



**PROCEEDINGS OF THE 24<sup>TH</sup>  
INTERNATIONAL APPLIED GEOCHEMISTRY SYMPOSIUM  
FREDERICTON, NEW BRUNSWICK, CANADA**



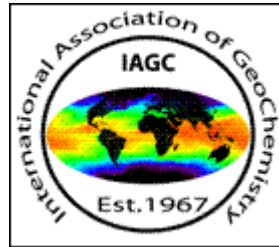
**JUNE 1<sup>ST</sup>-4<sup>TH</sup>, 2009**

**EDITED BY**

**DAVID R. LENTZ, KATHLEEN G. THORNE, & KRISTY-LEE BEAL**



**VOLUME I**



All rights reserved.  
This publication may not be reproduced in whole or in part, stored in a retrieval system or transmitted in any form or by any means without permission from the publisher.

ISBN 978-1-55131-136-4

©2009 AAG

**PROCEEDINGS OF THE 24<sup>TH</sup>  
INTERNATIONAL APPLIED GEOCHEMISTRY SYMPOSIUM  
FREDERICTON, NEW BRUNSWICK  
CANADA  
JUNE 1<sup>ST</sup>-4<sup>TH</sup>, 2009**

**EDITED BY**

**DAVID R. LENTZ  
KATHLEEN G. THORNE  
KRISTY-LEE BEAL**

**VOLUME I**



<b>NORTH ATLANTIC MINERALS SYMPOSIUM .....</b>	<b>501</b>
Mass change constraints and hydrothermal alteration of felsic volcanic rocks that host the Restigouche Volcanogenic Massive Sulfide Deposit, Bathurst Mining Camp, New Brunswick, Canada .....	503
<i>Amanuel Bein<sup>1</sup> &amp; David R. Lentz<sup>1</sup></i> .....	503
Results of 2008 exploration program Mount Pleasant Property: geochemistry, mineralogy, and deposit modeling of Sn-In and WO <sub>3</sub> -MoS <sub>2</sub> zones .....	507
<i>Trevor Boyd<sup>1</sup> &amp; Gustaaf Kooiman<sup>1</sup></i> .....	507
The Nash Creek Zn–Pb–Ag deposit, Tobique –Chaleurs Zone, New Brunswick, Canada .....	511
<i>Derek Brown<sup>1</sup> &amp; James Walker<sup>2</sup></i> .....	511
The Williams Brook gold discovery – northern New Brunswick .....	515
<i>Heather Campbell<sup>1</sup> &amp; Art Hamilton<sup>1</sup></i> .....	515
Age constraints and Grampian orogenesis of the Lower to Middle Ordovician Tyrone Igneous Complex, Northern Ireland .....	519
<i>Mark R. Cooper<sup>1</sup>, Quentin G. Crowley<sup>2,3</sup>, David M. Chew<sup>3</sup>, Steve P. Hollis<sup>4</sup> &amp; Stephen R. Noble<sup>2</sup></i> .....	519
Molybdenum and tungsten mineralization associated with late-stage granitoid magmatism in the Appalachian Orogen of Newfoundland: an overview and a summary of recent developments.....	523
<i>Andrew Kerr<sup>1</sup>, Tim van Nostrand<sup>1</sup>, Lawson Dickson<sup>1</sup>, &amp; Edward Lynch<sup>2</sup></i> .....	523
Distribution and geochemistry of Cu-rich massive sulfides at the Brunswick No. 12 Deposit, Bathurst Mining Camp, New Brunswick. ....	527
<i>Sean H. McClenaghan<sup>1</sup>, David R. Lentz<sup>2</sup>, &amp; Erin M. Powe<sup>2</sup></i> .....	527
Litho-geochemistry of Ordovician Sedimentary Rocks: Implications for VMS Exploration in the Bathurst Mining Camp (BMC), Canada .....	531
<i>Steven R. McCutcheon<sup>1</sup> &amp; James A. Walker<sup>1</sup></i> .....	531
Evaluating Bromine Geochemistry as a Prospecting Tool For Potash in Western Newfoundland	535
<i>Jackie O' Driscoll<sup>1</sup>, Robert Boehner<sup>2</sup>, Lawrence Winter<sup>1</sup> &amp; Roland Butler<sup>1</sup></i> .....	535
Mesothermal, auriferous quartz veins of the Golden Promise deposit, central Newfoundland: their setting and the nature of wall rock alteration .....	539
<i>Hamish Sandeman<sup>1</sup>, Heather Rafuse<sup>1</sup>, David Copeland<sup>2</sup> and Jeff Morgan<sup>3</sup></i> .....	539
Cathodoluminescence: A tool to discriminate the tectonic history in gold-bearing veins in the Brunswick Subduction Complex, Canada.....	543
<i>Sabine Schwarz<sup>1</sup>, David Lentz<sup>1</sup>, &amp; James Walker<sup>2</sup></i> .....	543
Ireland's historic mine sites inventory .....	547
<i>Gerry Stanley<sup>1</sup>, Eibhlin Doyle<sup>1</sup>, Vincent Gallagher<sup>1</sup>, Fionnuala Ni Mhairtin<sup>1</sup>, &amp; Jane Brogan<sup>2</sup></i> .....	547
Metallogeny of the gold-enriched Cambro-Ordovician rocks in the Annidale area, south-central New Brunswick, Canada.....	551
<i>Kathleen G. Thorne<sup>1</sup>, Susan C. Johnson<sup>2</sup>, Malcolm J. McLeod<sup>2</sup>, &amp; Leslie R. Fyffe<sup>1</sup></i> .....	551
Early Devonian felsic volcanic rocks and associated Zn–Pb mineralization, Tobique–Chaleurs Zone, New Brunswick, Canada.....	555
<i>James A. Walker<sup>1</sup></i> .....	555
Sulfide petrology and geochemistry of the Key Anacon Main Zone and East Zone massive sulfide deposits, Bathurst Mining Camp, NB, Canada .....	559
<i>Joseph D.S. Zulu<sup>1</sup>, David R. Lentz<sup>1</sup>, &amp; James A. Walker<sup>2</sup></i> .....	559

TECHNICAL EDITORS  
*(Listed in alphabetical order)*

Mark Arundell  
U. Aswathanarayana  
Roger Beckie  
Chris Benn  
Robert Howell  
Charles Butt  
Bill Coker  
Hugh deSouza  
Sara Fortner  
David Gladwell  
Wayne Goodfellow  
Eric Grunsky  
William Gunter  
Gwendy Hall  
Jacob Hanley  
Russell Harmon  
David Heberlein  
Brian Hitchon  
Andrew Kerr  
Dan Kontak  
Kurt Kyser

David Lentz  
Ray Lett  
Matthew Leybourne  
Steven McCutcheon  
Beth McClenaghan  
Nancy McMillan  
Paul Morris  
Lee Ann Munk  
Dogan Paktunc  
Roger Paulen  
Ernie Perkins  
David Quirt  
Andy Rencz  
David Smith  
Cliff Stanley  
Gerry Stanley  
Nick Susak  
Bruce Taylor  
Ed Van Hees  
James Walker  
Lawrence Winter

## **NORTH ATLANTIC MINERALS SYMPOSIUM**

EDITED BY:

**ANDREW KERR  
GERRY STANLEY  
LAWRENCE WINTER  
STEVE McCUTCHEON**



## Mass change constraints and hydrothermal alteration of felsic volcanic rocks that host the Restigouche Volcanogenic Massive Sulfide Deposit, Bathurst Mining Camp, New Brunswick, Canada

Amanuel Bein<sup>1</sup> & David R. Lentz<sup>1</sup>

<sup>1</sup>Department of Geology, University of New Brunswick, 2 Bailey Drive, Fredericton, New Brunswick, E3B 5A3 CANADA (e-mail: [u3x30@unb.ca](mailto:u3x30@unb.ca))

**ABSTRACT:** An immobile-element lithochemical study of the volcanic rocks that host the Restigouche volcanogenic massive sulfide (VMS) deposit in the Bathurst Mining Camp (BMC) discriminated seven geochemical units (A, B, C, D, E, F, and G). The units are stratigraphically in ascending order and the massive sulfide horizon occurs between units A-D and A-E. Hydrothermal alteration of these tholeiitic, transitional, and transitional-calc-alkaline volcanic rocks is characterized by general additions of MnO, MgO, Fe<sub>2</sub>O<sub>3</sub>, LOI (H<sub>2</sub>O), Zn, Ga, and Pb, and loss of Na<sub>2</sub>O, SiO<sub>2</sub>, and Ba. K<sub>2</sub>O, and CaO are leached from the footwall sequence, but CaO is enriched in the hanging wall. Using constant Al<sub>2</sub>O<sub>3</sub> with the isocon method of Grant (1986), the study demonstrates the immobile nature of TiO<sub>2</sub>, Zr, Nb, Y, Nd, and Th. Net mass loss in units B, C, D, F, and G and mass addition in the sulfide horizon between A and E are consistent with hydrothermal alteration and mineralization processes that formed the Restigouche VMS deposit. Also, compositional additions and losses of various components are attributed to chlorite, sericite, and carbonate alterations of the host rocks.

**KEYWORDS:** *Restigouche, massive sulfide, immobile elements, Isocon method, hydrothermal alteration*

### INTRODUCTION

The Restigouche massive sulfide deposit is located in the northwestern part of the Bathurst Mining Camp (BMC), 60 km west of the city of Bathurst, northern New Brunswick. The property is currently controlled by Blue Note Mining and the company reports show that the deposit has an estimated reserve of 1.3 Mt grading 6.53% Zn, 5.05% Pb, and 99.6g/t Ag as of 2007 (Art Hamilton, pers. communication).

The present study was commenced in order to define the geological and lithochemical characteristics of the volcanic rocks hosting the Restigouche deposit. Using lithochemical techniques, the first phase of this study discriminated hydrothermally altered volcanic rocks that host the Restigouche deposit into 7 geochemical groups, with chemostratigraphic significance (Bein & Lentz 2009). The second part of this lithochemical study involved mass

change calculations for 92 samples from the 7 geochemical groups.

### GEOLOGICAL SETTING

The Ordovician felsic volcanic pile that hosts the Restigouche massive sulfide deposit in the BMC is composed of 7 geochemically distinct groups; A, B, C, D, E, F, and G (Bein & Lentz 2009). The units A, B, C, D, E, and F are in stratigraphically ascending order and each group consists of hydrothermally altered effusive and volcanoclastic rhyodacitic-dacitic rocks of tholeiitic, transitional, transitional-calc-alkaline magmatic nature. The massive sulfide lens occurs between footwall unit A and hanging wall units D and E. Finlow-Bates & Stumpfl (1981) described that the felsic volcanic rocks that host the Restigouche VMS deposit are intensely altered to levels, where the normally immobile element Nb acted as a mobile component.

**HYDROTHERMAL ALTERATION**

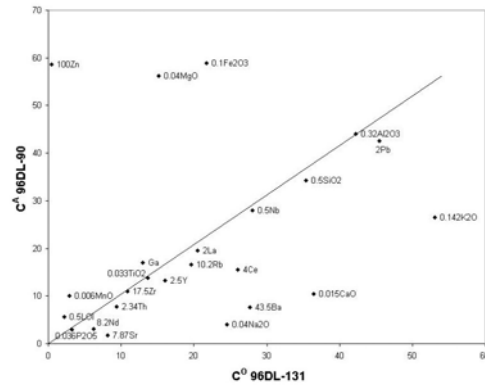
**Methodology**

XRF lithochemical analysis of 124 diamond drill core samples was performed at the Department of Geology, University of Ottawa. Accuracy and precision of the analysis is demonstrated by 9 runs for selected major and trace elements in a rhyolitic standard (RHY-94, Lentz 1995). The first step was selection of a least-altered sample for each of the 7 geochemical units. Least-altered samples were selected based on comparison of the lithochemical data of samples from the Restigouche deposit and composition of fresh felsic volcanic rocks. Based on arguments provided by Leitch & Lentz (1994) and coinciding syngenetic hydrothermal and post-hydrothermal metamorphic conditions of the Restigouche deposit, Al<sub>2</sub>O<sub>3</sub> is considered as the most immobile component. Also, Al<sub>2</sub>O<sub>3</sub> shows high Pearson Product correlation coefficients ( $r > 0.90$ ) with TiO<sub>2</sub>, Zr, and Nb and thus it can be considered as an immobile component. Thus the constant Al<sub>2</sub>O<sub>3</sub> Isocon method of Grant (1986) is used to demonstrate immobility of immobile elements and compositional changes of the hydrothermally altered volcanic rocks. Relation between compositional and mass changes is demonstrated using the procedures Barrett and Maclean (1999) used for a rhyolite unit that host the Phelps Dodge VMS deposit in Matagami, Quebec.

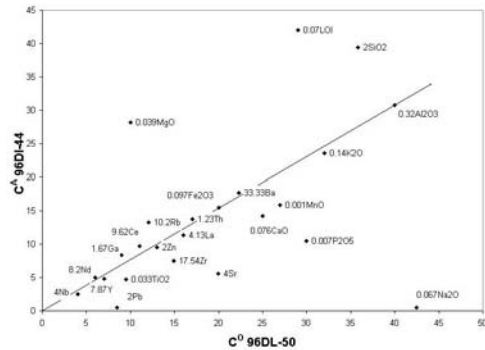
**Immobile Elements**

Isocon plot and mass balance calculations of altered samples from the Restigouche deposit demonstrated that TiO<sub>2</sub>, Zr, Nb, Y, Nd, and Th are immobile. Isocon plot of selected samples from the 7 geochemical units from the study area are shown in Figures 1-7. Yttrium, Nd, and Th show slight mobility in some samples, but considering the accuracy and precision parameters of the analysis they can still be considered as immobile components. Gallium shows some mobility, whereas La and Ce are moderately mobile. SiO<sub>2</sub>, Fe<sub>2</sub>O<sub>3</sub>, MnO, MgO, CaO, Na<sub>2</sub>O, K<sub>2</sub>O, and LOI are extremely mobile, and they are

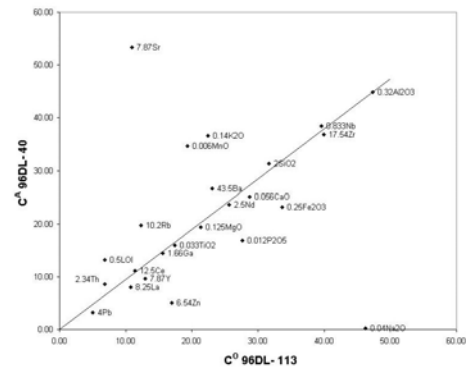
either added or leached. P<sub>2</sub>O<sub>5</sub> is moderately mobile with strong affinity of immobility in some samples (Figs. 3-7). Zn, Rb, Sr, Ba, and Pb are also mobile components.



**Fig. 1.** Scaled Isocon plot of sample 96DL-90 from unit A.



**Fig. 2.** Scaled Isocon plot of sample 96DL-44 from unit B.



**Fig. 3.** Scaled Isocon plot of sample 96DL-40 from unit C.

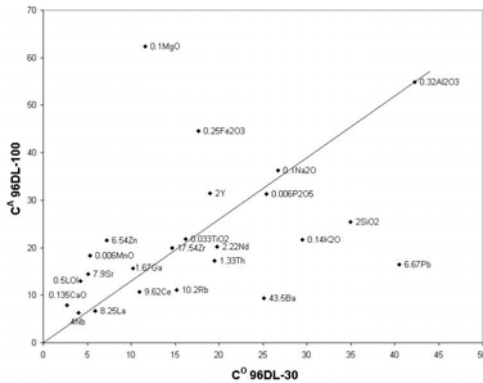


Fig. 4. Scaled Isocon plot of sample 96DL-100 from unit D.

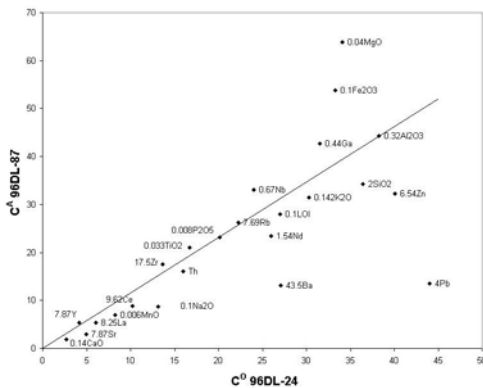


Fig. 5. Scaled Isocon plot of sample 96DL-87 from unit E.

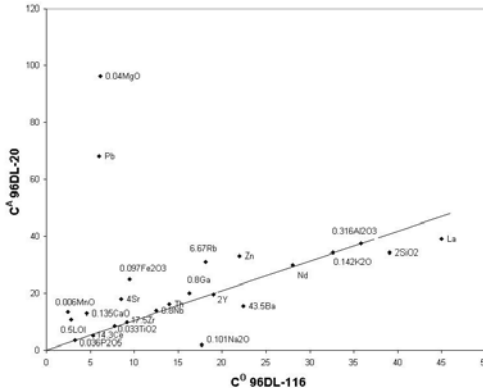


Fig. 6. Scaled Isocon plot of sample 96DL-20 from unit F.

**Compositional and Mass Change**

Compositional mass change calculations confirmed that both the hanging wall and footwall volcanic rocks that host the

Restigouche deposit are altered. General additions of MnO, MgO, Fe<sub>2</sub>O<sub>3</sub>, LOI (H<sub>2</sub>O), Zn, Ga, and Pb, and losses of Na<sub>2</sub>O, SiO<sub>2</sub>, and Ba characterize the hydrothermal alteration of the felsic geochemical units A, B, C, D, E, F, and G.

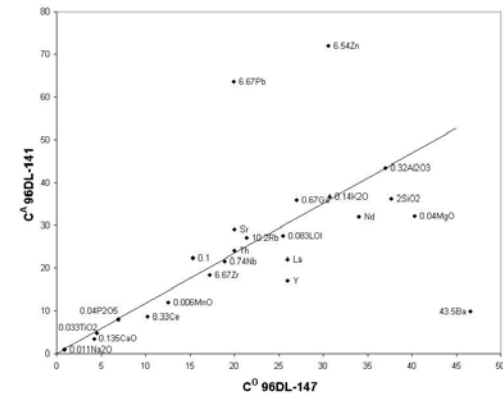


Fig. 7. Scaled Isocon plot of sample 96DL-141 from unit G.

The hydrothermal alteration is characterized by 2-31%, 1.5-5.5%, 0.7-8.3%, 2-21% and 0.3-10% mass loss of units A, B, C, F, and G and 0.6-6% and 2.4-13.4% mass addition in units A and E. 0.3-3.5, 0.3-2.4, 0.1-3.6, 0.2-1.1, and 0.1-3.4 wt.% MgO is added to units A, B, D, E, and F. 0.8-9, 1.8-3.8, 1-3.6, and 0.24-3 wt.% Fe<sub>2</sub>O<sub>3</sub> additions are also noted in units A, B, E, and F. However, 0.01-1.4 and 0.02-0.91 wt.% MgO losses from units C and G and 0.08-4.2 and 0.53-4 wt.% Fe<sub>2</sub>O<sub>3</sub> losses from units C and D are marked. 0.001 and 0.02-0.005 wt.% MnO is leached from units B and C, whereas 0.01-0.14, 0.002-0.084, 0.004-0.13, 0.001-0.11 and 0.01-0.5 wt.% MnO is added to units A, D, E, F, and G, respectively. 3-5581, 19-67, 3-99, 158-679, 2-67, 201-782 ppm Zn and 2-20, 1-3, 1-4, 2-8, 1-4, and 1-7 ppm Ga additions into units A, B, D, E, F, and G are also observed. However, 13-82 and 1-4 ppm Zn and Ga losses are marked in unit C. LOI (H<sub>2</sub>O) addition to all the units is characteristic. Lead is generally added on the levels of 9-2584, 4-53, 109-1068, and 16-322 ppm in units A, B, E, and F, but the component is leached from unit C, D and G on the level of 6-19, 32-269, and 17-132 ppm

respectively. Some samples from unit C and D show Pb enrichment on the levels of 22-228 and 601-705 ppm. Prominent leaching of SiO<sub>2</sub> and Na<sub>2</sub>O characterize all the 7 geochemical units except that substantial samples from unit A show 5-32 wt.% SiO<sub>2</sub> enrichment and unit G show 0.02-1.1 wt.% addition of Na<sub>2</sub>O. 4-8, 6-23, 9-24, 7-35, 9-41, 3-42, and 4-38 wt.% losses of SiO<sub>2</sub> in units A, B, C, D, E, F, and G and 0.6-1.3, 0.02-2.8, 0.8-1.84, 0.2-2.7, and 0.4-8 wt.% loss of Na<sub>2</sub>O in units A, B, C, D, E, and F, are observed. General loss of Ba is also characteristic in units A, B, D, E, F, and G where 428-1024, 115-285, 16-792, 158-865, 67-719, and 529-1716 ppm Ba leaching is observed. However, 55-573 ppm Ba enrichment in unit C is noted. 0.74-5.6, 0.2-2.9, 0.13-2.63, and 0.7-3.2 wt.% K<sub>2</sub>O is lost from units A, B, D, and G. 0.1-3 wt.% K<sub>2</sub>O is added to unit C and K<sub>2</sub>O is both added and lost in samples of units E and F where enrichment can reach as much as 0.7-1.3 and 0.03-1.2 wt.% respectively. 0.1-0.5, 0.5-1.2, and 0.13-1 wt.% CaO losses in the footwall units A, B, C and D and on the other hand 0.1-1.8 and 0.01-2.5 wt.% CaO additions in the hanging wall units E and F are also marked.

## CONCLUSIONS

This study has revealed that;

- (1) Despite the intense hydrothermal alteration of the volcanic rocks that host the Restigouche VMS deposit, immobility of TiO<sub>2</sub>, Zr, Nb, Y, Nd, and Th is demonstrated using the Isocon method of Grant (1986).
- (2) Both the hanging wall and footwall volcanic rocks are altered and it is confirmed that MnO, MgO, Fe<sub>2</sub>O<sub>3</sub>, LOI (H<sub>2</sub>O), Zn, Ga, and Pb are generally added to the rocks, whereas Na<sub>2</sub>O, SiO<sub>2</sub>, and Ba are leached. Leaching of Na<sub>2</sub>O from units A, B, C, D, E, and F and of CaO from footwall units A, B, and C, and addition of MgO to A, B, D, E, and F, Fe<sub>2</sub>O<sub>3</sub> to footwall units A and B, and K<sub>2</sub>O to units C, E, and F can be attributed to breakdown of feldspar and sericitization

and chloritization of the volcanic rocks. Besides, leaching of K<sub>2</sub>O and CaO from the footwall units accompanied by their respective addition in the hanging wall units is consistent with sericitization and carbonitization of the rocks which is reported in Bein and Lentz (2009). Fe<sub>2</sub>O<sub>3</sub> enrichment to the sulfide horizon between unit A and E and the hanging wall units E and F is related to chloritization of the footwall and siderite (carbonate) alteration of the hanging wall.

