

# Timing and Tectonic Setting of Volcanogenic Massive Sulphide Bearing Terranes within the Central Mobile Belt of the Canadian Appalachians

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## ABSTRACT

*The Central Mobile Belt of New Brunswick and Newfoundland consists of series of Cambro-Ordovician arc terranes and microcontinents related to the Iapetean realm that were accreted to Laurentia in response to the closure of Iapetus and its associated marginal basins. These sequences host many volcanogenic massive sulphide (VMS) deposits that cover the full spectrum deposit types, whether classified by metal content or host lithology. The distribution of the various types of VMS mineralization demonstrates the link between the form of VMS deposits and tectonic setting.*

*The primary tectonic constraint for VMS formation is that an extensional setting is required. The mafic volcanic dominated sequences of suprasubduction zone ophiolites and the oceanic crust forming spreading phase of a back-arc form VMS that are Cu-rich and Pb-poor. Examples of such VMS deposits are observed in the Baie Verte Oceanic Tract of Newfoundland. Felsic and felsic-dominated bimodal volcanic sequences are formed in extensional arcs and early phase continental back-arcs and can contain Zn- and Pb-rich VMS deposit, such as in the Bathurst Mining Camp, New Brunswick, and Buchans, Newfoundland. At least for the Central Mobile Belt, the rate of extension controls the location of VMS mineralization in a single arc – back-arc complex. If extension is relatively rapid than VMS deposits are restricted to the extensional arc tectonic setting (e.g., the Duck Pond Mine forming in the Penobscot arc), whereas slower extension produces VMS deposits in a back-arc setting (e.g., the Brunswick No. 12 Mine forming in the Tetagouche – Exploits back-arc).*

## INTRODUCTION

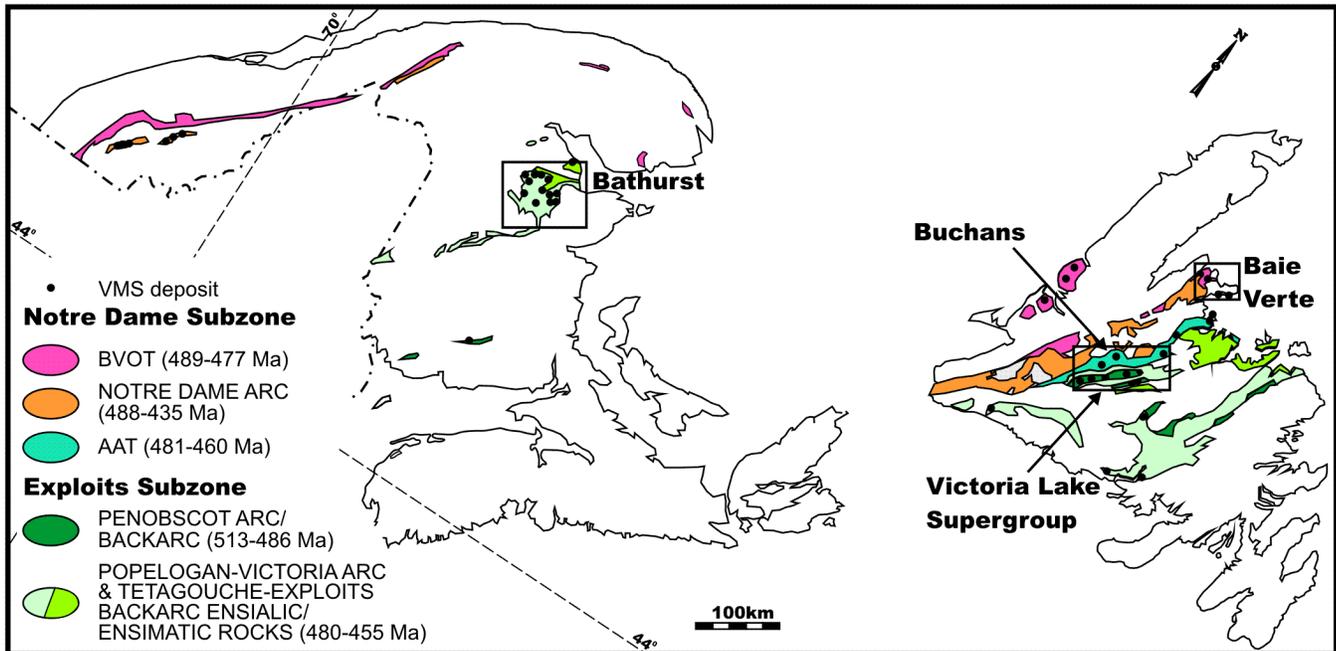
The Central Mobile Belt (CMB) of the Canadian Appalachians formed by the accretion of multiple arc terranes and microcontinents to Laurentia, in response to the closure of Iapetus and associated marginal basins. These Cambro-Ordovician sequences host numerous volcanogenic massive sulphide (VMS) deposits that range in type, timing and tectonic setting (Figure 1). This paper summarizes how the CMB evolved tectonically and relates how this affected the formation of the various types of VMS through both time and space (Figure 2).

