The Provenance of Heavy Minerals in the Mesozoic and Tertiary Formations, Venture B-13 Borehole, Offshore Nova Scotia, Canada*

By

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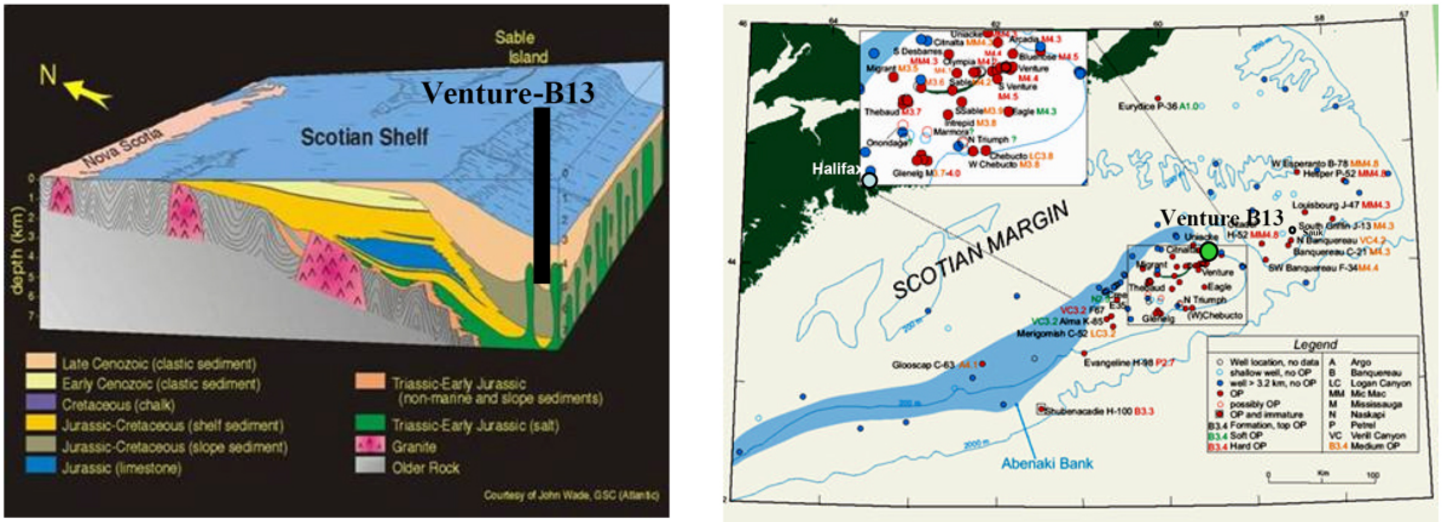
Introduction

The Venture gas field (Venture B-13 borehole) located ~11.3 km east of Sable Island (44°02’11.61’’N, 59 °32’03.54’’W) which was discovered in 1979, occupies the central part of the Sable delta complex (Figure1). It was drilled to a depth of 5368m to Mic Mac Formation and cored between 4692.7 mand 4734.4 m(Missisauga Formation) and 4949.0 m and 4967.30 m (Mic Mac Formation). Reservoir sediments are alternating sandstoneshale as part of Missisauga formation (Early Cretaceous) and Mic Mac Formation (Late Jurassic) (CNSOPB, 2000). These sediments were deposited under episodic deltaic, fluvio-shallow-marine environments. The composition of sandstones reflects the character of sedimentary provenance and the nature of sedimentary processes within the depositional basin. Provenance and depositional basin are governed by the tectonic regimes, which in turn control the distribution of types of sandstones. Many studies have correlated the composition of sandstones, their provenances, and tectonic settings (Dickinson and Suczek, 1979). In recent years additional tools have added more value to the provenance studies of these minerals. One such tool is determining the mineral chemistry of heavy minerals using electron microprobe analysis. Among the minerals used for such study by different authors are garnet (Sabeen et al., 2002; Morton and Hallsworth, 1999), tourmaline (Henry and Guidotti, 1985), zircon, rutile, amphibole, pyroxene, epidote and ilmenite. Heavy minerals proven to be most useful for provenance study are garnet and tourmaline because of their mineralogical and chemical diversity, abundance in sediments and rocks of different origin, and physical-chemical resistance and stability under various extreme geological conditions. Both, garnet and tourmaline were used as provenance indicators in this study.



Courtesy of John Wade, GSC (Atlantic)

Figure 1. Location map of the studied field (Venture B13) and schematic section of the Scotian Margin (Wade, 1990).