## ACKNOWLEDGEMENTS

We acknowledge Blue Note Mining and NB Department of Natural Resources for their assistance and support during the course of the study.

## REFERENCES

- BARRETT, T.J. & MACLEAN, W.H. 1999. Volcanic Sequences, Lithogeochemistry, and Hydrothermal Alteration in Some Bimodal Volcanic-Associated Massive Sulfide Systems. *Reviews in Economic Geology*, **8**, 101-131.
- BEIN, A. & LENTZ, D.R. 2009. Immobile Element Lithogeochemistry of felsic volcanic rocks hosting the Restigouche Volcanogenic Massive Sulfide Deposit, Bathurst Mining Camp, New Brunswick Canada. Proceedings of IAGS 2009.
- FINLOW-BATES, T & STUMPFL, E.F. 1981. The Behaviour Of So-Called Immobile Elements In Hydrothermally Altered Rocks Associated With Volcanogenic Submarine-Exhalative Ore Deposits. *Mineralium Deposita*, **11**, 319-328.
- GRANT, J.A. 1986. The Isocon Diagram-A Simple Solution To Gresens' Equation For Metasomatic Alteration. *Economic Geology*, **81**, 1976-1982.
- LEITCH, C.H.B. & LENTZ, D.R. 1994. The gresen approach to mass balance constraints of alteration systems: methods, pitfalls, examples, In: LENTZ, D.R., (ed) *Alteration and Alteration processes associated with Ore-forming systems*, Geological Association of Canada, Short Course Notes, **11**, 161-192.
- LENTZ, D.R. 1995. Preliminary evaluation of six in-house rock geochemical standards from the Bathurst Camp, New Brunswick. *New Brunswick Department of Natural Resources and Energy*, Minerals and Energy Division, Miscellaneous Report **18**, p. 81-89.

## Results of 2008 exploration program Mount Pleasant Property: geochemistry, mineralogy, and deposit modeling of Sn-In and WO<sub>3</sub>-MoS<sub>2</sub> zones

Trevor Boyd<sup>1</sup> & Gustaaf Kooiman<sup>1</sup>

<sup>1</sup>Adex Mining Inc., Suite 1402, 67 Yonge St., Toronto, Ontario, Canada  
(e-mail: [tboyd@adexmining.com](mailto:tboyd@adexmining.com))

**ABSTRACT:** During 2008, the Mount Pleasant Mine Property owned by Adex Mining Inc. underwent a major exploration program comprising extensive diamond drilling plus the additional re-sampling of material stored on-site from previous drill programs on the property. In addition, samples of the multi-metal porphyry mineralization from different zones on the property were chosen for quantitative mineralogical characterization.

The geochemical analyses generated from this program were compiled and incorporated into a computer database with the purpose of generating regulatory compliant physical deposit models and resource estimates of the mineralized bodies for both the Sn-In-Zn-Cu and WO<sub>3</sub>-MoS<sub>2</sub>-Bi zones on the property. In this presentation, Adex Mining discusses the results of the program and its context with respect to better understanding and integrating the geochemical and mineralogical variations within and among the zones. The purpose is to update and improve the evolving economic geology model of the polymetallic mineralization hosted on the property.

**KEYWORDS:** tungsten, tin, indium, quantitative mineralogy, porphyry mineralization

### INTRODUCTION

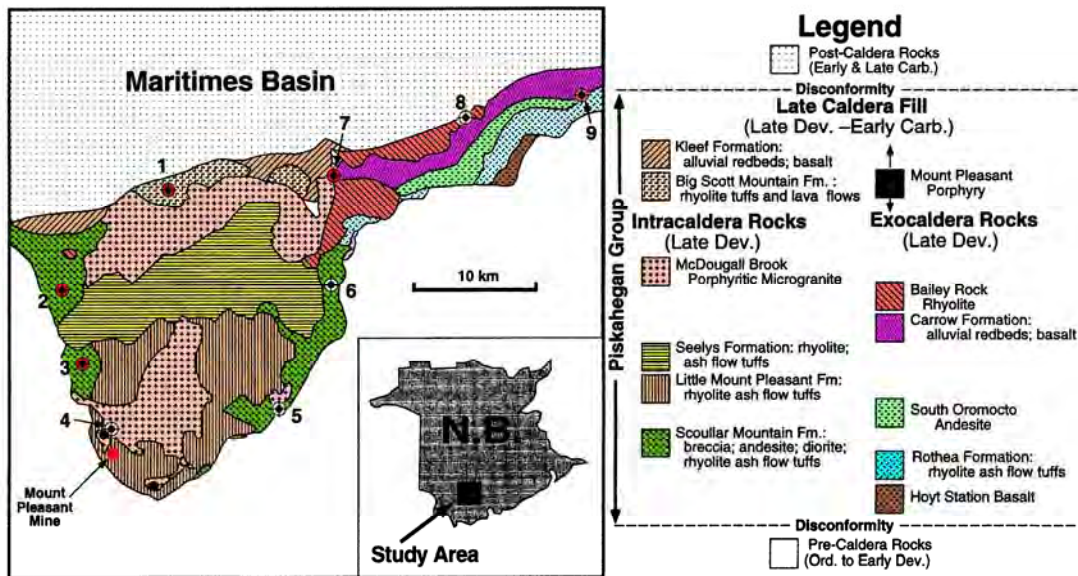
The Mount Pleasant Mine Property is located in Charlotte County, southwestern New Brunswick, Canada. The mineralization is divided into two main groups consisting of porphyry-type tungsten-molybdenum deposits, and vein and replacement-type tin polymetallic bodies. The deposits at Mount Pleasant are described in some detail in Kooiman *et al.* (1986) and Sinclair *et al.* (2006). Their petrogenetic character is discussed in Yang *et al.* (2003), Inverno & Hutchinson (2006) and Sinclair *et al.* (2007).

This presentation is an updated review of the economic geology at Mount Pleasant based upon our recent exploration results. There has been a resurgence of interest in these deposit types with the recent recovery of W, Mo, and Sn metal prices. Economic interest in the Mount Pleasant deposits has been heightened due to its hosting of metals that are increasingly important in high technology applications and medicine, such as indium and bismuth.

### GEOLOGICAL SETTING

The mineralized area lies within the Appalachian Orogen at the southwest margin of a Devonian caldera structure associated with the emplacement of multiple granitic intrusions (see Figure 1). The caldera rocks were emplaced in an anorogenic or post-collisional setting following the Acadian Orogeny and are bounded by highly deformed Ordovician and Silurian metasedimentary rocks and a late Silurian to Devonian granitic batholith (McLeod 1990).

Within the Mount Pleasant Mine Property, there are at least three stages of high-level, fine-grained to porphyritic intrusions. The granitic bodies and related mineral deposits are found at three main areas referred to as the Fire Tower Zone, North Zone, and between them the Saddle Zone, which are aligned along a northerly direction for two kilometres. There is evidence that the three zones are joined along a single continuously mineralized trend.



**Fig. 1.** Location of the Mount Pleasant W-Mo and Sn-Zn-In deposit, within the Late Devonian Caldera, southwestern New Brunswick (after McCutcheon 1990).

The W-Mo mineralization containing significant Bi, but negligible amounts of indium, is hosted by the early Granite I intrusion. The later Granite II intrusion hosts polymetallic tin mineralization that has indium grades of at least equal metal value to the Sn content, plus significant concentrations of Zn, Cu and Bi. The earlier Granite I episode of mineralization mainly focused within the Fire Tower Zone. This zone was mined for tungsten from 1983 to 1985 by Billiton Canada. The later Granite II episode occurs predominantly within the North Zone, although both types are found throughout the mineralized trend. The youngest Granite III episode underlies the other two at depths of greater than 450 metres and remains largely unexplored.

## DISCUSSION

During 2008, 13,300 metres of diamond drilling and greater than 5,200 analyses of the core and historical samples were completed for WO<sub>3</sub>, MoS<sub>2</sub>, Sn, In, Zn, Cu, Pb, Bi, and As. An additional 1900 historical samples were analysed for Indium only (Boyd 2008). Seven samples obtained from a wide variety of

mineralization types throughout the property underwent quantitative mineralogical characterization including QEMSCAN analysis and semi-quantitative XRD. In addition, EPMA was carried out on selected sulfide and oxide minerals to quantify the distribution of indium within the deposit (Prout *et al.* 2008).

Geochemical analyses from approximately 1500 drill holes were entered into separate GEMCOM 3-D wireframe computer models for the Fire Tower Zone and North Zone and used to generate regulatory compliant mineral resource estimates broken down into sub zones for both types of the mineralized bodies. To date, the Fire Tower Zone reports an indicated resource of 13,489,000 tonnes at 0.33 wt.% WO<sub>3</sub>, 0.21 wt.% MoS<sub>2</sub>, 0.06 wt.% Bi, and 0.57 wt.% As (Dunbar & El-Rassi 2008). The modelling and resource estimation results for the North Zone remain pending. Most mineralized bodies require more delineation drilling to fully outline their limits and remain open laterally for exploration.

## CONCLUSIONS

Final interpretations of the 2008 program remain pending depending upon the completion of the deposit modelling and release of geochemical and mineralogical analyses. The following tentative conclusions are presented, which largely support and build upon earlier work completed on the property.

The geochemistry and setting of the mineralization varies with respect to depth, as well as with host rock type and intrusive episode. For the Granite I type deposits, there is considerable compositional variation among separate sub-zones, however, overall the mineralization is zoned with the MoS<sub>2</sub> content and MoS<sub>2</sub>/WO<sub>3</sub> ratio increasing and As content decreasing with depth from 200 to 450 metres, especially within the Fire Tower Zone.

For the Granite II type deposits, the deeply (300–450 metres) emplaced Sn-bearing mineralization is largely controlled by the primary fracturing of the host granitic rocks. The deposits at these levels are Sn rich with relatively low indium and base-metal contents. Toward the surface, the setting of the Sn mineralization changes, becoming increasingly controlled and confined by erratically emplaced replacement-type narrow veins or “lodes”. However, indium and base-metal contents of the mineralization also significantly increase and occur as well within the highly brecciated wall-rocks to the lodes.

The result is that at shallow depths, the Sn-In-Zn-Cu-Bi-bearing mineralization (although lower grade in comparison to the deeper deposits) is more widespread than originally believed, and its lateral extent is in part controlled by the rough layering of the brecciated zones. The discovery of significant indium values within this widespread low-grade near surface mineralized halo presents the possibility of open pit exploitation opportunities at Mount Pleasant.

## ACKNOWLEDGEMENTS

We thank Adex Mining Inc. and CEO Kabir Ahmed for financial support and for

permission to present this paper. We acknowledge that our understanding of these mineral deposits draws upon the contribution of many workers over the past 50 years who have built and studied Mount Pleasant.

## REFERENCES

- BOYD, T. 2008. Results Of 2008 Exploration program and GemCom modelling of Sn-In-Zn-Cu and WO<sub>3</sub>-MoS<sub>2</sub>-Bi zones on the Mount Pleasant Mine Property, Charlotte County, southwestern New Brunswick (Oral Presentation). *Exploration, Mining and Petroleum, New Brunswick Open House, Fredericton*.
- DUNBAR, P. & EL RASSI, D. 2008. A Technical Review of the Mount Pleasant Property, Including an Updated Mineral Resource Estimate on the Fire Tower Zone, Southwestern New Brunswick. 43-101 Report to Adex Mining Inc. by Watt, Griffiths and McQuat Limited (available on SEDAR), 149p.
- INVERNO, C.M.C. & HUTCHINSON, R.W. 2006. Petrochemical discrimination of evolved granitic intrusions associated with Mount Pleasant deposits, New Brunswick, Canada. *Applied Earth Science (Trans Inst. Min. Metall. B)*, **116**, B23-39.
- KOOIMAN, G.J.A., MCLEOD, M.J., & SINCLAIR, W.D. 1986. Porphyry Tungsten-Molybdenum Orebodies, Polymetallic Veins and Replacement Bodies, and Tin-Bearing Greisen Zones in the Fire Tower Zone, Mount Pleasant, New Brunswick. *Economic Geology*, **81**, 1356-1373.
- MCCUTCHEON, S.R. 1990. *The Late Devonian Mount Pleasant caldera complex: stratigraphy, mineralogy, geochemistry and the geologic setting of a Sn-W deposit in southwestern New Brunswick*. Unpublished Ph.D. thesis, Dalhousie University, Halifax.
- MCLEOD, M.J. 1990. Geology, Geochemistry, and Related Mineral Deposits of the Saint George Batholith, Charlotte, Queens, and Kings Counties, New Brunswick. *Natural Resources and Energy, Mineral Resources, Mineral Resource Report*, **5**, 169 p.
- PROUT, S., GRAMMATIKOPOULOS, T., YEUNG, B., & MCKEEN, T. 2008. Quantitative characterisation of a multi-metal porphyry ore by automated mineralogy from the Mount Pleasant Mine, New Brunswick, Canada. *Winter Meeting of Mineral Deposit Studies Group/Applied Mineralogy Group, Mineralogical Society (UK)*.

SINCLAIR, W.D., KOOIMAN, G.J.A., MARTIN, D.A., & KJARSGAARD, I.M. 2006. Geology, Geochemistry and Mineralogy of Indium Resources at Mount Pleasant, New Brunswick, Canada. *Ore Geology Reviews*, **28**, 123-145.

SINCLAIR, W.D., KOOIMAN, G.J.A., & TAYLOR, R.P. 2007. Letter to the Editor: Petrochemical discrimination of evolved granitic intrusions associated with Mount Pleasant deposits, New Brunswick, Canada,

by C.M.C. Inverno, and R.W. Hutchinson. *Applied Earth Science (Trans Inst. Min. Metall. B)*, **116**, B23-39.

YANG, X-M, LENTZ, D.R., & MCCUTCHEON, S.R. 2003. Petrochemical evolution of subvolcanic granitoid intrusions within the late Devonian Mount Pleasant Caldera, southwestern New Brunswick, Canada: comparison of Au versus Sn-W-Mo-polymetallic mineralization systems. *Atlantic Geology*, **39**, 97-121.

## The Nash Creek Zn–Pb–Ag deposit, Tobique –Chaleurs Zone, New Brunswick, Canada

Derek Brown<sup>1</sup> & James Walker<sup>2</sup>

<sup>1</sup>SLAM Exploration Ltd. Miramichi NB (e-mail: [explore@slamexploration.com](mailto:explore@slamexploration.com))

<sup>2</sup>New Brunswick Department of Natural Resources, Geological Surveys Branch, P.O. Box 50, Bathurst New Brunswick, E2A 3Z1, Canada, (e-mail [jim.walker@gnb.ca](mailto:jim.walker@gnb.ca))

**ABSTRACT:** Nash Creek is the largest Zn–Pb deposit in the Tobique–Chaleurs Zone, and contains indicated and inferred resources of 7.8 Mt grading 2.72% Zn, 0.55% Pb and 18.26 g/t Ag and 1.2 Mt grading 2.66% Zn, 0.52% Pb and 18 g/t Ag, respectively. The deposit is hosted by Early Devonian bimodal volcanic and minor interlayered sedimentary rocks that were deposited in a trans-pressional rift. The host rocks sequence includes the Archibald Settlement Formation (rhyolite flows domes and related rocks), and the Sunnyside Formation (mafic lava flows and interlayered volcanoclastic and sedimentary rocks).

The deposit, which is divided into the Hayes and Hickey zones, lies near the western fault-bound limb of the Jacquet River Syncline and consists of sparsely disseminated to locally massive sulfide veins and replacements. Mineralization occurs in at least two phases; 1) early massive sulfide veins and replacement zones, and 2) late carbonate–quartz–sulfide veins. Drilling indicates that within the deposit mineralization is concentrated along steeply dipping structures that strike between 314 and 326°.

Alteration is spatially associated with, and extends beyond, mineralization and consists of v-fine-grained mixture of Fe-carbonate, Fe-oxide, sericite, calcite and minor chlorite. Additional clay alteration is controlled by faulting and is spatially related to sulfide emplacement.

**KEYWORDS:** *base metals, New Brunswick, Nash Creek, sulfides, VMS*

### INTRODUCTION

The Nash Creek Zn–Pb–Ag deposit is located approximately 50 Km northwest of the city of Bathurst, New Brunswick. This is the largest of several syngenetic sulfide deposits within the Tobique–Chaleurs Zone (Fig. 1), and contains an Indicated resource of 7.8 Mt grading 2.72% zinc, 0.55% lead and 18.26 g/t Ag and an additional Inferred resource of 1.2 Mt grading 2.66% Zn, 0.52% Pb and 18 g/t Ag. The deposit was discovered by AMEX during follow-up work on silt geochemical anomalies in 1954 (Moorhouse, 1955)

Previous drilling programs undertaken by Falconbridge and Texasgulf focused on the Hayes Zone where the Bulk of the resources have been outlined. The latest drilling program focused on expanding the Hickey Zone north and has added 52.5% to the total indicated tonnage

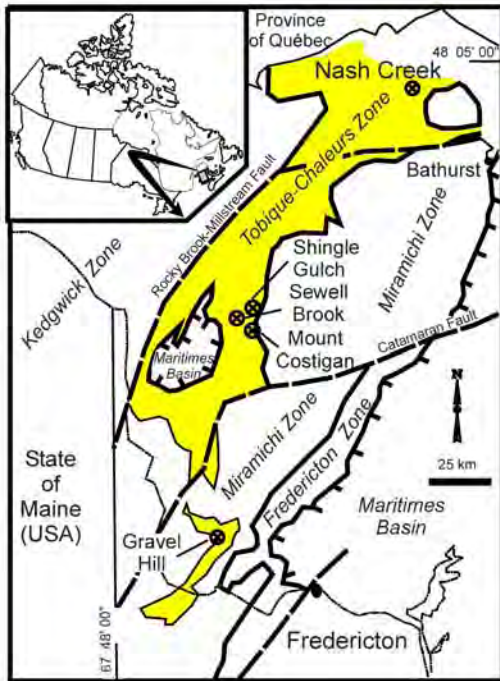
### GEOLOGICAL SETTING

Northern New Brunswick and the adjacent

Gaspé Peninsula in Quebec are divided into four north- to northeasterly-trending tectono-stratigraphic belts of Palaeozoic rocks. The Nash Creek deposit occurs in the Tobique–Chaleurs Zone (TCZ), the youngest of these belts (Walker and McCutcheon, 1995) that is interpreted to have formed in transpressional rift (Dostal et al. 1989). In the study area, the TCZ is divided into two groups. At the base, early to middle Silurian sedimentary and volcanic rocks of the Chaleur Group are in unconformable or fault contact with Ordovician rocks. The Chaleurs Group is disconformably to unconformably overlain by Early Devonian rocks of the Dalhousie Group.

The distribution of stratigraphic units in this part of the TCZ is controlled by the Km-scale, north-south trending, doubly plunging Jacquet River Syncline (JRS). Chaleurs group rocks exposed on the east limb of this JRS are vertical to eastward-overturned, whereas the disconformably overlying Dalhousie Group is shallowly to

moderately west dipping. On the west limb of the JRS Chaleurs Group rocks are not exposed, and very gently east-dipping Dalhousie Group rocks are in fault contact (Black Point–Arleau Brook Fault) with a structural block that contains northeast- to north-striking Ordovician (Matapedia Group) and Silurian (Chaleurs Group) rocks to the west (Fig. 2).



**Fig. 1.** Location of the Nash Creek, and other Zn–Pb deposit (circled X symbol) in the TCZ. Modified from (Walker 2005).

In the JRS the Dalhousie Group is divided into five formations (Walker and McCutcheon 1995). Only the upper three; Archibald Settlement, Sunnyside and Big Hole Brook formations (described below), are exposed in the vicinity of Nash Creek. The Archibald Settlement Formation is the lowermost of these and consists of massive flows and domes of orange to red, aphyric, commonly flow-layered rhyolite. Up section massive flows are interlayered with fine- to coarse-grained volcanoclastic rocks including heterolithic lapilli-tuff and agglomerate, as-well-as volumetrically minor feldspar-phyric rhyodacite. A U/Pb zircon age of 415.6 +/- 0.4 Ma has been returned from rhyolite of

the Archibald Settlement Formation collected at the Nash Creek deposit (Wilson and Kamo 2008).

The upper part of the Archibald Settlement Formation is conformably overlain, and in part interlayered with, the Sunnyside Formation. The base of the Sunnyside Formation consists of generally thin (< 10m) massive to amygdaloidal basalt flows and minor interbedded fine- to coarse-grained clastic and minor carbonate-bearing sedimentary rocks. Higher in this unit more massive mafic flows, hyaloclastite and tuff predominate (Fig. 2). Some of the clastic units near the base of the Sunnyside Formation locally contain abundant orange rhyolite clasts indicating that Archibald Settlement rocks were being eroded at the time the Sunnyside was being deposited.

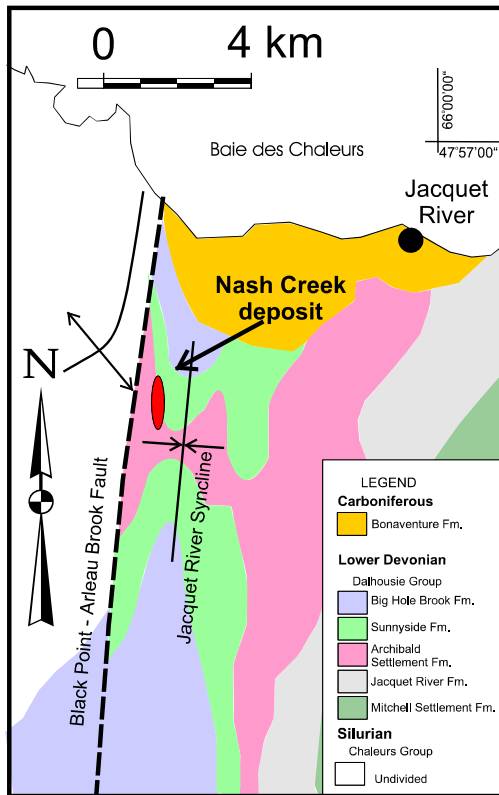
The Big Hole Brook Formation is the uppermost Formation in the Dalhousie Group and conformably overlies the Sunnyside Formation. The Big Hole Brook Formation consists of green-grey, micaceous, locally calcareous fine-grained thin- to thick-bedded sandstone and siltstone (Fig. 2). North of the deposit the Big Hole Brook Formation is unconformably overlain by clastic rocks of the Carboniferous Bonaventure Formation (Fig. 2).

