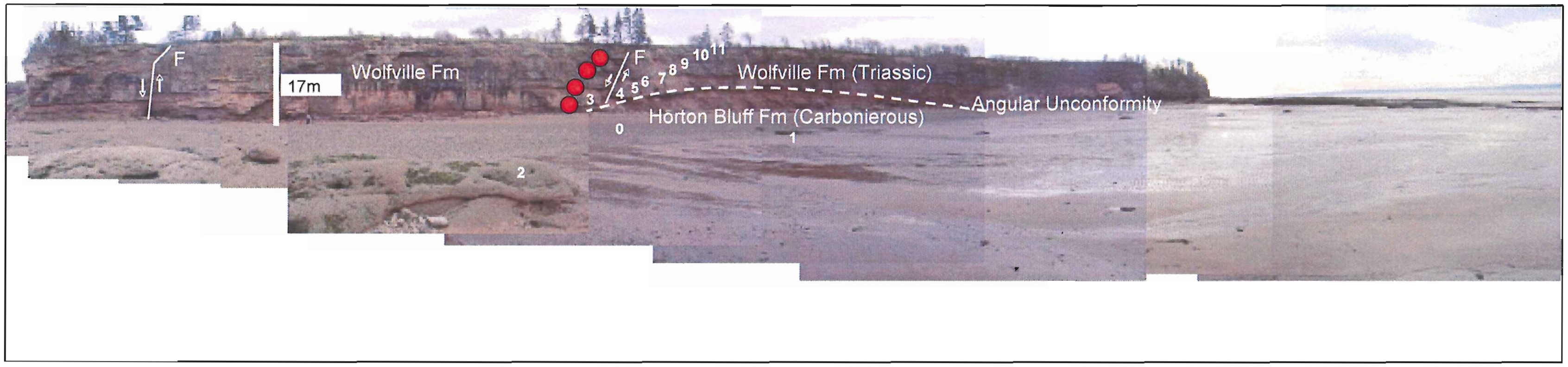


Fig.2.1: Panoramic view of the exposures of Wolfville formation and Horton Group rocks at the Cambridge Cove beach. The numbers indicate the eleven studied samples whose locations are shown relatively as they were taken from accessible places to the right or left of indicated spots. The red circles are the major sampled sandstone beds separated by thin brown siltstones/shales (for details see Fig. 2.2). Samples 1 and 2 are taken from the beach floor which represents the extension of the lower sandstone bed in the nearby vertical cliff whose overlying beds have been eroded by wave erosion; sample 0 is loose recent beach sand.

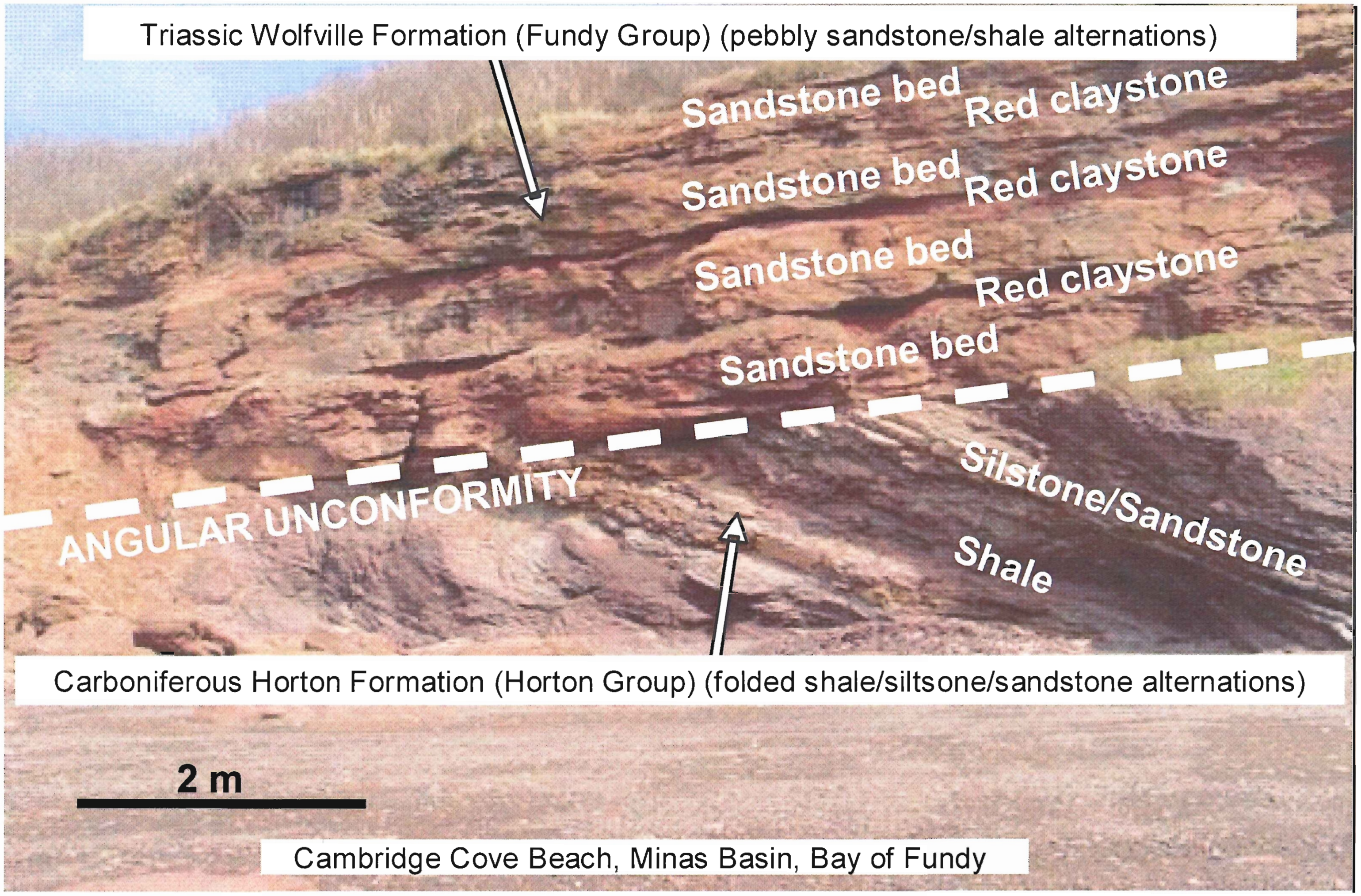


Fig. 2.2: Exposure view showing the sharp contact between Wolfville Formation (Triassic) and Horton Bluff formation (Carboniferous) and the angular unconformity between them. It also shows the studied four sandstone beds.

Fig.2.3: Steeply dipping normal faults and horst cutting the Wolfville and Horton Bluff formations in Cambridge Cove coastal cliff.

CHAPTER 3

PETROGRAPHY AND PROVENANCE

3.1 Introduction

Various methods are used to the study sandstones of Wolfville Formation to determine their grain-size properties, petrography, diagenesis, porosity, and heavy-mineral characteristics. Thin sections of both the sandstones and their heavy minerals separates were studied. The consistent grains and heavy minerals were counted and used in different plots to determine the tectonic setting and provenance of the Wolfville Formation.

3.2 Grain Size Parameters

Eleven sandstone samples from the Wolfville Formation at Cambridge Cove were sieved using standard sieves and Rotap (Table 3.1 and Fig. 3.1). The sieving results showed that the median grain size of the sandstones range from 196μm to 429μm (fine to medium sand) with an average of 299μm (medium sand); the majority are medium grained. They are poorly sorted, strongly fine skewed to fine skewed (the majority are fine skewed), and very platykurtic to leptokurtic (the majority are platykurtic). They also show unimodal distribution in grain size. The shape of slates and siltstones which are the dominant rock fragments in the studied sandstones are mostly disc shaped; the feldspars are mostly bladed in shape while the more resistant quartz, granites and quartzite grains are mostly equant to prolate in shape according to Zingg diagram terminology (Folk, 1968). The shapes of grains depend on the resistance of the grain to erosion during their transportation and also on their lithology and chemistry after deposition and during diagenesis.

Sample	1	2	3	4	5	6	7	8	9	10	11
Median(Φ) = Φ_{50}	196 µm	227 µm	279 µm	429 µm	233 µm	330 µm	379 µm	232 µm	359 µm	354 µm	268 µm
	Fine	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Graphic Mean (Φ)	2.63	2.48	2.15	1.67	2.36	1.91	1.49	2.46	1.93	1.93	2.37
Inclusive Graphic Standard Deviation (Dispersion or Sorting)	1.27	1.37	1.66	1.58	1.5	1.61	1.23	1.16	1.63	1.66	1.3
	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted
Simple Sorting Measure	1.79	1.99	2.31	2.4	2.12	2.45	2.25	1.94	2.32	2.43	1.87
Inclusive Graphic Skewness	0.21	0.24	0.17	0.47	0.15	0.18	0.19	0.27	0.29	0.26	0.4
	Fine Skewed	Fine Skewed	Fine Skewed	Strongly Fine Skewed	Fine Skewed	Fine Skewed	Fine Skewed	Fine Skewed	Fine Skewed	Fine Skewed	Strongly Fine Skewed
Simple Skewness Measure	0.53	0.55	0.5	1.4	0.36	0.5	1.22	0.69	1.01	0.85	1.22
Graphic Kurtosis	0.6	0.68	0.6	0.87	0.64	0.87	1.44	0.8	0.79	0.83	0.89
	Very Platykurtic	Platykurtic	Very Platykurtic	Platykurtic	Very Platykurtic	Platykurtic	Leptokurtic	Platykurtic	Platykurtic	Platykurtic	Platykurtic
Φ_1	Φ_1 = 0.10 =933 µm	Φ_1 = -0.13 =1094 µm	Φ_1 = -0.88 = 1840µm	Φ_1 = -0.95 =1932µm	Φ_1 = -0.75 = 1682µm	Φ_1 = -0.95 = 1932µm	Φ_1 = -1.00 = 2000 µm	Φ_1 = -0.10 = 1072µm	Φ_1 = -1.00 = 2000µm	Φ_1 = -0.99 = 1986µm	Φ_1 = 0.13 =914 µm
Φ_5	0.83	0.43	- 0.22	Φ_5= - 0.48	0.16	Φ_5 = -0.6	- 0.24	0.52	Φ_5 = -0.33	Φ_5 = -0.5	0.64
Φ_{95}	4.40	4.40	4.40	Φ_{95}= 4.32	4.40	Φ_{95} = 4.3	4.26	4.39	Φ_{95} = 4.3	Φ_{95} = 4.35	4.38
Φ_{16}	1.30	1.11	0.38	Φ_{16}= 0.18	0.77	Φ_{16} = 0.32	0.43	1.18	Φ_{16} = 0.3	Φ_{16} = 0.3	1.13
Φ_{84}	4.23	4.19	4.22	Φ_{84}= 3.6	4.20	Φ_{84} = 3.8	2.62	4.10	Φ_{84} = 4	Φ_{84} = 4	4.07
Φ_{25}	1.56	1.40	0.70	Φ_{25}= 0.44	1.15	Φ_{25} = 0.7	0.70	1.41	Φ_{25} = 0.6	Φ_{25} = 0.6	1.34
Φ_{75}	3.98	3.80	3.86	Φ_{75}= 2.7	3.88	Φ_{75} = 3	1.98	3.40	Φ_{75} = 3	Φ_{75} = 3	3.07
Φ_{50}	2.35	2.14	1.84	Φ_{50}= 1.22	2.10	Φ_{50} = 1.6	1.40	2.11	Φ_{50} = 1.48	Φ_{50} = 1.5	1.90

Table 3.1: Sieve analysis results and grain size parameters of Wolfville Formation sandstones Sample locations are shown in Fig. 2.1.

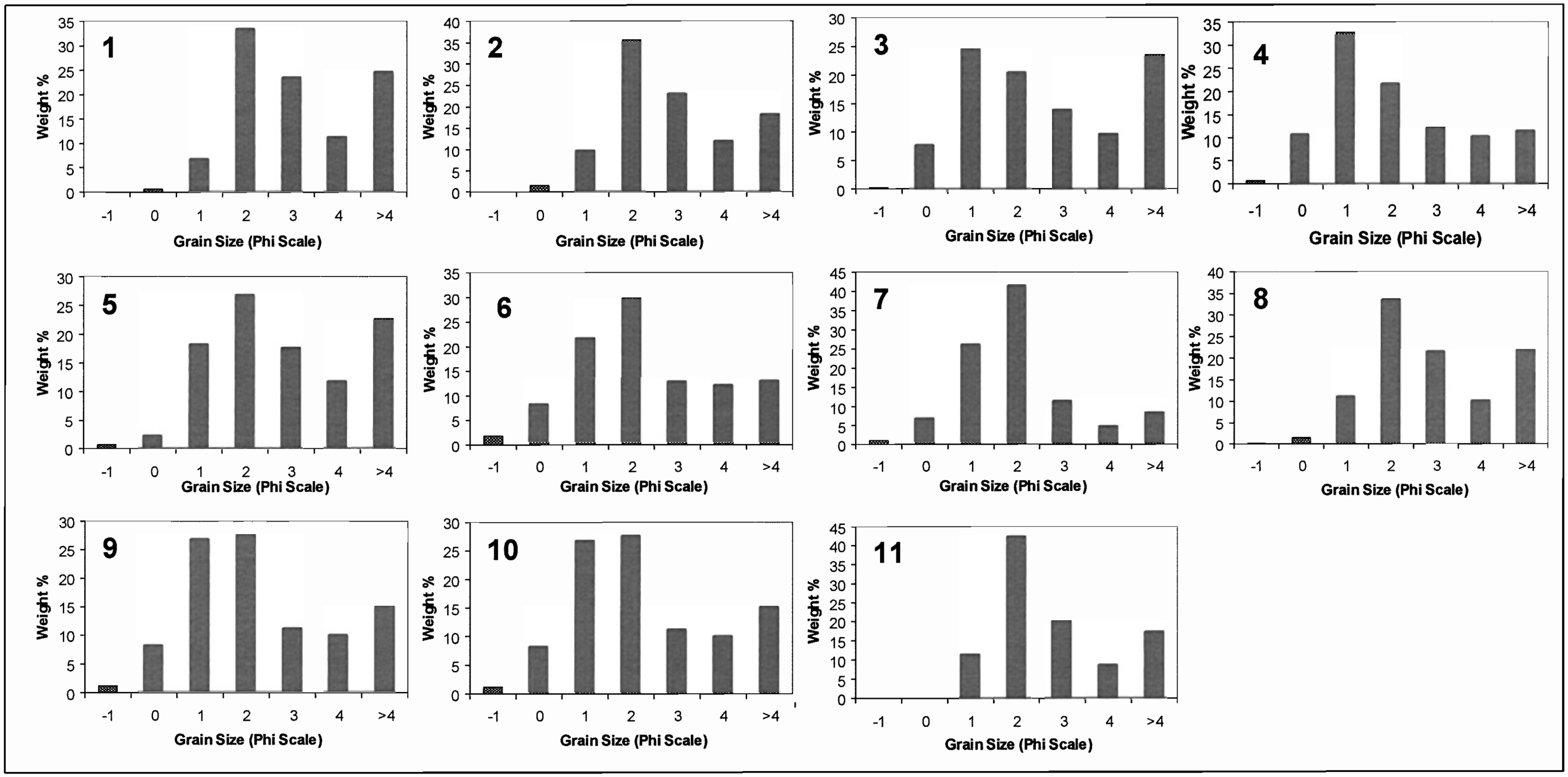


Fig.3.1: Histograms of sieve analysis of the Cambridge Cove sandstones showing unimodal distribution of sediment. Sample numbers are indicated from 1 to 11 and their locations are shown in Fig. 2.1.