Geology

The Scotian Basin extends for 1200 km in an NE-SW-trending direction between the eastern part of Georges Bank to the central Grand Bank and is one of many sedimentary basins forming the southeastern margin of Canada. (Wade and MacLean, 1990). The geology of Nova Scotia and its continental margin has been studied by many authors; e.g., Kidston et al. (2002), and Wade and MacLean (1990). This basin, which has attracted attention during the last three decades because it hosts some oil-gas potential, is part of an Atlantic-type continental margin (Falvey, 1974) which formed as a result of rifting and breakup of a continent platform during early Mesozoic. The mainland Nova Scotian geology is dominated by the folded metasediments of Meguma Group (Cambro- Ordovician), intruded by South Mountain Batholith (Devonian-Carboniferous), both of which form the pre- Mesozoic basement of the area, whereas the Permo-Carboniferous sediments are centered in the Gulf of St. Lawrence (Wade and MacLeon, 1990). Following the breakup and the formation of Scotian margin during Triassic, many basins formed along the rifted zone, and they were subsequently infilled during a number of major regression and transgression periods. This resulted in accumulation of a huge pile of sediments during Mesozoic and Cenozoic times; it began with evaporates and carbonates, followed by clastic fluviodeltaic sediments (sandstones, siltstones, and shales with ± carbonates), the characteristic sedimentary succession of the Scotian margin basins and adjacent basins.

Petrography

Representative samples from cuttings of all formations penetrated in Venture B13 borehole as well as core samples from the reservoir parts of Mic Mac and Missisauga formations were selected.. The fine and very fine sand fractions were added together for heavy mineral separation, using heavy liquids (Na-polytungstate). Polished thin-sections were prepared for petrographic study and counting heavy minerals. The sand samples were rich in quartz, and minor K-feldspars and plagioclase, with lesser amounts of lithics, such as chert, slates, granites, as well as mica, chlorite, and glauconite. Thin-sections showed that the cttings are rich in quartz, and minor K-feldspars and plagioclase with lesser amounts of lithics, such as chert, slates, granites, as well as mica, chlorite, glauconite and opaques.

The upper part of the studied core which cut through the reservoir rocks is made up of arenaceous fossiliferous oolitic limestone which gradually changes downward into fossiliferous calcareous sandstone and calcareous sandstone. The arenaceous, fossiliferous, oolitic limestones are made up of well rounded and sorted ooilites, 0.8 to 1 mm in average diameter, nucleated around sand grains (mostly quartz), forams, crinoids, corals, older ooilites, sparry calcite aggregates, quartzite, chert, feldspar, tourmaline, and other heavy minerals. They are mostly dark brown in color, well sorted and have multi-concentric thin layers around the nucleus. Few of them have thinner concentric rims with respect to larger cores. Pressure-solution effects have produced stylolite contacts between some oolites. The interspaces between oolites are filled by the same material occupying their cores, as well as muscovite, chlorite, biotite, rounded glauconite, and iron stains. Burrows as elongate tubular bodies are common and filled by fibrous calcite. Bluish green chlorite has probably formed from glauconite and/or clay minerals due to burial conditions. This shoal limestone covers a turbiditic succession of alternating sandstone, siltstone, and shale. Two types of sandstones are present; one is highly calcareous, non-porous or slightly porous sandstone, and the other is very poorly sorted, subangular, poorly cemented, highly porous sandstone. Bioturbation is present in most of the core, although structures such as cross-bedding, and parallel laminations are recognizable. The poorly cemented reservoir sandstones contain hydrocarbon remnants with small amounts of cement, mostly calcite, dolomite, ankerite, siderite, chert, and barite. Porosity is mostly intergranular, but intragranular secondary porosity is also present within the altered feldspars. Some feldspars are sericitized, kaolinized and/or carbonatized (mostly ankerite). Ankeritization of feldspars, along with other carbonates, is common. The sandstones consist of quartz, feldspars (K-Feldspars and plagioclase), rock fragments (chert, granite, slates), micas (muscovite/sericite and euhedral biotite at greater depth), bluish green pleochroic chlorite, glauconite, pyrite (mostly framboidal) as well as minor but common euhedral crystals of zircon, tourmaline, rutile, Fe-Ti oxides, with variable amounts of cementing materials, clay matrix, and hydrocarbon remains. The siltstones are composed of the same material as sandstones. The shales consist of variable clays (illite, smectite, kaolinite, mixed layers), sericite, bluish green chlorite, muscovite, and biotite, feldspars, pyrite, and carbonates. At great depth many clays have been transformed into illite, muscovite, biotite, and chlorite; the last is probably also derived from glauconite, which is abundant.

Results and Discussion

The Gazzi-Dickinson method was applied for counting 600 counts in 22 thin sections prepared for representative sand samples (cuttings) of both Mesozoic and Cenozoic formations taken from the Venture-B13 borehole. The samples represent Mic Mac, Missisauga, Logan Canyon, Dawson Canyon, and Banquereau formations. Triangular plots for these counts show that the vast majority of these sands fall in the field of litharenites, rarely quartz arenites and/or lithic arenites based on Folk's (1968) classification (Figure 2A). Triangular plots of Dickinson (1982), Dickinson et al. (1983), and Dickinson (1985), which relate sand provenances to the tectonic environments, were also plotted (Figure 2). QtFL, QpLvmLsm, and QmFLt plots show that almost all samples have continental block provenances (craton interior) and/or collision orogen sources, corresponding to the extreme end of the field of increasing maturity/stability from continental block provenances, respectively.