### MINERALIZATION

Four distinct zones of base metal sulfide accumulation have been identified on the Nash Creek property. All four are fracture controlled sub-parallel conduits striking between 314 and 326°.

The calculated resources are contained within two of these zones. The Hayes Zone, in the south hosts the largest tonnage, It consists of discontinuous to semi-continuous pods of sulfide mineralization over a strike length of 585 m. This zone is open to the southeast, and has been intersected over widths up to 55 m. The Hickey Zone consists of at least ten sub-parallel, steeply-dipping, discontinuous zones that range in length from 140 to 450 m. The thickest Zn-Pb accumulations are subparallel (implying a possible structural control), and occur

within a laterally extensive typically flat lying lower grade halo of mineralization. The Hickey Zone strikes to the north for 840 m. The mineralized structures are open in all horizontal directions. Limited



**Fig. 2.** North end of the Jacquet River Syncline showing position of Nash Creek deposit with respect Dalhousie Group Stratigraphy.

deep drilling (up to 500m vertical) indicates that additional base metal sulfide bearing lenses occur below the extensively explored near surface zones.

The Hickey and Hayes zones occur within a larger envelop of Zn–Pb–Ag–Fe sulfide mineralization that lies more or less along a north-south line straddling the contacts between the upper most flows and clastic rocks associated with the Archibald Settlement and bounding Sunnyside formations. Specifically, it is concentrated between and adjacent to subvertical, north–south striking faults that parallel the Black Point–Arleau Brook Fault.

A small dextral east-west offset in the geological units occurs between the Hickey and Hayes zones resulting in an apparent offset of the deposit. It is unclear whether this is a tectonic dismemberment and subsequent offset of a single mineralized zone or a reflection of the control on mineralization exerted by differences in rock type in a replacement type deposit.

In both the Hayes and Hickey zones mineralization occurs in three forms; Type I mineralization consists of massive (> 90%) sulfide veins that range from 1 to 5 cm in width. These veins are for the most part restricted to the massive rhyolite of the Archibald Settlement Formation. However, where Type I veins intersect carapace-breccias or marginal zones of flows characterized by zones of contorted flow-layering and/or auto-breccia development, sulfides fill and cement the interstices such that rhyolite appears to be cemented by sulfide.

Type II mineralization is replacement type mineralization occurring in the fragmental tops of mafic flows, within the Sunnyside Formation near its lower contact with the Archibald Settlement Formation. Type II Veins and veinlets are commonly intricately banded with zones of early rhythmically-layered amorphous silica and later sulfide commonly displaying framboidal textures.

Type III mineralization consists of late carbonate ± quartz veins with minor sulfides (≈ 20%). These veins cross cut Type I mineralization.

Hydrothermal alteration is laterally extensive and manifest as Fe-carbonate, Fe-oxide (supergene?), sericite, calcite and minor chlorite. Clay alteration is so pervasive that much of the core disintegrates via clay hydration processes after very short exposure to the atmospheric conditions. Although limited XRD work has not shown the presence of swelling clays sericite which is abundant does have the capacity to swell (Eberl et al. 1987). Additional intense clay alteration is controlled by faulting and is spatially related to sulfide emplacement.

## DISCUSSION AND CONCLUSIONS

The genesis of the Nash Creek deposit has been problematic as it does not fit easily into any one genetic model. The salient points to consider when formulating a model for this deposit are:

1. The rift setting in which the host sequence was deposited.
2. The absence of synvolcanic intrusions other than rhyodacite dikes
3. Sedimentary rocks in the section (calcareous shale, and sandstone), and volcanoclastic layers are rarely mineralized.
4. Porphyritic rhyodacite (dykes or flows?) are spatially related to base metal sulphide mineralization.
5. Mineralization appears concentrated along northwest trending zones with mineralization migrating outward along permeable horizons ultimately forming a laterally extensive area of alteration with disseminated sulfide.
6. The alteration zone has a significant clay component that expands when exposed to surface weathering conditions.

Based on the points outlined above Nash Creek best fits a VMS style deposit, and appears to have characteristics of the "Stratal Model". The deposit appears to be "Stratabound", dominantly Zn+Pb sulfide with variable amounts of pyrite.

Sufficient information is now available to consider the following in future studies: 1) relationship of grade with host rock, 2) SG in relation to mineralization and lithology, 3) possible relationship of Ag with the alteration halo, 4) Zn to Pb ratios as a predictive measure for late phase quartz-carbonate veining, 5) effective use of blank, standard, duplicate and split samples in delineation drilling.

## REFERENCES

- DOSTAL, J., WILSON, R.A., & KEPPIE, J.D. 1989. Geochemistry of Siluro-Devonian Tobique belt in northern and central New Brunswick (Canada). Tectonic Implications. *Canadian Journal of Earth Sciences*, **26**, 1282–1296.
- EBERL, D.D., ŚRODOŃ, J., LEE, M., NADEAU, P.H., & NORTHROP, H.R. 1987. Sericite from the Silverton caldera, Colorado: Correlation among structure, composition, origin and particle thickness. *American Mineralogist*, **72**, 914–934.
- MOOREHOUSE, W.W., 1955. Report of work on the Nash Creek option. New Brunswick Department of Natural Resources; Minerals, Policy and Planning Division, Assessment Report # 47197.
- WALKER, J.A. 2005. *Petrogenesis and tectonic setting of Devonian volcanic and related rocks and their control on mineralization at the Shingle Gulch East Zn–Pb–Ag sulfide deposit, northwest New Brunswick*. Unpublished Ph.D. thesis, University of New Brunswick, Canada, p. 430.
- WALKER, J. A. & McCUTCHEON, S.R., 1995. Siluro-Devonian stratigraphy of the Chaleurs Bay Synclinorium, northern New Brunswick. In Merlini, S.A.A. ed., *Current Research 1994*. New Brunswick Department of Natural Resources, Minerals, Policy and Planning Division, Miscellaneous Report **18**, 225–244.
- WILSON, R.A. & KAMO, S.L. 2008. New U-Pb ages from the Chaleurs and Dalhousie Groups: Implications for regional correlations and tectonic Evolution of Northern New Brunswick. In *Geological investigations in New Brunswick for 2007*. Edited by G.L. Martin. New Brunswick Department of Natural Resources: Minerals, Policy, and Planning Division, Mineral Resource Report 2005-1, 167–212.

## The Williams Brook gold discovery – northern New Brunswick

Heather Campbell<sup>1</sup> & Art Hamilton<sup>1</sup>

<sup>1</sup>Blue Note Mining Inc., 9361 Route 180, P.O. Box 26, Bathurst NB, E2A 3Z1 CANADA  
(e-mail: [ahamilton@bluenotemining.ca](mailto:ahamilton@bluenotemining.ca), [hcampbell@bluenotemining.ca](mailto:hcampbell@bluenotemining.ca))

**ABSTRACT:** Recent diamond drilling has confirmed significant gold mineralization on the Williams Brook Property, held by Blue Note Mining Inc. in northern New Brunswick. Two types of mineralization occur on the property; 1) sulfides in massive quartz veins with gold values of 11.16 g/t over 2.8 meter core length, including a 0.5 meter section grading 24.1 g/t Au and 2) disseminated pyrite and sulfide veinlets with gold values of 0.91 g/t Au over 28.0 meters (23.3 m estimated true width) including a 1.0 meter section grading 5.44 g/t Au. Mineralization occurs within potassically altered rhyolite and massive quartz veins that intrude the altered rhyolite. No mineralization is found in the drill holes in zones of unaltered rhyolite. Preliminary investigations of the geochemistry of drill hole WB08-11 reveals significant Spearman rank correlations between Au and As, Cu, Sb and Mo. Drill holes WB08-03 to WB08-06 show correlations between Au and Ag, Mo and S. Observations of alteration, mineralogy and element associations suggest that the gold is part of an epithermal system. These preliminary observations of the drill core along with the differing correlations in trace elements between the drill holes indicate that there may be two events contributing to mineralization in the Williams Brook property.

**KEYWORDS:** *gold, correlations, Devonian, trace element, geochemistry*

### INTRODUCTION

The Williams Brook gold property is located about 100m west of Bathurst and north of Highway 180 (Fig. 1) Significant gold mineralization in angular float was found by prospector David O'Neil who staked three claim blocks on the property which were later optioned by Blue Note Mining in 2006.

### GEOLOGICAL SETTING

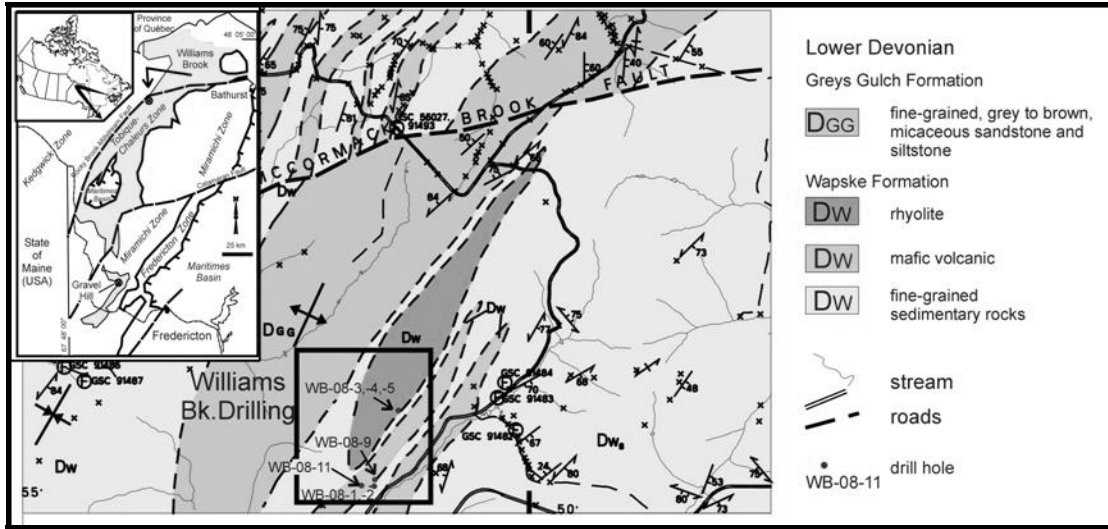
#### Regional Geology

The study area is situated in the Tobique–Chaleurs Zone, (TCZ) which contains early to middle Silurian sedimentary and volcanic rocks (Chaleurs group) that are disconformably overlain by Lower Devonian volcanic and sedimentary rocks of the Dalhousie and Tobique groups (Wilson 2004) and is bounded by the Rocky Brook–Millstream Fault to the northeast and the Mackenzie Gulch Fault to the north (Fig.1). The McCormack Brook Fault (a splay of the Rocky Brook–Millstream Fault) lies to the north of the

study area. Several Au showings east of the present study area are coincident with these large scale faults. These occurrences; Jonpol, Mulligan Gulch, Dalhousie Road, Simpson's Field, McCormack, Ramsay Brook, and Upsalquitch Forks, have returned assays of up to 12.4 g/t Au in rocks and 20 g/t Au in heavy metal concentrates in till (Rose & Johnson 1990).

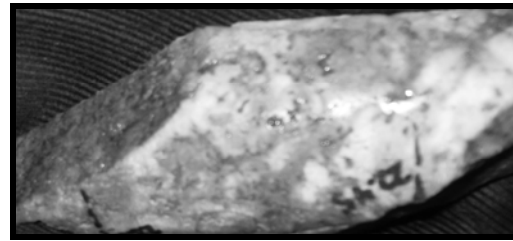
#### Local Geology

The Williams Brook area is underlain by the Wapske Formation (Tobique Group), that contains mafic and felsic volcanic rocks interlayered with fine-grained sedimentary rocks. Mineralization at Williams Brook is hosted within and/or is spatially related to red to pink rhyolites. The rhyolites were unknown in this area prior to the 2008 exploration program, but are tentatively assigned to the Wapske Formation. The Wapske Formation is conformably overlain by the Early Devonian Greys Gulch Formation that



**Fig. 1.** The Williams Brook property is located within the Tobique–Chaleurs Zone (inset-shaded), approximately 100 km west of Bathurst, NB. Locations of some of the drill holes are indicated by the boxed area.

consists of brown micaceous sandstones. Primary textures such as spherulites, pumice clasts, flow-layering and monomict breccias are common and are taken as evidence of autoclastic processes that are consistent with an effusive emplacement for these rocks. The host rhyolite is commonly salmon coloured, possibly reflecting potassic alteration, and is cut by micro-brecciated quartz and pyrite veinlets with sericite, occurring sub parallel to the main foliation. Large ( $\approx 2$  mm diameter) euhedral pyrite grains are observed overprinting the flow layering. Later stage milky, vuggy quartz veins crosscut flow layering and contain small (sub mm scale) gold grains in DDH-WB-08-11 (Fig. 2).



**Fig. 2.** Quartz vein with visible gold. Sample is from DDH WB-8-11 @ 22.43 m.

The rocks in the study have undergone zeolite facies regional metamorphism but locally intense penetrative fabrics are recognized in areas adjacent major faults.

### MINERALOGY

Preliminary work has shown that mineralization at Williams Brook includes the sulfide phases pyrite and honey-brown sphalerite. Oxide phases including magnetite and hematite are prevalent throughout the core and heavily concentrated in the first 10 m of the drill

cores, thus implying possible supergene alteration.

### ASSAYS

Trace element geochemical values for the Williams Brook project were obtained using INAA (Au), and Fire Assay (FA). Standards and blanks were typically submitted with every 20 samples. Correlation between FA and INAA was good ( $r_s=0.87$ ) except for isolated erratic values in some samples.

Significant assays include 11.16 g/t Au over 2.8 meter core length, including 0.5 meter grading 24.1 g/t Au in WB-08-11 and 0.91 g/t over 28.0 m core length (23.3 m true width) including 5.44 g/t over 1.0 m (0.8 m true width) in WB-08-04.

Assays from the 2.8m section of WB-08-11 were rerun using FA gravimetric metallic screen analysis because of erratic and high Au concentrations. One kg samples were run through 100 mesh sieves; the coarse (> 149 micron) and fine (< 149 micron) fractions were analyzed using gravimetric analysis. The < 149 micron portion was split and analyzed to provide replicate data. Results from this analysis indicate that 41% of the gold in the 2.8 m section is over 149 micron.

### GEOCHEMISTRY

Trace element geochemical values for the Williams Brook project were obtained using INAA (Au) ICP-OES-4 acid (total) digestion. Both geochemical packages are exploration grade. The alkali contents of the rock samples are relatively high; K<sub>2</sub>O values are up to 9.3 wt.% (average 4.09), whereas Na<sub>2</sub>O values up to 6.97 wt.% (average 3.65) with (Na<sub>2</sub>O+K<sub>2</sub>O) up to 13.7wt.% (average 7.7). Variations in gold and selected trace elements in DDH-WB08-04 are shown in Figs. 3 to 6. Higher concentrations of Au and Ag are seen in the highly altered rhyolites.

Trace element contents in rocks intersected by drill holes WB-08-03 to WB-08-06 are associated with altered rhyolite; Spearman rank correlation coefficients for Ag, Mo and S with Au are moderate to high. Correlation coefficients for Au with As, Cu, Sb and Mo in drill hole WB08-11 (vuggy quartz) are moderate to high. These element correlations suggest that mineralization may be related to an epithermal system (Panteleyev 1995).

### CONCLUSIONS

The Williams Brook property has yielded high gold assays. Preliminary work presents evidence suggesting that Au mineralization occurs in two forms: 1) as refractory Au in mm scale massive sulfide (dominantly pyrite) and disseminated veins that cut potassically altered rocks, and 2) as vuggy quartz veins as fine-grained (≤ mm) free gold. Trace element correlations indicate that Au may be related to epithermal mineralization as there are good correlations of Au with Ag,

Sb, and As. Likewise, the presence of vuggy (subsequently brecciated) open space quartz veins support this. High gold contents (41%) in the > 149 micron portion of the crushed core indicate that coarse gold may be a factor in variability in duplicate results.

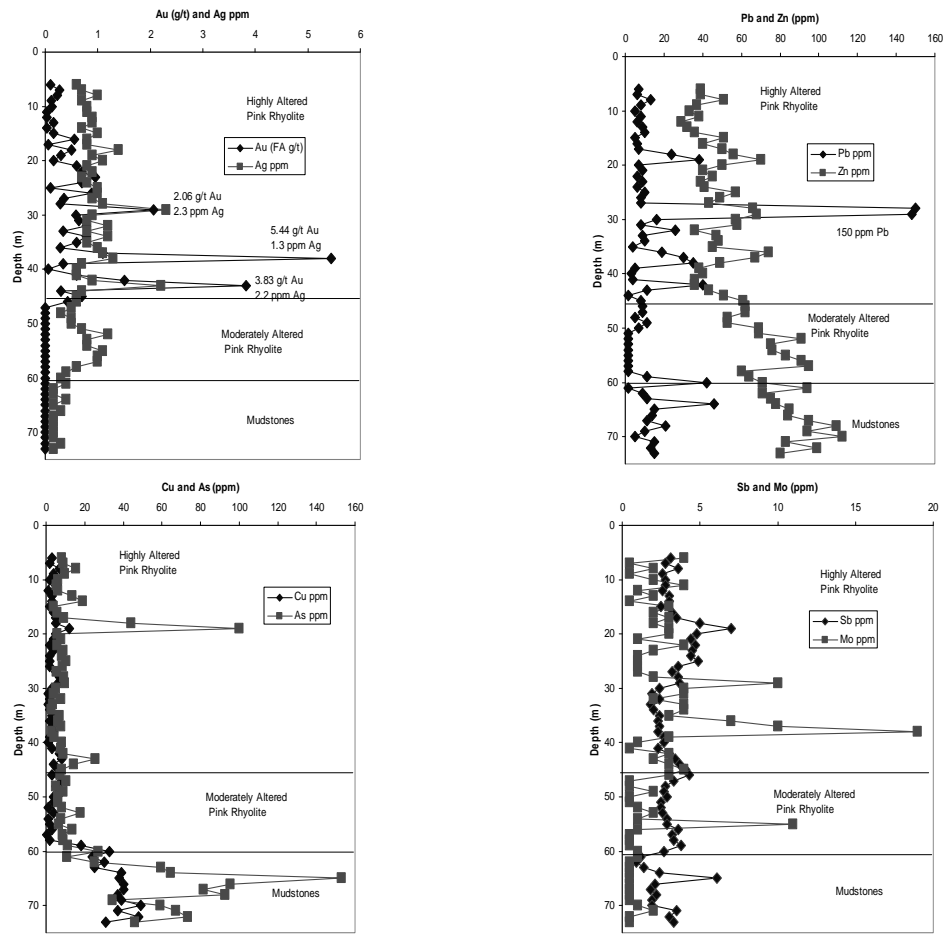
Further work is necessary to determine whether Au mineralization was emplaced in a single pulse or as multi pulses of mineralization. Detailed research including thin sections and whole rock geochemistry will provide better insight into the timing and nature of Au mineralization on the Williams Brook property and the extent of gold mineralization in the Williams Brook Property.

### ACKNOWLEDGEMENTS

We would like to acknowledge the New Brunswick Department of Natural Resources - Geological Surveys Branch for their assistance in reviewing the data and discussions on geology and geochemical results.

### REFERENCES

- MOORE, C. & LENTZ, D. 1995. Copper-Skarn associated felsic intrusive rocks in the MacKenzie Gulch area (NTS 21 O/10), Restigouche County, New Brunswick. In: CARROLL, B.M.W. (ed) Current Research, 1995. New Brunswick Department of Natural Resources, Minerals and Energy Division, Mineral Resource Report, **96-1**, 121-153.
- PANTELEYEV, A. 1995. Epithermal AU-AG-CU: In: Mineral Deposit Profile Tables - Listed by Deposit Group and Lithological Affinities; B.C. Ministry of Energy, Mines and Petroleum Resources, Open File 1995-8.
- ROSE, D. & JOHNSON, S. 1990. New Brunswick computerized mineral occurrence database. New Brunswick Department of Natural Resources, Minerals and Energy Division, Mineral Resource Report Energy, Mines and Petroleum Resources, Mineral Resource Report 3.
- WILSON, R., BURDEN, E., BERTRAND, R., ASSELIN, E., & MCCracken, A. 2004. Stratigraphy and tectono-sedimentary evolution of the Late Ordovician to Middle Devonian Gaspe Belt in northern New Brunswick: evidence from the Restigouche area. *Canadian Journal of Earth Science*, **41**, 527-551.



**Figs. 3-6.** Gold and trace element geochemical concentrations with depth in DDH-WB-08-04. Values are not corrected for mass loss or gains. Higher values of Cu, Zn and As exist in the mudstones underlying the rhyolites in hole WB-08-04.