3.3 Petrography

The sandstones consist of quartz, rock fragments, feldspars and minor amounts of mica, chlorite and few heavy minerals cemented by sparry calcite and minor amounts of iron oxide and clay (Fig.3.2 & 3.3 and Table 3.2). The ratio of cement to framework grains ranges between 15-47% (36.4% in average). Point counting of 1200 counts was conducted twice on each thin section and the results are shown in Tables 3.2, 3.3 and 3.4 and Figures 3.4 & 3.9. The first point counting included everything in the covered area within the thin section including all types of grains, cement and open spaces. This counting was based on Gazzi-Dickinson method (Dickinson 1985; Ingersoll and Suczek, 1979) which has the advantage of plotting the sand grain counts to determine their tectonic provenance. The calculated sandstone compositions was severely dependent on the size of detrital grains in previous methods of counting such as that of Pettijohn (1972) such that all parts of all polycrystalline grains are counted as lithic fragments, for example a rock fragment of granite irrespective of the size of the grain and/or the size of minerals within that grain (quartz, K-feldspar, plagioclase, etc) was considered as granitic lithic and plotted as part of the rock fragment group. Gazzi-Dickinson method has an advantage of reducing this effect of composition dependence on grain size by restricting lithic fragments to microcrystalline aphanetic material which contain no crystals larger than the silt size (62.5 μm) (Dickinson, 1970 and 1985). So during counting by this method single crystal coarser than 62.5 μm should be counted as mineral grains whether they exist within a rock fragment or as free separate individual mineral grain. A granite lithic containing quartz, K-feldspar, and plagioclase each of which is larger than 62.5 μm will be counted with the other individual separate quartz, K-feldspar and plagioclase grains within the slide and not as granite rock fragment. According to Gazzi-Dickinson method, minerals of sand size (>62.5μm) even if they are part of a rock fragment were considered as individual minerals added to free mineral grain. If a large grain containing minerals larger than silt size continues to move within the transporting agent, it will be broken into pieces and will finally end up as separate free mineral grains. In this way a large source rock containing crystals larger than the matrix limit (62.5 μm) can be found as lithic fragment in a coarse-grained sandstone, and as individual mineral grains in siltstone derived from the same source. The advantage of Gazzi-Dickinson counting method is that the results can be plotted on the triangular diagrams established by Dickinson and Suczek (1979) to find the tectonic provenance of sandstone grains. This is because of the fact that the tectonic setting of the provenance exerts primary control on the composition of sandstones (Dickinson et al, 1983). Dickinson and Suczek (1979) classified the tectonic provenances into major three groups which also contain some subdivions. The major groups are:

(1) Continental block: The sediment sources are the shields and platforms or the faulted basement blocks.

(2) Magmatic arc: The source of sediments is within active arc orogens of island arcs or active continental margins.

(3) Recycled orogen: The source of sediments are along collision orogens such as deformed and uplifted rock sequences in subduction zones or within foreland fold-thust belts

The second counting of 1200 counts was done only for rock fragments according to the traditional method of Pettijohn et al (1972) to show the relative abundance of rock fragments. A triangular plot of Folk (1968) (Fig.3.4) and Table 3.2 to 3.4 showed that the sandstones are of feldspathic litharenite type. Triangular plot of Dickinson (1985) (Fig. 3.4) shows that the sandstone fall mostly in the tectonic field of recycled orogen provenance. Detailed petrographic study of the thin sections of sandstone samples are given below.

3.3.1 Framework

The framework grains range in size from <0.2-2mm and have shapes ranging from angular to rounded depending on their lithology. They are mostly separated by sparry calcite cement and minor amounts of iron oxides and less of clays (Fig. 3.2).

3.3.1.1 Quartz

Quartz is the dominant grain type forming 31.5% on average with a range of 26-50% of the sandstone. The average grain size ranges from 0.5-1mm with angular to sub-rounded shapes. Some of the quartz grains contain inclusions of apatite and mica and some others show wavy extinction reflecting their origin from igneous and metamorphic rocks. Many of the quartz grains show microfracturing which was probably produced by overburden or tectonic pressures. These microfractures form an effective part of the secondary porosity in the sandstones.

3.3.1.2 Rock Fragments

Lithics are the next dominant type of grain type forming 13% of the sandstone ranging between 6-19%. They range in size from <0.2-2mm up to pebble size; their shape varies from sub-angular to rounded depending on the lithology of the rock fragments. The most important types of grains in the studied sandstones are metamorphites (slate, phyllite, schist and quartzite), psammites (siltstone, sandstone, limestone and chert) and magmatites (granitoids).

3.3.1.3 Feldspars

Feldspars form the third important framework grain type which exist as perthite, orthoclase and plagioclase. They generally have rectangular shape and some of them have rounded endings. Most of them show slight alterations to kaolinite, sericite and calcite. Few show strong alterations to these minerals. Many counted feldspars also exist as part of the granitic rock fragments. Some of the highly altered feldspars were dissolved and left behind pore spaces. They form 9.9% of the rock with an average of 5-15%. The ration of plagioclase/K-feldspar is 10.8% on average and range 4-23 %.

3.3.1.4 Mica and Chlorite:

Mica and chlorite occur in minor amounts forming 0-1.3% of the rock (0.5% average). They are present as tiny laths, and in some cases as elongate bands (~1 mm) squeezed and bent between other minerals and rock grains indicating their detrital origin. Chlorite is usually an alteration product of biotite.

3.3.1.5 Heavy Minerals:

Heavy Minerals exist as a few scattered grains. They are iron and iron-titanium oxides, tourmaline, garnet, zircon, apatite, chlorite, and mica. The iron oxides are mostly responsible for the ferruginous cementation and staining of these sandstones. They form 0.9% of the total ranging between 0.3-2.1%.

3.3.2 Cement and Matrix:

They form 36.4% of the sandstone with a range of 15-47%. Sparry calcite is the dominant cement with minor amounts of iron oxide and clays. Calcite forms 31% of the rock with a range of 11-43% separating most of the sand grains from each other and resulting in cement-supported type of sandstone. Ferruginous cement seems to be the earliest type of cement indicated by iron stain around most of the grains. This was followed by calcite as coarse crystalline infill and in many cases radiated crystals surrounding framework grains. Clay minerals (illite, montmorillonite, kaolinite and chlorite) also exist as fine grained booklets or spheriolitic aggregates filling some of the pore spaces. Timing of their relation to the calcite cements is not clear, as sometimes it seems to be earlier in formation and in other cases later. It looks like chert in appearance and is very similar to some photomicrographs given in Scholle (1979). Chert fragments have grain shapes but clay aggregates are characterized by having microporosity in them. Also, they fill the spaces between lithic grains. Microprobe work is possibly the best way to analyze them and confirm their identity. A crystal of siderite was observed in one thin section. It is observed that most of the oval to spheroidal shaped limestone lithics are surrounded by radiating sparry calcite crystal aggregates. In a few cases the calcite cement shows growth zones.

3.3.3 Alterations:

Most of the feldspars have undergone various degrees of alteration. The dominant alterations are sercitization, kaolinazation, and calcitization. Many empty spaces in the rock are probably the result of alteration and dissolution of some feldspars and dissolution of some calcareous cementing material.

3.3.4 Pore Spaces:

Many pore spaces can be observed within the cement or within the grains. The details of porosity will be explained later in section 3.4.

3.3.5 Diagenesis:

Mechanical properties of sand grains, and petrographic results, show that the detrital grains were transported by rivers and later cemented by carbonates and minor amounts of iron oxides and clays. The iron oxide cement seems to have been formed first followed by kaolinitic clays, and finally carbonate cement which was later recrystallized into coarse sparry calcite filling. This separated the framework grains from each other and resulted in cement supported sandstone. (Fig. 3.2). The sand grains contain many iron oxides which were later oxidized into other hydrated iron mineral and partly dissolved staining the sandstones and giving it brownish red color. Some pore spaces were left between the cement and grains giving the rock its porosity and some secondary porosity also formed later because of alterations of feldspars (kaolinization, sercitization and calcitization) and also along fractures and some detrital quartz and other minerals grains. Authigenic overgrowths on quartz grains are not common. Most of the quartz grains in the studied sandstones show fracturing. These fractures were probably formed by the effect burial and compaction which cause fracturing of quartz which is considered more brittle than the other types of grains. The effect of compaction and burial can be seen on some mica flakes which show bending but this burial effect was not strong to produce structures such as stylolites. The recrystallization of calcite cement into coarser sparry calcite which filled the spaces between framework grains and separated them from each other possibly reduced the effect of compaction on the grains. Some of the pore spaces still exist between grains and they apparently represent the primary porosity. Secondary porosity was also formed later during diagenesis represented by alteration and dissolution of some unstable minerals and lithics such as feldspars and granites. Other types of microporosity were also formed by dissolution of calcareous cement or breaking of fractured quartz and other grains under burial effects.

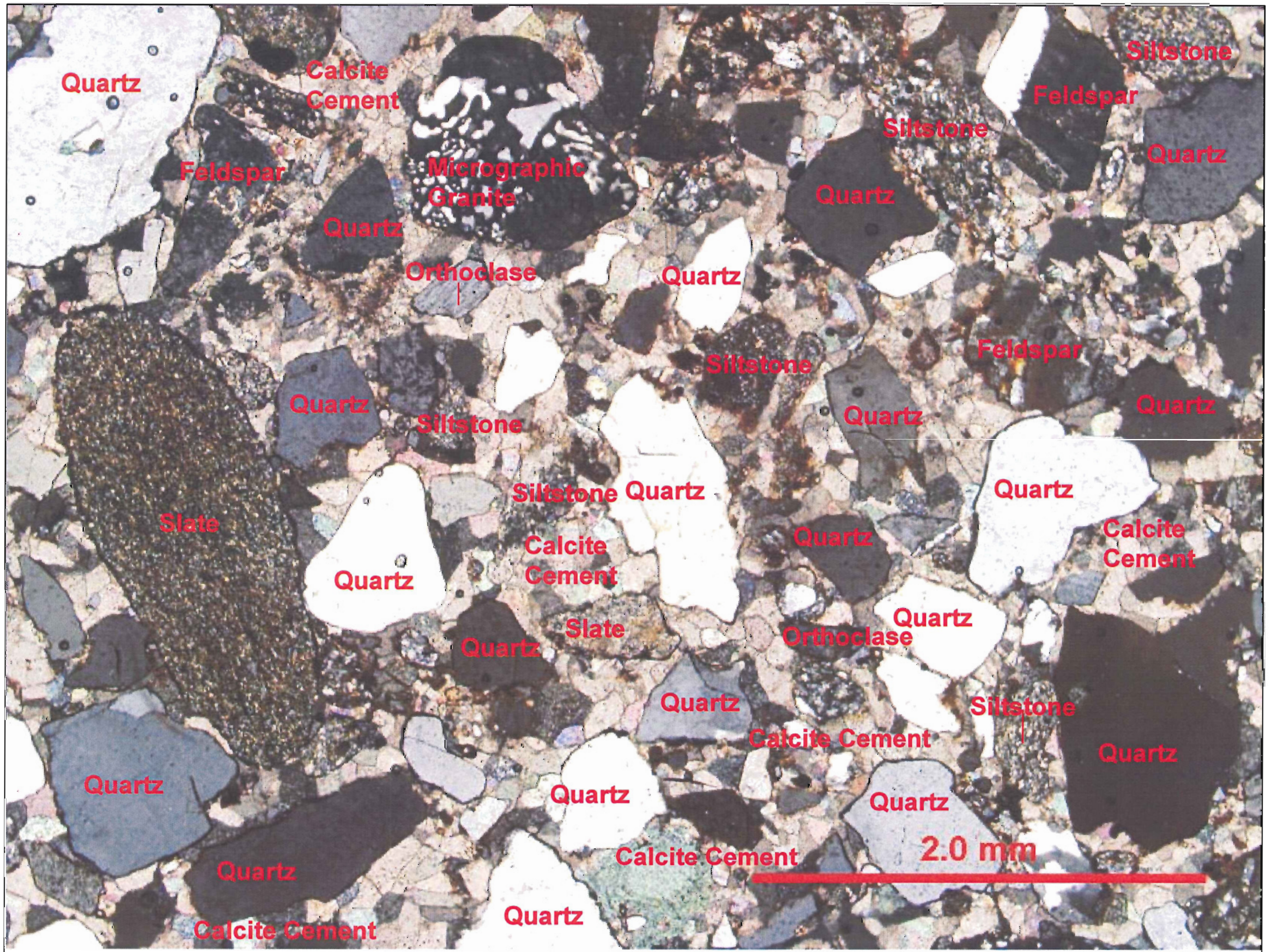


Fig.3.2: Calcite cemented sandstones of Wolfville Formation showing the main constituents