Heavy mineral study conducted on 22 polished thin sections. These sections were prepared from the heavy minerals separated from the combined fine and very fine sand fractions (250 - 63µm) of the same samples which were used for the sand composition analysis. Transmitted-reflected polarizing microscope was used to count 300 heavy minerals counts, including both transparent and opaque minerals. Results show variable amounts of opaques (magnetite, hematite, and ilmenite-ilmenorutile, as well as goethite and leucoxene as their alteration products), ultrastable (zircon, tourmaline, and rutile), stable (staurolite, garnet, apatite, and monazite), moderately stable (epidote and sillimanite-kyanite), and rarely unstable minerals such as hornblende, pyroxene, sphene, and spinel (Figures 3 and 4). Ultrastable minerals are dominant in all formations, whereas moderately stable minerals become more abundant in the Tertiary rocks. Triangular plots between epidote – staurolite - sillimanite [EpStSi] and garnet - total ultrastable minerals (zircon + tourmaline + rutile) (ZTR) - sillimanite [GnZTRSi] show isolations between the samples of the studied formations. In EpStSi triangle, there is good separation between the samples of Mic Mac, Missisauga, Logan Canyon, and Banquereau formations; and the GnZTRSi triangle shows separation between the heavy minerals of Missisauga, Logan Canyon, and Banquereau formations. Diagrams plotted between the relative abundance of heavy minerals and depth (Figure 4) show fluctuations but distinct trends of increase or decrease in abundance of the heavy minerals with depth for some minerals. This may reflect a gradual and systematic modification in the conditions affecting these minerals, such as changes in the rates of weathering/erosion, uplift, metamorphism, magmatism, and transporting agents as well as the conditions at sites of deposition and burial. In general there is an increasing upward trend in the relative rates of abundance of garnet, sillimanite-kyanite, epidote, magnetite, and ilmenite; decreasing upward trends of leucoxene, hematite, apatite, possibly goethite; and no obvious trends in the case of the other minerals. This relation clearly can also be seen in the relative abundance plots of some minerals which can be expressed as mineral index (ratio between two minerals). The results of relative abundance of these minerals and the ratios of abundance of hydraulically and diagenetically equivalent heavy mineral pairs recommended by Hurst and Morton (2001) are shown in Figure 5. Mineral indices between ilmenite-rutile (IRi), garnet-tourmaline (GTi), and garnet-zircon (GZi) show an increasing upward trend; the index of apatite-tourmaline (ATi) shows increasing downward, whereas the indices of rutile-zircon (RuZi) and TiO2 group-zircon (RZi) have no obvious trend.