Central Mobile Belt VMS deposits can be classified into four groups as per the scheme of Franklin et al. (2005). The first of these are mafic type deposits that are primarily hosted by ophiolitic rocks (i.e., Cyprus-type deposits). Examples of these are seen in the Lushs Bight Group, Newfoundland. The second type is the mafic bimodal deposits that are hosted by bimodal volcanic sequences where the volume of mafic volcanism exceeds that of felsic. Important examples of this type of deposit occur in the Pacquet Harbour and Robert's Arm groups,

Newfoundland (i.e., Rambler Mine). The third type of deposit is felsic bimodal, exemplified by Buchans, Newfoundland. In this case the volcanic sequence is bimodal, but dominated by felsic volcanic rocks. The final type is a deposit in a felsic-dominated, bimodal volcanic sequence that is hosted by sedimentary rocks and as such represents a volcanic-sediment hosted massive sulphide (VSMS), the prime example being the Bathurst Mining Camp, New Brunswick.

## GEOLOGICAL SETTING

The Canadian Appalachians were divided by Williams (1979) into a number of distinct tectonostratigraphic zones and subzones that reflect sharp contrasts in lithology, stratigraphy, fauna, structure, geophysics, plutonism and metallogeny of the Lower Palaeozoic and older sequences. From west to east, these divisions are the Humber, Dunnage, Gander, Avalon and Meguma zones. The Humber Zone represents the remnants of Laurentia's Appalachian margin involved in Palaeozoic orogenic events. The Gander, Avalon and Meguma zones,



**Figure 1:** Distribution of major VMS-bearing terranes within the Central Mobile Belt of the Canadian Appalachians (after van Staal, in press). BVOT – Baie Verte Oceanic Tract, AAT – Annieopsquotch accretionary tract.

represent peri-Gondwanan microcontinents (Ganderia, Avalonia and Meguma, respectively) that accreted to Laurentia during the closure of Iapetus (450-380 Ma). The Dunnage Zone, which is synonymous to the CMB, mostly contains the remnants of numerous accreted continental and oceanic arc terranes that formed within the realm of the Iapetus Ocean. Based on their provenance they have been subdivided into the peri-Laurentian Notre Dame and largely peri-Gondwanan Exploits subzones (Williams et al., 1988). The presence of multiple coeval arc systems indicates that several subduction zones were active within Iapetus, making it a complex ocean akin to the modern Pacific (van Staal et al., 1998). True Iapetan oceanic lithosphere that formed at mid-oceanic spreading centres, far removed from subduction zones, has not been identified and was probably lost by subduction.

