

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

Yawooz Kettanah

Muhammad Kettanah

Grant D. Wach

Department of Earth Sciences

Dalhousie University

Halifax, NS, B3H 4J1

Canada

e-mail: kettanah@dal.ca

ABSTRACT

The reservoir characterization and provenance of the Wolfville formation sandstones are investigated using petrography, heavy minerals and microprobe analysis of tourmaline and garnet. These fluvial sandstones are calcite cemented feldspathic litharenites to lithic feldsarenites and consist of quartz, lithics, feldspars, minor amounts of mica and heavy minerals. They are derived from metasedimentary and granitic rocks of Meguma terrane during early stages of rifting along the Minas sub-basin as part of the Fundy Basin rift zone postdating the earlier Paleozoic collision orogenies which were culminated by the Appalachian orogeny. Their heavy minerals are mostly iron oxides (magnetite, hematite, ilmenite and their alteration products) and garnet with minor amounts of apatite, chlorite, zircon, tourmaline, biotite and lesser amounts of rutile, staurolite, hornblende, and rarely epidote. They have a recycled orogenic provenance and the main source of these sediments are the Paleozoic rocks underlying the Wolfville Formation dominated by the Meguma supergroup, the South Mountain batholith, Horton and Windsor groups with a possible minor contribution from other Paleozoic formations. The lowermost part of the Wolfville Formation has relatively low porosity (~6%). The Wolfville formation has a considerable thickness beneath the Bay of Fundy where it overlies the Horton Bluff formation, Meguma and/or Avalon terranes which should be investigated further to determine the reservoir potentiality especially where it overlies the organic rich shales of the Horton Bluff formation, as a source rock.

Geology

The Bay of Fundy is an important part of the geological history of eastern Canada formed during early rifting of Pangaea in the early Mesozoic time along a wide valley in the direction of 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 margins of the Minas sub-basin, part of the northeastern Bay of Fundy (Fig.1). The exposed Mesozoic strata are relatively limited in comparison to their wide extent beneath the Bay of Fundy. Petroleum companies became interested in synrift sediments and explored in the Bay of Fundy during 1968-1983. Seismic surveys were conducted and two exploration wells were drilled in the southwestern part of the Bay of Fundy (Fig.2) (Wade *et al.* 1996).

The Bay of Fundy 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 or terranes". These terranes are from south to north: Meguma, Avalon, Miramichi (Gander), Dunnage and Humber. The Meguma terrane forms the southern part of Nova Scotia and the adjacent continental shelf; it comprises thick turbiditic sediments of the Cambrian-Ordovician Meguma

supergroup, Silurian metasediments and volcanics of White Rock, Kentville and New Canaan formations, and the 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 (Late Devonian) has intruded the older formations (Fig.1). The Avalon terrane 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 by Carboniferous formations in the northeastern parts of the Bay of Fundy and by Meguma and/or Avalon terrane rocks towards the southwestern part as indicated from the seismic profiles and sections studied by Wade *et al.* (1996) (Fig.2).