## Age constraints and Grampian orogenesis of the Lower to Middle Ordovician Tyrone Igneous Complex, Northern Ireland

Mark R. Cooper<sup>1</sup>, Quentin G. Crowley<sup>2,3</sup>, David M. Chew<sup>3</sup>,  
Steve P. Hollis<sup>4</sup> & Stephen R. Noble<sup>2</sup>

<sup>1</sup>Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Malone Lower, Belfast, Northern Ireland  
UNITED KINGDOM (e-mail: [mark.cooper@detini.gov.uk](mailto:mark.cooper@detini.gov.uk))

<sup>2</sup>NERC Isotope Geosciences Laboratory, British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham  
UNITED KINGDOM

<sup>3</sup>Department of Geology, Trinity College Dublin, Dublin 2, Ireland UNITED KINGDOM

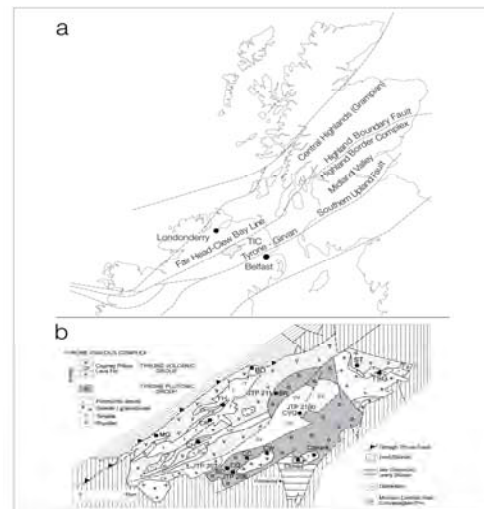
<sup>4</sup>School of Ocean & Earth Science, National Oceanography Centre, University of Southampton, Southampton,  
SO14 3ZH UNITED KINGDOM

**Abstract:** The Lower to Middle Ordovician Tyrone Igneous Complex forms part of the basement of the Midland Valley Terrane of UK and Ireland and correlates with the Notre Dame Subzone of the Dunnage Zone of Newfoundland. It is comprised of the ophiolitic Tyrone Plutonic Group and overlying volcanic arc-related Tyrone Volcanic Group. Together they structurally overlie sillimanite-grade paragneisses of the Tyrone Central Inlier and are pinned together by a suite of arc-related tonalitic-granitic intrusives. This paper presents U-Pb zircon age constraints and biostratigraphical correlation for the Tyrone Igneous Complex. Eight U-Pb ages from the Tyrone Volcanic Group and arc-related intrusive suite range from c. 473 - 464 Ma. The  $473 \pm 0.8$  Ma age is from a high level rhyolite which occurs at a similar level within the Tyrone Volcanic Group to a biostratigraphical correlation of graptolites close the base of the Middle Ordovician. A U-Pb zircon age of  $480 \text{ Ma} \pm 1 \text{ Ma}$  for the ophiolitic Tyrone Plutonic Group is significantly older and allows time for northwards directed obduction (c. 475 Ma) of the Tyrone Plutonic Group related to southwards directed subduction, followed by the establishment of northwards directed subduction and the development of the Tyrone Volcanic Group arc during Grampian orogenesis

**Keywords:** *Tyrone Igneous Complex, Grampian, ophiolite, volcanic arc, age constraints*

### INTRODUCTION

Geological relationships and age constraints for the Lower to Middle Ordovician Tyrone Igneous Complex are contributing to the understanding of Grampian orogenic amalgamation of the Caledonides in the UK and Ireland. The Tyrone Igneous Complex is part of the basement of the Midland Valley Terrane of UK and Ireland (Fig. 1), and links internationally with the Notre Dame Subzone of the Dunnage Zone of Newfoundland (van Staal *et al.* 1998). The tectonomagmatic setting of Tyrone Igneous Complex points to the potential for VMS mineralization similar to that seen in the Bathurst Mining Camp of New Brunswick (Goodfellow & McCutcheon 2003).



**Fig. 1.** (a) Location of the Tyrone Igneous Complex (TIC) and basement terranes across UK and Ireland. (b) Simplified geology and abbreviations of sites named in text.

Current geological survey, academic research and exploration activity is focused on improving geological understanding both regionally and internationally.

**GEOLOGICAL BACKGROUND**

The Tyrone Igneous Complex extends over an area of approximately 350km<sup>2</sup> of counties Tyrone and Londonderry in Northern Ireland. It is comprised of the Tyrone Plutonic Group and overlying Tyrone Volcanic Group (Cooper 2004). Together, they structurally overlie sillimanite-grade paragneisses of the Tyrone Central Inlier which, based on detrital zircon age profiling, appear to be of Upper Dalradian Laurentian affinity (Chew *et al.* 2008). The Tyrone Igneous Complex and Tyrone Central Inlier are pinned together by a suite of arc-related tonalitic-granitic intrusives.

The Tyrone Plutonic Group comprises a basic igneous association of layered, isotropic and pegmatitic gabbros, doleritic sheeted dykes and rare basaltic pillow lavas first recognized as ophiolitic by Hutton *et al.* (1985).

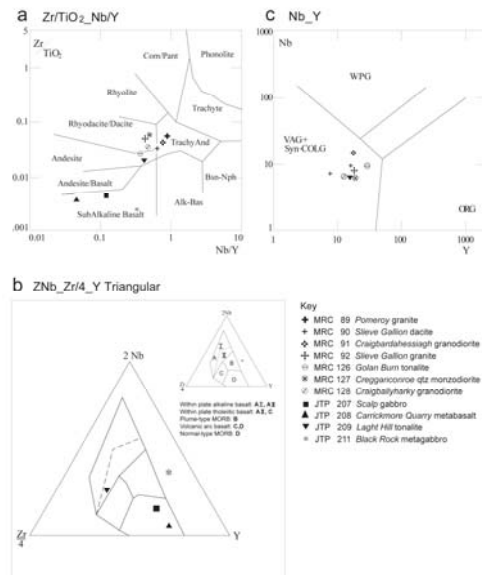
The Tyrone Volcanic Group sequence comprises basaltic pillow lavas, tuffs of basic to intermediate composition, rhyolites, cherts, siltstones and dark grey mudstones representing up to three volcanic cycles. From base to top of each cycle and through the sequence as a whole, the Tyrone Volcanic Group becomes progressively more acidic in composition.

**GEOCHEMISTRY**

Though limited, the geochemistry presented herein serves to show the broad compositional differences (Fig. 2a) between the ophiolitic, normal-type MORB (Fig. 2b) and the volcanic arc-related granitoids (Fig. 2c). Current geochemical research, targeted towards the location of potential VMS mineralization, will expand and improve this area of investigation.

**BIOSTRATIGRAPHY**

Graptolites from close to the top of the



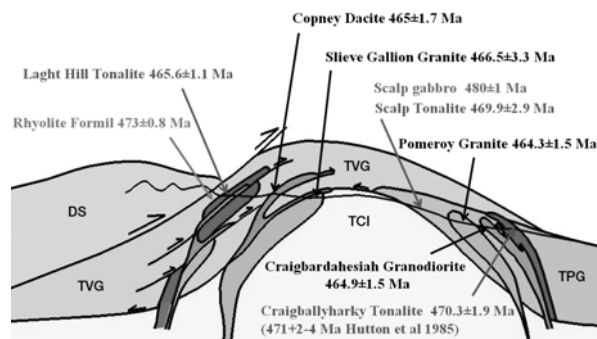
**Fig. 2. (a-c).** Geochemical plots for Tyrone Plutonic and Volcanic Groups.

Tyrone Volcanic Group on Slieve Gallion (Fig. 1b – ST) have been assigned (Cooper *et al.* 2008) to the *Isograptus victoriae lunatus* Zone of the Australasian graptolite succession (VandenBerg & Cooper 1992), and to the lowest Ca1 subdivision of the Castlemainian Stage, which is now taken internationally to represent the base of the Middle Ordovician (Cooper 1999). In terms of the British succession, this horizon is approximately equivalent to a level at the top of the Whitlandian Stage of the Arenig.

**U-Pb ZIRCON ISOTOPIC AGES**

Until now the age of Tyrone Igneous Complex has been based on a magma mixing relationship between gabbro and tonalite at Craigballyharky. The tonalite has been dated at 472 +/- 4 Ma, and was taken as evidence for the age of the ophiolite and for the timing of obduction (Hutton *et al.* 1985). Although their mixing with gabbro is clear, the tonalites have a volcanic arc geochemical signature and geological scenario would therefore require obduction of contemporaneous ophiolite and an active volcanic arc.

Presented herein are eight U-Pb zircon ages from the Tyrone Volcanic Group and



**Fig. 3.** (a) Schematic cross section through Tyrone Central Inlier (TCI), Tyrone Plutonic Group (TPG) and Tyrone Volcanic Group (TVG) indicating the U-Pb zircon ages. Dalradian Supergroup (DS).

arc-related intrusive suite, which range from 473 - 464 Ma (Fig. 3). The 473 ± 0.8 Ma age is from a high-level rhyolite from Formil (Fig 1b – FH), which occurs at a similar level within the Tyrone Volcanic Group to the biostratigraphical correlation close the base of the Middle Ordovician.

A U-Pb zircon age of 480 ± 1 Ma from layered gabbros at Scalp (Fig 1b – SC) provides the only direct age for the ophiolitic Tyrone Plutonic Group so far. This age date negates the need for the obduction of contemporaneous ophiolite and an active volcanic arc and simplifies the tectonomagmatic evolution.

The difference in age between the ophiolitic Tyrone Plutonic Group (c. 480 Ma) and Tyrone Volcanic Group (c. 473 - 464 Ma) allows time for northwards directed obduction (c. 475 Ma) of the Tyrone Plutonic Group related to southwards directed subduction (Fig. 4c), followed by the establishment of northwards directed subduction and the development of the Tyrone Volcanic Group arc (Fig. 4d).

### CONCLUSIONS

A U-Pb zircon age of 480 ± 1 Ma provides the first direct isotopic age for the ophiolitic Tyrone Plutonic Group.

The isotopic age range of the Tyrone Volcanic Group is c. 473 - 464 Ma and is based on eight U-Pb zircon dates.

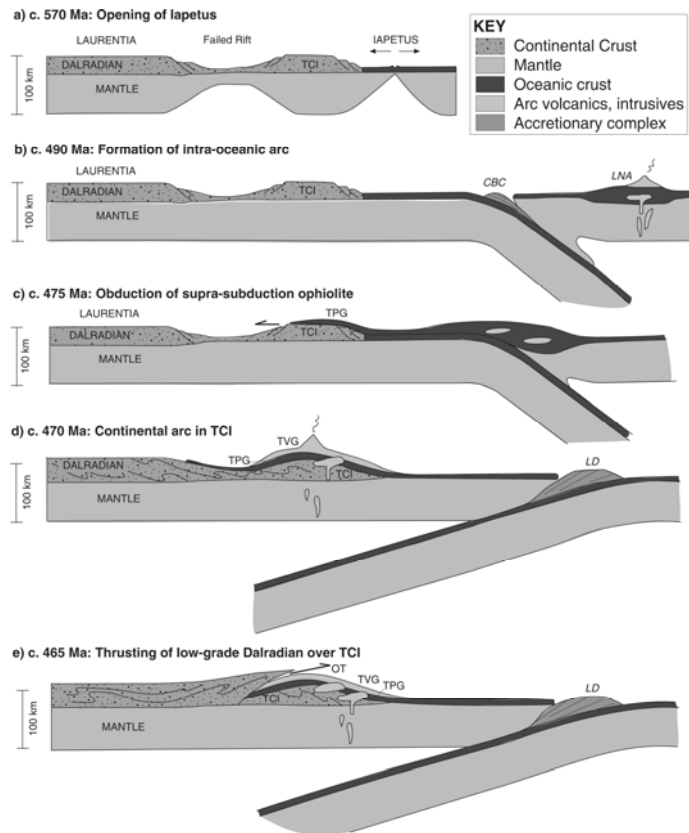
The 473 ± 0.8 Ma age is from a high-level rhyolite that occurs at a similar level within the Tyrone Volcanic Group to a

biostratigraphical correlation close the base of the Middle Ordovician.

The difference in age between the ophiolitic Tyrone Plutonic Group and Tyrone Volcanic Group allows time for northwards directed obduction of the Tyrone Plutonic Group related to southwards directed subduction, followed by the establishment of northwards directed subduction and the development of the Tyrone Volcanic Group arc.

### REFERENCES

- CHEW, D.M., FLOWERDEW, M.J., PAGE, L.M., CROWLEY, Q.G., DALY, J.S., COOPER, M.R., & WHITEHOUSE, M.J. 2008. The tectonothermal evolution and provenance of the Tyrone Central Inlier, Ireland: Grampian imbrication of an outboard Laurentian microcontinent? *Journal of the Geological Society, London*, **165**, 675-685.
- COOPER, M.R. & MITCHELL, W.I. 2004. Midland Valley Terrane. In: *The Geology of Northern Ireland-Our Natural Foundation*, Mitchell, W. I. (ed). (Second Edition) Geological Survey of Northern Ireland, Belfast.
- COOPER, M.R., CROWLEY, Q.G. & RUSHTON, A.W. A. 2008. New age constraints for the Ordovician Tyrone Volcanic Group, Northern Ireland. *Journal of the Geological Society, London*, **165**, 333-339.
- COOPER, R. A. 1999. The Ordovician time scale – calibration of graptolite and conodont zones. *Acta Universitatis Carolinae – Geologica*, **43** (1/2), 1-4.
- GOODFELLOW, W. D. & McCUTCHEON, S. R. 2003. Geologic and Genetic Attributes of Volcanic Sediment-Hosted Massive Sulfide Deposits of the Bathurst Mining Camp,



**Fig.4 .** Schematic reconstruction of the Late Neoproterozoic–Early Palaeozoic tectonic evolution of the Tyrone Central Inlier. TCI, Tyrone Central Inlier; TPG, Tyrone Plutonic Group; TVG, Tyrone Volcanic Group; OT, Omagh Thrust; CBC, Clew Bay Complex; LD, Longford–Down terrane; LNA, Lough Nafooy Arc (from Chew *et al.* 2008).

Northern New Brunswick – A Synthesis. *Economic Geology Monograph*, **11**, 245-301.  
 HUTTON, D.H.W., AFTALION, M., & HALLIDAY, A. N. 1985. An Ordovician ophiolite in County Tyrone, Ireland. *Nature*, **315**, 210-212.  
 VANDENBERG, A. H. M. & COOPER, R. A. 1992. The Ordovician Graptolite Sequence of Australasia. *Alcheringa*, **16**, 33-85.  
 VAN STAAL, C.R., DEWEY, J.F., MAC NIOCAILL, C.,

& MCKERROW, W.S. 1998. The Cambrian–Silurian tectonic evolution of the northern Appalachians and British Caledonides: history of a complex, west and southwest Pacific-type segment of Iapetus. In Blundell, D.J. and Scott, A. C. (eds) *Lyell: The Past is the Key to the Present*. Geological Society, London, Special Publications, **143**, 199-242.

## Molybdenum and tungsten mineralization associated with late-stage granitoid magmatism in the Appalachian Orogen of Newfoundland: an overview and a summary of recent developments

Andrew Kerr<sup>1</sup>, Tim van Nostrand<sup>1</sup>, Lawson Dickson<sup>1</sup>, & Edward Lynch<sup>2</sup>

<sup>1</sup>Geological Survey of Newfoundland and Labrador, Department of Natural Resources, PO Box 8700, St. John's, NL, A1B 4J6 CANADA (e-mail: [andykerr@gov.nl.ca](mailto:andykerr@gov.nl.ca))

<sup>2</sup>Department of Earth Sciences, National University of Ireland, Galway, Ireland.

**ABSTRACT:** Molybdenum mineralization was first discovered in Newfoundland in the 1880s, and tungsten mineralization has been known for over 50 years. Molybdenum is best-known in the Devonian Ackley Granite, where it forms syngenetic, endocontact, disseminated deposits in evolved granitoid rocks, close to the original roof of the magma chamber. Locally, these occurrences have high grades (up to 0.5% Mo), but are of limited extent. However, buried extensions of the Ackley Granite may exist, and these could be associated with both endocontact and exocontact mineralization. In the Grey River area, a potentially significant, bulk-tonnage Mo deposit consists of epigenetic, sheeted to stockwork-style quartz veins in an older (unrelated) granitoid pluton. This is considered to be a porphyry-style deposit. Although grades are relatively low (<0.1% Mo), this is a large system that also contains Cu mineralization. The vein system is probably linked to a subsurface granite pluton that locally forms sheets and dykes within the deposit. These veins contain disseminated syngenetic molybdenite, suggesting a close genetic and temporal relationship. Widespread molybdenum mineralization recently delineated in south-central Newfoundland is also associated with sheeted and stockwork-style quartz veining, and may have similar origins, although such genetic connections remain to be established. Vein-style tungsten mineralization is also best known in the Grey River area, where one such deposit contains a significant resource. It seems probable that this mineralization is genetically connected to the same buried pluton implicated for nearby Mo mineralization, and associated base-metal ( $\pm$  Au, Ag) veins may also be part of a larger zoned hydrothermal system. Skarn-type W mineralization is uncommon, but it occurs in central Newfoundland, spatially associated with a large leucogranite pluton.

**KEYWORDS:** *Tungsten, Molybdenum, Granites, Newfoundland, Mineral Deposits*

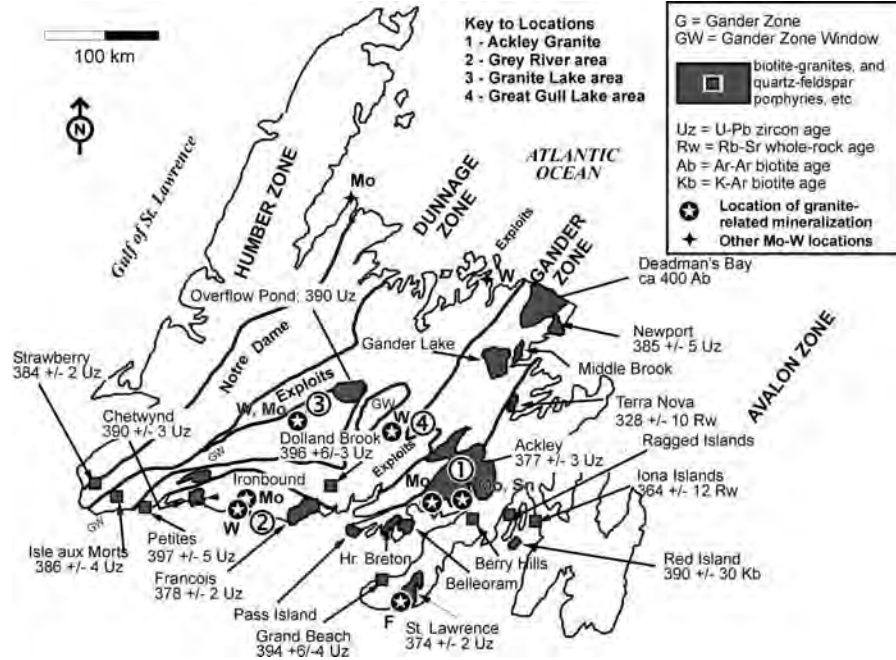
### INTRODUCTION

The increased interest in Mo and W due to commodity price increases since 2006 has created a need for a synthesis of information on known deposits and potential exploration environments within the province of Newfoundland and Labrador. This review is drawn from the historical database of exploration and scientific studies, but it also provides some essential geological information concerning recent exploration developments in Newfoundland. Further information is provided in a recent article by Kerr *et al.* (2009). Molybdenum mineralization also occurs in Precambrian granites in Labrador, but these deposits presently lie within Inuit lands that are

currently closed to exploration and are not discussed here.

### GEOLOGICAL SETTING

The formation of Mo and W deposits in Newfoundland is linked to its plutonic history, which has a much looser link to its accretionary tectonics. Although granites in Newfoundland range in age from Neoproterozoic to Devonian, the most abundant (at least in terms of areal extent) formed during the Silurian and the Devonian (Kerr 1997). The major pulse of magmatism postdates both the accretion of peri-Laurentian and peri-Gondwanan arcs to Laurentia, and the final collision of Laurentia and Ganderia. The youngest Devonian plutonic rocks also postdate any



**Fig. 1.** Locations of late-stage granitoid plutons and related mineralization in Newfoundland. Numbers refer to locations discussed in text.

later juxtaposition of Ganderia and Avalonia, because they intrude the boundary between these regions. The plate-tectonic setting of the widespread Silurian-Devonian plutonic suites is keenly debated, and the divergent viewpoints reflect contrasting interpretations of Ganderia–Avalonia relationships. In some models, these granitoid suites are viewed as ‘distal’ manifestations of subduction-zone magmatism (e.g., van Staal 2007), whereas in others they are interpreted as post-collisional and largely ensialic (e.g., Kerr 1997).

The distribution of Devonian plutonic suites is indicated in Figure 1, together with the locations of the main occurrences of granite-related mineralization, including tungsten and molybdenum. Available data indicate a gradual southeastward shift in the locus of magmatic activity through time (Kerr 1997). The youngest granites have a much more restricted distribution; most are located along the south coast of the island, and on both sides of the Gander–Avalon boundary. This broad northwest to southeast age progression could be interpreted in terms of subduction rollback, or attributed to

propagating lithospheric delamination, or could even be viewed as migration of conjoined Laurentian and Gondwanan blocks across a relatively static thermal anomaly (Kerr 1997).

### MOLYBDENUM

Molybdenum mineralization is widely distributed in Newfoundland, but the most significant examples are located on or near to the south coast of the island.

The Ackley Granite (Fig. 1) is a large polyphase granitic batholith in which high-level, evolved phases representing its fossil roof are preserved. In several areas, disseminated molybdenite is associated with alaskitic rocks adjacent to its contact with Precambrian country rocks. The grades in some of these deposits are interesting (~ 0.5% Mo), and there were some early attempts at mining them, but the tonnages appear to be small. Regional geological considerations suggest that evolved granites (and possible cupolas) may exist in the shallow subsurface south of the main part of the pluton, and there is direct evidence for these in the form of mineralization associated with a small plug on an offshore island. The Ackley

Granite was previously dated at  $377 \pm 3$  Ma (U-Pb zircon) and recent Re-Os determinations at three prospects indicate an age of  $380 \pm 2$  Ma, indicating that mineralization is indeed syngenetic (Lynch *et al.* 2009).

In the Grey River area on the south coast of Newfoundland, exploration in the 1990s located widespread molybdenite and chalcopyrite-bearing quartz veins within foliated and altered granodiorites of presumed Silurian age. It was recognized at the time that such mineralization was extensive, but it was not delineated in detail. This deposit, known as "Moly Brook", is now the subject of an advanced exploration program aimed at defining a large-tonnage, low-grade target. The style of mineralization consists of sheeted to stockwork-like quartz veins developed over a wide area, and the system extends to considerable depths. The grades are generally low (<0.1 % Mo), but the true size of the zone has yet to be established. Most holes have ended in mineralization, and the longest intersection to date was 360 m of 0.07% Mo. The mineralization is considered to be epigenetic and to have no direct relationship to its altered host rocks. The latter contain a widespread regional alteration of broadly propylitic type, and zones of intense veining and mineralization are commonly associated with potassic (argillic) alteration, which is superimposed on the regional alteration. Initial results of alteration studies using visible-infrared reflectance spectroscopy (VIRS) confirm this general pattern, but also hint at the complexity of its details. Rare examples of fine-grained granite dykes that contain disseminated molybdenite are considered to represent apophyses from a buried pluton. The nearest pluton of strongly evolved character is the François Granite, dated at  $378 \pm 2$  Ma (U-Pb zircon), and this is a possible correlative for the largely hidden source of mineralizing fluids. The precise age of the mineralization remains unknown but is presently under investigation using both U-Pb and Re-Os techniques.