Grain Groups		Grain Type	Sample Numbers											Minimum	Maximum	Average
			1	2	3	4	5	6	7	8	9	10	11			
		Quartz	397	362	384	349	355	312	395	337	363	313	600	312	600	378.8
	Qm	Quartzite	25	14	37	12	31	22	12	13	10	9	35	9	37	20.0
Qt	Qp	Chert	3	2	18	7	0	10	1	1	1	0	1	0	18	4.0
		K-feldspar	120	105	62	133	114	99	143	63	105	108	112	62	143	105.8
F		Plagioclase	14	12	3	7	13	8	33	8	17	12	4	3	33	11.9
		Slate	146	127	65	88	49	96	73	95	59	66	35	35	146	81.7
Lt=L+Qp	L	Siltstone	40	40	144	50	63	60	113	78	106	33	40	33	144	69.7
Carbonates		Limestone	7	7	46	17	24	21	19	11	21	23	0	0	46	17.8
		Calcite	223	244	311	444	467	462	255	474	461	510	128	128	510	361.7
		Iron stain	25	13	35	34	6	18	3	17	4	2	5	2	35	14.7
Cement		Clay+sericite	126	104	22	21	2	10	98	0	1	2	17	0	126	36.6
		Muscovite	1	5	0	0	4	5	1	4	1	2	8	0	8	2.8
		Biotite	6	3	0	0	2	2	0	1	1	2	7	0	7	2.2
Mica & Chlorite		Chlorite	1	2	0	0	1	0	1	0	0	0	1	0	2	0.5
Heavy Minerals			18	11	25	4	15	8	14	6	4	4	6	3	32	10.5
Others (highly altered grains)			7	15	14	1	20	10	2	48	15	6	2	1	48	12.7
Pore Spaces			41	134	34	33	34	57	37	44	31	108	199	31	199	68.4
TOTAL COUNTS			**1200**	**1200**	**1200**	**1200**	**1200**	**1200**	**1200**	**1200**	**1200**	**1200**	**1200**	**1200**	**1200**	1200.0
Porosity (%)			3.4	11.2	2.8	2.8	2.8	4.8	3.1	3.7	2.6	9	16.6	2.6	16.6	5.7
Cement Counts			374	361	368	499	475	490	356	491	466	514	150	150	514	413.1
Total counts -Pores			1159	1066	1166	1167	1166	1143	1163	1156	1169	1092	1001	1001	1169	1131.6
Cement/ Grain Counts (%)			32	34	32	43	41	43	31	42	40	47	15	15	47	36.4
(Quartz/Total Counts)%			33	30	32	29	30	26	33	28	30	26	50	26	50	31.5
(Lithics/Total Count)%			16	14	19	12	9	14	16	15	14	8	6	6	19	13.0
(Feldspars/Total Counts)%			11	10	5	12	11	9	15	6	10	10	10	5	15	9.9
(Plagioclase/K-Feldspars)%			12	11	5	5	11	8	23	13	16	11	4	4	23	10.8
(Cement/Total Counts)%			31	30	31	42	40	41	30	41	39	43	13	13	43	34.6
(Calcite/Total Counts)%			19	20	26	37	39	39	21	40	38	43	11	11	43	30.3
[(Mica+Chlorite)/Total Counts]%			0.7	0.8	0	0	0.6	0.6	0.2	0.4	0.2	0.3	1.3	0	1.3	0.5
(Heavy Minerals/Total Counts)%			1.5	0.9	2.1	0.3	1.3	0.7	1.3	0.5	0.3	0.3	0.5	0.3	2.1	0.9

Table 3.2: Grain counts summary and statistics including porosity and cement to grain ratio for Wolfville Formation sandstone

Rock Type	Metamorphic			Sedimentary				Magmatic	Altered	Total
Sample No.	Slate	Schist	Quartzite	Siltstone	Sandstone	Limestone	Chert	Granite	Others	Counts
1	670	3	34	309	35	72	6	58	13	1200
2	631	3	19	325	116	49	0	57	0	1200
3	391	1	50	524	63	77	11	83	0	1200
4	275	5	44	218	48	71	93	436	10	1200
5	271	20	99	400	71	94	0	237	8	1200
6	353	14	42	294	42	88	82	283	2	1200
7	304	8	44	388	60	108	8	280	0	1200
8	445	32	74	261	103	103	20	136	26	1200
9	323	7	46	294	153	117	6	252	2	1200
10	638	2	21	307	23	64	6	134	5	1200
11	213	97	372	365	88	0	0	65	0	1200

Table 3.3: Rock grain counts in Wolfville Formation sandstone samples counted according to the traditional method (Pettijohn et al,1972)

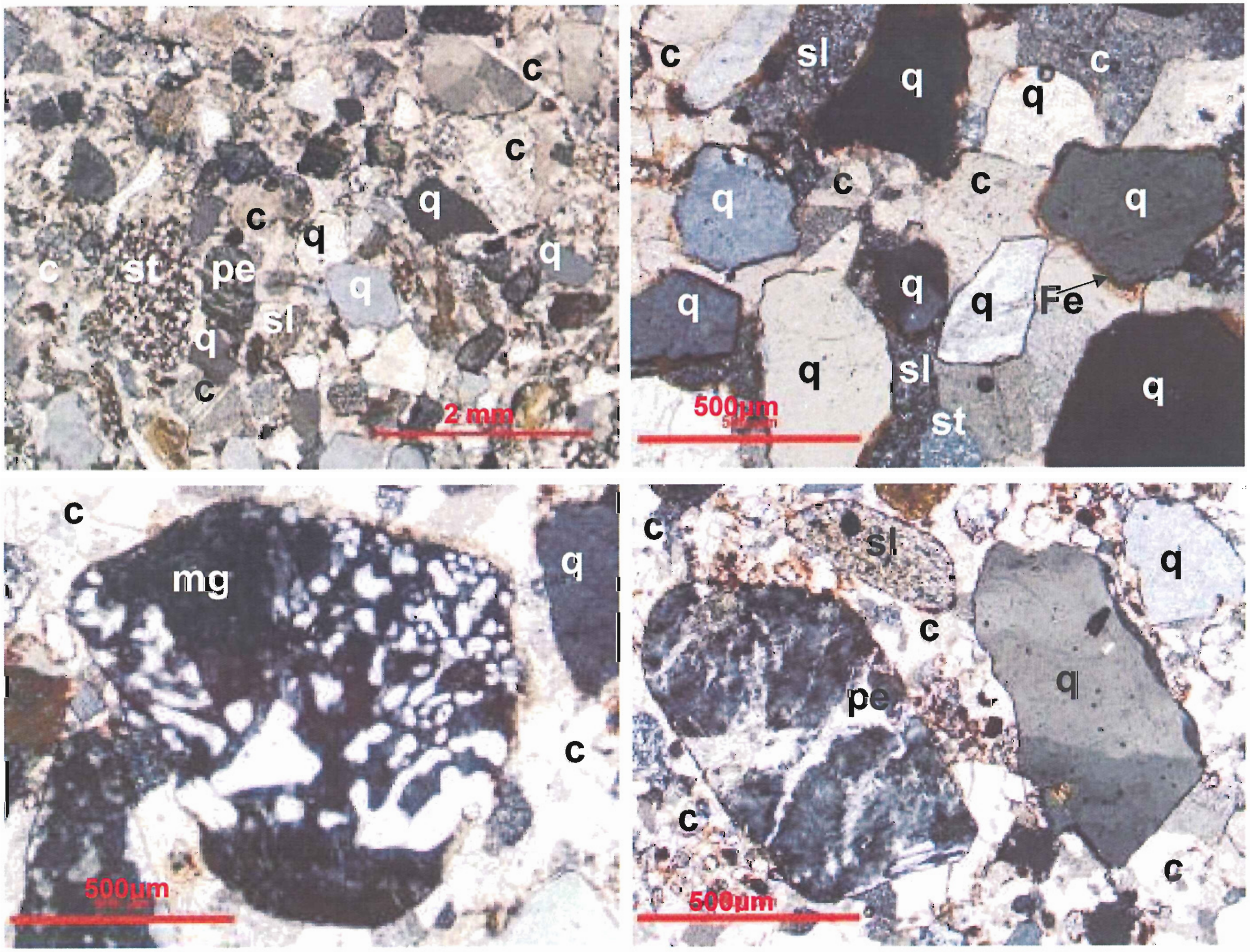


Fig.3.3: Cement supported calcareous sandstone: Framework grains: quartz (q), slate (sl), siltstone (st) and perthite feldspar (pe), micrographic granite (mg) surrounded by a thin film of iron stain (Fe) and cemented by intergranular sparry calcite (c).

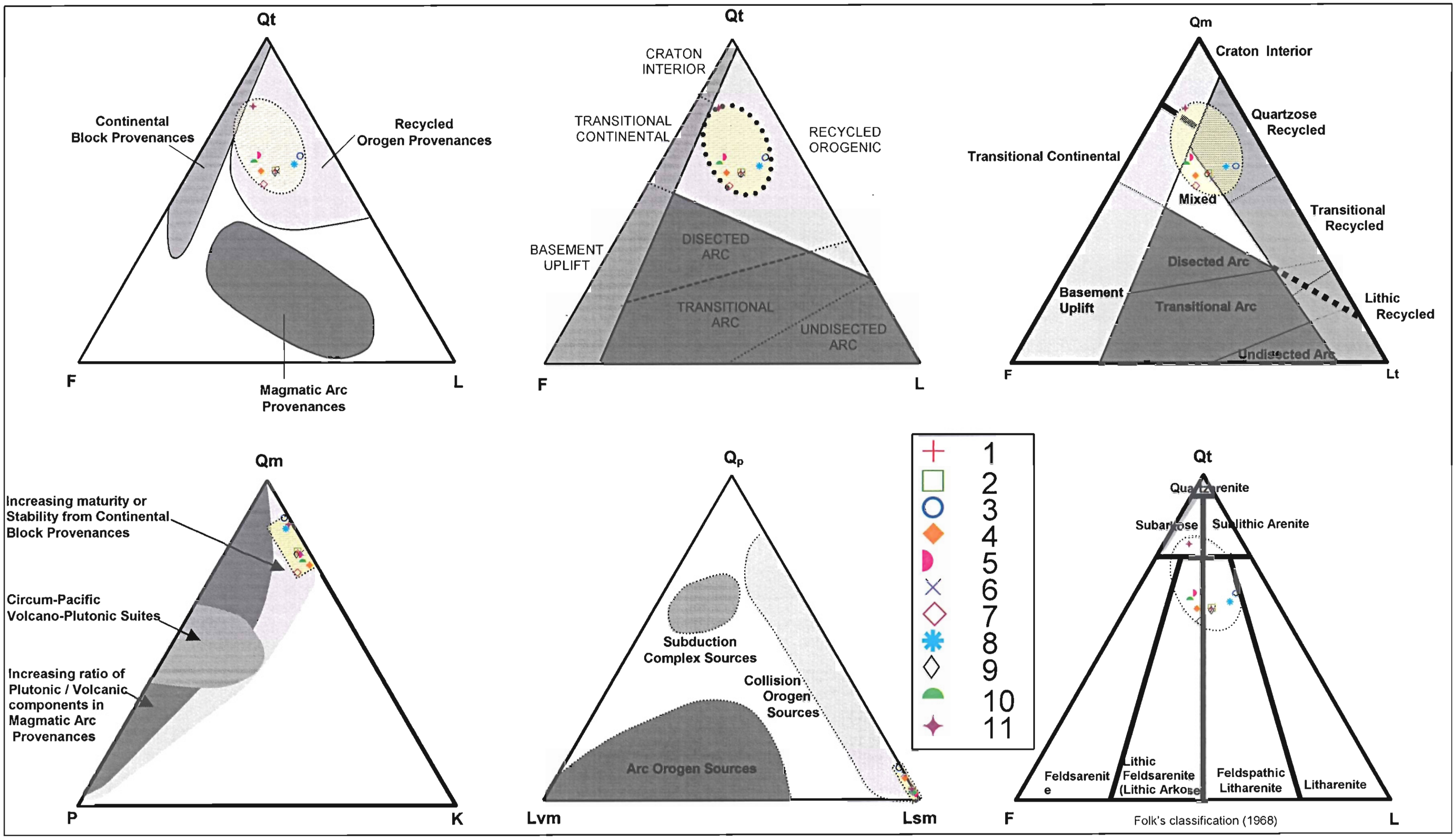


Fig.3.4: Triangular diagrams of the main constituents of Wolfville Formation sandstones plotted on Folk (1968) and Dickinson (1985) diagram to show the type of sandstone and the tectonic provenance; the symbols are described in Table 3.4.