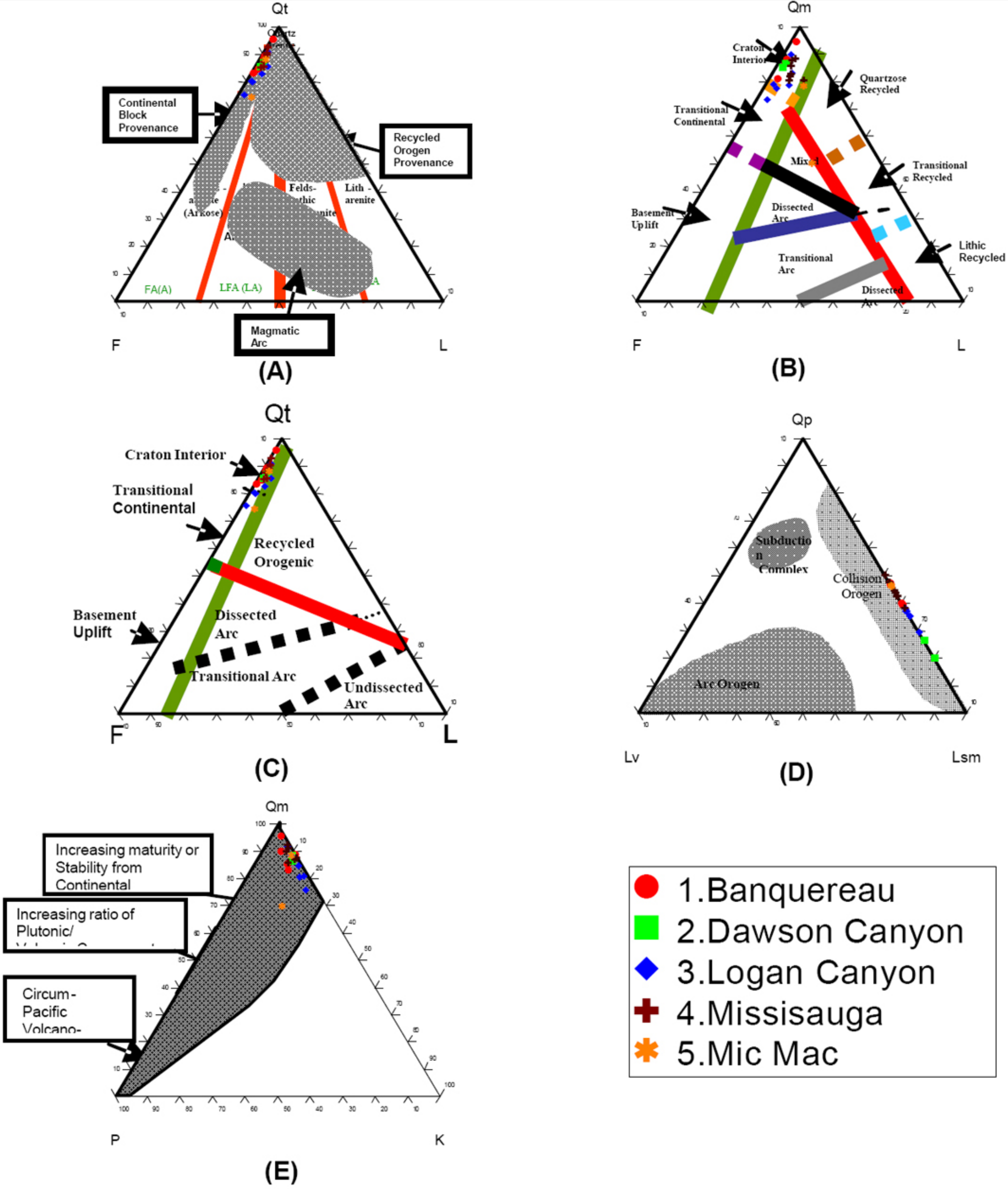


Figure 2. Triangular diagrams showing the types of sandstones [(after Folk, 1968) (A)], and the provisional compositional fields indicative of sand derivation from different types of provenances [(after Dickinson et al., 1983) (B and C) and (after Dickinson,1982) (A, D, and E)] of Mesozoic and Cenozoic formations in Venture-B13 borehole, Venture Gas Field.

The GTi, GZi, ATi, RuZi, and RZi indices (mineral ratios) were used by Hurst and Morton (2001) as indicators for sediment transport paths of deep-water turbidites. According to this concept, ATi and GZi have contrasting trends for deep-water sandstones, of similar age and derived from the same overall source area, a difference which can be attributed to the contrasting sediment transport paths. Deep-water sandstones with fluctuating indices are inferred to have been derived directly from alluvial basins, bypassing any contemporaneous shallow-marine shelf; whereas those with homogeneous indices are inferred to be fed by sediments that originally accumulated on shallow-marine shelves. Possibly these heavy mineral ratios cannot be applied so easily in the same manner in the case of the studied thick pile of Scotia offshore sediments because they have a wide age range between Early Mesozoic to Late Cenozoic; however, supposing that the same land mass was effectively the main source of the offshore sediments, these ratios might have some similar implications. The ATi ratio in this study shows fluctuations but a clear upward decreasing trend, whereas those for GZi, GTi, and IRi have fluctuations but distinct upward increasing trends. These might indicate that these sediments feeding the Scotian offshore basin were derived from alluvial basins along canyons, bypassing the shallow-marine Scotian Shelf and accumulating at the continental margin and slope.