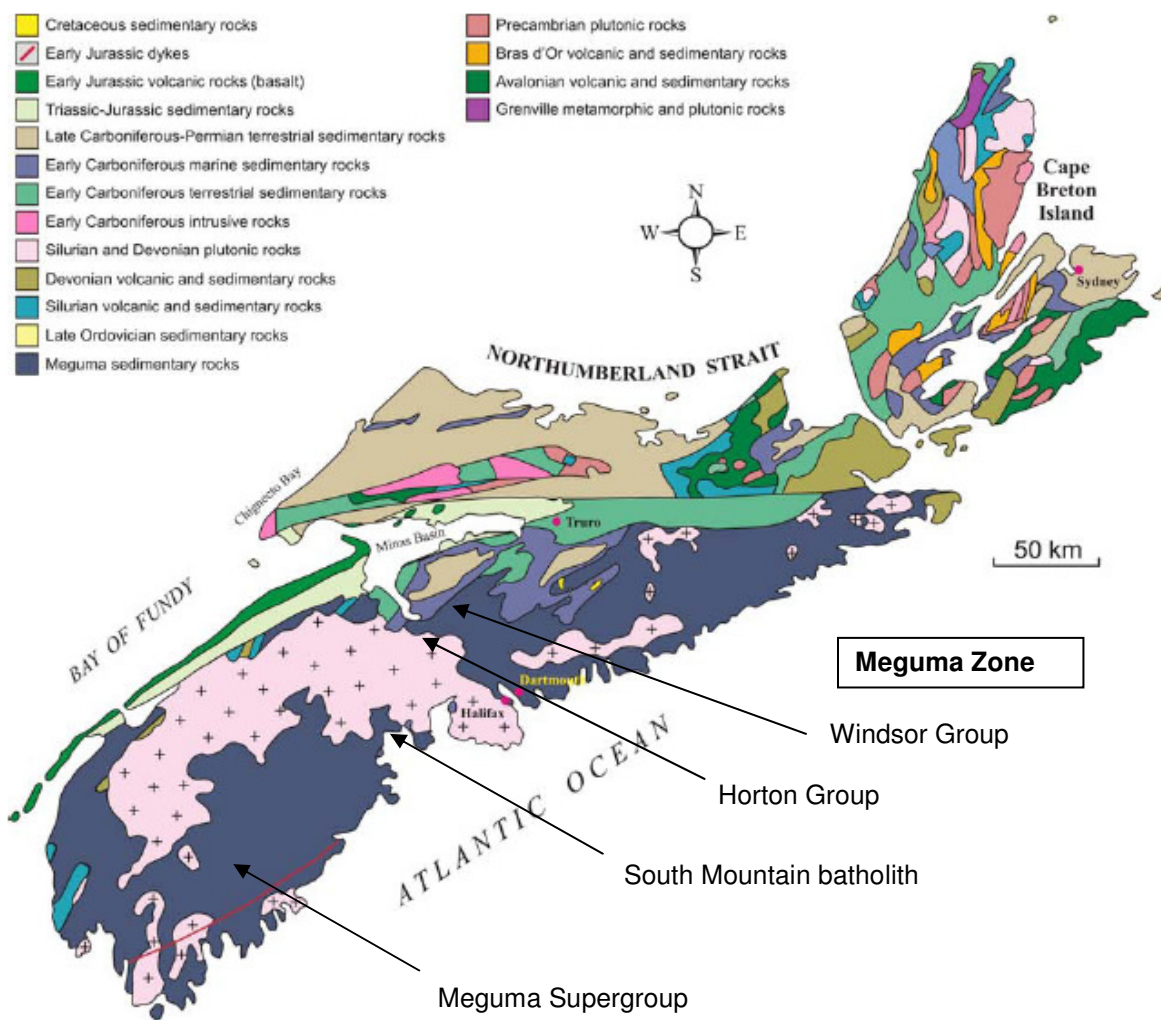


Fig. 1: Geology of Nova Scotia (Fensome and Williams 2001) showing the location of Cambridge Cove.

The Horton group in the Minas Basin covers a large area and rests unconformably on lower Paleozoic rocks of the Meguma Supergroup and is conformably to unconformably overlain by Windsor group of Early Carboniferous age (Fig.1). The Mesozoic formations underlying the Fundy sub-basin (Fundy Group) in these sections are from older to younger: Wolfville, Blomidon, North Mountain Basalt, and Scots Bay/McCoy Brook (Fig.2). The Wolfville formation (Fig.1) is exposed on both coasts of the Minas subbasin and Cobequid Bay and also in the Annapolis Valley (Keppie 1979). It unconformably overlies Carboniferous and older Paleozoic sedimentary/metasedimentary rocks (sandstones, conglomerate and minor siltstones and shale) or granitoids of the South Mountain batholith. 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 color of these sediments indicates that they were deposited in an oxidizing subaerial environment.

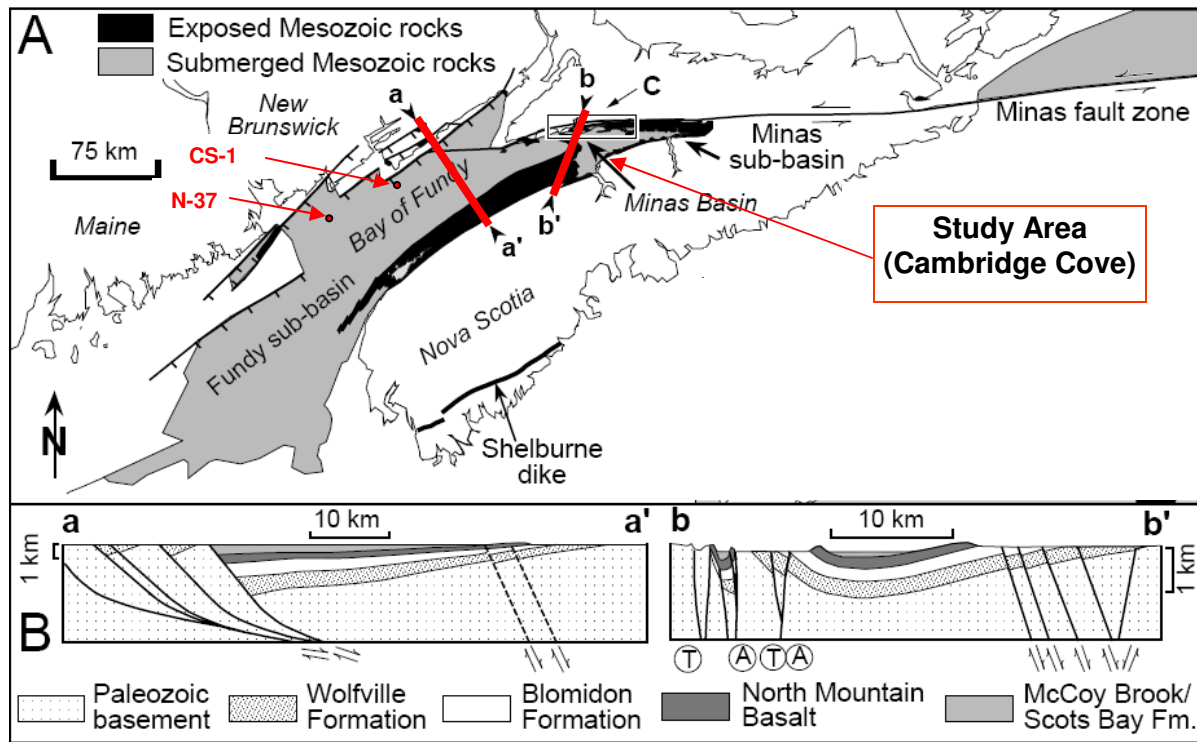


Fig. 2: Map of Fundy basin and a cross section through the Minas Basin showing the stratigraphy of Mesozoic formations beneath the basin and onshore (from Olsen and Schliche 1990). N-37 = Chinampas N-37 well; CS-1 = Cape Spencer No.1 well.