In the Granite Lake area of south-central Newfoundland, disseminated and vein-style molybdenum and tungsten mineralization has been known since the 1980s, but no significant deposits were outlined. Recent exploration has now documented more widespread molybdenite associated with a swarm of quartz veins present to vertical depths of some 100 m. The style of mineralization in this deposit resembles that observed at Moly Brook and, not surprisingly, it has been christened "Moly Hill". On a regional scale, molybdenite is present in at least three granitoid units of different inferred ages, and it may not have a genetic relationship to any of them. However, there is presently no direct evidence for a buried pluton, nor are there any direct constraints on the age of the mineralization.

+

#### **TUNGSTEN**

Tungsten mineralization in Newfoundland is more restricted in distribution than molybdenum. The best known deposit is in the Grey River area (Fig. 1) and is very close to the Moly Brook deposit (see above). However, it lies within a different package of host rocks, dominated by late Precambrian metasedimentary and metavolcanic rocks.

Wolframite-bearing veins were initially discovered in the 1950s, and two such veins were explored in detail. The largest of these can be traced for about 2 km, and was assessed via underground exploration, but considered too small for commercial development. Its average width is about 1 m. The deposit is now again under assessment and a resource estimate completed in 2007 indicates about 850,000 tonnes at 0.86% WO<sub>3</sub>. The tungsten-bearing veins appear to be some of the youngest elements of the local geology. Their paragenesis is complex, with an initial stage containing molybdenite, followed by the main W-bearing veins (Higgins 1985). The later stages consist of other base-metal sulfides (e.g., galena, sphalerite and pyrite and are locally gold-rich) followed by veins containing fluorite, calcite, and barite

(Higgins 1985). Although it may not be especially large, the Grey River deposit was once described as “one of the largest typical wolframite-quartz deposits in Canada”, and it is possibly indicative of much wider potential for W in the general area.

The timing of mineralization at Grey River is not well constrained. K–Ar data from muscovites in greisen zones, suggests that they formed between 387 and 370 Ma (Higgins 1985). The concept of a hidden plutonic body that provided the fluids was outlined many years ago, and local leucocratic granite veins were correlated with the nearby 378 Ma François Granite. The relationship between the numerous W-bearing veins, base-metal veins and the nearby Mo-bearing vein system at Moly Brook is a subject of some interest, and it is hard to believe that all are coincidentally associated.

Tungsten mineralization of possible skarn affinity is located in central Newfoundland, where it is associated with calc-silicate horizons in siliciclastic sedimentary rocks. The mineralized units are generally thin, and contain variable amounts of scheelite, clinopyroxene, garnet, and chlorite. The grades range up to 2.7% WO<sub>3</sub>, but are more commonly < 1% WO<sub>3</sub>. The host rocks show signs of contact metamorphism, and are cut by leucocratic granite veins and pegmatites, possibly related to the nearby Middle Ridge Granite, dated at ca. 410 Ma. Scheelite and fluorite mineralization is also locally present in tourmaline-bearing granite veins that cut the sedimentary rocks. A link to magmatic fluids derived from the Middle Ridge Granite is suspected.

Other tungsten occurrences in Newfoundland are minor in extent, and most of these represent veins, some of which also contain minor gold mineralization.

## CONCLUSIONS

There is a long history for these commodities in Newfoundland, dating

back to the 1880s for molybdenum and to the 1950s for tungsten. Although none of these examples have ever produced metals, recent exploration work is encouraging both in terms of resources, and in terms of the wider potential for new discoveries in the region. Ongoing research work by the NL Geological Survey and by other agencies will hopefully provide better age constraints and geochemical references that will allow plutonic suites of specific ages and compositions to be targeted.

## ACKNOWLEDGEMENTS

We thank Tenajon Resources and Playfair Mining for hospitality in the field and for many interesting geological discussions. Edward Lynch acknowledges support from the Ireland-Newfoundland partnership and a scholarship from SEG.

## REFERENCES

- HIGGINS, N.C. 1985. Wolframite deposition in a hydrothermal vein system: The Grey River tungsten prospect. *Economic Geology*, **80**, 1297-1397.
- KERR, A. 1997. Space-time-composition relationships amongst Appalachian-cycle plutonic suites in Newfoundland. *Geological Society of America*, Memoir **191**, 193-220.
- KERR, A., VAN NOSTRAND, T., DICKSON, L., & LYNCH, E. 2009. Molybdenum and tungsten in Newfoundland: An overview and a summary of recent exploration developments. *Geological Survey of Newfoundland and Labrador, Report 2009-1*, 43-80.
- LYNCH, E., SELBY, D., FEELY, M., & WILTON, D. 2009. New constraints on the timing of molybdenite mineralization in the Devonian Ackley Granite suite, southeastern Newfoundland: Preliminary results of Re-Os geochronology. *Geological Survey of Newfoundland and Labrador, Report 2009-1*, 225-234.
- VAN STAAL, C. 2007. Pre-Carboniferous tectonic evolution and metallogeny of the Canadian Appalachians. *Geological Association of Canada, Mineral Deposits Division, Special Publication 5*, 793-818.

## Distribution and geochemistry of Cu-rich massive sulfides at the Brunswick No. 12 Deposit, Bathurst Mining Camp, New Brunswick.

Sean H. McClenaghan<sup>1</sup>, David R. Lentz<sup>2</sup>, & Erin M. Powe<sup>2</sup>

<sup>1</sup>Geological Surveys Branch, New Brunswick Department of Natural Resources, P.O. Box 50, Bathurst, NB E2A 3Z1 CANADA (e-mail: [Sean.McClenaghan@qnb.ca](mailto:Sean.McClenaghan@qnb.ca))

<sup>2</sup>Department of Geology, University of New Brunswick, Fredericton, NB E3B 5A3 CANADA

**ABSTRACT:** The super-giant Brunswick No.12 volcanogenic massive sulfide deposit is largely syngenetic in origin with 329 Mt of Zn–Pb–Cu–Ag-type pyritic sulfides forming an intimate relationship with a laterally extensive Algoma-type iron formation. Development of a large replacement-style basal sulfide facies, confined between an exhalative Zn–Pb-rich banded sulfide facies and an underlying stringer sulfide zone, is characterized by an increased modal abundance of chalcopyrite, pyrrhotite, and native bismuth. Analyses from the basal sulfide facies reveal an enrichment in Co (avg. 475 ppm), Bi (16 ppm), Se (21 ppm), and Cu (1.3%) with values reaching up to 3.4%. The composition of sphalerite from the basal sulfide facies (avg. 8.8 wt.% Fe) is similar to compositions reported for the exhalative banded sulfide facies, indicating a common vent-proximal origin. Remnant masses of sphalerite exhibiting chalcopyrite disease, suggest that the basal sulfide facies likely represents an exhalative sulfide facies that has undergone hydrothermal recrystallization (zone refining) by high-temperature Cu-bearing hydrothermal fluids.

**KEYWORDS:** *Copper, Brunswick No. 12, Main Zone, Bathurst Mining Camp, Volcanogenic Massive Sulfide*

### INTRODUCTION

The Brunswick No. 12 volcanogenic massive sulfide (VMS) deposit is presently host to the world's largest underground Zn mine and is the fourth-largest Zn producer, worldwide. Since production began in 1964, over 124 Mt of ore grading 8.8% Zn, 3.5% Pb, 0.36% Cu, 103 g/t Ag, and 0.6 g/t Au have been extracted from the Brunswick No. 12 Mine. Additional low-grade massive sulfides with elevated Cu contents are distributed throughout the deposit, and are generally concentrated in a basal Cu zone. This potential Cu resource could be exploited as incremental ore, extending mining production, which is currently expected to end in 2011.

### GEOLOGICAL SETTING

The Bathurst Mining Camp (BMC) occurs within a Middle-Ordovician bimodal volcanic and sedimentary sequence in the northern Appalachians of New Brunswick. Volcanic rocks were emplaced within an intra-continental back-arc basin inboard of

the Popelogan–Victoria volcanic arc at the eastern margin of the proto-Atlantic (Iapetus) Ocean (van Staal *et al.* 2003). Closure of the back-arc basin by northwest-directed subduction from the Late Ordovician to Silurian led to polyphase deformation and associated greenschist facies metamorphism (van Staal & Williams 1984).

The oldest rocks in the BMC consist of a continentally derived Cambro–Ordovician turbidite sequence of quartz wacke, siltstone, and black shale of the Miramichi Group. These rocks are conformably to disconformably overlain by pyroclastic rocks of the Nepisiguit Falls Formation, comprising quartz–feldspar crystal tuff and tuffaceous sedimentary rocks. These rocks form the footwall to Brunswick No. 12 (Fig. 1) and are overprinted by stringer sulfide mineralization and a large alteration halo, resulting from hydrothermal fluid circulation during VMS formation (Luff *et al.* 1992; Lentz & Goodfellow 1996). Massive sulfides are for the most part syngenetic, with the bulk

of the sulfides occurring in a Zn–Pb-rich banded sulfide facies that, in the vicinity of Brunswick No. 12 (Fig. 1), forms an intimate relationship with a laterally extensive Algoma-type iron formation, and defines the Brunswick Horizon. The Nepisiguit Falls Formation is overlain by more effusive felsic volcanic rocks of the Flat Landing Brook Formation and the mafic dominated Little River Formation (upper Tetagouche Group).

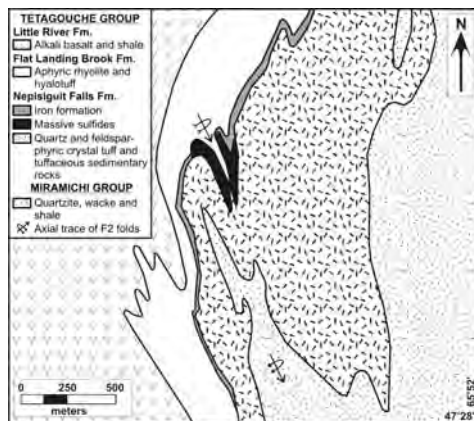


Fig. 1. Geological map of Brunswick No. 12 (after van Staal & Williams 1984).

### BRUNSWICK NO. 12

The geometry of the Brunswick No. 12 deposit has been affected by syn-metamorphic polyphase deformation (heterogeneous) with a large amount of strain accommodated by exhalative sedimentary rocks. As a result, massive sulfides dominated by ductile sulfides (sphalerite, galena, chalcopyrite, and pyrrhotite) are commonly attenuated along limbs of folds and thickened in fold noses. The most prominent folds seen in the mine sequence consist of tight to isoclinal asymmetrical F2 folds, which overprint an overturned north-facing F1 synform (Fig. 1) and define a sheath structure extending to deeper levels to the south (van Staal & Williams 1984). The massive sulfide body bottoms out at a depth of 1125 m (below surface) with altered footwall rocks fully enveloping the basal keel of the deposit (Fig. 2). Despite the deformation, metals exhibit zonation from a Cu-rich footwall to overlying Zn–Pb-rich massive sulfides and

iron formation that indicates younging to the northwest (van Staal & Williams 1984; Luff *et al.* 1992).

The Brunswick No. 12 deposit can be broadly divided into four key ore zones: the Main, West, East, and V2 zones (Luff *et al.* 1992), which merge at depth in the nose of an F2 structure (Fig. 1), and represent a dismembered, but originally continuous sulfide body (van Staal & Williams 1984). The Main Zone (Fig. 2) contains the bulk of the deposit, whereas the West Zone is smaller but has somewhat higher grades in base metals. Massive sulfides total 329 Mt; of which, 163 Mt are distributed amongst 10 principal ore lenses with an average grade of 10.4% Zn, 4.2% Pb, 0.34% Cu, and 115 g/t Ag. The remaining 166 Mt of low-grade sulfides (1.7% Zn, 0.54% Pb, 0.71% Cu and 41 g/t Ag) occur in six massive pyrite (+/- pyrrhotite) lenses, of which 5.4 Mt grade 1.5% Cu (Powe 2008).

### PETROLOGY

Based on mineralogy and stratigraphic relationships, massive sulfides can be divided into two principal facies: 1) a layered Zn–Pb-rich banded (bedded) sulfide facies, containing most of the resources recovered to date; and 2) a Cu-rich basal sulfide facies, sometimes referred to as the basal Cu-zone or vent complex. The Zn–Pb-rich banded sulfide facies is composed of pyrite, sphalerite, and galena with minor chalcopyrite and

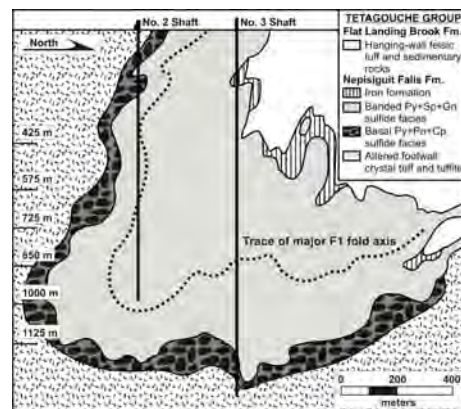
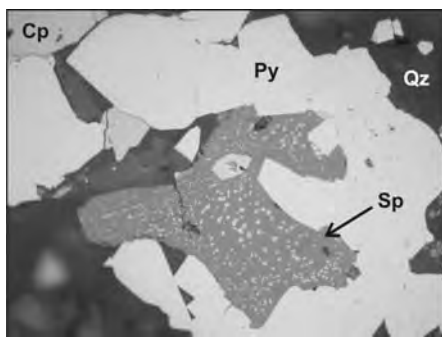


Fig. 2. Longitudinal section of the Main Zone, coincident with an F2 axial trace (after van Staal & Williams 1984).

tetrahedrite, and locally contains sub-economic sections of barren pyrite.

In stratigraphically lower parts of the sequence, Cu-rich massive sulfides (pyrite, pyrrhotite, chalcopyrite, and sphalerite) form a basal keel (Fig. 2) to the Zn–Pb-rich banded sulfide facies and are best developed towards the south end of the Main Zone. The abundance of Cu is primarily a function of chalcopyrite with lesser amounts of chalcocite, bornite, stannite, and Cu-bearing sulfosalts. Other trace phases recognized in the basal sulfide facies include arsenopyrite, magnetite, galena, and cassiterite. Overall, chalcopyrite occurs chiefly as free grains (anhedral) with only minor amounts occurring as inclusions in sphalerite. Sphalerite contents are low, with <10% of the total sphalerite grains exhibiting chalcopyrite disease (Fig. 3), a texture that is unique only to the basal sulfide facies. Average Fe contents for diseased (8.2 wt.% Fe) and non-diseased (9.9 wt.% Fe) varieties of sphalerite are consistent with electron microprobe (EPMA) compositions reported for the Main zone (Lentz 2002).



**Fig. 3.** Sphalerite mass exhibiting chalcopyrite disease, basal sulfide facies, 1125m level, Main Zone.

Pyrite has undergone variable degrees of recrystallization during metamorphism with porphyroblast development facilitated in sections with increased contents of pyrrhotite and gangue minerals (quartz and carbonate) in the matrix. Pyrrhotite and chalcopyrite exhibit extensive recrystallization and plastic flow features, with pyrrhotite-rich sections exhibiting durchbewegung textures. Pyrrhotite in the

Cu zone is abundant (up to 40%) and dominantly monoclinic, with lesser hexagonal forms also present suggesting incomplete retrograde equilibration. Analyses of pyrrhotite by EPMA revealed elevated contents of Co and Se accounting for their enrichment in the basal sulfide facies.

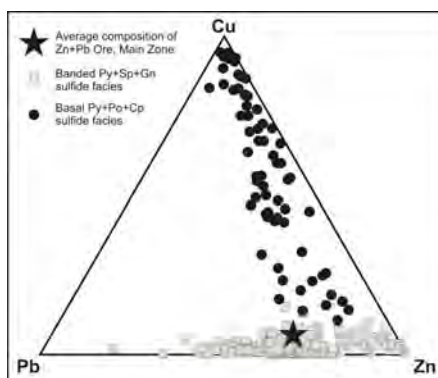
### GEOCHEMISTRY

Bulk geochemical analyses reveal two distinct trace-element associations that are consistent with recognized sulfide facies (McClenaghan *et al.* 2009). The banded sulfide facies commonly exhibits enrichment in Zn, Pb, Ag, Sb, As, Au, Sn, In, and Tl; whereas the basal sulfide facies is comparably enriched in Cu, Bi, Co, and Se. These associations have been documented throughout the BMC (Goodfellow & McCutcheon 2003; MacLellan *et al.* 2006), and are consistent with a zone refining model (see Large 1977).

Hydrothermal recrystallization has resulted in higher Fe contents (avg. 44.0% Fe<sub>2</sub>O<sub>3T</sub>) - a result of an increased modal abundance of pyrite, pyrrhotite, and chalcopyrite, and lesser sphalerite and galena. Massive sulfides (n=78) from the basal Cu-zone (1125m level) average 1.1% Zn, 0.28% Pb, 1.3% Cu, with notable contents of As (0.4%), Bi (0.03%), and Co (0.08%). Ratios of Pb/Zn average 0.4, equivalent to those from the banded sulfide facies. However the basal sulfide facies exhibits considerable enrichment in Cu (Fig. 4) with values as high as 3.4%, and accompanied by increased contents of Bi (avg. 16 ppm), Co (475 ppm), and Se (21 ppm). Enrichment of Cu, Bi, Co, and Se are accompanied by concomitant depletions in Zn, Pb, Ag, Au, Sb, Sn, and In, which characterize the banded sulfide facies. Contents of As average 0.14% reflecting the arsenian nature of pyrite and the presence of arsenopyrite, the most abundant trace-sulfide phase in the Main Zone.

### CONCLUSIONS

The high-temperature hydrothermal signature (Cu–Co–Bi–Se) characterizing the basal sulfide facies of the Brunswick No.



**Fig. 4.** Cu-Pb-Zn plot displaying metal ratios for the Brunswick No. 12 deposit.

12 deposit is consistent with its occurrence above a stringer sulfide zone; the proximity of the basal Cu zone to the vent is common to both the Brunswick No. 12 and No. 6 exhalative deposits. This distribution of metals within the deposit is interpreted to reflect an exhalative sulfide zone that has undergone extensive hydrothermal recrystallization (replacement) during zone refining. This is corroborated by the high abundance of chalcopyrite, arsenopyrite, and native bismuth all of which have higher temperature sensitive solubilities than sphalerite and galena, resulting in elevated ratios of Cu/Zn and Cu/Pb within the basal sulfide facies.

Although the Brunswick No. 12 deposit is mined primarily for Zn and Pb in the banded sulfide facies, significant Cu resources exist in the basal sulfide facies. The predominance of free chalcopyrite grains, recoverable during the milling process, may allow for its exploitation as an incremental ore.

#### ACKNOWLEDGMENTS

Electron-microprobe analyses were conducted by Douglas Hall (UNB). Funding was provided by Xstrata Canada Corp. and the NB Museum. Thanks to P. Bernard, T. Babin, B. Drolet, S. Wells, and A. Huard for access to the Brunswick No. 12 Mine.

#### REFERENCES

GOODFELLOW, W.D. & McCUTCHEON, S.R. 2003. Geologic and genetic attributes of volcanic

sediment-hosted massive sulfide deposits of the Bathurst Mining Camp, northern New Brunswick – a synthesis. *Economic Geology Monograph*, **11**, 245–302.

LARGE, R.R. 1977. Chemical evolution and zonation of massive sulfide deposits in volcanic terrains. *Economic Geology*, **72**, 549–572.

LENTZ, D.R. 2002. Sphalerite and arsenopyrite at the Brunswick No. 12 massive-sulfide deposit, Bathurst Camp, New Brunswick: constraints on P–T evolution. *Canadian Mineralogist*, **40**, 19–31.

LENTZ, D.R. & GOODFELLOW, W.D. 1996. Intense silicification of footwall sedimentary rocks in the stockwork alteration zone beneath the Brunswick No. 12 massive sulphide deposit, Bathurst, New Brunswick. *Canadian Journal of Earth Sciences*, **33**, 284–302.

LUFF, W.M., GOODFELLOW, W.D., & JURAS, S. 1992. Evidence for a feeder pipe and associated alteration at the Brunswick No. 12 massive sulphide deposit. *Exploration and Mining Geology*, **1**, 167–185.

MACLELLAN, K.L., LENTZ, D.R., & McCLENAGHAN, S.H. 2006. Petrology, geochemistry, and genesis of the copper zone at the Brunswick No. 6 volcanogenic massive sulfide deposit, Bathurst Mining Camp, New Brunswick, Canada. *Exploration and Mining Geology*, **15**, 53–76.

McCLENAGHAN, S.H., LENTZ, D.R., MARTIN, J., & DIEGOR, W.G. 2009. Gold in the Brunswick No. 12 volcanogenic massive sulfide deposit, Bathurst Mining Camp, Canada: Evidence from bulk-ore analysis and laser-ablation ICP–MS data on sulfide phases. *Mineralium Deposita*, in press.

POWE, E.M. 2008. *Petrology, geochemistry and distribution of the copper zones at the Brunswick No. 12 volcanogenic massive sulfide deposit, Bathurst Mining Camp, New Brunswick*. BSc Thesis, University of New Brunswick, Fredericton, New Brunswick.

VAN STAAL, C.R. & WILLIAMS, P.F. 1984. Structure, origin and concentration of the Brunswick 12 and 6 orebodies. *Economic Geology*, **79**, 1669–1692.

VAN STAAL, C.R., WILSON, R.A., ROGERS, N., FYFFE, L.R., LANGTON, J.P., McCUTCHEON, S.R., McNICOLL, V., & RAVENHURST, C.E. 2003. Geology and tectonic history of the Bathurst Supergroup, Bathurst Mining Camp and its relationship to coeval rocks in southwestern New Brunswick and adjacent Maine—a synthesis. *Economic Geology Monograph*, **11**, 37–60.

## Lithogeochemistry of Ordovician Sedimentary Rocks: Implications for VMS Exploration in the Bathurst Mining Camp (BMC), Canada

Steven R. McCutcheon<sup>1</sup> & James A. Walker<sup>1</sup>

<sup>1</sup>New Brunswick Geological Surveys Branch, P.O. Box 50, Bathurst, NB E2A 3Z1, CANADA  
(e-mail: [steve.mccutcheon@gnb.ca](mailto:steve.mccutcheon@gnb.ca))

**ABSTRACT:** Volcanic-hosted massive sulfide deposits of the BMC formed during the early stage of back-arc basin development (circa 470 Ma). The pre-existing volcanic arc is represented by volcanoclastic sedimentary rocks that overlie Cambro-Ordovician, continental-margin flysch. The sulfide deposits are within the felsic volcanic pile that overlies these “older” sedimentary rocks. The felsic rocks give way up-section to mafic volcanic rocks that are capped by post-volcanic (circa 460 Ma), deep-water shale and chert, i.e., “younger” sedimentary rocks. Evolution from a continental margin to a back-arc basin setting is reflected in the lithogeochemistry. Most “older” sedimentary rocks can be distinguished from “younger” ones by a line of slope  $y/x = 0.2$  on a V/Nb versus Zr/Cr diagram; older rocks have higher Zr/Cr and younger ones have higher V/Nb. Sedimentary rocks intercalated with the felsic volcanic pile plot with the older population indicating that the old-young transition is stratigraphically higher than previously thought. Log  $\text{Fe}_2\text{O}_3^T$  versus log MnO, Al versus Si, and Si versus Zr diagrams do not effectively discriminate older and younger rocks.