#### NOTRE DAME SUBZONE

The Notre Dame Subzone is exposed in Newfoundland and southern Quebec. It lies immediately to the east of the Humber zone separated by the Baie Verte – Brompton Line. Its eastern boundary with the Exploits subzone is defined by the Red Indian Line, which juxtaposes rocks that formed on the opposite sides of Iapetus.

The Notre Dame subzone in Newfoundland comprises three distinct Cambrian to Middle Ordovician (507-462 Ma) oceanic

terranes and a continental magmatic arc (the Notre Dame arc). The Notre Dame arc was built on Dashwoods, a ribbon-shaped microcontinent that rifted from Laurentia at circa 560 Ma (Waldron and van Staal, 2001), and was intermittently active between ca. 488 and 435 Ma. The oldest oceanic rocks occur in the Middle to Upper Cambrian (510-501 Ma) Lushs Bight Oceanic Tract (Fig. 1, 2; LBOT; Swinden et al., 1997) that is characterized by pillow basalts, sheeted dikes, gabbro and rare ultramafic rocks. The abundance of boninite and primitive island-arc tholeiite indicate a suprasubduction zone setting (Swinden et al., 1997). The LBOT is host to numerous economically significant syngenetic  $\text{Cu} \pm \text{Zn} \pm \text{Au}$  VMS deposits that are commonly spatially associated with occurrences of boninitic lavas and/or dykes. Crustally contaminated intrusions require the LBOT to have been obducted by 490 Ma (van Staal, in press). Subsequently, a new suprasubduction zone oceanic tract was formed during stepping back of the east-dipping subduction zone into the Humber Seaway. The remnants of this oceanic tract are preserved mainly as a narrow fault-bounded wedge along the Baie Verte – Brompton Line and are referred to as the Baie Verte Oceanic Tract (BVOT; Fig. 1, 2). The c. 489 Ma (Dunning and Krogh, 1985) ophiolitic component of the BVOT is significantly younger than the LBOT and forms the basement to a Tremadoc to early Arenig, oceanic Snooks Arm arc – back-arc complex (Bédard et al., 2000). The ophiolitic members of the BVOT host numerous economically important  $\text{Cu} \pm \text{Zn} \pm \text{Au} \pm \text{Ag}$  VMS

deposits in the Baie Verte Peninsula, of which the Tilt Cove (> 8M tonnes), Betts Cove (118,000 tonnes of 10% Cu), and Rambler-Ming (4.5M tonnes) have been mined. The Snooks Arm arc and first phase of the continental Notre Dame arc are coeval and likely parts of a single arc system.

The Notre Dame arc formed during three distinct periods between c. 488 and 435 Ma, with the two significant magmatic gaps believed to represent collisional events (Whalen et al., 2003). The first phase is represented by c. 488-477 Ma granodiorite to diorite plutons (Dubé et al., 1996). Arenig collision between Dashwoods and the Humber margin (Waldron and van Staal, 2001) led to a c. 10 m.y. gap in magmatism. The second phase of the Notre Dame arc peaked from 464-456 Ma with a major flare-up of tonalite intrusions (Whalen et al., 1997). The third phase, mainly represented by calc-alkaline gabbro to quartz diorite that lasted from 445 to 435 Ma (Whalen, 1989) was caused by west-directed subduction of Exploits back-arc oceanic lithosphere beneath Laurentia (van Staal, 1994). There is no known significant mineralization in the infrastructure of the Notre Dame arc in Newfoundland.