The Wolfville formation has been studied by many authors since 1828 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, the oldest formation in the Fundy Group, varies in outcrop from 60m to 833m (Williams *et al.* 1985). It is exposed on both sides of Minas subbasin. The thickness of the Wolfville Formation beneath the Bay of Fundy increases toward the southwest from 1308m in the Irving Cape Spencer-No.1 well to >1718m in the Chinampas N-37 well, and is believed to increase to >3000 m east of Grand Manan Island (Wade *et al.* 1996). 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 (Fig.3), and the nearby Rainy and Clemment coves.

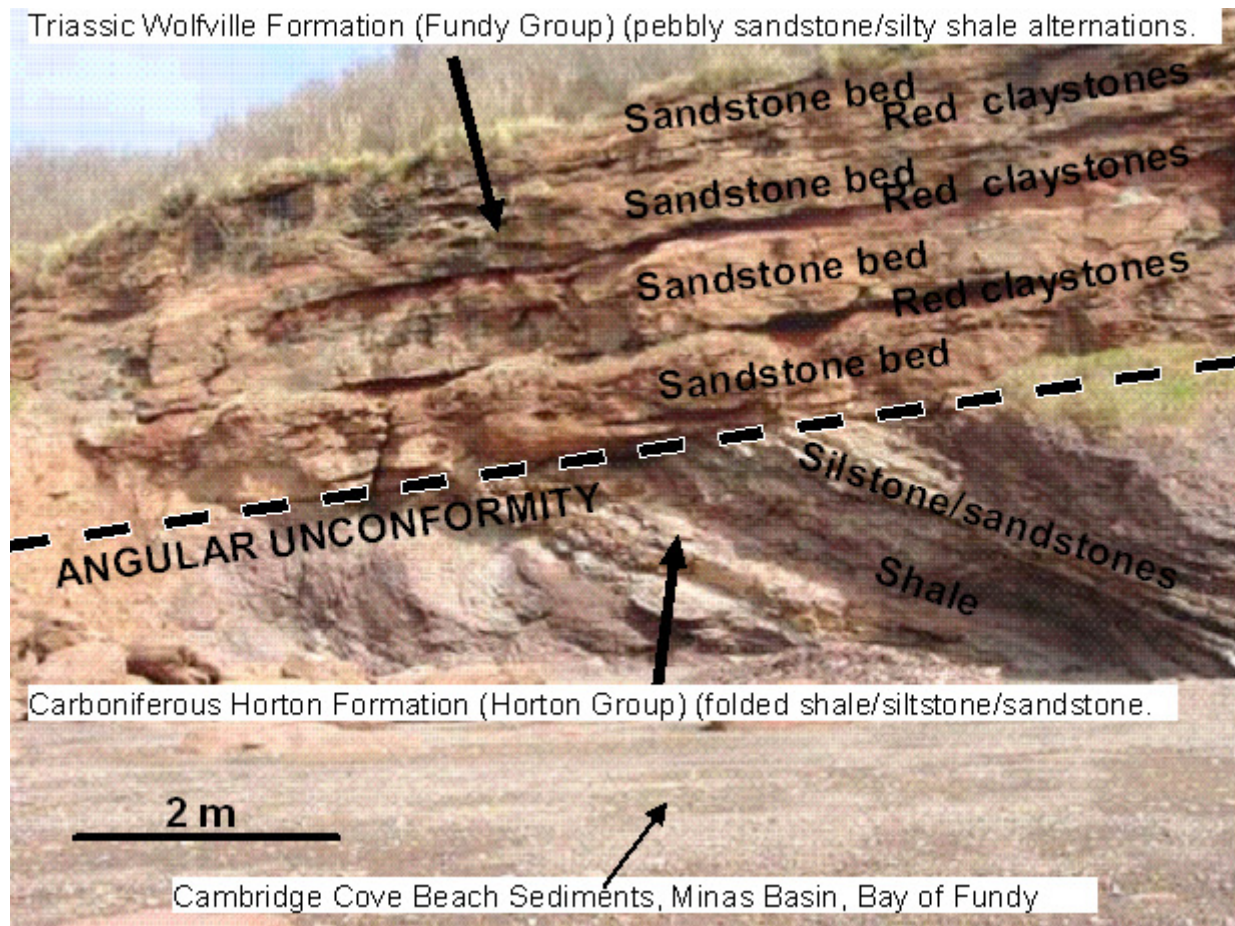


Figure 3. Field view of the unconformity between the Triassic Wolfville formation and the Late Devonian-Early Mississippian Horton Bluff formation at Cambridge Cove, Minas Basin, Bay of Fundy.

The Early Carboniferous Horton Bluff formation has a thickness of 325m and is disconformably overlain by the Cheverie formation and together they 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). 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 sublitharenitic 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.3). The siltstones are homogeneous in grain size and the quartz grains are cemented by calcite. Two wells (Kennetcook #1 and #2) were drilled in 2007 in the Windsor Basin of Nova Scotia investigating hydrocarbon potential of the Horton Bluff formation shales (The Oil & Gas Magazine Online, June 24, 2008). Related news release in January 30, 2008 announced the discovery of substantial amounts of gas with an estimated resource of 89 to 109 Bcf of OGIP per square mile (<http://www.wallstreet-online.de/diskussion/1137920-neustebeitraege/news-news-triangle-pet>). According to this news release, the total gas content of the shales range from 7.9 to 190 ft³/ton with an average TOC of 10% for all shales containing organic matter of type II/III to III which have a maturity of 1.53% to 2.07% placing them within the peak window for natural gas generation.