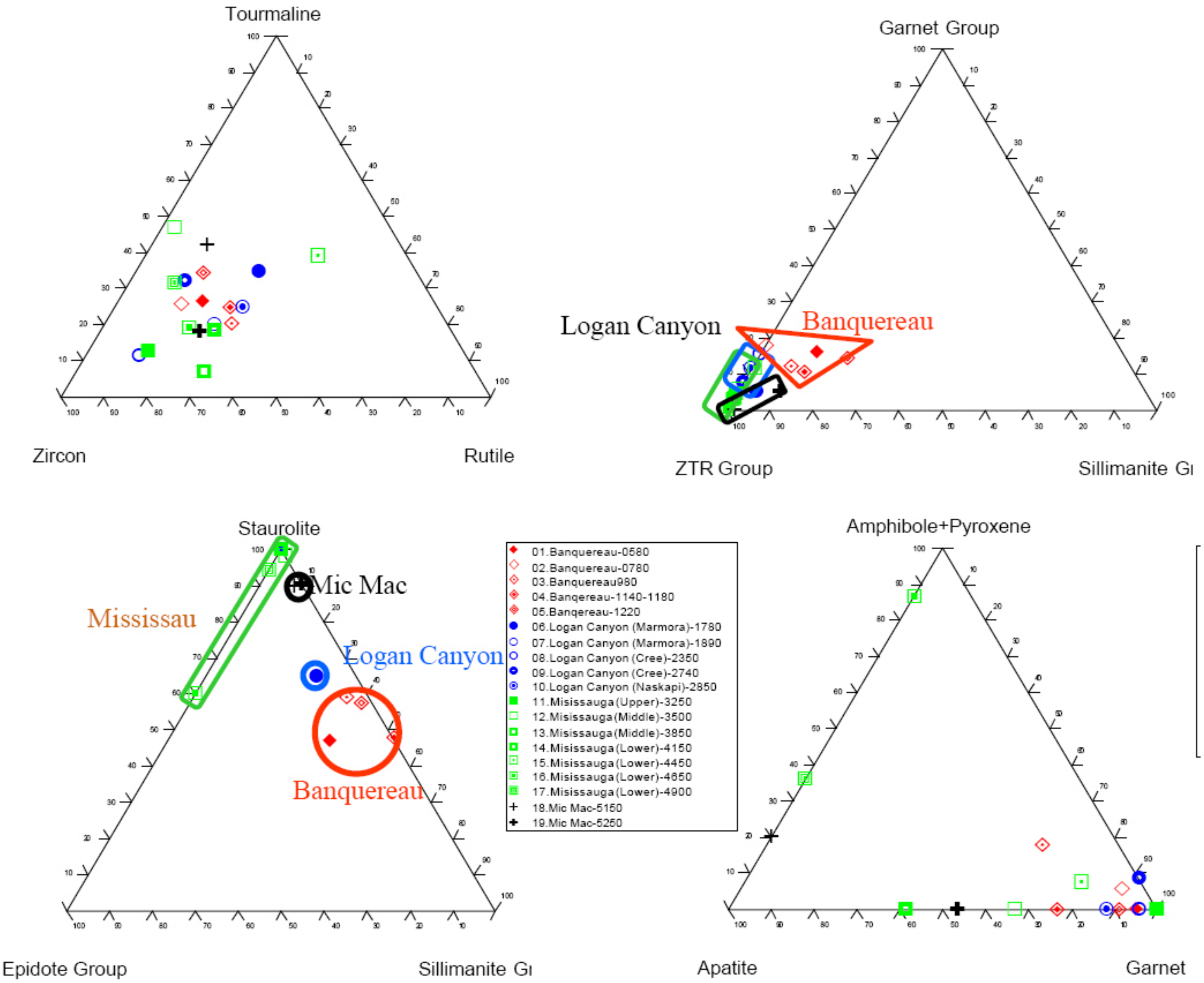


Figure 3. Heavy minerals triangular diagrams for Venture B13 borehole.

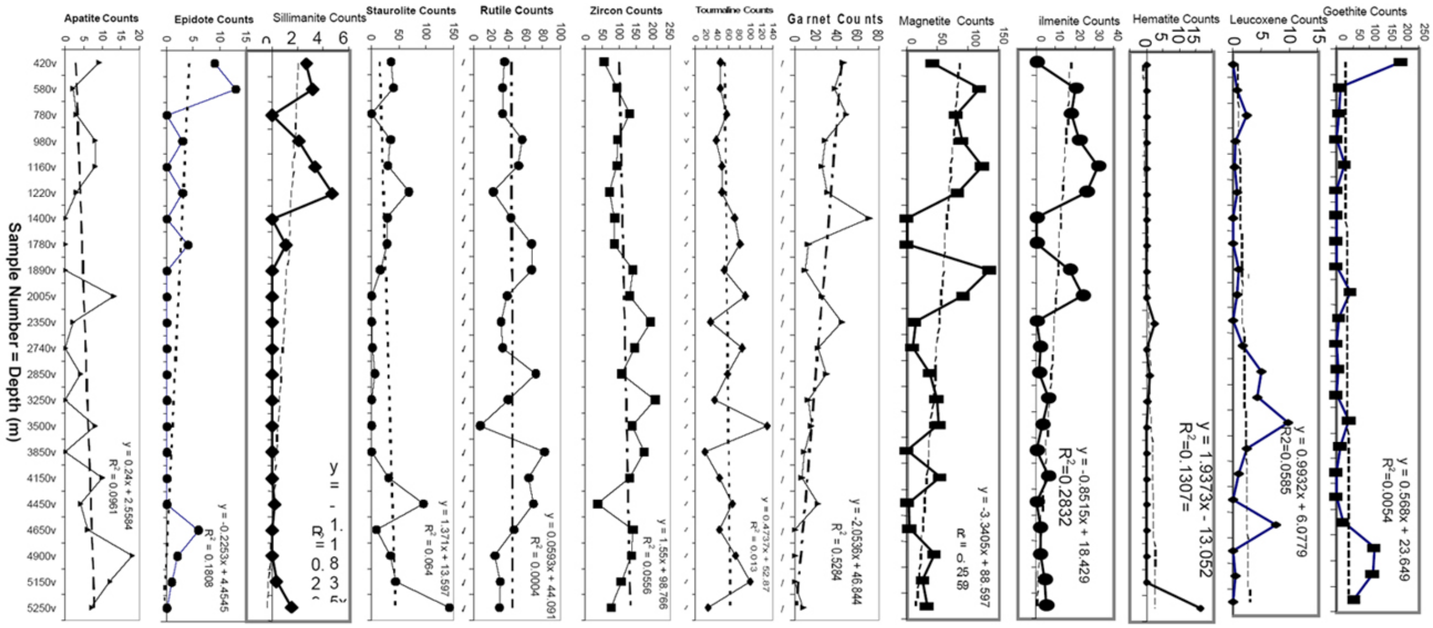


Figure 4.Variation of the relative abundance of heavy minerals with depth along the studied Venture- B13 borehohole.