<table>
<tr><td colspan="3">A: Counted according to Gazzi-Dickinson method and used in FQtL, FQmLt, PQmK and LvmQpLsm triangular diagrams (Figs. 5 and 6)</td></tr>
<tr><td>1</td><td>QUARTZOSE GRAINS
(Qt = Qm + Qp)</td><td>Qt = Total quartzose grains
Qm= Monocrystalline quartz (>62.5μm) + polycrystalline quartz (>62.5μm) as quartzite
Qp = Polycrystalline quartz (< 62.5μm) as chert</td></tr>
<tr><td>2</td><td>FELDSPAR GRAINS
(F = P + K)</td><td>F = Total feldspar grains
P = Plagioclase grains
K = K-feldspar grains</td></tr>
<tr><td>3</td><td>UNSTABLE ROCK FRAGMENTS (LITHICS)
(L = Lm + Ls + Lv = Lsm + Lvm)</td><td>Lm = Metamorphic rock grains (slates, phyllite and schist)
Ls = Sedimentary rock grains (siltstones)
Lv = Volcanic rock grains
Lsm = Sedimentary and metasedimentary rock grains (slates, phyllite, schist and siltstones)
Lvm = Volcanic and metavolcanic rock grains
Ca = Calcarenite rock fragment (detrital limestone) (not included in L)</td></tr>
<tr><td>4</td><td>TOTAL ROCK FRAGMENTS (LITHICS)
(Lt = L + Qp)</td><td></td></tr>
<tr><td colspan="3">B: Counted according to Pettijohn et al; (1972) method and used in RsRgRm triangular diagram (Fig. 10)</td></tr>
<tr><td>5</td><td>Rock Fragments (Litics)
(Rm, Rg, Rs)</td><td>Rm = metamorphic rock grains (slates, phyllite, schist and quartzite)
Rg = Magmatic rock grains (granitoids)
Rs = Sedimentary rock grains (siltstones and sandstone)</td></tr>
</table>

Table 3.4: Classification, terminology and symbols used in point counting and related triangular diagrams.

3.4 Porosity:

The pebbly sandstones of the Wolfville Formation are cement supported. The framework grains are cemented by sparry calcite with minor amounts of iron oxides and occasionally clays. The porosity of these sandstones was measured by two different methods, the PropPlus software and mechanical point counter. The ProPlus software is integrated to a high resolution digital camera attached to the Olympus Research Polarized Microscope.

The ProPlus software can detect and accurately count spots on photomicrograph images which have the same colour tone. The thin sections were prepared by impregnating the samples with blue coloured epoxy which allow detection of large pore spaces as well as micro-pores within grains. The blue epoxy can be highlighted with one colour and the rest of the view with another color so their areas are automatically measured and compared giving the porosity of the image. Since only part of the slide can be imaged, the slide area was divided into grids of equal areas and an image covering each of them was taken. The porosity of each image was measured and the average of all measured images was taken to represent the overall porosity of the slide and thus the rock sample.

A mechanical/electric point counter attached to the microscope's stage was used to count all the constituents in the slide including the pore spaces. 1200 counts were taken in each slide and the porosity was measured by taking the ratio of counts representing the pores relative to total count numbers.

The results of both porosity measurement methods are given in Table 3.5. The results are reasonably comparable with an average of 6.11% (for ProPlus software) and 5.96% (for point counter). The range of both is 1.70-16.58%. Samples taken from the exposed outcrops on the floor of the beach show considerably higher porosity because they are under the daily effect of tides resulting in dissolution of large parts of the calcite cement which can easily be recognized from thin section study.

Sample Number / Measurement Method	1	2	3	4	5	6	8	9	10	11	**Av.**
Point Counter	3.42	11.17	2.83	2.75	2.83	4.75	3.67	2.58	9.00	16.58	**5.96**
ProPlus Software	4.42	9.64	3.57	/	1.70	/	7.48	/	/	9.82	**6.11**
Average of both	3.92	10.40	3.20	2.75	2.27	4.75	5.57	2.58	9.00	13.20	**5.77**

Table 3.5: Porosity measurement methods and comparison.

Detailed microscopic study showed both primary and secondary porosity in these rocks (Fig. 3.5 and 3.6). The porosity classification is mostly based on that described by Scholle (1979) as follows:

3.4.1 Primary Porosity:

This represents the areas left unoccupied by the original sparry calcite cement between grains (Fig.3.5). They are relatively large spots but sporadic in distribution.

3.4.2 Mixed Primary and Secondary Porosity

Primary pore spaces are surrounded and/or protected by secondary intracement porosity especially the kaolinite booklets (Fig.3.5).

3.4.3 Secondary Porosity

Many types of porosity were produced after the cementation stages. These secondary porosities can be divided into:

3.4.3.1 Dissolution Microporosity

This type of porosity was produced by dissolution of some framework grains and/or cement. It is particularly common in highly altered feldspars which are mostly kaolinized and sericitized k-feldspars (Fig.3.5). Some of these dissolved grains are totally removed leaving open spaces while others are partially removed. Parts of the calcite cement are also selectively dissolved leaving large areas as pore spaces which are mostly observed on samples which are under the tide effects exposed on flat tidal areas.

3.4.3.2 Microfracture Microporosity

The majority of quartz grains are intensely fractured, which can be seen as a network on these grains. These fractures represent microporosity as well as paths of permeability between grains. Many of these grains were brecciaed under overburden pressure effects which resulted in widening of pore spaces helping interconnectivity between adjacent grains (Fig.3.6).

3.4.3.3 Grain-boundary Microporosity

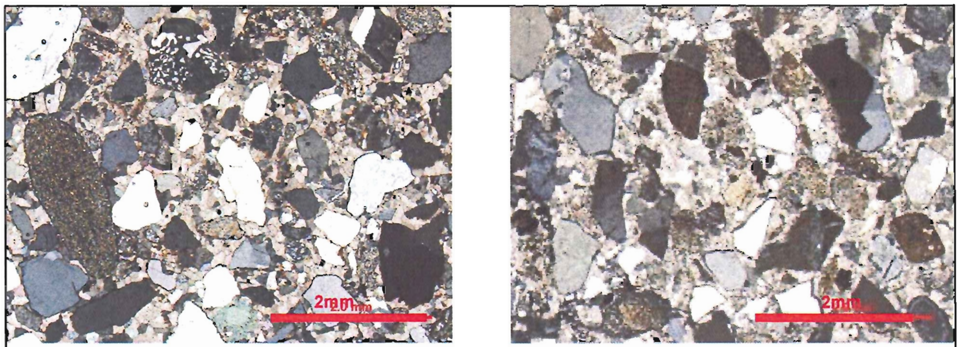
Many grains are surrounded with a narrow rim separating them from the surrounding cementing material and acting as microporosity paths (Fig.3.6).

3.4.3.4 Intragranular Microporosity

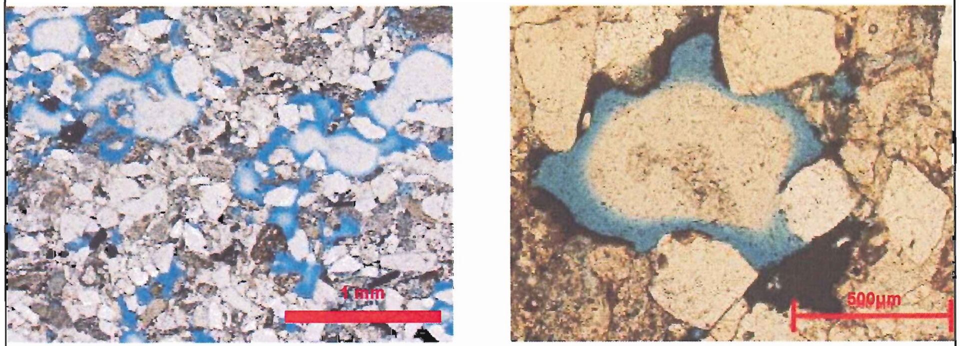
This type of porosity can be observed along the cleave planes and alteration paths within feldspars and also within the kaolinite stacked aggregates (Fig.3.6).

3.4.3.5 Intracement Microporosity

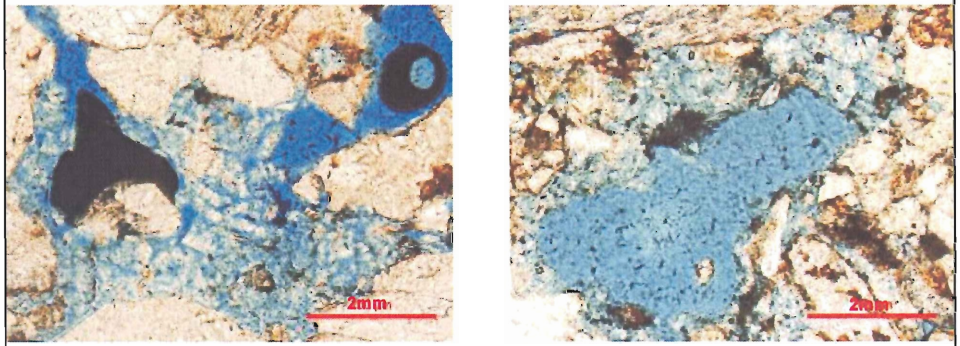
It mostly exists between the kaolinite clay which is acting as matrix and/or cement between the framework grains. These clays are showing stacked tiny crystal books which leave micropore spaces between them (Fig.3.6).



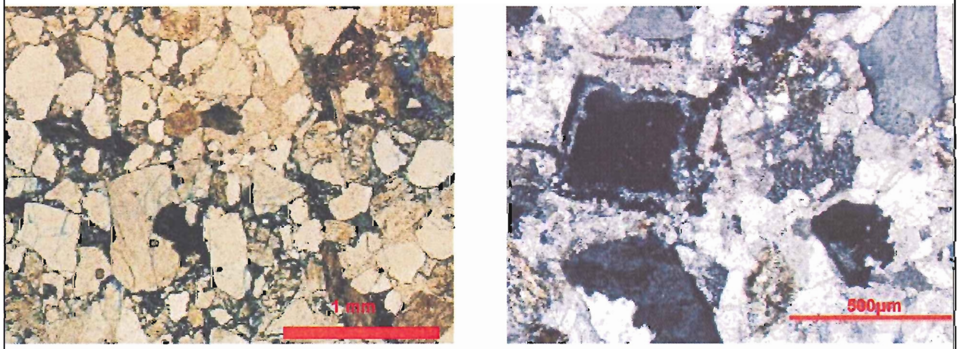
Well cemented with no porosity



1. PRIMARY POROSITY

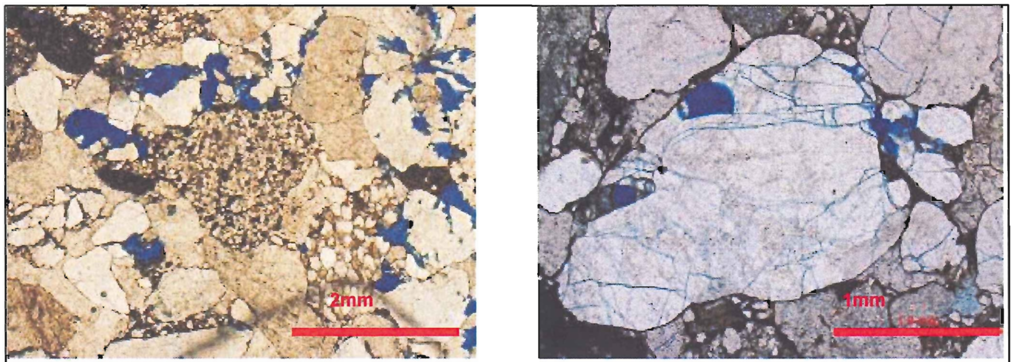


2. MIXED PRIMARY AND SECONDARY POROSITY

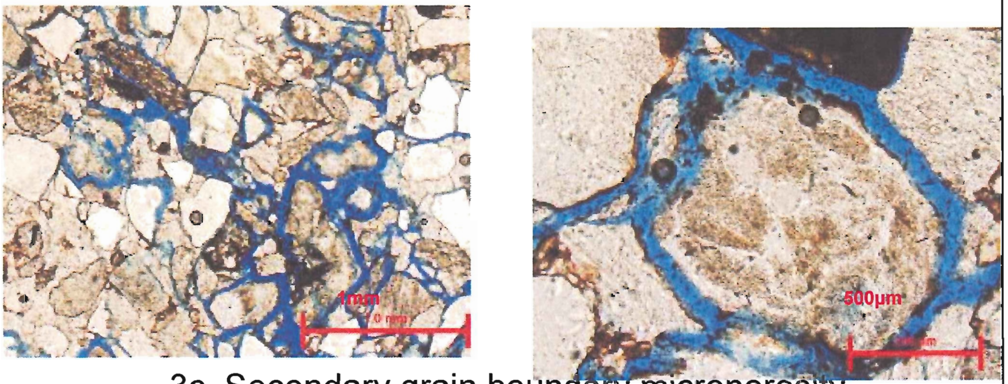


3a. Secondary dissolution microporosity

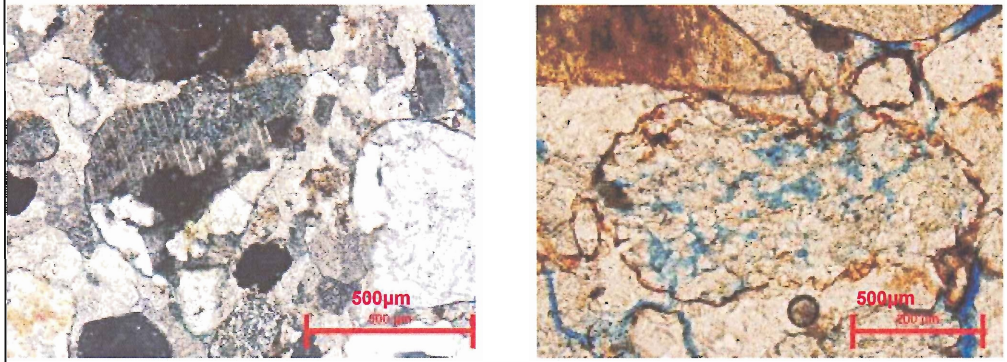
Fig.3.5. Photomicrographs of the types of porosity in Wolfville Formation sandstones.