**KEYWORDS:** Bathurst, VMS, Ordovician, sedimentary (or sediment) lithogeochemistry

### INTRODUCTION

The volcanic-sediment-hosted massive sulfide (VMS) deposits of the Bathurst Mining Camp (BMC) formed during the initial stage of opening of the Tetagouche – Exploits back-arc basin, which developed behind a volcanic arc on the Ganderian (peri-Gondwanan) continental margin of the northern Appalachians. This basin began to form during the Middle Ordovician (circa 470 Ma) as a result of westward migration of the ensialic arc. Felsic volcanism predominated in the early stage of basin development but gave way to mafic volcanism in the later stages of rifting, ultimately producing oceanic crust (van Staal *et al.* 2003a).

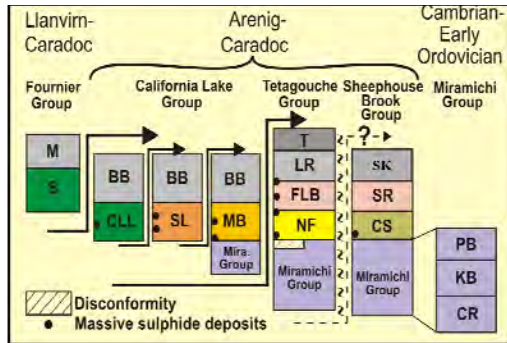
Volcanic rocks in this basin are conformably underlain by, intercalated with, and gradationally overlain by sedimentary rocks that can provide broad constraints on the depositional setting of VMS deposits within the volcanic pile. Goodfellow *et al.* (2003) suggested that anoxic shale from beneath the volcanic pile can be distinguished from oxidized shale within the pile on the basis of lithogeochemistry, i.e., using Si/Al, Zr/Si,

and  $\text{MnO}/\text{Fe}_2\text{O}_3^T$  ratios. Furthermore, Rogers *et al.* (2003) proposed that the sedimentary rocks beneath the pile (“older” group) can generally be distinguished from those within and above the pile (“younger” group) on the basis of their V/Nb versus Zr/Cr ratios. If such geochemical discriminants work, they have practical application in poorly exposed and complexly deformed terrain, such as the BMC, where it is difficult to assign a particular sedimentary rock to the correct formation on the basis of its appearance. Because the nomenclature and correlation of rock units in the BMC were still in a state of flux when the above authors collected their samples in the 1990s, a re-evaluation of their rock-unit assignments was undertaken. Also, a comparison of their data to others from stratigraphically well constrained samples was made to test the utility of their proposed discriminants.

### STRATIGRAPHY

In the BMC, sedimentary rocks underlying the volcanic pile are assigned to the Miramichi Group (MG), whereas those

within and overlying the pile are assigned to the Bathurst Supergroup (van Staal *et al.* 2003a), which comprises the California Lake (CLG), Fournier (FG), Sheephouse Brook (SBG), and Tetagouche (TG) groups (Fig. 1).



**Fig. 1.** Schematic tectonostratigraphy of the Bathurst Mining Camp showing inferred positions of known deposits. Formations as follows: BB-Boucher Brook, CLL-Canoe Landing Lake, CR-Chain of Rocks, CS-Clearwater Stream, FLB-Flat Landing Brook, KB-Knights Brook, LR-Little River, M-Millstream, MB-Mount Brittain, NF-Nepisiguit Falls, PB-Patrick Brook, S-Sormany, SK-Slacks Lake, SL-Spruce Lake, SR-Sevogle River, T-Tomogonops.

From apparent base to top, the MG comprises the CR, KB, and PB formations that collectively are referred to as “older sediments” (Fig. 1). The CR Formation consists of thickly bedded, greenish grey, quartz wacke with minor shale. The KB Formation is similar compositionally to the CR, but the rocks are dark grey, and shale is more voluminous. The PB Formation generally has more shale than the KB Formation; it also contains minor dark grey, quartz wacke ( $\pm$  volcanic quartz) and coarse-grained, feldspathic wacke. The PB Formation, unlike the CR and KB, reflects two sediment sources, one from the continental margin and the other from the volcanic arc.

Sedimentary rocks within the lower (mainly felsic) part of the volcanic pile are highly variable and not voluminous. Greenish grey to dark grey mudrocks and volcanoclastic rocks occur locally in the FLB, MB, NF, SL and SR formations (Fig.

1). Some of them look lithologically similar to those of the PB Formation.

Sedimentary rocks in the upper (mainly mafic) part of the pile are predominantly mudrocks, but they have an exhalative component. Maroon shale and chert are present in the BB, LR, and SK formations (Fig. 1). Notably, maroon shale and chert are abundant in the CLL Formation and also occur locally near the top of the FLB and SR formations. Caradocian black shale and pelagic chert of the BB, LR, and SK formations mark the end of volcanic activity in the BMC. In places, these rocks grade upward into flysch of the M or T formations (Fig. 1).

## LITHOGEOCHEMISTRY

### Data and Methods

In total, 590 analyses were used in our evaluation of sedimentary rocks of the BMC, including 234 from Goodfellow *et al.* (2003), 133 from Rogers *et al.* (2003), and 108 from various reports of the NB Geological Surveys Branch. All of these data were collected during the federal-provincial EXTECH-II Project (1994-1998); an additional 115 samples, acquired subsequently, were analysed at Activation Laboratories Ltd. using their lithium metaborate/tetraborate fusion ICP whole rock package (Code 4B) and trace element ICP-MS package (Code 4B2).

Each reported sample location was cross referenced with the 1:100,000 scale geological map of the BMC (van Staal *et al.* 2003b) to determine if the given rock unit matched the one on the map, or subsequent revisions to it. This resulted in the re-assignment of 52 samples to other formations. The resulting dataset ( $n = 590$ ) comprises 87 BB, 19 CLL, 16 FLB, 40 KB, 54 LR, 61 M, 8 MB, 60 NF, 138 PB, 13 SK, 71 SL, 3 SR, and 20 T samples. All samples were plotted on the proposed discrimination diagrams and the results inspected and interpreted. The data were then filtered as follows: BB, LR, M, and T samples with  $V/Nb > 8$ ; CR, KB, PB, and NF samples with  $Zr/Cr > 5$ ; and all samples with  $Al/(Al+Fe+Mn) < 0.45$  were removed from the dataset, leaving only the most problematic samples to

discriminate. The remaining 282 samples (37 BB, 18 CLL, 9 FLB, 19 KB, 5 LR, 12 M, 7 MB, 45 NF, 57 PB, 1 SK, 69 SL, 3 SR, and 0 T) were then re-plotted and interpreted.

### Results

On a V/Nb versus Zr/Cr diagram, a line ( $y/x = 0.2$ ) passing through the origin separates most of the “older” group (CLL, KB, MB, NF, PB, SR, and SL formations) from the “younger” ones (BB, LR, M, SK, and T formations). Specifically, it correctly discriminates 145/178 MG, 132/150 TG, 105/185 CLG, 6/16 SBG, and 50/61 FG samples, which represents success rates of 82%, 88%, 56%, 38%, and 82%, respectively. In the MG, 30 PB samples plot with the younger group, which is not surprising considering that this formation received erosional detritus from the Popelogan Arc (van Staal *et al.* 2003a). In the TG, 11 NF samples plot with the younger group but 8 of them come from one area suggesting that these samples were assigned to the wrong formation. In the CLG, 45 BB samples plot with the older group and 28 SL samples plot with the younger one, yielding a low success rate (56%). However, these two formations are everywhere tectonically interleaved and the sedimentary rocks in both look much alike. This low success rate may reflect incorrect assignment of samples to each formation. The success rate for the SBG is the lowest (38%), but the sample population ( $n = 16$ ) is small.

A binary  $Al/(Al+Fe+Mn)$  versus  $Fe/Ti$  plot reveals that 57/590 samples have  $Al/(Al+Fe+Mn) < 0.45$  and  $Fe/Ti > 20$ , i.e., in the “hydrothermal field” of Böstrom (1973). Notably, 33 of them are PB samples, all but three of which come from drill cores in the vicinity of the Brunswick No.12 mine, no doubt reflecting addition of iron to the footwall rocks. Surprisingly, only 24/412 samples from the Bathurst Supergroup plot in this hydrothermal field as follows: TG (2 NF, 3 FLB, 2 LR), CLG (1 CLL, 1 SL, 8 BB), and SBG (7 SK).

Ternary diagrams (Sc-Th-Zr/10 and Th-La-Sc) show that the majority of the samples plot in or near the “continental

island arc” field of Bhatia & Crook (1986). Notably, the MG samples show the same distribution on these diagrams as those from the Bathurst Supergroup.

On a  $\log Fe_2O_3^T$  versus  $\log MnO$  binary diagram, most formations show a similar distribution, with samples clustering along a line ( $y/x = 0.9$ ) that passes through 1.5 log units on the x-axis. Samples from the KB, FLB, MB, NF, and T formations plot towards the bottom end (0.01-0.2 MnO) of this line, whereas SK samples plot towards the top end (1-10); samples from the BB, CLL, LR, M, PB, and SL formations span the length of the line.

On an Al versus Si binary diagram, most of the data plot along a line ( $y/x = -1.7$ ) that passes through 18 wt.% Al. A number of samples from the BB, CLL, LR, M, NF, PB, SK, SL, and T formations plot below this line, but virtually none plot above it. Samples from individual formations generally span the entire length of the line. Goodfellow *et al.* (2003) indicated that a line of slope 5 ( $Si/Al = 5$ ), passing through 3 wt.% Al, separates BB, CLL and LR shales from those of the PB and SL formations; however, there is no indication of this from our data.

These authors also suggest that a Si versus Zr binary diagram can be used to help distinguish BB, CLL, and LR shales from PB and SL shales, i.e., the former rocks generally have lower Zr/Si ratios than the latter. Our data cluster along two broad trends: one ( $y/x = -8$ ) that passes through 45 wt.% Si and another ( $y/x = 40$ ) that passes through 25 wt.% Si. Most BB, LR, M, SK, and T samples have  $< 250$  ppm Zr and plot along the first trend, but the CLL, FLB, MB, PB, and SL samples plot along both trends.

Examination of the filtered dataset reveals additional information. On a V/Nb versus Zr/Cr binary diagram, most of the samples that do not plot where expected are from the BB (31/37), LR (4/5), M (8/12), NF (11/45), PB (15/57), SL (20/69), and SR (3/3) formations. Of the 31 BB samples that are not classified correctly, 23 of them have a “hydrothermal” component and 5 others could be from the SL Formation. Similarly, 2/4 LR samples

could be from the SL Formation. Of the 8 samples from the M Formation, 3 have a hydrothermal component. Of the 11 NF samples, 7 are from one area and may reflect incorrect unit assignment. Of the 15 PB samples, 8 are from drill cores near the Brunswick No.12 mine. Of the 20 SL samples, 11 could be from the BB and LR formations.

## CONCLUSIONS

Our re-evaluation of geochemical data (n=590) from sedimentary rocks of the BMC indicates the following: 1) A line ( $y/x = 0.2$ ) passing through the origin on a V/Nb versus Zr/Cr diagram discriminates most “older” sedimentary rocks from “younger” sedimentary rocks. 2) The transition between older and younger appears to be near the top of the felsic volcanic pile, not near the bottom as reported by Rogers *et al.* (2003). 3) Overall, this discriminant is most effective for the TG (88%), followed by the MG (82%), and FG (81%); it is least effective for the CLG and SBG (56%). 4) Low percentages for the BB (49%) and SL (60%) formations reduce the overall total for the CLG; this probably reflects incorrect assignment of samples to these two formations. 5) Over half of the 57 “metalliferous sediments” in the dataset come from the PB Formation, specifically from drill cores near Brunswick No. 12, suggesting that iron was added to the footwall rocks during hydrothermal alteration. 6) Log  $\text{Fe}_2\text{O}_3^T$  versus log MnO, Al versus Si, and Si versus Zr binary diagrams do not effectively discriminate older and younger rocks of the BMC.

## REFERENCES

- BHATIA, M.R. & CROOK, K.A.W. 1986. Trace element characteristics of greywackes and tectonic setting discrimination of sedimentary basins. *Contributions to Mineralogy and Petrology*, **92**, 181–193.
- BÖSTROM, K. 1973. The origin and fate of ferromanganoan active ridge sediments. *Stockholm Contributions to Geology*, **27**, 147–243.
- GOODFELLOW, W.D., PETER, J.M., WINCHESTER, J.A., & VAN STAAL, C.R. 2003. Ambient marine environment and sediment

provenance during formation of massive sulphide deposits in the Bathurst Mining Camp: importance of reduced bottom waters to sulphide precipitation and preservation. In: GOODFELLOW, W.D., McCUTCHEON, S.R., & PETER, J.M. (eds), *Massive sulphide deposits of the Bathurst Mining Camp, New Brunswick, and northern Maine*, Economic Geology Monograph **11**, 129–156.

- ROGERS, N., VAN STAAL, C.R., WINCHESTER, J.A., & FYFFE, L.R. 2003. Provenance and chemical stratigraphy of the sedimentary rocks of the Miramichi, Tetagouche, California Lake, and Fournier groups, northern New Brunswick. In: GOODFELLOW, W.D., McCUTCHEON, S.R., & PETER, J.M. (eds), *Massive sulphide deposits of the Bathurst Mining Camp, New Brunswick, and northern Maine*, Economic Geology Monograph **11**, 111–128.

- VAN STAAL, C.R., WILSON, R.A., ROGERS, N., FYFFE, L.R., GOWER, S.J., LANGTON, J.P., McCUTCHEON, S.R., & WALKER, J.A. 2003b. A new geologic map of the Bathurst Mining Camp and surrounding areas – a product of integrated geological, geochemical and geophysical data. In: GOODFELLOW, W.D., McCUTCHEON, S.R., & PETER, J.M. (eds), *Massive sulphide deposits of the Bathurst Mining Camp, New Brunswick, and northern Maine*, Economic Geology Monograph **11**, 61-64.

- VAN STAAL, C.R., WILSON, R.A., ROGERS, N., FYFFE, L.R., LANGTON, J.P., McCUTCHEON, S.R., McNICOLL, V., & RAVENHURST, C.E. 2003a. Geology and tectonic history of the Bathurst Supergroup, Bathurst Mining Camp, and its relationships to coeval rocks in southwestern New Brunswick and adjacent Maine – a synthesis. In: GOODFELLOW, W.D., McCUTCHEON, S.R., & PETER, J.M. (eds), *Massive sulphide deposits of the Bathurst Mining Camp, New Brunswick, and northern Maine*, Economic Geology Monograph **11**, 37–60.

## Evaluating Bromine Geochemistry as a Prospecting Tool For Potash in Western Newfoundland

Jackie O' Driscoll<sup>1</sup>, Robert Boehner<sup>2</sup>, Lawrence Winter<sup>1</sup> & Roland Butler<sup>1</sup>

<sup>1</sup>Altius Resources Inc., P.O. Box 385, St. John's, Newfoundland, A1C 5J9 CANADA  
(e-mail: [jodriscoll@altiusminerals.com](mailto:jodriscoll@altiusminerals.com))

<sup>2</sup>P.O. Box 1365, Montague, Prince Edward Island, C0A 1R0 CANADA

**ABSTRACT:** Salt deposits of Early Carboniferous age (~325-335 Ma) Windsor Group are known throughout the Atlantic Provinces. These marine evaporite sequences were precipitated from seawater in a series of restricted basins, which formed in the larger Maritimes Basin. Intermittent exploration work including mapping, diamond drilling, and geophysical surveys in the St. George's Bay area of western Newfoundland over the last sixty years has resulted in the recognition of salt and potash, analogous to those evaporite sequences of New Brunswick and Nova Scotia. Altius currently holds mineral claims covering 46,250 hectares in the St. George's Bay area, which are currently being evaluated for the potential to host economic potash deposits.

Previous geochemical bromine profiling of Eastern Canadian salt deposits and occurrences has illustrated the usefulness of this technique in this region (Baar 1965). Several salt intersections from previous drilling in the St. George's Bay area were sampled for a bromine geochemical study. Geochemical data are pending at the time of writing. The presentation will summarize the results and compare the data to representative profiles from Nova Scotia and New Brunswick.

**KEYWORDS:** *Evaporite, Potash, Bromine, Carboniferous, Codroy Group*

### INTRODUCTION

The Carboniferous sediments of the Maritimes Basin were originally deposited as red-green interstratified continental to marginal siliciclastics, marine limestone, dolostone, gypsum, anhydrite, halite, and locally, potash. The salt deposits vary from stratified, with only minor structural complications, to those that have been tectonized into pillows, anticlines (e.g., Penobscus Deposit) and diapirs or domes. In the latter cases, structural complexities make the stratigraphic position of many of these deposits uncertain.

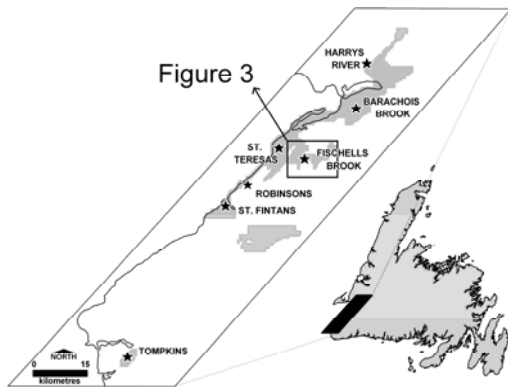
The St. George's Bay Sub-basin of western Newfoundland is contained within the Carboniferous Maritimes Basin (Fig. 1) and hosts sedimentary rocks assigned to the Codroy Group. The Codroy Group is equivalent to the Windsor Group, which hosts potash deposits and occurrences in Nova Scotia and New Brunswick, including Potash Corporation's Penobscus Mine in Sussex. Annual production from this deposit comprises 0.7



**Fig. 1.** Regional map of Atlantic Canada outlining the known limits the Maritimes Basin.

million tonnes KCl and 0.6 million tonnes of salt (Moore *et al.* 2008).

Altius currently holds mineral licenses covering 46,250 hectares in the St. George's Bay area, which hosts several potash prospects (Fig. 2). This area has established infrastructure, excellent road access, and is adjacent to deep water port facilities currently being utilized for shipping base metal concentrate.



**Fig. 2.** Property location map with Altius claims shaded and potash prospects shown as stars.

The potash occurrences within the St. George's Bay area consist mainly of halite (NaCl) with variable siliciclastics and potash minerals including sylvite (KCl) and carnallite ( $\text{KMgCl}_3 \cdot 6\text{H}_2\text{O}$ ).

Phase I exploration work by Altius included a compilation of all publicly available data from previous diamond drill holes, petroleum exploration wells, and geophysical surveys (gravity and seismic) for incorporation into an integrated 3D model. Phase II of the work program is currently ongoing and consists of a new ground gravity survey, re-assessment and re-sampling of previous drill core, and assessment of previous seismic data. This presentation will summarize the exploration methodology and focus on the use of bromine as a geochemical vector for potash.

## **GEOLOGICAL SETTING**

### **Regional Geology**

The St. George's Bay area is located within the Humber Zone of western Newfoundland; the westernmost tectono-stratigraphic subdivision of the Newfoundland Appalachians. The Humber Zone represents the ancient continental margin of eastern North America (Williams 1995) and is partly bounded to the east by the Cabot Fault.

The "Maritime Disturbance" refers to tectonic activity that mainly occurred within the basin areas of the Late Paleozoic

overstep sequence. The Appalachian basement fragmented resulting in subsidence and uplift creating areas for deposition of Carboniferous sediments. Deformation caused local and regional compression represented by broad open folds, reverse and normal faulting, and salt tectonism (Williams 1995).

The St. George's Bay Sub-basin formed as a strike-slip successor basin adjacent to, and west of, the northeasterly trending Long Range Fault. This fault is a major strike-slip structure that is part of the Hercynian Cabot Fault system in western Newfoundland. Dextral strike-slip movements began in Middle or Late Devonian time and ended in the Early Carboniferous. The sub-basin comprises a 22 kilometre wide zone between St. George's Bay and the Long Range Mountains, extending 125 kilometres from the coast near Codroy Valley, north-east to the vicinity of Stephenville, covering an area totalling 2700 square kilometres (Knight 1983).

### **Local Geology**

The rocks of the St. George's Bay Sub-basin are divided into three groups: the Anguille, Codroy, and Barachois Groups, which are correlated to the Horton, Windsor, and Canso (Mabou) Groups, respectively, in Nova Scotia and New Brunswick (Knight 1983). The Anguille Group is a sequence of non-marine siliciclastic rocks defining the oldest strata in the basin. It is conformably overlain by a series of marine evaporite and carbonate rocks and locally dominant non-marine clastic rocks comprising the Codroy Group. The Codroy Group is conformably overlain by a variably interbedded sequence of non-marine sandstone, siltstone and shale of the Barachois Group (Knight 1983). The Carboniferous sedimentary rocks in the St. George's Sub-basin lie upon anorthosite and mafic and felsic orthogneiss of the Late Proterozoic Long Range Complex.

The marine sedimentary rocks of the Codroy Group host the evaporite sequence of interest and are divided in ascending order into the Ship Cove

Formation, the Journois Pond Formation, the Woodville Formation, the Jeffrey's Village Formation, and the Highlands Formation.

The lower limestone, gypsum, and anhydrite units of the Ship Cove and Journois Pond Formations are overlain by a 200-1000 metre thick sequence of salt and grey shale of the Woodville Formation. The Woodville Formation has been subdivided into four members: Basal, Middle and Upper Halite Members, and an overlying shale member with pseudomorphs of halite and gypsum veinlets.

The potash units occur within the rock salt sequences of the Woodville Formation. Sylvite is disseminated or occurs as distinct sylvinite beds within the upper portion of the Middle Halite. The lower portion of the unit consists of fine-grained metallic copper-red disseminated carnallite and vug fillings. Minor potash-bearing intervals are also found in the Upper Halite, typically with interbedded clays.