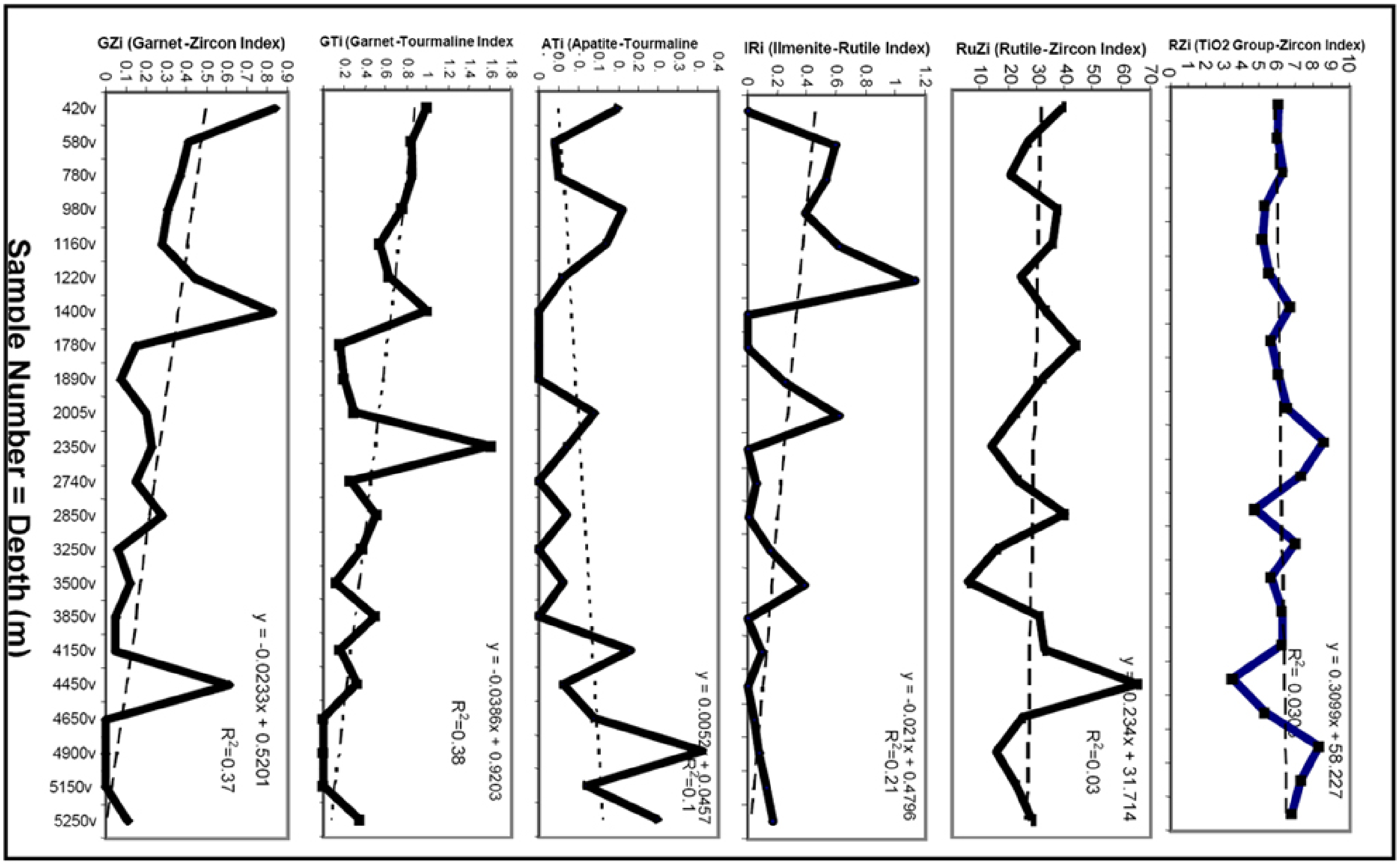


Figure 5. Distribution of the ratio of heavy mineral pairs (expressed as index) with depth: Mineral Index = 100 [mineral1/(mineral1+mineral2)].

Heavy mineral compositions of few heavy minerals, analyzed by electron microprobe, can serve to predict provenance of these indicator minerals. Garnet, tourmaline, and others were analyzed and used in this study. Al50Fe50-Al-Al50Mg50 and Fe-Ca-Mg ternary diagrams of Henry and Guidotti (1985) indicate that the tourmalines (dravites and schorlites) are of aluminous metapelite and metapsammite / Ca-poor metapelite, metapsammite, and quartz-tourmaline rocks in provenance for Banquereau and Logan Canyon formations.