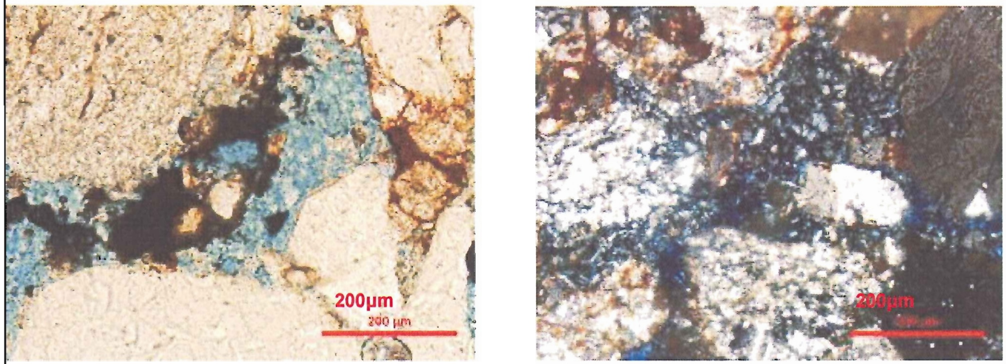
3b. Secondary microfracture microporosity



3c. Secondary grain boundary microporosity



3d. Secondary intragranular microporosity



3e. Secondary intracement microporosity

Fig.3.6. Photomicrographs of the types of porosity in Wolfville Formation sandstones.

3.5 Heavy Minerals and Provenance

I counted 1200 from the heavy minerals thin sections. Mange and Maurer (1992) was used in the identification of heavy minerals. Microscopic heavy mineral studies and point counting show that opaque minerals (Fe and Fe-Ti-oxides) are the predominant heavy minerals (75.9%), followed by garnet (mostly euhedral in shape) (13.6%), apatite (3.3%), zircon and tourmaline with negligible amounts of rutile (ZTR group) staurolite, hornblende as well as many chlorites, biotite and muscovite (Table 3.6 and Fig 3.7 and 3.8). The ultrastable ZTR group forms 2.8% of the heavy minerals. The abundance of iron oxides is mostly responsible for the red colouration of sandstones because of their oxidation to secondary iron minerals and stains. The opaques are mostly magnetite, hematite, ilmenite, and their alteration products such as goethite, limonite and leucoxene. The triangular diagrams of the major groups of these heavy minerals (Fig. 3.5) shows that all the samples are clustered together along the opaque-garnet side close to the opaque end indicating relatively low percentages of apatite and (ZTR). The apatite-garnet-ZTR group triangle again shows dominance of garnet relative to the others which have nearly the same concentration. Study of heavy minerals in one sample taken from the recent beach sands close to the samples taken from the Wolfville Formation outcrop (Table 3.6) showed the same group of minerals observed in the sandstones and nearly the same relative percentages, which indicates that the beach sand was derived from the nearby Triassic Wolfville Formation outcrops. However the only difference between the beach sands and the sandstones is that the beach sand contains pyroxene and epidote. The source of pyroxene and epidote is clearly from basalts because many basaltic rock grains exist in these recent sediments which are most probably derived from the North Mountain Basalt and some other basaltic intrusions and dykes exposed on both sides of the Bay of Fundy.

	Beach Sand	Triassic Wolfville Formation Sands											Average
Number	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**1 to 11**
Opaques	962	780	842	978	934	1013	1047	699	972	851	993	902	910
Garnet	131	176	137	59	142	141	97	313	109	278	180	185	165
Apatite	25	70	51	62	60	9	21	59	29	24	16	28	39
Zircon	4	13	11	43	45	2	15	4	12	22	6	12	17
Tourmaline	10	19	17	38	7	4	8	28	12	11	2	11	14
Rutile	1	1	0	2	0	0	0	0	1	2	0	1	1
Hornblende	2	0	0	0	0	0	0	0	2	1	1	0	0
Staurolite	2	0	0	0	2	0	2	2	1	3	0	1	1
Epidote	9	0	0	0	0	0	0	0	1	0	0	0	0
Pyroxene	21	0	0	0	0	0	0	0	0	0	0	0	0
Chlorite	24	107	75	14	7	27	10	89	55	5	0	36	39
Biotite	8	30	66	4	3	3	0	6	6	2	2	24	13
Muscovite	1	4	1	0	0	1	0	0	0	1	0	1	1
TOTAL	1200	100	1200	1200	1200	1200	100	1200	1200	1200	1200	1200	1200

Table 3.6: Heavy Minerals count in the heavy mineral fractions of the Wolfville Formation sandstones.
ZTR = zircon+tourmaline+rutile.

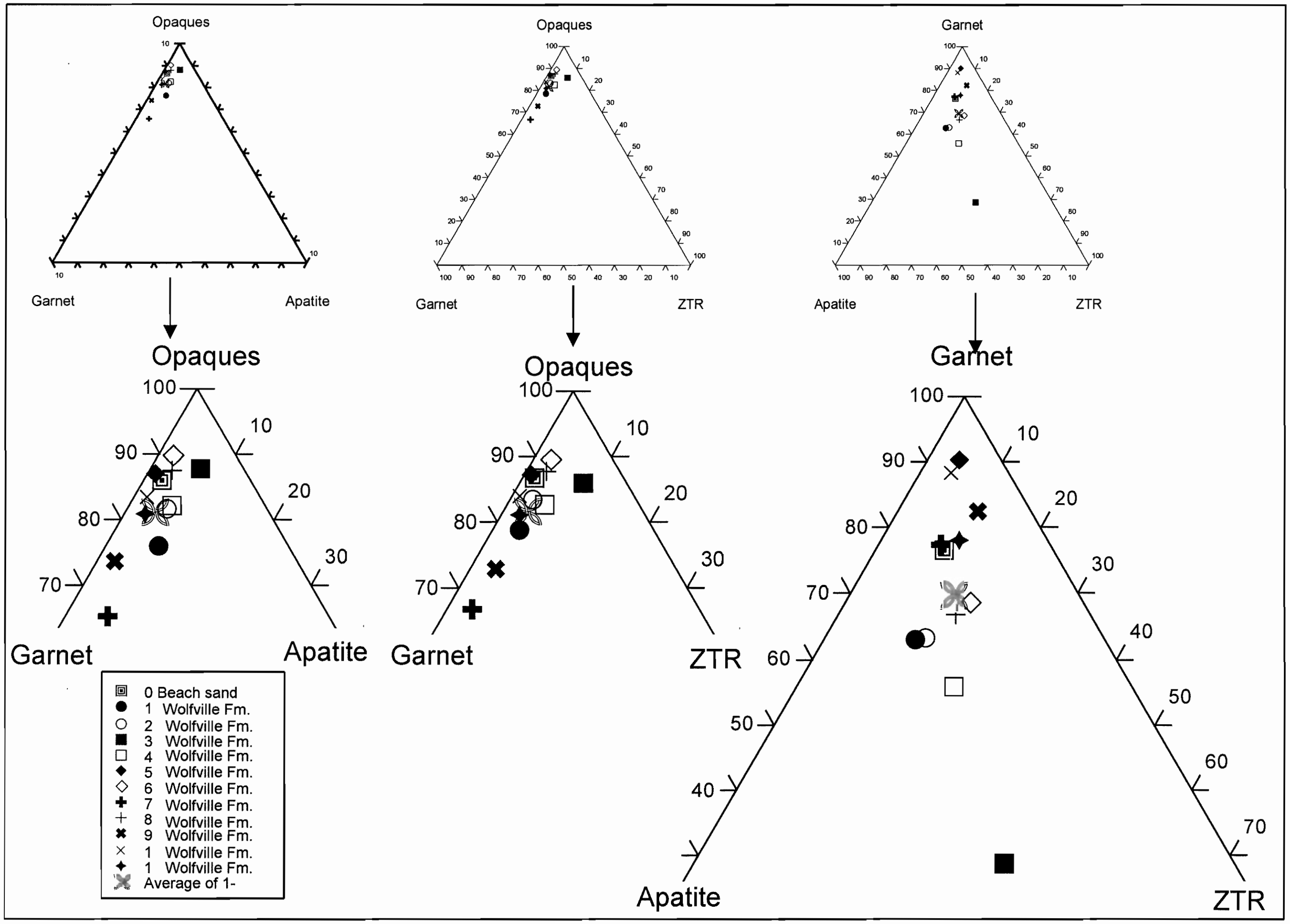


Fig.3.7: Heavy minerals distribution triangular diagrams in the sandstones of Wolfville Formation

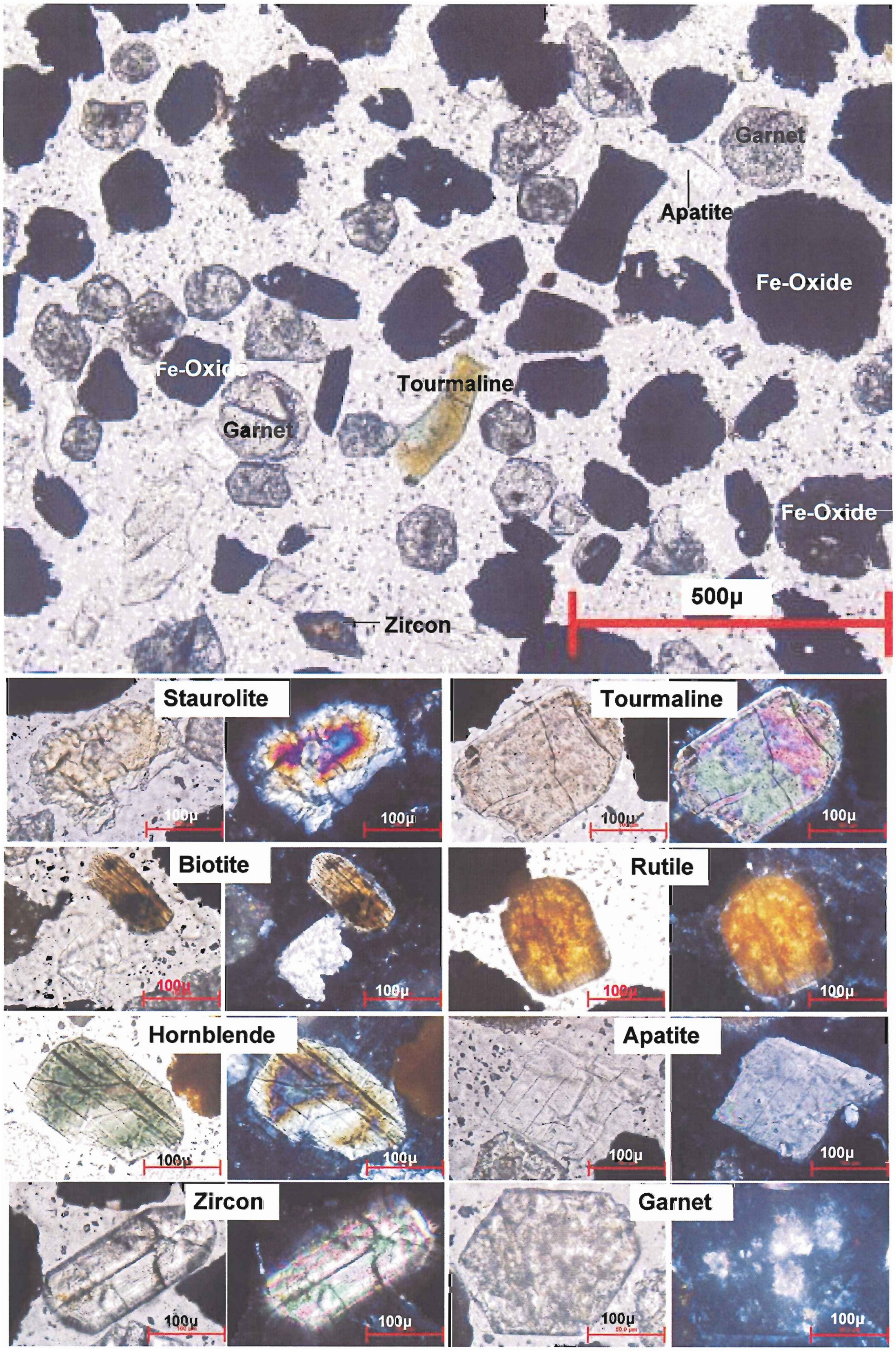


Fig. 3.8: Photomicrographs of common heavy minerals in the Wolfville Formation Sandstones.

3.6 Tectonic Settings and Provenance

The results of grain counts are given in Table 3.2 and 3.3. Two methods of counting were made on each thin section. In the first counting method, 1200 points were counted for all material in the slides including individual monominerals, rock fragments (lithics), as well as cementing material and pore spaces (Table 3.2 and Figs. 3.2 & 3.3). This counting followed the Gazzi-Dickinson method (Ingersoll and Suczek, 1979; Dickinson, 1985; Graham et al., 1976). According to this method single crystals coarser than 62.5µm were considered as mineral grains even if they exist as part of a rock fragment. For example, a quartz grain >62.5µm in diameter within a granite rock fragment was counted as quartz and added to the counts of free mono-quartz grains; feldspars are treated similarly, and so on. All rock fragments were counted including the detrital limestone which was not added to the other unstable rock fragments for the triangular plots because of their different geochemical characteristics and behavior during weathering and diagenesis (Dickinson, 1985). The method and terminology used for point counting and triangular diagrams are given in Table 3.4 based on the classifications of Ingersoll and Suczek (1979), Dickinson, (1985) and Graham et al. (1976). In the second counting, 1200 points were counted only for sand size rock fragments following the traditional method which considers all minerals within the rock fragment as lithics rather than individual minerals even if they are coarser than silt size as Gazzi-Dickinson method requires (Pettijohn, et al., 1972) (Table 3.3 and Fig. 3.9).