Petrography and Diagenesis

Eleven sandstone samples from the thickest part of the Wolfville formation at Cambridge Cove were studied. The samples were chosen to represent the dominant thick sandstone/conglomerates beds which have average thicknesses of 2 to 4 m. These beds are channel fills and some times become thinner as shown in Fig.3; they are separated by thin silty claystones. Sieving results showed they are mostly medium grained, poorly sorted, fine skewed and platykurtic.

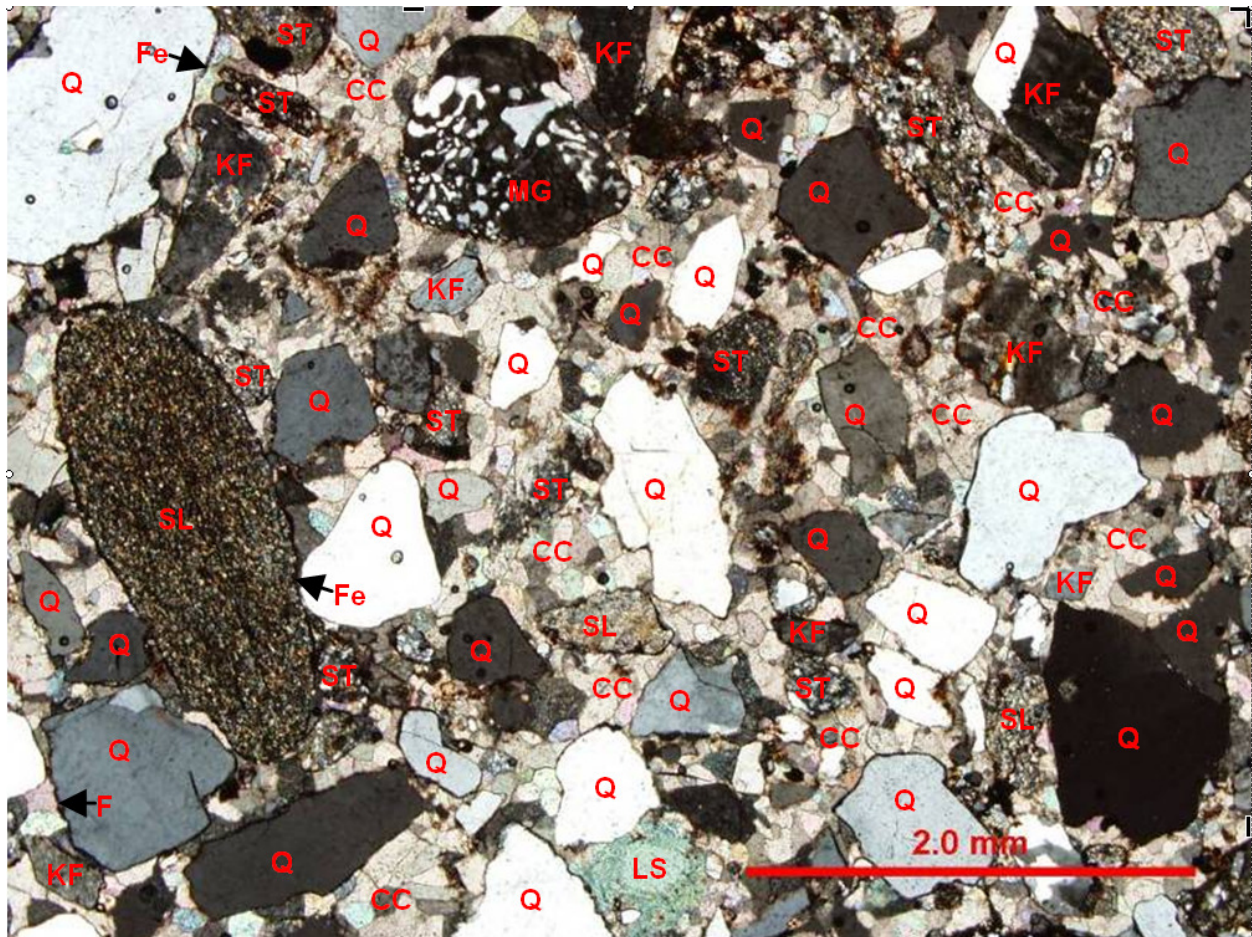


Fig.4: Calcite cemented sandstones of Wolfville Formation showing the main constituents. [Q=quartz; KF=K-feldspar; SL=slate; ST=siltstone; LS=limestone; MG=micrographic granite; CC=calcite cement; Fe=iron rim (cement)]

The Wolfville sandstones are mostly feldspathic litharenites and lithic feldsarenites (Fig.4 and 5E). They consist of cement (dominated by sparry calcite and minor iron oxide and clays) (36.4%), quartz (31.8%), lithics (16.1%), feldspars (9.9%), heavy minerals (0.8%), and mica and chlorite (0.5%) with the remainder representing pore spaces (Fig.4). The average percentage of alkali feldspars/plagioclase is 10.4%. The lithics are in their order of abundance: slate, siltstone, granite, limestone, sandstone, quartzite, chert, and schist. These percentages were obtained by separately counting 1200 points in each thin section of the rock and their heavy mineral fraction. Counting of framework grains was done according to the Gazzi-Dickinson method (Gazzi 1966; Dickinson 1970) which has the advantage of using the data for provenance interpretation (Dickinson 1985; Dickinson *et al.* 1983; Dickinson and Suczek 1979; Ingersoll and Suczek 1979). The Gazzi-Dickinson method reduces the effect of composition dependence on grain

size used in traditional methods by restricting lithic fragments to microcrystalline aphanetic material which contains no crystals larger than the silt size (62.5 μm). Traditional methods, following the procedure of Pettijohn (1972) were also performed for counting the relative abundance of lithics in these sandstones (Fig.5F). XRD analysis of clay fraction separates from the studied sandstones showed that they consist of illite, montmorillonite, kaolinite and chlorite.