The Arenig – Llanvirn (480-462 Ma) Annieopsquotch Accretionary Tract (Fig. 1: AAT; Zagorevski et al., 2006) comprises a tectonic collage of c. 480-473 Ma infant arc ophiolite (e.g., Annieopsquotch ophiolite belt), arc – back-arc terranes (e.g., Buchans – Robert's Arm belt) that formed as a result of west-directed subduction outboard of Dashwoods (Fig. 2). No VMS deposits are known in the c. 480 Ma Annieopsquotch ophiolite belt of the AAT. The 473 to 464 Ma Buchans – Robert's Arm Belt is host to the important Buchans VMS deposits, which yielded 16,196,876 tonnes of high grade ore (14.51% Zn, 7.56% Pb, 1.33% Cu, 126g/t Ag and 1.37g/t Au) during mining between 1928 and 1984 (Thurlow, 1990). Pilley's Island, Gullbridge (3M tonnes at 1.1% Cu), Lake Bond and Shamrock are other examples of VMS deposits in this arc sequence (Swinden and Dunsworth, 1995). The Buchans arc was rifted during the Middle Ordovician, which led to opening of the small Skidder back-arc basin at c. 465 Ma. The ensimatic Skidder basalt is host to a cupriferous VMS deposit with reserves of c. 200,000 tonnes grading c. 2% Cu and 2% Zn.

## EXPLOITS SUBZONE

The Exploits Subzone is exposed in Newfoundland, between the Red Indian and Gander River Ultrabasic Belt (GRUB) lines. The c. 514 to 486 Ma, peri-Gondwanan Penobscot arc – back-arc produced the oldest Iapetean volcanic rocks in the Exploits Subzone (Colman-Sadd et al., 1992; van Staal et al., 1998). Penobscot arc rocks form part of the ensialic Victoria Lake Supergroup (Rogers et al., 2006) and are restricted to the western portion of the Exploits Subzone (Fig. 1). Related back-arc ophiolitic rocks (GRUB, Coy Pond and Pipestone Pond complexes) are Upper Cambrian (c. 494 Ma; Dunning and Krogh, 1985) and are restricted to the eastern Exploits Subzone, localized along the faulted boundary with the Middle Cambrian - Upper Tremadoc arenites and shales of the Gander Zone that were deposited on the leading edge of the Gander margin (van Staal, 1994). Penobscot arc - back-arc volcanic rocks also occur in New Brunswick (Fig. 1) in the 497-493 Ma Annidale

(McLeod et al., 1992) and New River belts (Johnson and McLeod, 1996).

The oldest known VMS deposits of the Exploits Subzone occur in the Lower Cambrian (c. 513 Ma) Tally Pond volcanic rocks of the Victoria Lake Supergroup. These include the Duck Pond, Boundary and Burnt Pond deposits, of which the Duck Pond has reserves of c. 4.3M tonnes grading 3.58% Cu, 6.63% Zn, 1.05% Pb, 68.31g/t Ag, and 1g/t Au. A slightly younger phase of the Penobscot arc is represented by the predominantly felsic volcanic rocks of the c. 498 Ma Tulks Group, which hosts the Tulks Hill, Tulks East, Daniel's Pond, Bobby Pond and Victoria Mine VMS deposits. The economically most important, the Tulks Hill deposit, contains 750,000 tonnes grading 6% Zn, 2% Pb, 1.3% Cu, 41g/t Ag and 0.4g/t Au. Early Tremadoc (488-485 Ma) volcanic rocks of the Pats Pond (Victoria Lake Supergroup), Wild Bight and Exploits groups represent the youngest phase of the Penobscot arc. These sequences contain a number of VMS deposits, of which the rhyolite hosted Point Leamington deposit is the largest (13.8M tonnes at 1.92% Zn, 0.48% Cu, 18.1g/t Ag, and 0.9g/t Au).

The Arenig Penobscot complex and Gander margin sedimentary rocks are locally overlain by the Middle Ordovician Popelogan – Victoria arc and Tetagouche – Exploits back-arc rocks (van Staal and Williams, 1991). The abundant 478 to 545 Ma volcanic rocks of the western portion, which form the post-Tremadoc parts of the Victoria Lake Supergroup, and Wild Bight and Exploits groups in Newfoundland, and the Balmoral and Meductic groups and Bathurst Supergroup in New Brunswick (van Staal et al., 1998; 2003), are the remnants of its active margin. Whereas the largely sedimentary rocks east of the Davidsville, Baie d'Espoir, Bay du Nord and Harbour le Cou groups in Newfoundland (Valverde-Vaquero et al., in press), and the Meductic and upper part of the Cookson Group in New Brunswick (van Staal et al., 2003) form the passive margin of the Tetagouche – Exploits back-arc (Fig. 1, 2).