The petrography of sandstones is a good tool for determining the origin and tectonic setting of detrital rocks (Dickinson 1970 and 1985; Pettijohn et al; 1972; Zuffa, 1985). The results of the all grain counts (minerals and lithics) were plotted on triangular diagrams of Ingersoll and Suczek, (1979), Dickinson (1985) and Dickinson, et al. (1983) (Fig. 3.4). The results show that all the samples fall in the field of the Recycled Orogen Provenance in FQtL triangular diagram; or in Quartzose Recycled and Mixed fields in FQmL triangular diagram (Fig. 3.4). PQmK triangular diagram indicated that all samples fall within the field of increasing maturity or stability from Continental Block Provenances. The LvmQpLsm triangular diagram shows that all samples fall in the field of Collision Orogen Sources close to the Lsm corner which indicates that the sandstones contain metasediment rock fragments as dominant constituents with very few chert fragments and no metavolcanic lithics. The RsRgRm triangle (Fig.3.9) shows that all the samples fall near the middle of Rs-Rm line at the base of the triangle and relatively far from the Rg corner which means that the metasedimentary rocks were more abundant as the source rocks rather than the granitic sources. The relative abundance of rock fragments are in the order: slate-siltstone-granite-limestone-sandstone-quartzite-chert-schist-others (Fig.3.10). These diagrams indicate that the Triassic Wolfville sandstones were deposited from a Recycled Orogen Provenance suggesting that quartz, feldspars and metasedimentary grains were the dominant constituents which were derived from metasedimentary rock formation and magmatic granitic intrusions, with no contribution from any volcanic rocks. This means that there were no volcanic rocks in the source area during the deposition of the Triassic Wolfville Formation. The Wolfville Formation is underlain by many formations which are, from older to younger, Meguma Supergroup, Kentville, Torbrook, and South Mountain batholith, Horton Group, Windsor Group and Canso (Mabou) (Williams, et al., 1985) (Table 3.7). Comparison between the lithology of these formations with the grains found in Wolfville Formation suggests that these formations were the main source of Wolfville sediments.

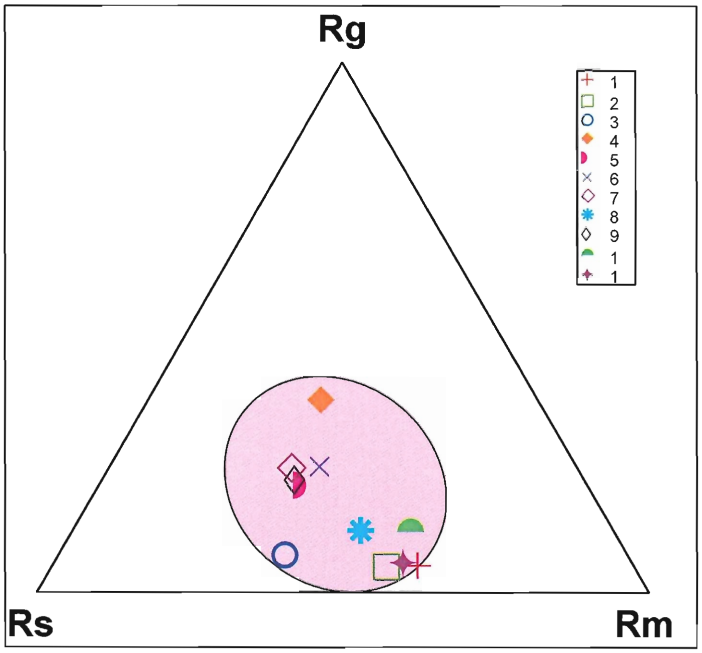
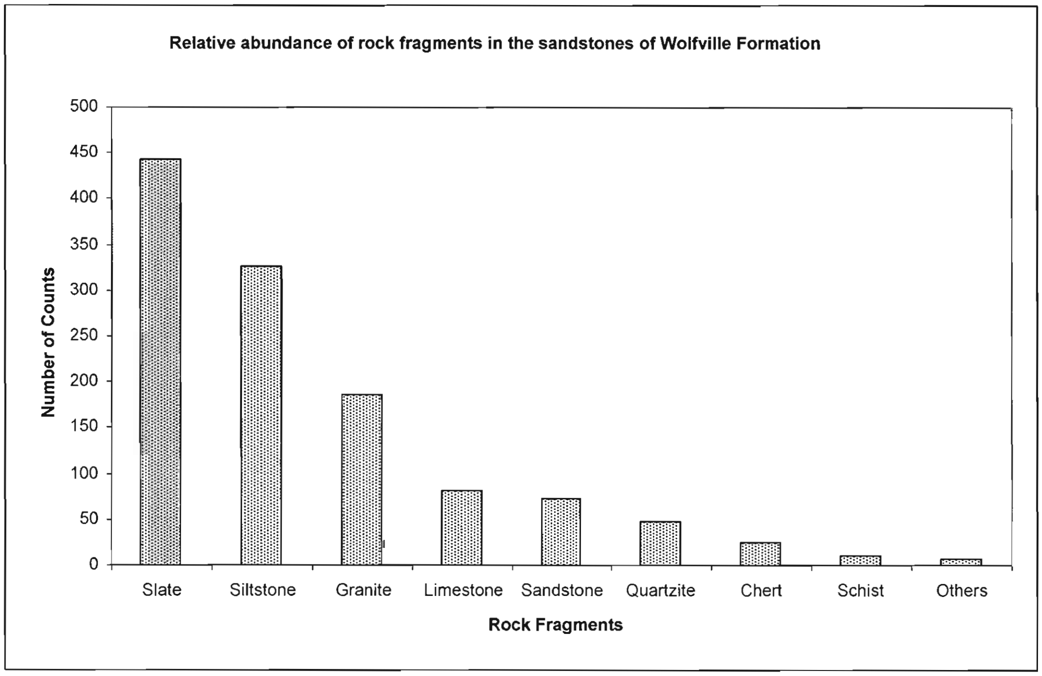


Fig. 3.9: Triangular diagram of the rock fragments counted according to the traditional method (Pettijohn et al; 1972). Rs, Rg and Rm are sedimentary, granitic and metamorphic rock fragments respectively.



	Slate	Siltstone	Granite	Limestone	Sandstone	Quartzite	Chert	Schist	Others	Total
%	37	27	15	7	6	4	2	1	1	100

Fig.3.10: Relative abundance of rock fragments in the sandstones of Wolfville Formation.

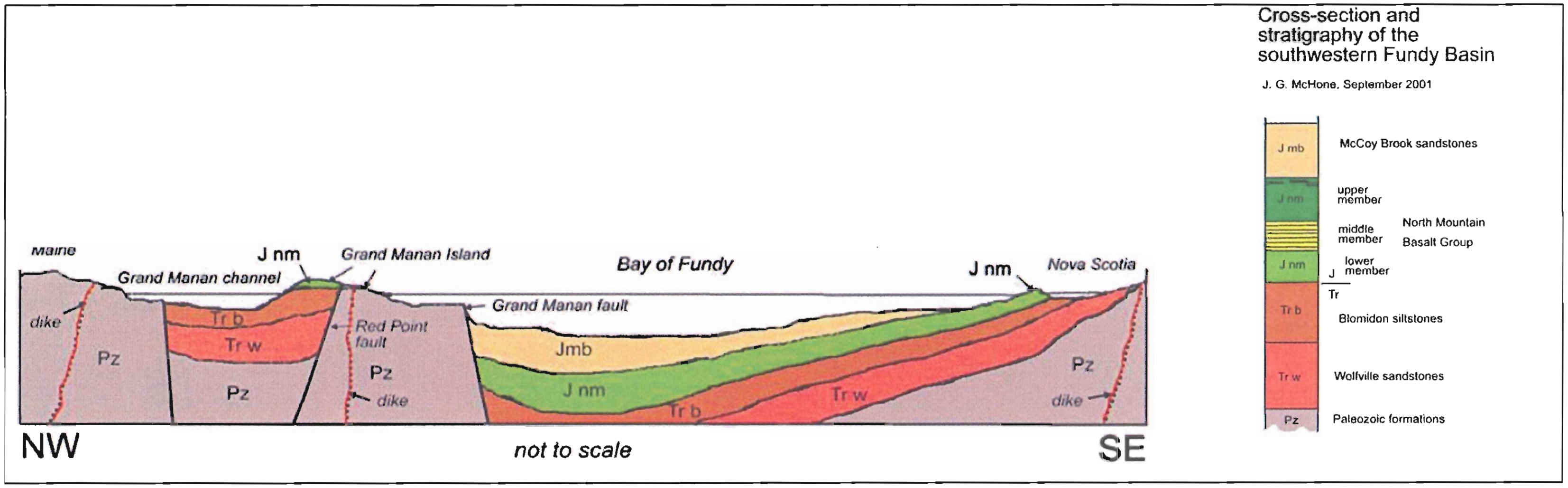


Fig.3.11: Cross section and stratigraphy of the southwestern Fundy Basin (McHone, 2001) showing the relation of Triassic Wolfville formation to the surrounding rock units and their extension underneath the Bay of Fundy.

Formation	**Age**	**Lithology**	**Environment of Deposition**
Wolfville	Late Triassic	Conglomerate, sandstone, siltstone, claystones	Alluvial, Fluvial , aeolian
Canso (Mabou)	Late Carboniferous	Shale, sandstone, thin limestone	Non-Marine
Windsor Group	Early Carboniferous	Limestone, evaporite, sandstone, marl, siltstone, claystone	marine
Horton Group	Early Carboniferous	Gray-black clastics: shale, sublitharenite-orthoquartzite, conglomerates	Fluvial-lacustrine
South Mountain Batholith	Late Devonian to Early Carboniferous	Granodiorite,Granites, monzonite, monzogranite, aplite pegmatite, porphyry, greisen	Magmatic
Torbrook	Early Devonian	Quartzite, shale, siltstone, minor shaly limestone, iron formation,	Marine, shelf and reduced stagnant basin
Kentville	Silurian	Slate, minor siltstone	Shallow marine
Meguma Supergroup	Cambrian to Ordovician	Halifax: Slate, siltstone, sandstone Goldenville: Metasandstone , slate	Marine

Table 3.7: List of the formations underlying the Wolfville Formation and their characteristics (from Williams, et al; 1985).

Chapter 4

INTERPRETATION AND CONCLUSIONS

The result of the grain size analysis, petrography and heavy mineral studies of Cambridge Cove sandstones concludes that:

1. The sandstones are feldspathic litharenite, poorly sorted, fine to strongly fine skewed, platykurtic to very platykurtic and medium in grain size.
2. These sandstones have been deposited fluvially by rivers.
3. They predominantly consist of quartz as well as considerable amounts of rock fragments and feldspars as detrital grains which were cemented by calcite and minor iron oxides and clays.
4. Iron oxides and garnets are the predominant heavy minerals in these sandstones as well as minor amounts of apatite, zircon and tourmaline and negligible amounts of others. These minerals are of low grade metamorphic and silicic (granitic) igneous rock provenances. Unstable minerals are very rare.
5. The porosity of the studied sandstones range between 1.70-16.58% with an average of 6%. They have both primary and secondary types of porosity. The Wolfville formation is overlaying the Carboniferous Horton Bluff formation which is made up of organic-rich shales, siltstones and sandstones. They both extend below the Bay of Fundy area at depth for considerable extent. With the availability of sealing rocks to Wolfville sandstones, the system could be attractive hydrocarbon target since the organic-rich shales of Horton Bluff formation can act as source rock and the Wolfville formation as reservoir rocks since they have the necessary porosity.
6. The Wolfville sediments were transported by rivers and deposited as channel fills and on flood plains. The detrital grains were buried, compacted and cemented by iron oxides, followed by carbonates which were recrystallized later to form sparry calcite cement filling the spaces between sand grains. Clay minerals of detrital origin as well as alteration products of feldspars have also partially filled some open spaces. Compaction of these sediments probably affected quartz grains and fractured them because they are more brittle than the other grains. Compaction and cementation has also affected the porosity of these rocks but still some of the

original pore spaces survived and some others were formed during diagenesis by partial alteration, fracturing and dissolution of some grains and cementing material.

7. The triangular diagrams of the grain counts indicated that these sandstones are of Recycled Orogenic Provenance. This means that they are derived from the Pre-Triassic Paleozoic rock units which were part of the Appalachian Mountains formed under collision tectonic settings. The geologic map of the area around the Bay of Fundy where the Wolfville Formation is located in both outcrops and subsurface shows that the most probable source rocks of the studied sandstones are the Meguma Supergroup, the South Mountain Batholith with possible contributions from the Carboniferous and Permian sedimentary and plutonic rocks exposed in New Brunswick to the north of the Bay Fundy area. The complete absence of any volcanic rock fragments among the studied sandstones grains; and also the absence of heavy minerals which could be of volcanic origin such as pyroxenes indicates either the absence of pre-Triassic volcanic body exposures in the area, or that the contribution of rock units in New Brunswick which contain Devonian and Silurian volcanic rocks was very limited. The Recent beach sediments contain the same heavy mineral suites and with nearly the same proportions as the nearby Wolfville Formation, the source for the heavy minerals but they also contain basalt rock fragments and considerable amount of heavy minerals which has basaltic origin such as pyroxene and epidote; this means that volcanic outcrops of North Mountain Basalt are the source of these basaltic rock fragments and the pyroxene. The Wolfville sandstones and conglomerates contain quartz, various feldspars (alkali and plagioclase) and rock fragments (slate/schist, siltstone/sandstone, granitoids, quartzite, limestone, and chert (Table 3.3). The Wolfville Formation is underlain by formations ranging in age between Cambrian to Carboniferous (Table 3.7). These formations contain all lithologies which exist in Wolfville Formation which suggest that they are the dominant source of the studied sandstones and conglomerates of Wolfville Formation. The Meguma Group is possibly the dominant source of the clastic metasediments (slate, schist, siltstone, sandstone, and quartzite). The South Mountain Batholith is the source of

granitoids, and the Windsor Group is a possible source of limestone. The other formations are also the possible source of some of these deposits because there is more than one type of each rock grain. The rocks of the New Brunswick and Appalachian Mountains might have very little role as the source of the Wolfville Formation. Based on the little evidence of volcanics the Meguma Supergroup and the South Mountain Batholith are possibly the major source of the studied sandstones. This is because of the similarity of the rock fragments (slates some of which are garnetiferous, siltstones, quarzites, and micrographic granites) and the heavy minerals (iron oxide, garnet, apatite and ultrastable minerals – zircon, tourmaline-rutile, as well as few staurolites, hornblende, and micas) to the main lithology of these two major rock units which are widely exposed in Nova Scotia. The abundant garnet as the major heavy mineral among the non-opaque rock group is particularly important indicator for the provenance because most of them are euhedral in shape and possibly of sperssartine type (Mn-rich), and many of the slate rock fragment also contain abundant garnet crystals similar to the garnet rich Meguma slates.