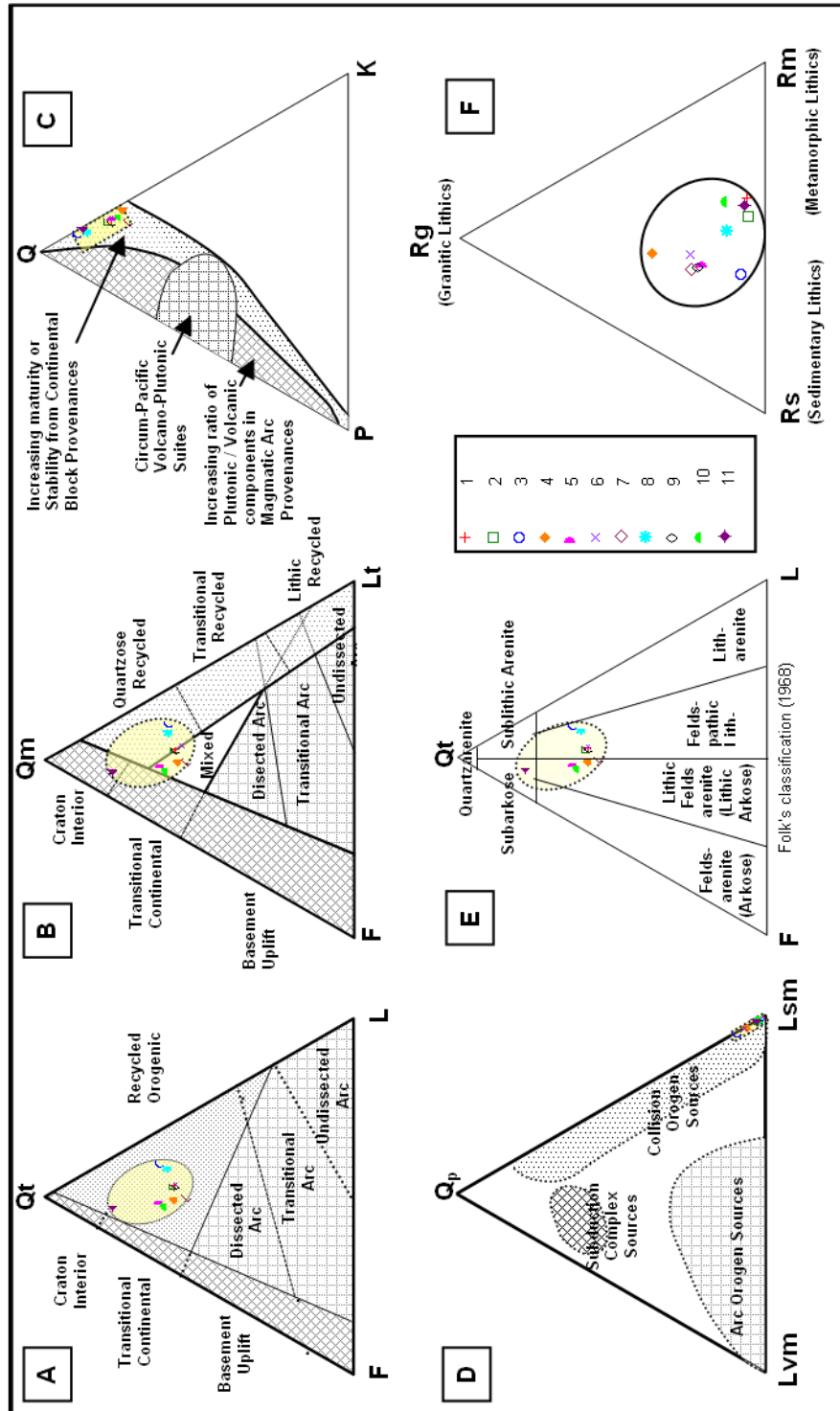
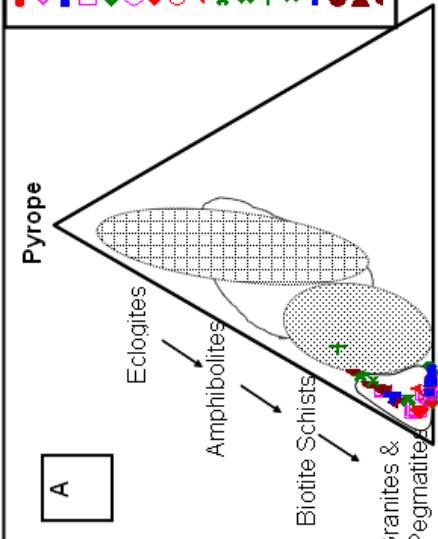