The Popelogan – Victoria arc has no significant VMS mineralization, although related calc-alkaline plutons in New Brunswick do host some Cu-Mo-Au porphyry mineralization. Economically important VMS deposits are abundant in the associated Tetagouche – Exploits back-arc basin, in both New Brunswick and Newfoundland. In New Brunswick these include the economically very important VMS deposits of the Bathurst Mining Camp (van Staal et al., 2003). The giant Brunswick No. 12 Mine contained 229M tonnes of ore grading 7.66% Zn, 3.01% Pb, 0.46% Cu, 91 ppm Ag and 0.46% Au. In Newfoundland these deposits include the Strickland (260,000 tonnes grading 5.25% combined Pb and Zn), Facheux Bay and the Barasway de Cerf deposits, hosted by the Bay du Nord and Baie d'Espoir groups. These VMS deposits, hosted by ensialic back-arc volcanic rocks, formed on continental crustal blocks and are relatively Pb-rich. Those hosted by ensimatic mafic volcanic rocks, representing remnants of back-arc oceanic crust, are Cu-rich. The Great Burnt Lake deposit (680,000 tonnes at 3% Cu) hosted by oceanic basalts of the Cold Spring Pond Formation, Newfoundland and the Turgeon deposits (up to 2M tonnes at 4% Zn and 1.5% Cu) hosted by the ophiolitic Fournier Group in northern New Brunswick belong to this group.

### DISCUSSION: RELATING VMS DEPOSIT TYPE TO TECTONIC SETTING

The diversity of VMS deposit types represented within the CMB of New Brunswick and Newfoundland, in combination with the very detailed understanding of the regions tectonic evolution, makes this area ideal for relating deposit type to tectonic setting. A common feature of VMS deposits is that they are formed in extensional tectonic environments (Galley et al., in press). Although VMS depositional processes are observed on the modern seafloor at oceanic spreading centres (Herzig and Hannington, 1995), this setting is poorly preserved in the geological record because of subduction. Consequently the majority of VMS deposits are related to the more robust extensional tectonic settings (i.e., oceanic or continental nascent-arc, rifted arc and back-arc environments).

The restriction of VMS deposits to extensional tectonic environments is because these settings enable the development of focused hydrothermal systems due to the related effects of faulting, crustal thinning, mantle depressurization and the generation of magma. Other tectonic environments can also induce hydrothermal systems (i.e., compressional arcs such as the Andes); however these are not suitable for VMS development as they do not provide a mechanism for sulphide preservation. The crustal composition along with its thickness and density determines the nature of magmatism (i.e., mafic, bimodal, etc.) and sedimentation; thus, the nature of the hydrothermal cells which are set-up and also the type of VMS deposited.

Irrespective of whether a VMS deposit is classified by metal content, as per the schemes of Franklin et al. (1981) or Large (1992), or by the dominant host-rock lithology (Barrie and Harrington, 1999), the underlying control is the tectonic setting. For example, a VMS deposit within an ophiolite, is necessarily hosted by a sequence dominated by mafic lithologies. The high heat-flow within this environment results in a high-temperature convection system that produces Cu-rich deposits. Furthermore, as Pb is concentrated in continental crust, it is not present in significant amounts within an ophiolitic sequence and thus this type of VMS is Pb-poor.