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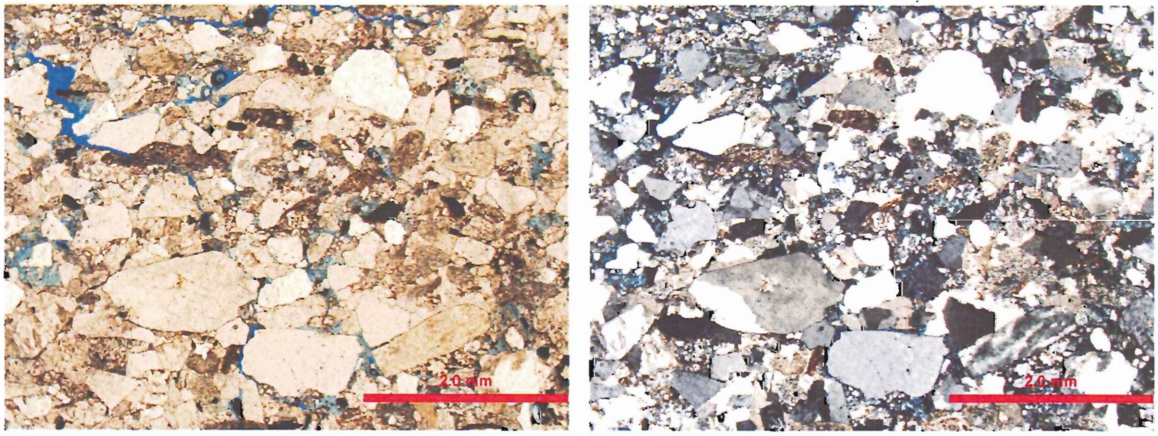
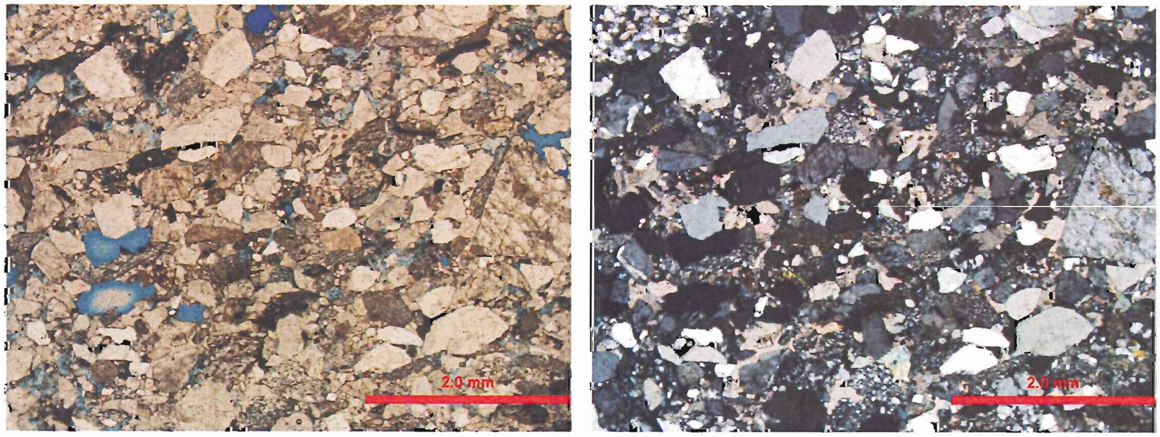
APPENDIX
Petrography of Wolfville Formation sandstones.

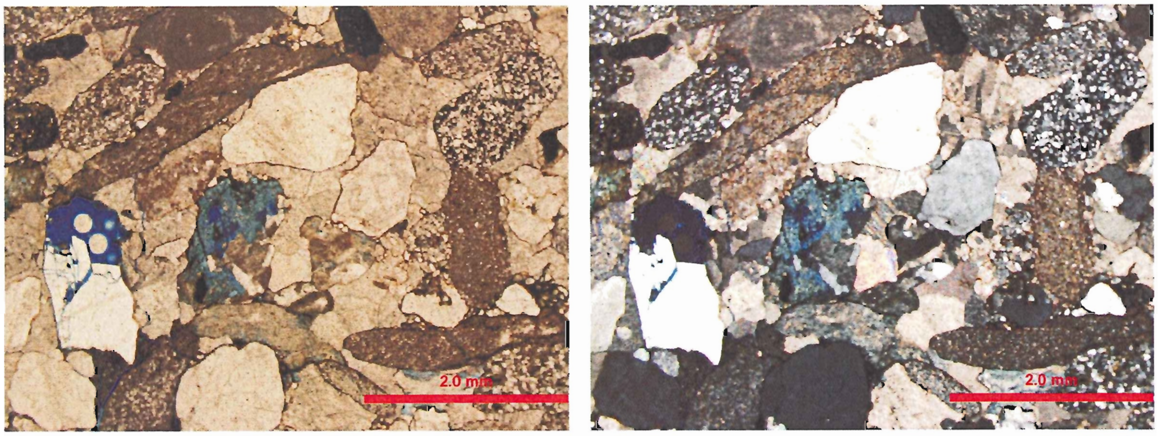
No.1: Sandstone: Coarse grained (0.5 mm), subangular to subrounded, calcite cement-supported. It consist of quartz of variable sizes, feldspar (perthite, plagioclase and orthoclase), lithics (slate, siltstone, granite, limestone and quartzite), mica (fe muscovite, biotite and chlorite) and heavy minerals (opaque and euhedral garnet)



No.2: Sandstone: Coarse grained (0.4 mm), calcite-cement supported framework of subangular to subrounded shape. It consist of quartz, feldspar (perthite, plagioclase and orthoclase), lithics (slate, siltstone, iron-cemented siltstone, granite, limestone and quartzite), mica (muscovite and biotite) and heavy minerals (opaque and brown tourmaline).

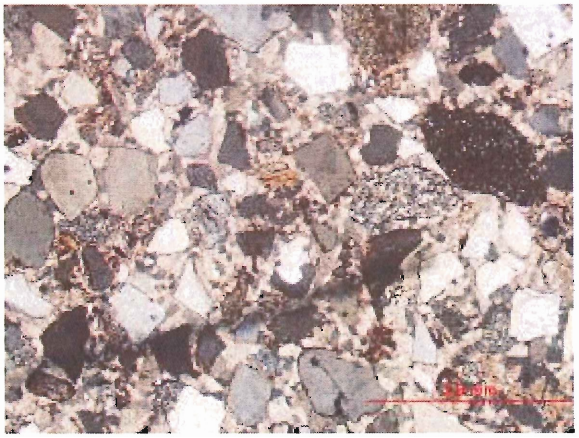


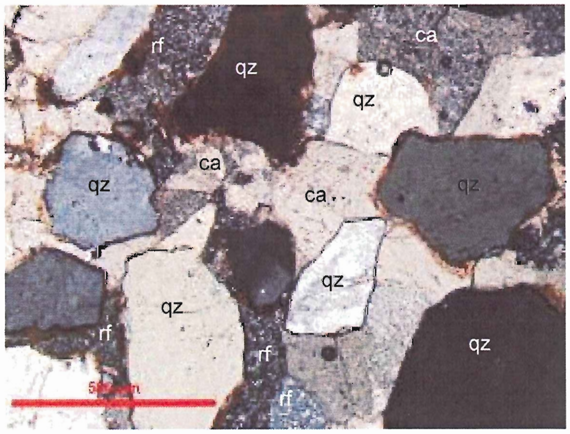
No. 3: Sandstone: Calcite cement-supported, coarse grained (1.2 mm) sandstone with subangular to subrounded grains and very rich in siltstone and slate lithics. It consist of highly fractured quartz, feldspar (perthite and orthoclase), rock fragments (mostly siltstone and slate, and less quartzite, limestone, and minor granite), rare mica (biotite and muscovite) and heavy minerals (opaques and rounded tourmaline).



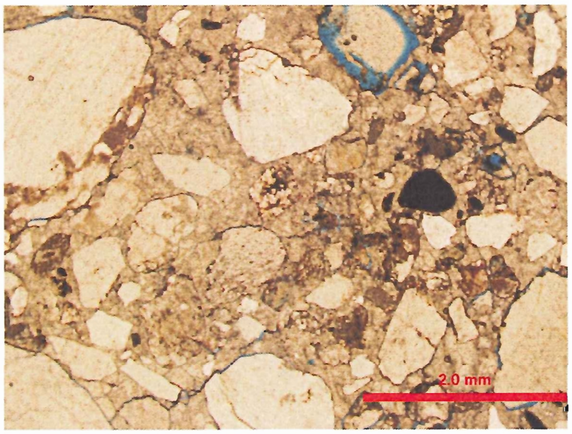
No.4: Sandstone:

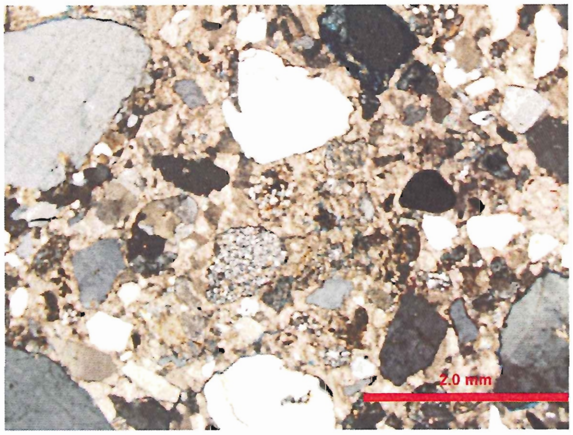
The rock consists of quartz, rock fragments, feldspars and minor amounts of mica and few heavy minerals; all of which are cemented by sparry calcite and minor amounts of iron oxide and chert. The ratio of framework to cement is nearly 1:1. The grains range in size from <0.2-2mm in dimension and have shapes ranging angular to rounded depending on their lithology. They are separated by sparry calcite cement. The grains are angular to sub-rounded in shape. The rock fragments are the next dominant type of grains (~40%) ranging in size from <0.2-2mm and have shapes ranging from sub-angular to rounded. They are slate, granites, quartzite, and chert. Feldspars exist as perthite, orthoclase and plagioclase. Few heavy minerals exist as scattered grains; they are iron oxides, tourmaline, garnet, zircon, muscovite and biotite. The iron oxides are mostly responsible for the ferruginous cementation and staining of these sandstones. Calcite form about ~50% of the rock and separate framework grains from each other as cement. as well as minor amounts of iron oxide and chert. Most of the feldspars have suffered various degrees of alterations such as sercitization, kaolinazation, and calcitization.





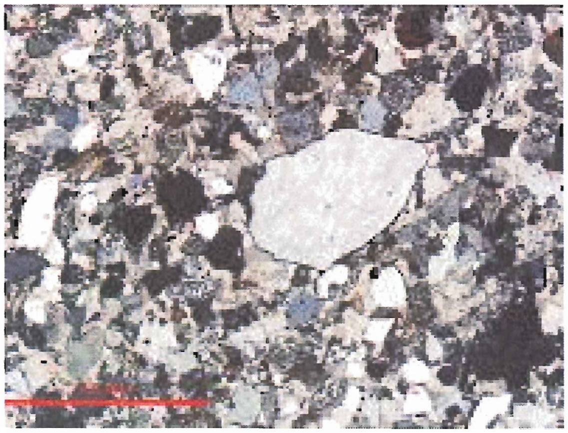
No. 5: Sandstone: Coarse grained (0.5 mm), calcite cement-supported, subangular to subrounded rock. It consist of quartz (few are fractured), feldspar (perthite, plagioclase and orthoclase), lithics (rich in many types of quartzite and limestone and less siltstone, slate, and granite), mica (muscovit and biotite) and heavy minerals (opaque).