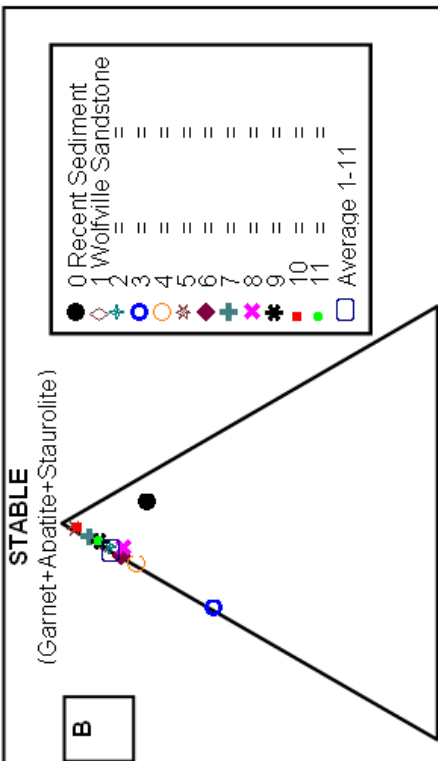
Fig. 5: Detrital constituents of the Wolfville Formation sandstones plotted on the provenance indicator triangular diagrams of Dickinson (1985), and Dickinson and Suczek (1979) (A, B, C, D) and on Folk's (1968) sandstone classification triagle (E), (F). (F) Lithic fragment's triangular diagram; Qm=monocrystalline quartz; Qp=Polycrystalline quartz (chert & quartzite); Qt=Qm+Qp; F=feldspars; L=Lithics; Lsm=MetasedimentaryLithics; Lvm=Metavolcanic lithics; Rg=Granitic lithics; Rs=Sedimentary lithics; Rm=Metamorphic lithics.

Decreasing Grade of Regional Metamorphism / Increasing Grade of Contact Metamorphism



- 2- Gray euhehedral
- 2- Pink anhedral
- 5- Gray euhehedral
- 5- Pink anhedral
- 8- Gray euhehedral
- 8- Pink anhedral
- Meguma (C.M.)
- Meguma (R.M.)
- Coticules
- Granodiorite (L.C.)
- ME
- PM(eSMB)
- PXC
- XLTH
- SMB-Group I
- SMB-Group II
- SMB-Group III

- 0 Recent Sediment
- 1 Wolfville Sandstone
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10
- 11
- Average 1-11

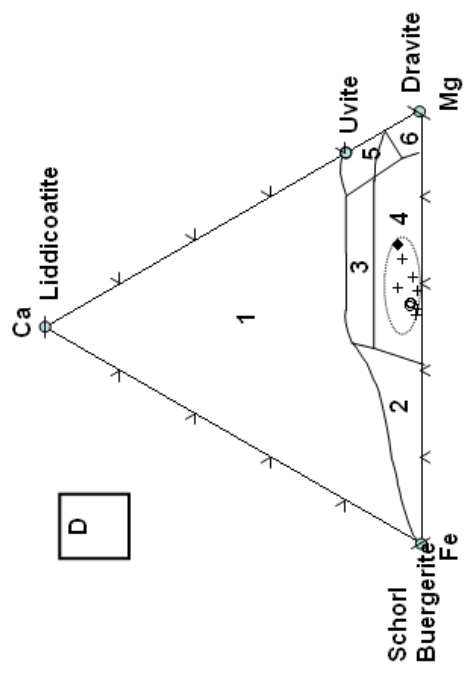
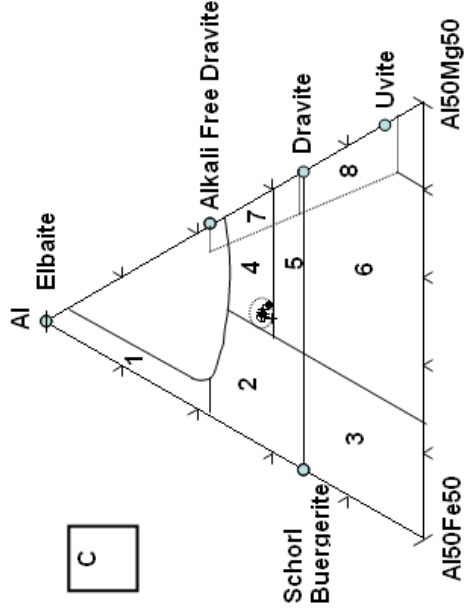


Almandine+Spessartine

Grossular

ULTRASTABLE
(Zircon+Tourmaline+Rutile)

MODERATELY STABLE & UNSTABLE
(Epidote+Hornblende+Pyroxene)



- 1= Li-rich Granitoids, Pegmatites & Aplites
- 2= Li-poor granitoids and their associated pegmatites and aplites
- 3= Fe3+-rich quartz-tourmaline rocks (hydrothermally altered granites)
- 4 = **Metapelites and metapsammities coexisting with an Al-saturating phase**
- 5 = Metapelites and metapsammities not coexisting with an Al-saturating phase
- 6 = Fe3+-rich quartz-tourmaline rocks, calc-silicate rocks, and metapelites
- 7 = Low-Ca metaultramafics and Cr, V-rich metasediments
- 8 = Metacarbonates and meta-pyroxenites

- 1. Li-rich granitoid pegmatites and aplites
- 2. Li-poor granitoids and their associated pegmatites and aplites,
- 3. Ca-rich metapelites, metapsammities and calc-silicate rocks.
- 4. **Ca-poor metapelites, metapsammities and quartz-tourmaline rocks.**
- 5. Metacarbonates
- 6. Metaultramafics