Further they indicate mostly Li-poor granitoid, pegmatite, and aplite and less Ca-poor metapelite, metapsammite, and quartz-tourmaline rocks provenances for Missisauga Formation. Triangular plots of garnets (almandine-spessartine) using Wright's (1938) diagram (Figures 6 and 7) show that Banquereau Formation garnets are in the field of granite and granite pegmatites; those for the Mic Mac and Logan Canyon are in the field of amphibolite; whereas those for the Banquereau Formation are distributed between biotite schist and amphibolite fields. Furthermore, the chemistry of analyzed garnets were compared with those studied by Cameron and Zentilli (1997) from South Mountain Batholith (granodiorites and monzonites of Liscomb Complex) near Eastville, Nova Scotia, as well as the surrounding Goldenville and Halifax formations of the Meguma Group metasediments, and those studied by Allan and Clarke (1981) from granodiorite, monzogranites, and leucocratic monzogranites of South Mountain Batholith from various locations in southwestern Nova Scotia. The comparisons show very good similarities between these garnets in their overall geochemistry, indicating their common origin. Very good similarities were also noticed between the studied staurolites with those studied by Cameron and Zentilli (1997) from Meguma metasediments.

The Scotian Basin, as part of the Atlantic-type continental margin, was developed as the result of rifting and breaking down of a continental platform which covered the whole region (Ravenhurst et al., 1990). It is part of an accreted wedge of Mesozoic-Cenozoic sediments on the eastern flank of the Appalachian orogen (Wade and MacLean, 1990). The pre-Mesozoic basement of this area consists of the metasediments of Meguma Group (Cambro-Ordovician) and the intruded granitoids of South Mountain Batholith (Devonian- Carboniferous) (Grist et al., 1997). The petrographic sand-grain-count diagrams and the identity, distribution, and chemistry of heavy minerals in the Venture B13 borehole suggest that the provenance of the studied subsurface sediments within the Scotian basin is the South Mountain Batholith and the surrounding Meguma Group metasediments, which originated from the Appalachian orogen. Petrographically the quartz grains and other associated detritus are subangular to subrounded in shape, and the sandstones are dominantly of subarkosic composition; they lack volcanic rock fragments and are characterized by a high K-feldspar/plagioclase ratio, indicating proximity of the source rocks and dominant effect of granitoids. Compositional grain-count diagrams show indicators of continental block provenance (craton interior). Most sands represent increasing maturity or stability of continental block provenances. The prevalence of ultrastable heavy minerals and metastable heavy minerals also show a granitic-metamorphic origin of these sediments. Comparisons of specific indicator heavy minerals, such as garnet and tourmaline from the studied borehole and those studied by other authors from the South Mountain batholith and the surrounding Meguma Group metasediments, also strongly support this conclusion. Tourmalines indicate granitic and low-grade metamorphic provenances. Garnets also show granitic and metamorphic sources (schist to amphibolites), also reflecting the fact that the possible Meguma Group source suffered from regional metamorphism on a large scale and, more locally around the contacts of the South Mountain Batholith, from contact metasomatism (Kontak and Corey, 1988). Existence of heavy minerals of metamorphic origin in some of the studied formations, such as sillimanite, staurolite, epidote, and others, is also strong evidence that their source is the Meguma metasediments, which contain these minerals (Raeside et al., 1988). Euhedral perfect six-sided biotite crystals were found in the Mic Mac formation; it might have been derived from the seamount eruptions which were reported in the Scotian Basin, and some of these volcanic episodes may be of early Late Jurassic age (Wade and MacLean, 1990)