### EXPLORATION HISTORY

Previous exploration circa late 1940's demonstrates the area's high potential for potash deposits. However, there has been limited sustained exploration in this region, emphasized by the presence of gravity lows throughout the area, which have not been extensively tested. Moreover, recent salt or potash intersections discovered during drilling of petroleum exploration wells (e.g., Flat Bay-101-1 and Captain Cook-1) further illustrate the potash potential of the region. These were not expected, and are not associated with gravity lows. Potash assays up to 20.4% K<sub>2</sub>O were reported from Captain Cook-1 in 2008 (Vulcan 2008).

Historical exploration has highlighted the Fischell's Brook salt/potash prospect as a possible analog to the Sussex deposits in southern New Brunswick. The prospect is located approximately 15 kilometres south of the Town of St. George adjacent to and underlying the Trans-Canada Highway. The deposit is associated with a gravity anomaly that is approximately 10.5 x 8.5

kilometres in size. Historical drilling of this gravity anomaly has identified a significant body of salt.

In the 1968 discovery hole (Hooker-1; Hooker Chemical Inc.), approximately 750 metres of salt was intersected with the hole terminating in salt at 1099 metres. Sylvite was intersected at a vertical depth of 381.0 to 402.3 metres and assayed up to 15.1% K<sub>2</sub>O with insoluble content up to 11.6%.

### PRINCIPLES OF BROMINE

#### GEOCHEMISTRY

Bromine (Br) is the most important genetic trace element for potash within salt deposits. Bromide minerals do not form during the crystallization of salts from seawater; rather bromine tends to accumulate with increasing brine concentration and occurs only as a trace in solid solution as a substitute for chlorine in the precipitating chloride minerals.

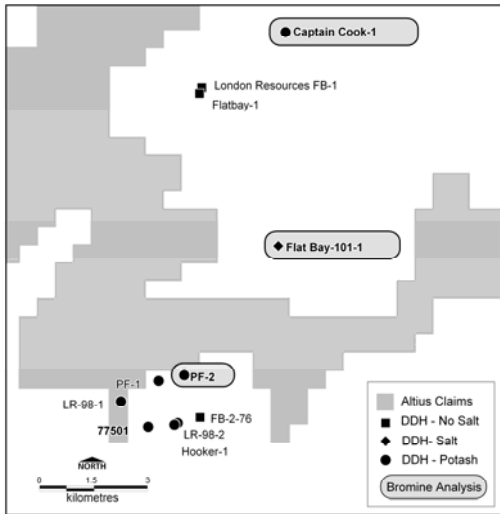
Bromine has an ionic radius of 1.96 Å and thus easily substitutes for chlorine (1.81 Å) in the halite crystal lattice as well as in the other chloride salts. The distribution coefficients for bromine in chloride salts deposited from seawater is less than 1 (Warren 2006).

The bromine content of halite is characteristic for each sequence of the evaporitic strata. The bromide level in a halite crystal also increases with increases in parent brine temperature and with the speed of crystallization (Warren 2006).

Typical marine water contents of Br are 65 ppm. The first chloride salt precipitated in an evaporite basin is halite (70-75 ppm Br). Bromine content of halite increases to >230 ppm Br as the first potassium mineral crystallizes (Valyashko 1956).

Thus, the trends of Br content in halite sampled systematically in profiles of salt sequences may be used as a guide to:

- 1) saline evaporite mineral depositional history and stratigraphic trends,
- 2) remnant high Br indicative of former high order evaporite deposition (potash salts),
- 3) salt sequence anomalies including potential structural repetition or dissolution intervals,



**Fig. 3.** Location of drill holes in the Fischells Brook and Flat Bay areas illustrating salt and potash intercepts and highlighting PF-2, Flat Bay-101-1 and Captain Cook-1, selected for the current bromine geochemistry study.

- 4) regional basin correlation and comparison to areas with economic deposits, and
- 5) post depositional alteration/diagenesis of these highly soluble rocks.

### 2009 BROMINE GEOCHEMISTRY STUDY

Altius' current bromine geochemical study utilizes core samples from holes PF-2, Flat Bay-101-1 and Captain Cook-1 (Fig. 3). This study was undertaken to establish baseline bromine profiles for the St. Georges Bay region.

The data will assist in evaluating the potash potential in each area, especially where structural complexities present challenges with stratigraphic interpretations.

### CONCLUSIONS

- (1) The St. Georges Sub-basin is considered prospective but underexplored for potash deposits.
- (2) Bromine geochemistry has been proven as a useful prospecting tool for potash mineralization in various regions.
- (3) Ongoing exploration work by Altius Resources, including bromine geochemistry, will further our understanding of the potash mineralization in western Newfoundland.

### REFERENCES

BAAR, C.A. 1965. Bromine investigations on eastern Canada salt deposits. In: RAU, J.L. (ed) *Second Symposium on Salt*. Northern Ohio Geological Society, 276-292.

KNIGHT, I. 1983. *Geology of the Carboniferous Bay St. George sub-basin, western Newfoundland*. Mineral Development Division, NDME, Memoir 1, 358 p.

MOORE, G. et al. 2008. *National Instrument 43-101 Technical Report on Penobsquis & Picadilly Potash Deposits, Kings County, New Brunswick, Canada*. Potash Corporation of Saskatchewan Inc., 83 p.

VALYASHKO, M.G. 1956. Geochemistry of bromine in the processes of salt deposition and the use of the bromine content as a genetic and prospecting criterion. *Geochemistry*, 6, 570-589.

VULCAN MINERALS INC., 2008. "Potash Assays up to 20.4% K<sub>2</sub>O", news release Sept 25, 2008.

WARREN, J.K. 2006. *Evaporites. Sediments, Resources and Hydrocarbons*, 1035 p.

WILLIAMS, H. 1995. *Geology of the Appalachian-Caledonian Orogen in Canada and Greenland*. Geological Survey of Canada, Geology of Canada Series, 6, 944 p.

## Mesothermal, auriferous quartz veins of the Golden Promise deposit, central Newfoundland: their setting and the nature of wall rock alteration

Hamish Sandeman<sup>1</sup>, Heather Rafuse<sup>1</sup>, David Copeland<sup>2</sup> and Jeff Morgan<sup>3</sup>

<sup>1</sup>Geological Survey of Newfoundland and Labrador, Department of Natural Resources, PO Box 8700, St. John's, NL, A1B 4J6 CANADA (e-mail: [hamishsandeman@gov.nl.ca](mailto:hamishsandeman@gov.nl.ca))

<sup>2</sup>Paragon Minerals Corporation, 85 Thorburn Road, Suite 202, St. John's, NL, A1B 3M2 CANADA

<sup>3</sup>Crosshair Exploration and Mining Corporation, Suite 202, Kenmount Business Centre, 66 Kenmount Road, St. John's, NL, A1B 3V7 CANADA

**ABSTRACT:** The Golden Promise gold deposit is located ca. 10 km southwest of the community of Badger in central Newfoundland within the Exploits sub-zone of the Appalachian orogen. The deposit is poorly exposed and comprises a series of likely en-echelon, ENE-trending auriferous quartz veins hosted in shales and greywackes of the Upper Victoria Lake Supergroup. Native Au occurs in association with pyrite, arsenopyrite and rare galena within cockscomb-textured and stylolitic quartz veins. Alteration associated with the mineralization comprises visibly bleached zones proximal to the veins with bleached spotted zones up generally  $\leq 10$  m outward from the veins. Close spatial overlap between a suite of E-W trending intermediate dykes, the quartz veins and the characteristic spot-texture and widespread alteration of the dykes themselves, obfuscates petrogenetic-paragenetic relationships. Preliminary VIRS spectrometry, petrographic analysis and EDS electron microprobe studies indicate that the alteration assemblage is dominated by Fe-chlorite+sericite+CaCO<sub>3</sub>. Two generations of quartz veins are observed, an early series of coarse cockscomb quartz veins are cut by a younger series of apparently thinner, mosaic-textured fine-grained quartz. Visible Au and economic mineralization appears to accompany early, coarse-grained veins.

**KEYWORDS:** *gold, infrared spectrometry, alteration, mineralization*

### INTRODUCTION

The Golden Promise deposit was discovered by prospector William Mercer in 2002 after a forest fire razed thick brush in heavily drift covered areas immediately south of the community of Badger. The initial discovery consisted of coarse-grained, comb-textured and stylolitic quartz boulders exposed on sub-cropping, bedrock-cored ridges. A composite sample from ~10 of these boulders assayed ca. 30 g/t Au. The deposit was immediately optioned by Rubicon Minerals Corporation in 2002 and has since been explored under a number of joint venture projects involving Rubicon Minerals Corporation, Paragon Minerals Corporation, Placer Dome Ltd., and Crosshair Exploration & Mining Corporation. Since 2002, the property has been subjected to intense scrutiny including: the completion of 8,250 line

kilometres of airborne magnetic and electromagnetic surveys; a regional soil sampling program that included ca. 6000 B-horizon samples; intensive prospecting and mapping and; 98 near-surface (<314 m) NQ drill holes totalling 15,310 m. A NI-43-101F1 resource calculation on the deposit (Pilgrim & Giroux 2008) outlines a total of 921,000 tonnes averaging 3.02 g Au/t (89,500 contained ounces of gold), with a cut-off grade of 1 g/t Au. Golden Promise therefore represents the first significant gold resource in this part of central Newfoundland, wherein low metamorphic grade sedimentary rocks were previously considered non-prospective for mineralization.

### REGIONAL SETTING

The Golden Promise deposit lies within the Exploits subzone of the Dunnage Zone of the Appalachians, ca. 8 km east of the

Red Indian Line. Within the Dunnage zone, rocks of the Exploits subzone lie to the east of the Red Indian Line and are considered to have peri-Gondwanan affinities. In contrast, rocks of the Notre Dame subzone, which are of peri-Laurentian affinity, lie to the west of the Red Indian Line (Williams 1995). In the Exploits subzone, rocks of the Cambrian-Ordovician Victoria Lake Group (now Supergroup; cf., Evans & Kean 2002; Rogers & van Staal 2002) comprise at least three volcanic–rock dominated sequences that are stratigraphically and structurally intercalated with marine sedimentary rocks consisting of vari-coloured shales along with volcanoclastic sandstones and wackes. Many of these, particularly those of the study area, have recently been assigned to the Stanley Waters Formation by Rogers *et al.* (2005). Collectively, rocks of the Victoria Lake Supergroup are conformably(?) overlain by polymictic conglomerates, medium-grained quartz-rich sandstones, and sparse shaley horizons constituting the continentally-derived, overlap, Ordovician-Silurian Badger Group considered to have been deposited in restricted oceanic basins during closure of Iapetus Ocean (Williams & O'Brien, 1991; Williams 1995).

Historical geological maps (e.g., Kean & Jaysinghe 1982) suggest that the host rocks of the Golden Promise veins belong to the subsequently defined Badger Group (cf., Williams 1995). In this area of poor exposure, however, modern, airborne magnetic and resistivity studies (Copeland & Newport 2005) have significantly improved our knowledge of the 3-D architecture of the rocks of the region. These investigations have outlined persistent and continuous magnetic and conductive *versus* poorly-magnetic and non conductive horizons within the rocks of the study area. In conjunction with key, but rare, well exposed bedrock outcrops, the geophysical surveys have led to a more sound and informed subdivision of the distribution of rock-types and, in particular, has led to more accurate delineation of the drift-covered contacts between the Victoria Lake Supergroup

and the Badger Group. The recent detailed field work and regional geophysical surveys have yielded new interpretive maps (Copeland & Newport 2005) that clearly indicate that the auriferous quartz veins of the Golden Promise Deposit are hosted by upward-fining marine clastic sedimentary rocks of the Upper Victoria Lake Supergroup rather than the siliciclastic flysch sequences of the Badger Group (Williams & O'Brien, 1991; Pilgrim & Giroux 2008).

### LOCAL GEOLOGY AND MINERALIZATION

The host rocks to the Golden Promise vein systems are very poorly exposed. A number of the ridge-crests in the immediate area of the main Jaclyn veins (Fig. 1) host broken, angular boulders that may represent possible subcrop. Perhaps the best bedrock exposure in the area is that at Little Red Indian Falls, ca. 7 km to the SW of the deposit on the Exploits River. There, a ca. 300m long section preserves, vari-coloured, dm-scale bedded siltstones grading upwards into grey and black mudstones and into black, pyritic Caradocian shales capping the Victoria Lake Supergroup. The upward fining nature, the scale of bedding and the character of the sedimentary rocks are identical to those observed in the upper stratigraphic sections of drill core from the Golden Promise Deposit.

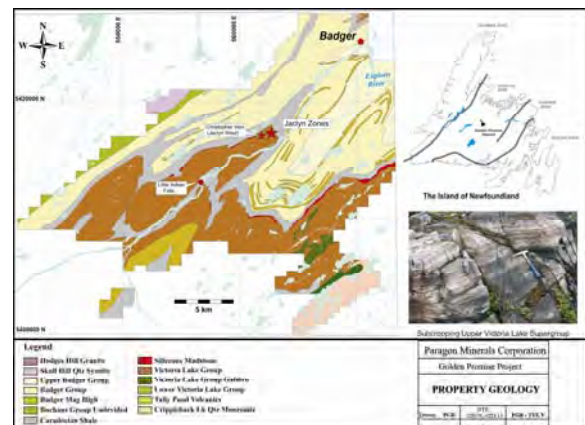


Fig. 1. Regional setting and geology of the Golden Promise Deposit, Newfoundland.

Trenches excavated across the veins are typically flooded by surface water; however, three partially flooded trenches have exposed bedrock. From small ( $\leq 5\text{m}^2$ ) outcrops exposed in three of the trenches, it is apparent that the average grain size of the clastic sedimentary rocks and the abundance of coarse-grained detritus, increases from NE to SW away from the buried Caradocian shale, with arkosic sandstone most abundant in the SW near the Christopher vein. An extensive array of 98 drill holes provides excellent downhole, 3-D control on our understanding of the geology.

Collectively the field, drillcore, and regional data yield a number of first order conclusions.

1) The deposit is hosted by fining-upwards, right-way-up clastic sedimentary units that are dominated by plagioclase-rich intermediate to mafic volcanic and fine-grained pelagic sedimentary debris. These are distinctly different in composition from quartzose conglomerates, sandstones and shales of the proximal Badger Group.

2) The deposit lies in the core of a 2-3 km wavelength, tight, shallow to moderate Northeast-plunging anticline that folds the Upper Victoria Lake Supergroup, the black, pyritic Caradocian shale, and the Badger Group.

3) Two distinct styles of veining are recognized: stratigraphy discordant veins dominant at the Jaclyn Main and Christopher deposits, and stratigraphy parallel veins dominating at the Jaclyn North vein system. These have been inferred to represent: 1) vein systems developed roughly axial planar to regional anticlinal axes, and; 2) saddle-reef style veins developed along bedding surfaces in the limbs of the same regional folds.

4) Upright veins cross-cut bedding in the host sedimentary rocks at a high angle, trend  $075\text{-}090^\circ$  and dip ca.  $70\text{-}80^\circ\text{S}$ . Jaclyn North veins roughly parallel bedding, similarly trend  $075\text{-}090^\circ$  and dip  $35\text{-}45^\circ\text{N}$ .

5) Upright veins are subparallel to two distinct suites of dykes that exhibit well-defined chill margins; a) typically fine-

grained, flow-aligned basaltic andesite dykes with abundant saussuritized plagioclase, and; b) medium-grained clinopyroxene+plagioclase gabbro dykes that are commonly fresh.

6) Strong bleaching and alteration of host siltstones only occurs proximal ( $\leq 2$  m) to the veins, whereas spot-bleaching occurs more distally ( $\leq$  ca. 10 m) and is commonly not spatially associated with quartz veining. Alteration in coarse-grained sedimentary rocks is subtle and is accompanied by an increase in sulfides (typically pyrite) along with chlorite+sericite (white mica) and carbonate.

7) Quartz veined, high-grade zones range up to 4 m but individual veins are typically  $< 1\text{m}$  in thickness. These stylonitic and massive comb-textured veins containing abundant free gold and pyrite along with trace arsenopyrite, pyrrhotite, sphalerite and galena.

#### **VIRS (VISUAL AND INFRARED SPECTROMETRIC ANALYSIS)**

We have examined a range of selected drill core and outcrop samples using VIRS in conjunction with petrography. In drill hole GP07-86, unaltered host rocks generally reveal low reflectance, whereas spotty alteration is marked by spectra indicating the presence of sericite and iron-rich chlorite. With increasing depth, towards the quartz veins, there is a marked increase in iron as well as an increase in the amounts of illite and other clay minerals. Proximal to the quartz veining, spectra indicate carbonate alteration in the adjacent altered host rocks as well as within the veins. Moreover, the relative VIRS response of iron-rich chlorite increases significantly, however, only 1 m below the quartz veins, the host rocks are much less altered, and show little to no reflectance in the VIRS range.

In drill hole GP07-92, a strong VIRS response to sericite and chlorite occurs in host rocks up to 15 m structurally above a quartz vein intercept, whereas a sample of lithic greywacke, 5 m below a ca. 3 m wide quartz veined zone (22.2-25.9 m) yields

no VIRS response. This pattern is similar to that seen in GP07-86. A sample of similar greywacke (at a depth of ca. 44 m) having no proximal quartz veining, however, shows a sericite and chlorite VIRS signature comparable to that observed in rocks from immediately above the quartz veins. Clearly, detailed and systematic VIRS analysis of a number of representative drill holes may help clarify the nature and extent of the alteration and may provide a vector towards further hidden quartz veins.

#### LITHOGEOCHEMISTRY

Although preliminary in nature, lithogeochemical studies help to provide insight into the extent and nature of the alteration associated with mineralization. Quartz veins and their immediate altered wall-rocks, as well as having elevated Au, are typically enriched in As, Sb, Pb and Ag relative to visually unaltered rocks. Closer integration between VIRS, petrographic and electron microprobe analysis and lithogeochemistry may help elucidate the relative elemental variations associated with veining and alteration.

#### CONCLUDING STATEMENT

Field, drill hole, and limited petrographic information suggest that the mineralized systems at Golden Promise are comparable to turbidite-hosted gold mineralization of the Meguma Zone in Nova Scotia and those of southeastern Australia. Future work will incorporate <sup>40</sup>Ar-<sup>39</sup>Ar geochronology, extensive regional and down-hole lithogeochemistry, mineral geochemistry, fluid inclusion and stable isotopic studies. These investigations will examine the relationships between the vein systems (mineralization), alteration and the two generations of cospatial mafic dykes. Significant attention will be directed to the origin and distribution of the notable "spotty" alteration in the host rocks, which may provide a vector towards such Au mineralization.

#### ACKNOWLEDGEMENTS

We thank Paragon Minerals Corporation and Crosshair Exploration & Mining Corporation for access to their drill holes and databases. Andy Kerr graciously reviewed an earlier version of this contribution.

#### REFERENCES

- COPELAND, D.A. & NEWPORT, A. 2005. Supplementary 2<sup>nd</sup> year assessment report on soil sampling, prospecting, geological mapping, trenching and diamond drilling on the Golden Promise Property, central Newfoundland NFLD/2910.
- EVANS, D.T.W. & KEAN, B.F. 2002. The Victoria Lake Supergroup, central Newfoundland - its definition, setting and volcanogenic massive sulphide mineralization. Open File NFLD/2790, 80 p.
- KEAN, B.F. & JAYASINGE, N.R. 1982. *Geology of the Badger Map area (12A/16), Newfoundland*. Newfoundland Department of Mines and Energy, Mineral Development Division, Report **81-2**, 37 p.
- PILGRIM, L.R. & GIROUX, G.H. 2008. *Form 43-101F1 technical report for the Golden Promise, south Golden Promise and Victoria Lake properties Badger, Grand Falls, Buchans and Victoria Lake areas (NTS 12a/06, 09, 10, 15, 16 and 02d/13), Newfoundland and Labrador*. SEDAR filing.
- ROGERS, N. & VAN STAAL, C. 2002. Toward a Victoria Lake Supergroup: a provisional stratigraphic revision of the Red Indian to Victoria Lakes area, Central Newfoundland. In: Current Research, Newfoundland Department of Mines and Energy Geological Survey, Report **02-1**, 185-195.
- ROGERS, N., VAN STAAL, C., & MCNICOLL, V.J. 2005. *Geology, Badger, Newfoundland and Labrador*; Geological Survey of Canada, Open File 4546, scale 1:50,000.
- WILLIAMS, S. H. & O'BRIEN, B. H. 1991. Silurian graptolites from the Bay of Exploits, north-central Newfoundland and their geological significance. *Canadian Journal of Earth Sciences* **28**, 1534-1540.
- WILLIAMS, H. 1995. Chapter 4 – Middle Paleozoic rocks. In: WILLIAMS, H. (ed) *Geology of the Appalachian-Caledonide Orogen in Canada and Greenland*. Geological Survey of Canada, Geology of Canada Series No. **6**, 315-446.

## **Cathodoluminescence: A tool to discriminate the tectonic history in gold-bearing veins in the Brunswick Subduction Complex, Canada**

**Sabine Schwarz<sup>1</sup>, David Lentz<sup>1</sup>, & James Walker<sup>2</sup>**

<sup>1</sup>*University of New Brunswick, Department of Geology, Fredericton, NB, E3B 5A3 CANADA  
(e-mail: [s.vetter@unb.ca](mailto:s.vetter@unb.ca))*

<sup>2</sup>*Geological Surveys Branch, Department of Natural Resources-Minerals, Bathurst, NB, E2A 3Z1 CANADA*

**ABSTRACT:** Transmitted light microscopy in combination with cathodoluminescence (CL) can be a useful tool for determining the tectonic history of hydrothermal veins. The Elmtree and Guitard Brook Au deposits that occur in the poly-deformed Ordovician sedimentary and volcanic rocks of the Elmtree Inlier, and its Silurian sedimentary cover sequence (northern New Brunswick), are the subject of this study. These occurrences are located on minor fault zones that contain at least four generations of quartz-calcite-sulfide veining. These veins contain pyrite, arsenopyrite, and chalcopyrite with small gold inclusions or refractory gold, as well as later base-metal veins with galena, sphalerite, and chalcopyrite. In this study, cathodoluminescence imaging using the Gatan Chroma-CL system in combination with the scanning electron microscope was applied to examine quartz veins from these two deposits.