Fig. 6: (A) Composition diagram of Wolfville Formation sandstones plotted on slightly modified (Almandine+Spessartine) – (Pyrope) – (Grossular) triangular diagram of garnets of Wright (1938) (in Preston et al., 2002). The plotted data are from the study area (numbers 2, 5, and 8) as well as Meguma Group and South Mountain Batholith (SMB), Nova Scotia taken from other references. R.M. are averages of representative garnet analysis from low grade regionally metamorphosed Meguma Group slates and sandstones (Halifax Formation - Mosher's Island Member); C.M. are representative garnet analysis from the contact metamorphic zone of Meguma Group sandstones (Halifax Formation - Mosher's Island Member) with South Mountain batholith, southern Nova Scotia around Mahon Bay (from Hicks, R.J., 1996). SMB are averages of three groups of garnets from South Mountain batholith around Halifax and in the central part of the Batholith (from Allen and Clarke, 1981). L.C. is a garnet analysis from granodiorite body in Liscomb Complex, South Mountain Batholith (Cameron and Zentilli, 1997). ME, PM (eSMB), PXC and XLTH are averages of many garnets from xenoliths within South Mountain Batholith and its contact zones with the Meguma Group (Halifax Formation), Nova Scotia (from Erdmann, 2006). (B) Triangular diagram of the transparent heavy minerals of Wolfville Formation sandstones. (C and D) Composition diagram of Wolfville Formation sandstones plotted on the triangular plots of Henry and Guidotti (1985).

Soon after the deposition of Wolfville formation sandstones, paragenesis commenced by early compaction which appears to have limited effect indicated from the nature of sandstones, as most of the detrital grains do not have common contacts, but are separated by calcite cement. Iron cement was the earliest to develop around the detrital grains as thin rims. The source of iron was the detrital Fe and Fe-Ti oxide grains which are the most abundant heavy minerals. Oxidation of these grains to hydrous oxides resulted in staining the water in pore spaces and their subsequent deposition as thin films around the detrital grains. This was followed by the enrichment of the pore space water by calcium carbonates derived from the source terranes which were drained by rivers; and also from the detrital carbonate grains within the sandstones which have spherical and ovoidal shapes, possibly developed by systematic dissolution of their boundaries and/or by transportation effect. The carbonate enriched pore water was then precipitated as sparry calcite filling most of the pore spaces and resulted in a calcite cement-supported sandstone. Minor amounts of fibrous radiating clays were also deposited at the same time as calcite filling minor portions of pore spaces.

Further burial caused another stage of compaction indicated by selective microfracturing and breaking of most quartz grains which are more brittle than the accompanying feldspars and lithics. These quartz grains either possessed microfractures prior to deposition and under burial compaction were broken along these planes of weaknesses; or due to their brittle nature were fractured and broken during effective compaction pressure. Dissolution has partly affected the calcite cement and also the feldspars some of which were already partially altered in the source rocks and/or during transportation and deposition. Fracturing and breaking of quartz grains and partial dissolution of feldspar grains and calcite cement produced secondary porosity. Dissolution of altered feldspars resulted in the production of kaolinite which was deposited in vermicular form with noticeable intercrystalline porosity filling few pore spaces. The final stage of compaction produced sandstones of limited complex porosity. The average porosity of these sandstones is 6% (1.7 to 15.6%) in the form of primary and secondary porosity. Most of the primary intergranular pores were filled by sparry calcite cement; however many types of secondary porosity were developed during diagenesis. The secondary porosity types are dissolution, microfracturing (particularly of quartz), grain-boundary, intracement and intragranular.

Tectonic Provenance

The counting results based on Gazzi-Dickinson methodology were plotted on the provenance indicator triangular diagrams of Dickinson (1985), and Dickinson and Suczek (1979) (Fig.5). The sandstone falls in the field of “recycled orogenic provenance” (FQtL diagram) (Fig.5A), “mixed” and “quartzose recycled” (FQmLt diagram) (Fig.5B), “increasing maturity or stability from continental block provenance” (PQmK diagram) (Fig.5C) and “collision orogen source” (LvmQmLsm diagram) (Fig.5D). 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 main source of the studied synrift sediments is the Meguma terrane which has a collision contact relation with the older Avalon terrane to the north of the Cobequid fault system. Both terranes are part of the Appalachian Mountains and were also affected by the mid-Paleozoic Acadian Orogeny (Wade *et al.* 1996). The geologic map of the Bay of Fundy area, where the Wolfville formation is located in both in outcrops and subsurface, shows that the most probable source rocks of the studied sandstones are the Meguma supergroup and the South Mountain batholith. The 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 to the north of the Bay of Fundy in New Brunswick which contain Devonian and Silurian volcanic rocks was very limited. The Recent beach sediments at Cambridge Cove contain the same heavy mineral suites with nearly the same proportions as the nearby Wolfville formation, but they also contain basalt rock fragments and heavy minerals which have a basaltic origin such as pyroxene. This means that volcanic outcrops of North Mountain Basalt (earliest Jurassic) are the source of these basaltic rock fragments and the pyroxene.

The Wolfville sandstones and conglomerates contain quartz, various feldspars (alkali feldspars/plagioclase ≈ 11) and rock fragments (slate-schist, siltstone-sandstone, granitoids, quartzite, limestone, and chert). The Wolfville formation is underlain by formations ranging in age between Cambrian to Carboniferous which contains all lithologies that exist in Wolfville formation suggesting that they are the dominant source of the studied sandstones and conglomerates of Wolfville formation. The Meguma group is probably the dominant source of the major part of rock fragments (slate, schist, siltstone, sandstone, and quartzite). The South Mountain batholith is the source of granitoid lithics, and the Windsor group is a possible source of limestone lithics. 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 absence of volcanic lithics and/or heavy minerals of volcanic origin such as pyroxene preclude sources other than the Meguma supergroup and the South Mountain batholith as the major source of the studied sandstones. This is because of the similarity of the rock fragments (slates some of which are garnetiferous, siltstones, quartzites, 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 major part of quartz, K-feldspars, plagioclase, granitoid lithics, mica, and some heavy mineral (ultrastable group) are derived from the South Mountain batholith which occupies important part of central Nova Scotia as well as tens of scattered smaller similar outcrops to the east and west. The source of most lithics (excluding granitoids), part of quartz, feldspars, chlorite and many heavy minerals is Meguma Supergroup which occupies large areas of Nova Scotia (Fig.1).