A number of distinct extensional settings occur within arc – back-arc systems, each of which produces a specific suite of volcanic rocks. A fore-arc spreading centre is typified by mafic and/or mafic-dominated bimodal volcanism. This type of setting includes both suprasubduction zone ophiolites and incipient arc volcanism. An extensional arc is typified by felsic-siliciclastic dominated bimodal sequences, whereas the more evolved intra-arc rifting produces mafic – siliciclastic bimodal volcanic rocks. An early back-arc setting can often be considered as an extension of intra-arc rifting and thus is associated with similar lithologies; however, this setting may also include continental crustal blocks that caught-up within a back-arc, and this tends to produce more felsic dominated bimodal volcanic sequences. The final extensional setting is a fully developed back-arc, which is typified by mafic volcanism.

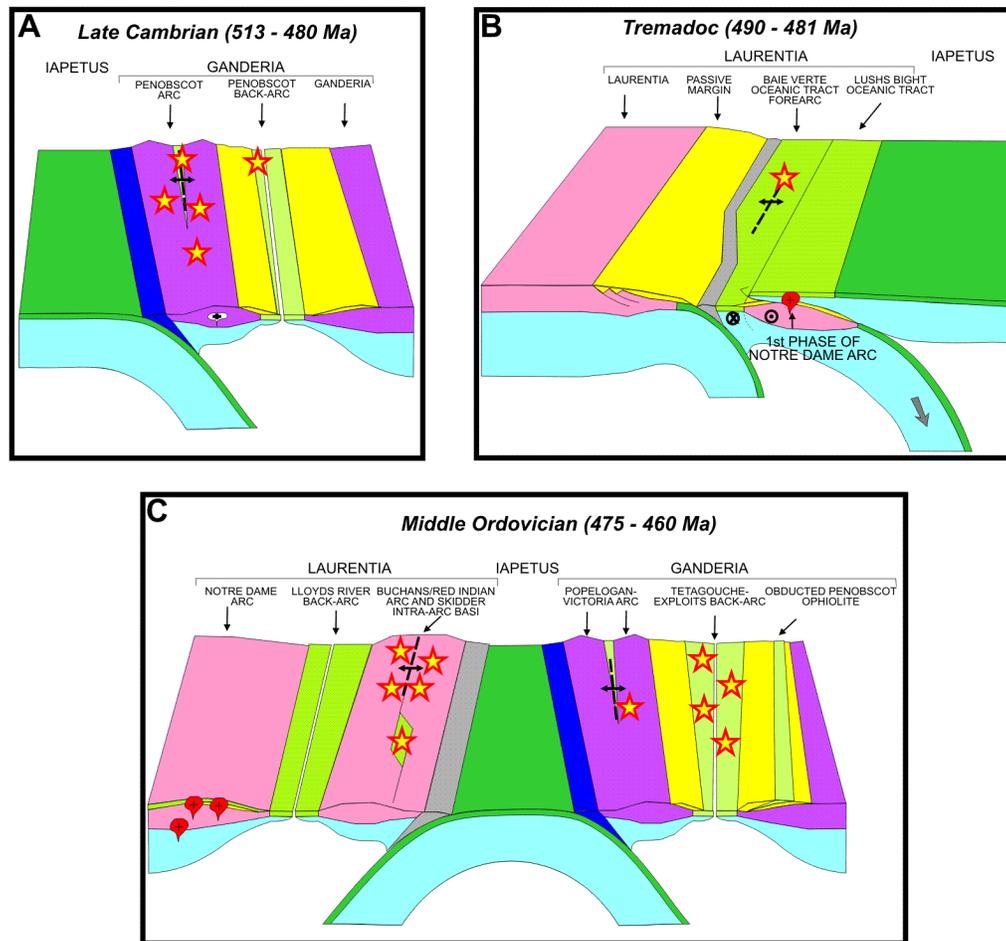
The Appalachians represents a complex orogen characterized by development of multiple Cambro-Ordovician

arc systems and marginal basins forming on both sides of Iapetus (Fig. 2). The closure of these multiple oceanic basins resulted in multiple orogenic episodes and complex structural histories. A consequence of this is that the extensional settings that host VMS deposits occur repeatedly over time and space within the CMB.