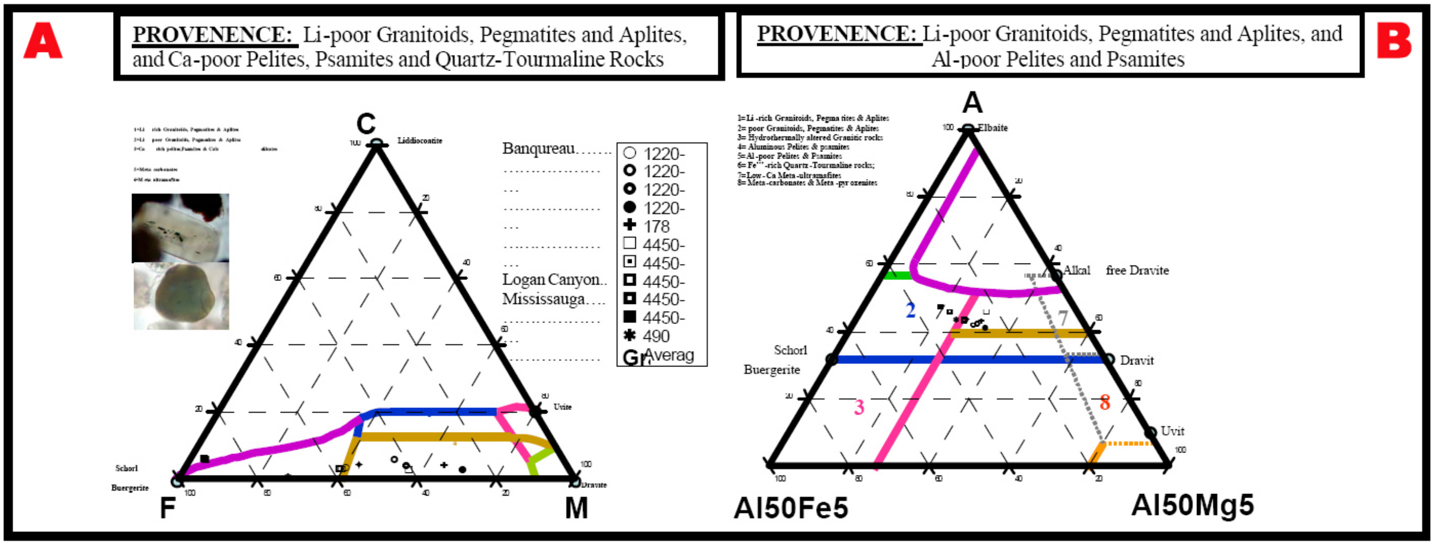


Figure 6A. Fe-Ca-Mg diagram of Henry & Guidotti (1985) for tourmalines from Venture B-13 borehole, Offshore Nova Scotia.

Figure 6B. Fe-Al-Mg diagram of Henry & Guidotti (1985) for tourmalines from Venture B-13 borehole, Offshore Nova Scotia.

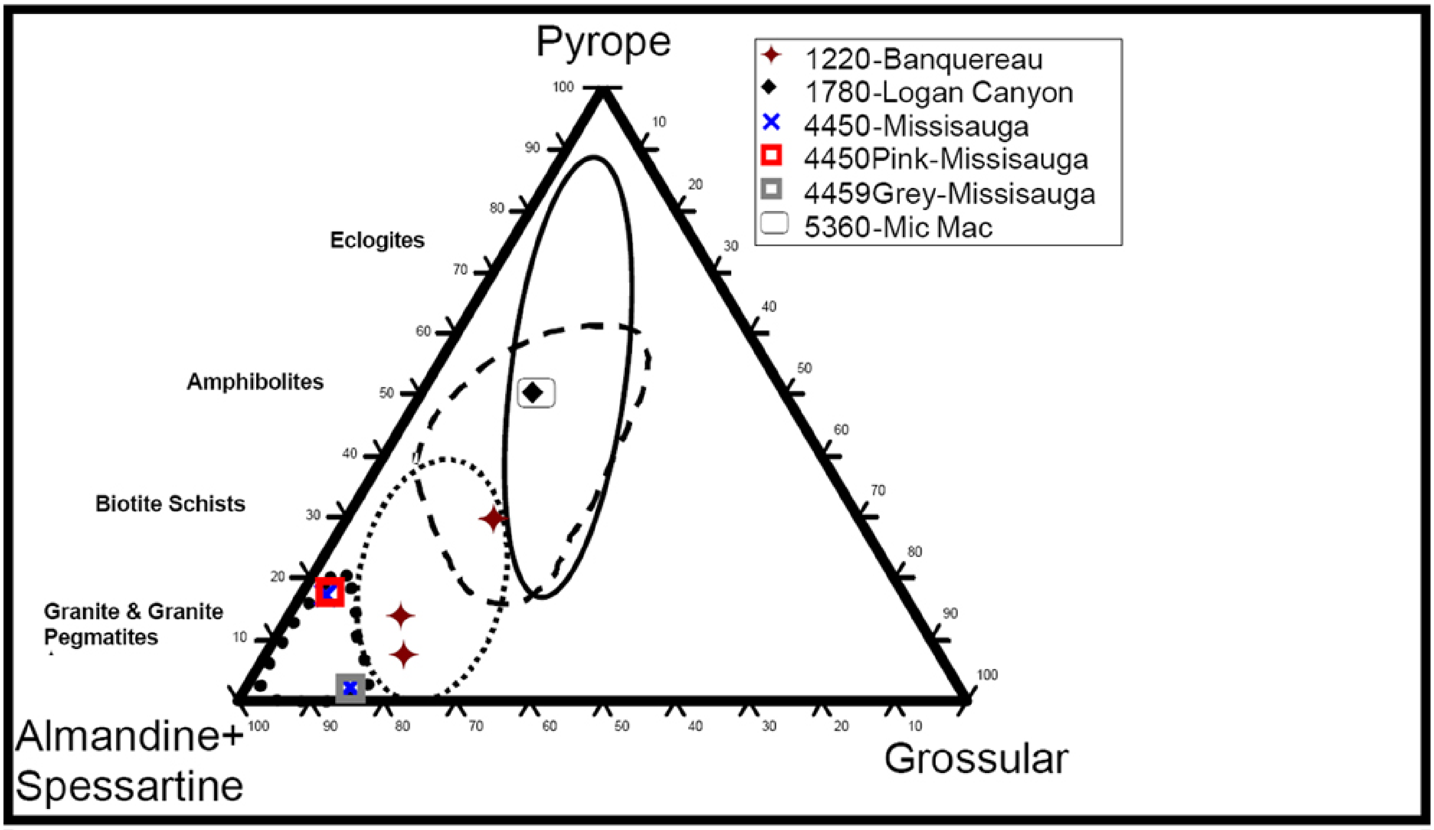


Figure 7. Almandine-Spessartine (AS), Pyrope (P) and Grossular (G) end-member fields for garnets representing metamorphic and igneous rock types [after Wright (1938), in Peterson (2002)].

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