Heavy Mineral Provenance

The heavy minerals consist of Fe and Fe-Ti oxides (magnetite, hematite, ilmenite, and their alteration products: goethite, limonite and leucoxene) (76%), garnet (13.6%), apatite (3.3%), chlorite (3.3%), zircon (1.4%), tourmaline (1.3%), biotite (1%) and minor amounts of rutile, staurolite, hornblende, and rarely epidote. Triangular diagram of the transparent heavy minerals (Fig.6B) showed that the stable heavy minerals are the dominant group followed by the ultrastable group with negligible amount of the unstable and moderately stable group.

For comparison, a sample of recent beach sediments indicated the presence of moderately stable minerals (pyroxene, epidote and hornblende) in addition to the groups which are present in the Wolfville sandstones; these moderately stable heavy minerals are obviously derived from the volcanic outcrops in the area including North Mountain Basalts which were not formed during the deposition of Wolfville formation sediments. Garnets and tourmalines are very useful provenance indicator minerals because of

their diversity and stability (Morton 1991; Wright 1938; Preston *et al.* 2002; Henry and Guidotti 1985). These two minerals, which are abundant in the Wolfville formation sandstones were analyzed by electron microprobe and their compositions plotted on the provenance triangles of Wright (1938) and Preston *et al.* (2002) for garnet (Fig. 6A), and Henry and Guidotti (1985) for tourmaline (Fig. 6C, D). All garnets were plotted in the field of “pelites and granites and granite pegmatites” in the (Almandine+Spessartine)-(Pyrope)-(Grossular) triangle (Fig. 6A). The tourmalines were plotted in the field of “metapelites and metapsammites that coexist with an Al-saturating phase” and “Ca-poor metapelites, metapsammites and quartz-tourmaline rocks” in the $Al_{50}Fe_{50}$ -Al- $Al_{50}Mg_{50}$ and Fe-Al-Mg triangles respectively (Fig. 6C, D).

The abundant garnet as the major transparent heavy mineral in the studied sandstones is particularly important as a provenance indicator. Two types of garnet exist: a dominant euhedral, gray under the microscope, rich in inclusions and spessartine in type; and minor amounts of anhedral, clear, pink under the microscope and almandine in type but still Mn-rich. Both types fall in the field of pelites, granites and granite pegmatites in the (pyrope)-(almandine+spessartine)-(grossular) triangle (Fig. 6A) suggesting Meguma supergroup and SMB as their provenance. The spessartines are closely clustered near the almandine+spessartine corner along the grossular line direction while the almandine is sparser and fall closer to the almandine+spessartine corner but mostly along the pyrope line direction (Fig. 6A). One of the characteristic features of the Meguma supergroup (particularly the Halifax formation) is that they contain spessartine garnets. Comparisons were made with those garnets which exist as xenoliths in the SMB and its contact zone with Meguma supergroup in central Nova Scotia studied by Erdmann (2005). The studied almandines also have similarities with those studied by Allen and Clarke (1981) from various parts of the SMB and also with those studied by Cameron and Zentilli (1997) from SMB (Liscomb complex).

Garnet was also reported by Cullen (1984) as accessory grains in the metaquartzites and schists of Folly River in Bass River Complex, Cobequid Highland within the Avalon zone of Maritimes; however they were not analyzed to allow chemical comparison with the garnets of Wolfville formation. Triangular provenance diagrams of Henry and Guidotti (1985) (Figs. 6C, D) showed that the studied tourmalines fall in the field of “metapelites and metapsammites coexisting with an Al-saturating phase” and “Ca-poor metapelites, metapsammites and quartz-tourmaline rocks” again suggesting Meguma supergroup sediments and possibly SMB as their source. The vast majority of the rock-forming minerals as well as most of the heavy minerals found in the sandstones of Wolfville formation were also found and mostly analyzed by Hick (1996) which included quartz, albite, biotite, muscovite, chlorite, carbonates, apatite, epidote, garnet, rutile, titanite, tourmaline, zircon, and hematite.

Conclusions

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

(1) The Wolfville formation sandstones transported by braided rivers and deposited as channel fills and on flood plains are mostly feldspathic litharenite, poorly sorted, fine to strongly fine skewed, platykurtic to very platykurtic and medium in grain size.

(2) 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.

(3) Iron oxides and garnets are the predominant heavy minerals in these sandstones with 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.

(4) The provenance indicator triangles for results of detrital grains and heavy minerals in general, and those of tourmaline and garnet in particular, indicated that the Wolfville Formation sediments have recycled orogenic provenance (collision setting) and derived mostly from the Meguma terrane located to the south of Cobequid (Minas) fault zone. The main source rocks are the Meguma supergroup and South Mountain batholith with minor contributions from the carbonate-bearing formations such as the Windsor Group. The lack of rock fragments and heavy minerals attributable to volcanics and high grade

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