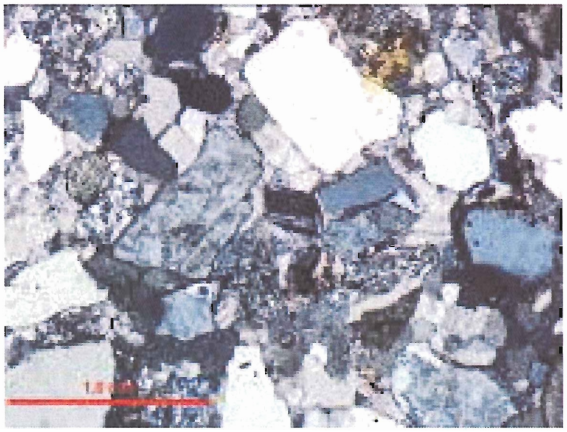




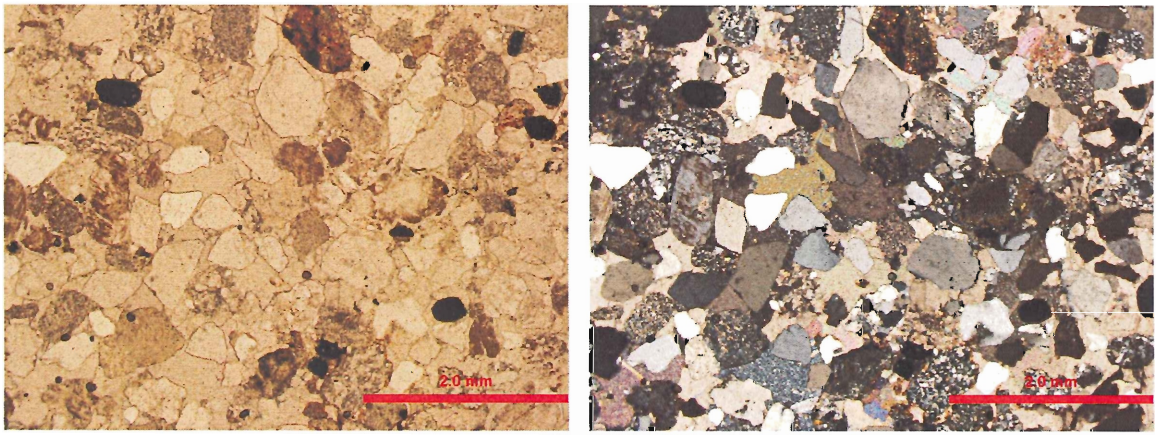
No. 6: Sandstone

The rock consist of framework (quartz, rock fragments, feldspar and others such as heavy minerals) cemented by sparry calcite minor amounts of chert, iron oxide. The ratio of frame to cement is ~40-45 to 60-55%. The cementing material separates the framework grains from each other and surrounds almost all grains. Porosity 2-3%. The grains range in size between <0.1mm-1cm with average size of 0.5-1mm and has bimodal. The shape of the grains range from angular to rounded but the majority are sub-angular to sub-rounded in shape depending on the composition of the grains for example most of the quartz are sub-angular to sub-rounded, the majority of rock fragments are sub-rounded to rounded in shape while most of the feldspars are rectangular in outlines. The framework consist of quartz (~45%), rock fragments (~40%) and feldspars (~15%) as well as minor amounts of heavy minerals.The lithics are slate, schist, siltstone, granites, quartzite, chert and carbonates. Feldsaprs are common constituents of the framework either individually or within the rock fragments. They usually have rectangular elongate shapes with sharps angles or less commonly with rounded outlines. They are k-feldspars perthite and orthoclase) or plagioclase. Most of them show slight kaolinization, calcitization and or sercitization. Many heavy minerals exist as individual free grains or associated with other rock fragments; they are garnet, tourmaline, zircon, biotite, muscovite and chlorite. Calcite is the main cementing material as well as minor amounts of iron oxides, chert and clays.

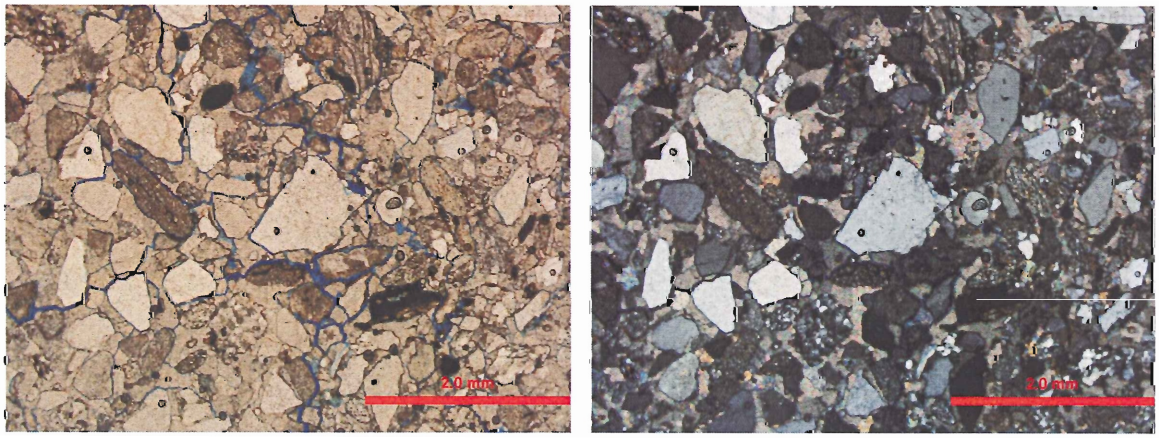




No.7: Sandstone: Coarse grained (0.4-0.5 mm), calcite cement-supported, subangular to subrounded sandstone. It consist of quartz (few are fractured), feldspar (perthite, plagioclase and orthoclase), lithics (siltstone, slate, quartzite, granite and limestone), mica (rare muscovite) and heavy minerals (opaque and two types of garnet: clear, pink, anhedral garnet and euhedral cloudy garnet).

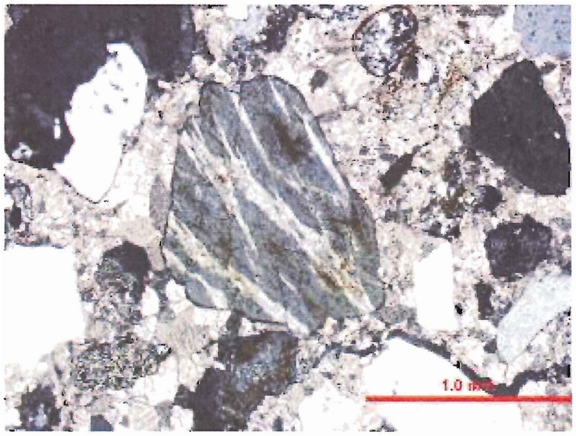


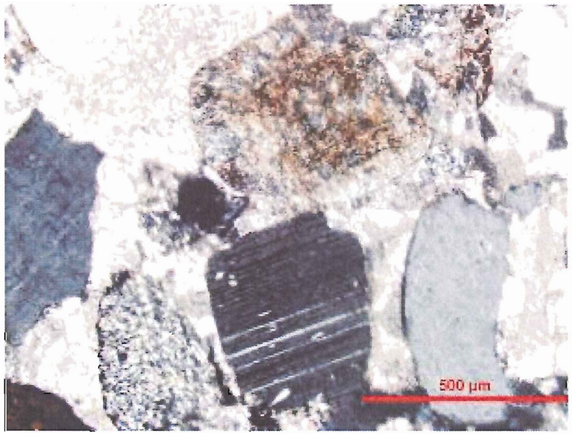
No.8: Pebbly sandstone: Pebbles and sand grains (0.4 mm) of subangular to subrounded shape cemented by sparry calcite. Very rich in rock fragments dominated by slate and siltstone. It consist of quartz (some of them are fractured), feldspar (perthite, orthoclase and plagioclase), lithics (mostly slate and siltstone, and less sandstone, quartzite, granite and limestone), mica (biotite) and heavy minerals (opaques and brown tourmaline)



No.9: Sandstone

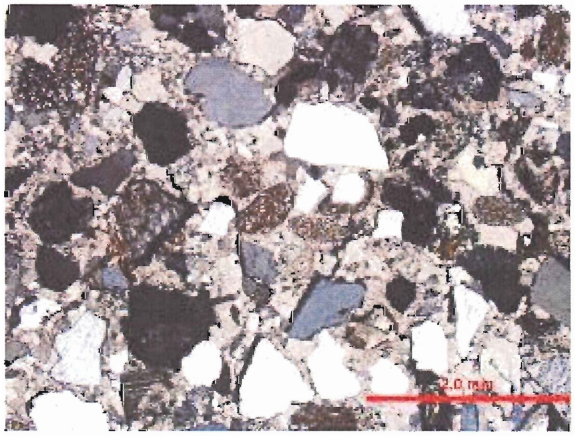
The rock consist of framework (quartz, rock fragments, feldspar and others such as heavy minerals) cemented by sparry calcite minor amounts of chert, iron oxide. The ratio of framework to cement is ~45-50 to 55-50%. The cementing material separates the framework grains from each other and surrounds almost all grains.The grains range in size between <0.1mm-1cm with average size of 0.1-2mm and ~1mm in average, it is bimodal. The shape of the grains range from angular to rounded but the majority are sub-angular to sub-rounded in shape_The framework consists of quartz (~45%), rock fragments (~35%) and feldspars (~20%) as well as minor amounts of heavy minerals. Quartz is the dominant mineral and has different shapes and sizes. Many different types of rock fragments ranging from slates, schist, siltstone, granites, quartzite, chert and carbonates. Feldsaprs are common constituents of the framework either individually or within the rock fragments, they usually have rectangular elongate shapes with sharps angles or less commonly with rounded outlines. They are k-feldspars perthite and orthoclase) or plagioclase. Most of them show slight kaolinization, calcitization and or sercitization. Many heavy minerals exist as individual free grains or associated with other rock fragments. They are garnet, tourmaline, zircon, biotite, muscovite and chlorite. Calcite is the dominant cement as well as minor iron oxides, chaer and clays.

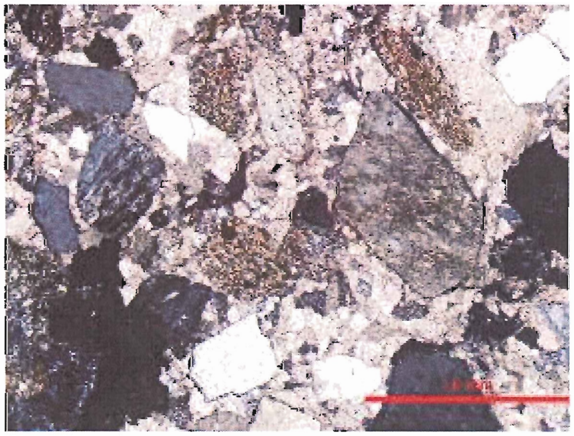




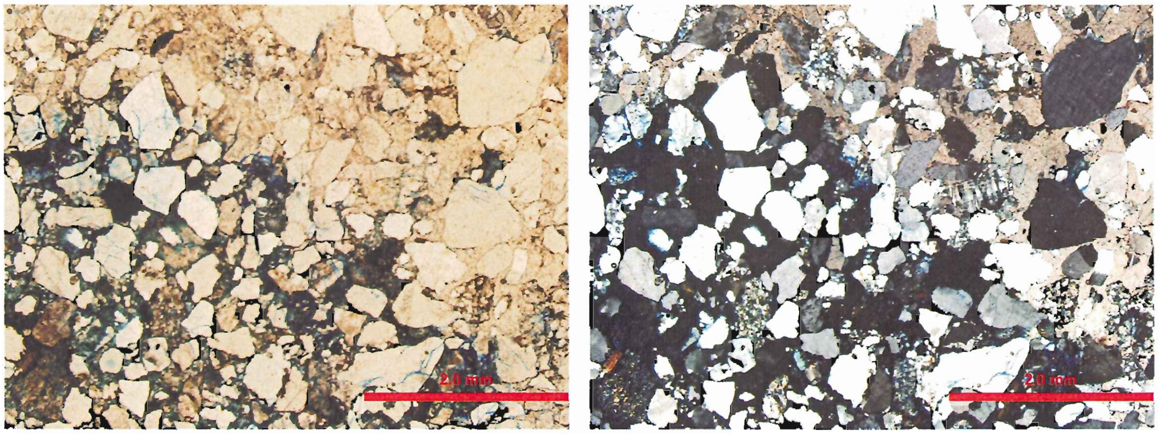
No.10: Sandstone

The rock consist of framework (quartz, rock fragments, feldspar and others such as heavy minerals) cemented by sparry calcite minor amounts of chert, iron oxide. The ratio of framework to cement is ~45-50 to 55-50%. The cementing material separates the framework grains from each other and surrounds almost all grains. The grains range in size between <0.1mm-1cm with average size of 0.1-2mm and ~1mm in average, it is bimodal. The shape of the grains range from angular to rounded but the majority are sub-angular to sub-rounded in shape The framework consists of quartz (~45%), rock fragments (~35%) and feldspars (~20%) as well as minor amounts of heavy minerals.Quartz is the dominant mineral and has different shapes and sizes. Rock fragments are slates, schist, siltstone, granites, quartzite, chert and carbonates. Feldsaprs are common constituents of the framework either individually or within the rock fragments; they usually have rectangular elongate shapes with sharps angles or less commonly with rounded outlines. The feldspars are perthite, orthoclase and plagioclase, and most of them show slight kaolinization, calcitization and or sercitization. Many heavy minerals exist as individual free grains or associated with other rock fragments; they are garnet, tourmaline, zircon, biotite, muscovite and chlorite. Calcite is the main cement and separate grains; minor iron oxides and clays also exist.





No.11: Sandstone: Coarse grained (0.6 mm in average), highly porous because of dissolutions of calcite cement. Calcite cemented supported and consist of quartz, feldspars (mostly microcline, perthite, orthoclaseand very few plagioclase), and lithics (granite, quartzite, siltstone, slate and schist), mica (muscovite and biotite) and heavy minerals (opaque and brown tourmaline). The rock is very rich in alkali feldspars and granitic in composition



The boundary between Horton Bluff & Wolfville Formations: There is very sharp angular unconformity between the two formations which is microscopically characterized by a thin layer of recrystallized dolomitic carbonates from which carbonate veinlets spread into the siltstones of the Horton Bluff Formation. The siltstones of Horton Bluff Formation are homogeneous in grain size (0.04 mm in average), very compact and well cemented by carbonates and also shows microlaminations with muscovite (sericite) long flakes marking their orientation; they also contain iron-stained spots and it is non-porous. The sandstones of Wolfville Formation are calcite cement supported and consist of quartz, feldspars and rock fragments as well as minor amounts of mica and heavy minerals.