Not all extensional events have VMS mineralization associated with them (Fig. 2). In some circumstances the absence of VMS can be related to regional environmental effects that prevent deposition. For example, a wholly oxygenated water column is not conducive to VMS deposition even if a suitable hydrothermal system were present as the base metals in the fluids are converted to soluble oxides and not preserved. Such circumstances do not however explain why contemporaneous extensional environments (whether part of a single arc – back-arc system or across several distinct, but coeval subduction systems) can in one case be VMS-bearing when other extensional terranes are barren of deposits. For example, the ophiolitic sequences of the BVOT and Annieopsquotch ophiolite belt both formed at c. 480 Ma in peri-Laurentian marginal basins, but only the BVOT contains VMS mineralization. Similarly the peri-Gondwanan VMS deposits of the Penobscot arc – back-arc system are restricted to the arc volcanic sequences (i.e., the Duck Pond and Tulks deposits, Victoria Lake Supergroup). This is in stark contrast to the younger arc – back-arc system that dissects and overlies the Penobscot arc and back-arc, where the distribution of VMS formation is reversed. In this case the Popelogan – Victoria arc is effectively devoid of any significant VMS mineralization, whereas the Tetagouche – Exploits back-arc has numerous major deposits, such as the world-class Brunswick No. 12 mine.

In each of these above examples the constraining factor that dictates where VMS mineralization occurs is the rate of extension. The barren Annieopsquotch ophiolite belt was formed under conditions of very rapid extension (Lissenberg et al., 2005), in comparison to the BVOT has many VMS deposits, and underwent slower extension (Bédard et al., 2000). This relationship to extensional rate and VMS formation is repeated within each of the arc – back-arc systems observed within the CMB of New Brunswick and Newfoundland. This is believed to be a result of a relatively restrictive set of circumstances that are conducive to VMS formation. Thus an extensional arc – back-arc system that is experiencing rapid slab roll-back and is conducive to VMS formation in intra-arc rift zones, as opposed to back-arc (i.e., the Penobscot arc). Where the extension is slower the opposite situation applies and it is the back-arc that is liable to contain VMS deposits (i.e., the Victoria – Popelogan arc/Tetagouche – Exploits back-arc).

The likely reasons for these relationships are that an environment that is experiencing very rapid extension is not able to support the large-scale long-lived convection system required to produce economically significant VMS formation. In contrast the regions with slower extension rates are not conducive to VMS formation as the required convective system is not established; this can be due to insufficient heat-flow where the rate of volcanism is low, or the convection cells being too restricted in size and duration if the rate of volcanism is high.



**Figure 2:** Tectono-stratigraphic setting of major VMS terranes in the Canadian Appalachians. A: Late Cambrian to Early Ordovician Penobscot arc – backarc system; B: Early Ordovician Baie Verte Oceanic Tract; and C: Middle Ordovician Popelogan – Victoria arc – Tetagouche – Exploits back-arc system and Annieopsquotch Accretionary Tract (after van Staal, in press).

## CONCLUSION

The potential for the formation of a VMS deposit is dependant on many parameters that are fundamentally linked with tectonic processes. Irrespective of whether the type of VMS is classified by the metal content or dominant host lithology, the controlling factor is the tectonic setting within which the VMS was formed, as this is what dictates the range of volcanic and/or sedimentary rocks that occur in a sequence. The first order constraints are that the tectonic setting must be extensional and that the global palaeoenvironmental conditions allow for preservation of sulphides. The second order constraints are the ones that dictate where mineralization may occur within an extensional system that can form a VMS deposit. Second order constraints include the rate of volcanism that can control whether a suitable convection system can form. These also include the overall rate of extension of an arc – back-arc system, as is demonstrated from the CMB. In these cases the rapidly extending systems form VMS in the arc, whereas the slower ones develop VMS deposits in the back-arc.

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