Results indicate that in both deposits early quartz with growth textures outlined by blue/red CL colors likely formed during the Salinic Orogeny. Subsequently, these veins were brecciated and partly dissolved during the exhumation/ongoing orogeny resulting in metamorphic quartz (red-brown CL colors) in microfractures and microshear zones or as mantles on early quartz. Finally, late-stage quartz (bright yellow CL), occurring in veinlets and cutting earlier quartz, is likely related to hydrothermal intrusion-related base-metal quartz-carbonate veining.

**KEYWORDS:** *cathodoluminescence, Brunswick Subduction Complex, hydrothermal, orogenic gold, Elmtree Inlier*

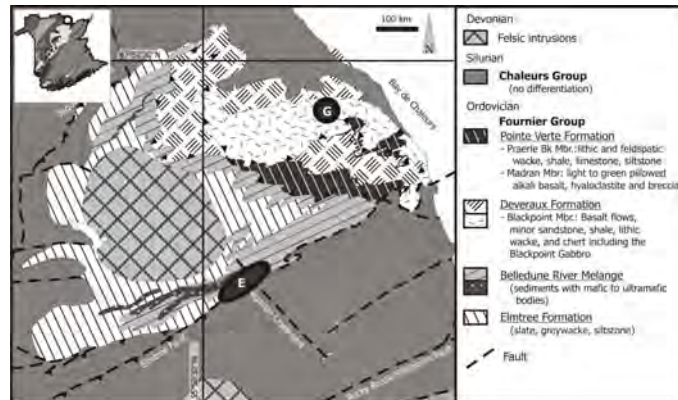
### **INTRODUCTION**

The Elmtree Inlier (EI) hosts more than 85 mineral occurrences or deposits, the majority of which can be linked to hydrothermal orogenic or intrusion-related systems. Two of these, the Elmtree deposit (ED) and the Guitard Brook occurrence (GB), are the most significant in terms of gold mineralization with best grades up to 23 g/t Au and 12 g/t Au, respectively. Mineralization at both deposits is hosted within shear zones and both display characteristics typical of hypozonal- to epizonal-orogenic gold systems. Late intrusion-related base-metal veins also occur at both the ED and GB.

The purpose of this study is to determine the relative timing of Au mineralization in the context of the regional tectonic history. This was accomplished by using cathodoluminescence to study gangue quartz in auriferous sulfide-quartz-carbonate veins.

### **GEOLOGICAL SETTING**

The EI consists of mafic intrusive and extrusive rocks and related sedimentary rocks of the Fournier Group that were deposited in the Middle Ordovician Tetagouche-Exploits back-arc basin (Fig.1). Closure of the back-arc basin in the Late Ordovician to Early Silurian, resulted in the accretion of these rocks to Laurentia (Salinic Orogeny). The EI is the polydeformed imbricated thrust stack that resulted from obduction of the Fournier Group. The Fournier Group is divided into the Devereaux, Pointe Verte, and the Elmtree formations (van Staal & Fyffe 1991; Langton 1993; Fig. 1). The Belledune River Mélange (BRM) also occurs within the EI and is a tectonic unit that marks the thrust contact between the Elmtree and Pointe Verte formations (Fig. 1). The units are unconformably overlain by the Silurian Chaleurs Group sedimentary rocks (Fig. 1). Major and



**Fig. 4.** Geological map of the Elmtree Inlier showing the Elmtree (ED) and Guitard Brook deposit (GB) located near faults (NBDNRE, 2005).

minor faults, such as the Elmtree and the Nigadoo lineament cut through the area. Late tectonic felsic intrusions are related to the accretion of the Avalonian microcontinent during the Acadian Orogeny in the Middle Devonian.

#### DEPOSITS

The ED, located in the southern EI, is divided into West Gabbro, Discovery, and South Gold zones that are hosted by the BRM, the Elmtree Formation, and/or by the Chaleurs Group. The Discovery Zone (DZ) consists of several zones of poly-metallic base-metal veins, whereas the South Gold Zone and WGZ consists of fine-grained disseminated sulfides and very minor base-metal veins.

The Guitard Brook deposit (GB) located in the northeast EI is hosted by tholeiitic basalt and gabbro of the Devereaux Formation, specifically the Black Point Gabbro and associated trondhjemitic, diabasic dykes, and basaltic flows (Langton, 1993).

The GB mineralization is characterized by narrow veins concentrated in several larger zones each approximately 50 cm wide and 60 m long, all of which occur within a larger shear zone.

#### METHODS AND RESULTS

Cathodoluminescence activates electrons in the mineral, which then emit characteristic light rays of distinct wavelengths that can be collected with the CL system. CL imaging is used to

recognize subtle variation (i.e., growth zoning) in quartz (and other phases) as defined by crystal defects and/or minor variation in trace element contents all of which result in variation in CL color. This method can be used to determine mineral paragenesis and link various stages of mineralization (i.e., different pulses of mineralizing fluid) with different stages in the regional tectonic history.

This study relied on a combination of transmitted light- and scanning electron-microscopy (SEM) and cathodoluminescence (CL) imaging in order to determine textural relationships that are indiscernible using normal (visible spectrum) light microscopy or with the backscattered SEM alone. The SEM used in this study was equipped with a Gatan Chroma-Cathodo-luminescence mirror operating at 15nA and a current of 15kV. The CL was captured live and mixed into color images using DigiScan software.

The CL images and colors were compared to literature (Table 1). Normally hydrothermal quartz shows short-lived green to blue or yellow (high temperature related) colors whereas red and intense blue CL colors stand for volcanic related quartz. Brown to red CL imaging quartz is related to metamorphism.

Work concentrated on gangue quartz in main gold-bearing sulfides veins, and in late stage intrusion-related (?) base-metal veins. Polished sections were first investigated by transmitted and reflected light microscopy to find suitable samples

**Table 1.** Cathodoluminescence colors of quartz (and inferred geologic environment) from the Elmtree Deposit (ED) and Guitard Brook occurrence (GB).

CL color	Environment	Seen in	Ref.
Intense blue	Igneous, volcanic	ED	1, 2, 3
red to red brown	metamorphic	ED, GB	1, 2, 3
Red	volcanic	GB	1, 3
Transient blue	alpha-quartz in aqueous solutions	ED, GB	1, 3
Short lived green/blue	hydrothermal, pegmatitic	ED, GB	2, 3
Yellow	hydrothermal	ED, GB	3

1) Boggs & Krinsley (2006), 2) Zinknagel (1978), 3) Goetze *et al.* (2005)

containing different phases of veining and (or) gold grains.

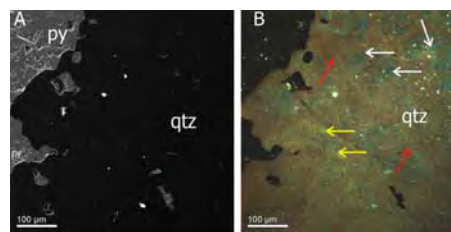
Five different vein phases (Types I to V) are recognized at both deposits, all have variable amounts of carbonates and quartz gangue. Type I veins contain only brecciated quartz and carbonate minerals and at ED are spatially associated with disseminated arsenopyrite, chalcopyrite, pyrrhotite, and pyrite in the mafic host rock. Type II veins in both deposits are partly brecciated and contain 5-80% sulfides of dominantly pyrite, arsenopyrite, and at GB chalcopyrite. Type III veins are quartz–calcite–tetrahedrite–bismuthinite microveins that cut both Types I and II veins. The fine-grained sulfides replace and enclose arsenopyrite and pyrite in Type II veins and are also visible in microfractures within the Type II sulfides. Type IV veins are base-metal rich and characterized by galena, sphalerite, chalcopyrite, pyrite, and stibnite with a maximum width of 20 cm. The Type V veins are late barren-carbonate veins cutting all previous veins and textural features.

In both deposits, refractory gold occurs in arsenopyrite and pyrite of Type II veins analyzed by EPMA. At GB, gold is also located in chalcopyrite as electrum microinclusions.

At ED, Type I and Type II veins contain primary quartz cores that have blue to green CL colors, which define subtle

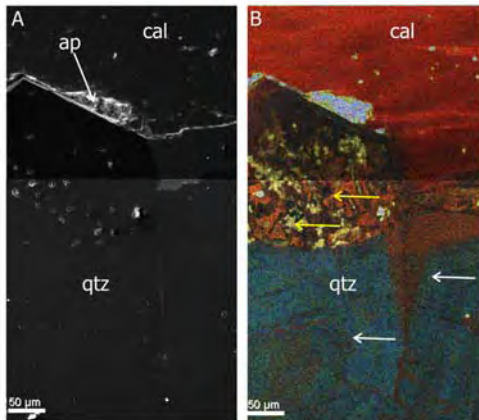
growth zoning. The early quartz was brecciated, partially dissolved and mantled by a matrix of fine-crystalline metamorphic quartz (brown CL; Table 1). The metamorphic quartz contains small crystals of apatite with bright blue CL colors. Bright yellow CL colored quartz veinlets cutting Type II veins are a sign of later hydrothermal fluid, likely related to late brittle-ductile deformation and infilling of fractures by fluids. Similar CL features are observed in quartz from Type IV base-metal veins. Here unbrecciated quartz (blue CL), with growth zoning mantles sulfides. Dark blue CL quartz from Type IV veins is in contact with quartz and red luminescent calcite from the Type II veins and is characterized by less brecciation than the Type II vein quartz. A later hydrothermal quartz veinlet (yellow CL), fills a fracture that developed during tectonic stress between quartz and sulfide.

Cathodoluminescence images from the GB deposit show primary quartz of Type II veins (blue CL), with visible growth zoning in CL. These are crosscut by later hydrothermal Type III vein quartz that exhibits growth textures in short-lived blue and red CL colors. Both Type-II and -III veins are weakly to moderately brecciated and are overprinted by later fluids that modified the primary quartz to red and/or yellow hydrothermal quartz characteristic of higher temperature and likely reflects



**Fig. 5.** (A) Backscattered SEM image of quartz (qtz) and pyrite (py) from the ED showing no textures, (B) CL imaging of area in (A) showing blue-green growth textures in primary quartz (top right, white arrows) surrounded by fine-grained metamorphic brown quartz (red arrows). Hydrothermal quartz veinlets (yellow CL) cut through the section (yellow arrows). Sample is from DDH DZ-2006-05 at 61.00 m.

interaction with a fluid of volcanic hydrothermal origin (Fig. 3; Table 1). This is also visible in quartz from Type II veins that are overprinted by metamorphic quartz with red-brown luminescence. Later hydrothermal quartz (bright yellow CL) also occurs at GB as thin fractures in and between the early and metamorphic quartz (red-brown CL).



**Fig. 6.** (A) Backscattered SEM image of quartz (qtz) from GB, (B) CL imaging of (A) showing green-blue to red growth textures (white arrows), and a red calcite (cal). The contact is marked by yellow and red hydrothermal quartz (yellow arrows) Sample is from DDH HM-2003-08 at 53.04 m.

## CONCLUSIONS

The results of the CL study for the ED and GB deposits are summarized as follows:

- (1) Hydrothermal euhedral quartz (blue-green/red CL colors), of Type II veins exhibit growth textures and are related to sulfide mineralization during early Salinic Orogeny.
- (2) The microbrecciation and dissolution of primary quartz in Type II and IV veins and subsequent overprinting by metamorphic quartz (red-brown CL), is attributed to the ongoing Salinic Orogeny and exhumation of the Brunswick Subduction Complex.
- (3) Later volcanic/hydrothermal base metal-containing quartz-carbonate bearing Type IV veins are recognized as thin veinlets with bright yellow CL color. These are likely related to epizonal mineralization during the emplacement of middle Devonian felsic intrusions.

## ACKNOWLEDGEMENTS

We thank the Department of Natural Resources for funding this project and for logistical support. Additional funding was provided with a NSERC Discovery grant to DL.

## REFERENCES

- BOGGS, S. & KRINSLEY, D. 2006. *Application of cathodoluminescence imaging to the study of sedimentary rocks*, Schweizerbart'sche Verlagsbuchhandlung, 165p.
- GOETZE, J., PLOETZE, M., & TRAUTMANN, T., 2005. Structure and luminescence characteristics of quartz from pegmatites. *American Mineralogist*, **90**, 13-21.
- LANGTON, J. P. 1993. *Stratigraphy, structure, and geochemistry of the ophiolitic inlier, Northern New Brunswick*. Unpublished MSc thesis, Queen's University.
- NBDNRE 2005. Bedrock Geology of New Brunswick, Map NR-3, Scale 1:20000, New Brunswick Department of Natural Resources and Energy.
- VAN STAAL, C.R., WHALEN, J.B., MCNICOLL, V.J., PEHRSSON, S.J., LISSEBERG, C.J., ZAGOREVSKI, A., VAN BREEMEN, O., & JENNER, G.A., 2007. The Notre Dame arc and the Taconic Orogeny in Newfoundland. In: Hatcher, Jr., Carlson, M.P., McBride, J.H. and Martínez Catalán, J.R. (ed), *The 4D Framework of Continental Crust*, Geological Society of America Special Paper, **200**, 511-552.
- ZINKNAGEL, U. 1978. *Cathodoluminescence of quartz and its application to sandstone petrology*. Contributions to Sedimentology, 65 p.

## Ireland's historic mine sites inventory

Gerry Stanley<sup>1</sup>, Eibhlin Doyle<sup>1</sup>, Vincent Gallagher<sup>1</sup>,  
Fionnuala Ni Mhairtin<sup>1</sup>, & Jane Brogan<sup>2</sup>

<sup>1</sup>Geological Survey of Ireland, Beggars Bush, Haddington Road, Ballsbridge, Dublin 4, Ireland  
(e-mail: [gerry.stanley@gsi.ie](mailto:gerry.stanley@gsi.ie))

<sup>2</sup>Environmental Protection Agency, PO Box 3000, Johnstown Castle Estate, Co. Wexford, Ireland

**ABSTRACT:** Ireland has a long history of mining dating back to the Bronze Age. The main commodities exploited included Cu, Au, Pb, Zn and coal. Many of the early mines consisted of small vein type deposits, whereas more recent mining (20<sup>th</sup> century) has included exploitation of VMS and Irish Type Zn/Pb deposits using modern mining and processing techniques at industrial scales. Many of these historic mines were abandoned or closed with little or no remediation. The Historic Mine Site Inventory project aimed to compile a comprehensive list of all past mining sites which are now abandoned or closed. One of the principal drivers for this project was Directive 2006/21/EC of the European Parliament and of the Council on the management of waste from the extractive industries. A relative scoring system was developed which used the source, pathway, receptor paradigm. Over one hundred individual mine sites were assessed, in some cases mine sites were grouped into districts where appropriate resulting in 27 mine sites/districts. This paper will present the scoring system that was developed and the overall results of the project.

**KEYWORDS:** *Ireland, closed mines, environment, risk categorization*

### INTRODUCTION

The European Union passed the 'Extractive industries waste directive' in 2006. The full title of the directive is:

'Directive 2006/21/EC of the European Parliament and of the Council on the management of waste from extractive industries and amending Directive 2004/35/EC'

Most of the directive deals with how extractive industry waste is to be dealt with in the future within Member States. However, one article addresses legacy waste facilities by requiring Member States to draw up an inventory of such facilities. The text of Article 20 is:

'Member States shall ensure that an inventory of closed waste facilities, including abandoned waste facilities, located on their territory which cause serious negative environmental impacts or have the potential of becoming in the medium or short term a serious threat to human health or the environment is drawn up and periodically updated. Such an inventory, to be made available to the public, shall be carried out by 1

May 2012, taking into account the methodologies as referred to in Article 21, if available.'

The reference to Article 21 relates to the methodology to be used in drawing up the inventory. Specifically:

'Such methodologies shall allow for the establishment of the most appropriate risk assessment procedures and remedial actions having regard to the variation of geological, hydrogeological and climatological characteristics across Europe.'

A waste facility is defined in the directive as:

'waste facility" means any area designated for the accumulation or deposit of extractive waste, whether in a solid or liquid state or in solution or suspension.

Such facilities are deemed to include any dam or other structure serving to contain, retain, confine or otherwise support such a facility, and also to include, but not be limited to, heaps and ponds, but excluding excavation voids into which waste is replaced, after

extraction of the mineral, for rehabilitation and construction purposes’.

For practical purposes this means any tailings facility or rock tip or heap – whether either is contained or not.

The GSI (Geological Survey of Ireland) and the EPA (Environmental Protection Agency (of Ireland)) embarked upon creating this inventory in 2006 for those waste facilities associated with closed or abandoned metal, industrial mineral and coal mines. The project was completed in early 2009 and is known as the Historic Mine Site – Inventory and Risk Categorization project or HMS for short.

**SITE PRE-SELECTION**

The known number of mineral deposits worked in Ireland runs to several hundred. It would be impractical to include every site in the inventory, especially as the inventory has to include aggregate and stone operations as well. Indeed, another Member State (Italy) has records of over 20,000 stone operations and over 3,000 metal mines.

As a starting point the GSI, like most geological surveys, has a mineral locality database. The database contains records for some 5,000 individual sites ranging in size from the recordings of field geologist of outcrop description of sphalerite occurrences to the largest zinc mine in Europe – the Navan deposit in Co. Meath operated by Boliden Tara mines Limited. Also in the database are records relating to aggregates quarries and sand and gravel pits. Below is a list of the locality type and the number of locations within each category.

The entries shaded are candidate sites for inclusion in the inventory giving a total of 460 (mine and tip heap/spoil) plus the unknown category (511 locations) giving a total of some 971 sites.

Next ‘expert knowledge’ was used to reduce further the number of sites to be included in our investigations. This involved GSI staff with knowledge of mining in Ireland assessing the 971 localities and from their knowledge of the sites determining whether the site was

Locality Type	No.
Borehole .....	206
Coastal section .....	6
Float.....	30
Man-made excavation .....	32
Mine.....	456
Natural exposure .....	1,916
Other.....	35
Pit .....	554
Quarry.....	1,297
Sub outcrop .....	16
Temporary exposure .....	2
Tip heap/Spoil .....	4
Unknown .....	511
Well.....	6
Total.....	5,071

sufficiently significant for inclusion. Significance was determined by reference to the mineral worked at the site and the size of the operation. This resulted in some 106 individual sites being visited in the field.

Several of these sites occur in clusters and for ease of working a District name was given to these. This was especially the case for the coalfields. A number of the sites did not warrant inclusion in the inventory as all evidence of mining has been removed and any waste at the sites either removed for other uses nearby, such as filling in subsidence features caused by the former mine activity or had been completely remediated and in either case the waste material is indistinguishable from the surrounding countryside. When both of these factors are taken into account 27 mine districts and individual mines were include in the inventory with reports generated for some 82 sites.

**ASSESSMENT METHODOLOGY**

The HMS Project created an inventory of closed mine waste facilities on a risk basis. However, it is emphasized that this is NOT a risk assessment of the sites. Rather the sites have been ranked on a risk basis so as to determine a relative ranking.

At each mine site all waste heaps, tailings facilities and discharges are

identified and scores assigned based on the parameters to be measured.

In order to carry out the field work a systematic method was needed so a Generalized Conceptual Model was developed. This guided data collection in the field but would not be so rigid as to prevent the recoding of features unique to any one site. Later a conceptual model may assist with the identification of remedial strategies.

### **Conceptual Model**

The conceptual model uses the Source – Pathway – Receptor Paradigm. The paradigm requires that each of the parameters within the model are documented, estimated, measured or recorded. The model identifies the source of any contamination; identifies who or what is affected (the receptor); and identifies how the source may reach the receptor (pathway). The collection of field data, observations and estimates confirms whether a linkage exists between the source and receptor.

Sources are the origin of contaminants that may issue from an historic mine site. The cause or source of the contamination is identified as well as its location. The possible sources of contamination are:

Liquid (water): - Adit discharges and Seeps.

Solids: - Waste piles, Tailings impoundments and Stream sediments.

Receptors are those elements of the paradigm that are affected by the potential contamination emanating from the various sources via the different pathways. A receptor is any person, animal, plant, ecosystem, waterbody, protected site, or property. Receptors, in the context of the Historic Mine Site project include:

People: - Local inhabitants, Workers and Visitors to the site

Farm animals: Livestock

Ecosystems and waterbodies: -

Rivers, Estuaries and Groundwater.

Protected areas: - National Parks, National Heritage Areas (NHAs), Special Protection Areas (SPAs),

### **Special Areas of Conservation (SACs) and Nature Reserves**

Five pathways were assessed during the project: Groundwater, Surface water, Air pathway, Direct contact, and Stream sediments.

### **Scoring System**

Each of the inputs to the paradigm is scored. In the first instance a hazard score is developed for each source. The hazard score is determined from the amount of contaminants, the relative toxicity of these contaminants and the volume (or area) within each source.

Next the **Likelihood of release**, of a contaminant, from a waste pile or discharge is considered. It is an assessment of whether there have been releases of contaminants to the environment in the past and addresses whether the waste pile or discharge is in any way contained. The former determines whether there have been releases of the contaminants from the mine site in the past while the latter issues may affect whether there is likely to be releases from the source in the future. In all cases any contaminant must be attributable to the mine site.

The individual waste facilities are characterised so that a **Hazard** number is developed. This is then modified by the **Likelihood of release** and **Receptor** factors for each Pathway. Once the final score for the mine site is obtained it is assigned to one of the following groups (Table 1)

### **RESULTS**

Of the 27 individual districts/sites investigated, three are classified in the Group I, one in Group II, two in Group III, five in Group IV and the remaining 16 as Group V (Table 2).

### **ACKNOWLEDGEMENTS**

We would like to thank Roger Olsen, Jim Lavelle, Paul Nathanail, Jimmy McLaughlin, and Tessa Grealley for useful discussions in the development of the scoring system.

**Table 1.** Groups into which the closed mine sites are classified.

Group	Score	Description
I	>2,000	Sites which should have a full site specific risk assessment carried out.
II	1,000 – 2,000	Sites requiring general monitoring of most or all waste piles, discharges or stream sediments on an annual basis.
III	300 – 1,000	Sites requiring general monitoring of most or all waste piles, discharges or stream sediments on a biennial basis.
IV	100 – 300	Sites requiring specific monitoring on particular waste piles, discharges or stream sediments on a five yearly basis.
V	<100	Sites not requiring any specific monitoring.

**Table 2.** Closed Irish mine sites classified in this study.

Mine / District	No. of Sites	Total Score	Group
Silvermines	6	2,884	I
Tynagh	4	2,712	I
Avoca	7	2,439	I
Glendalough /Glendasan	8	1,122	II
Caim	1	559	III
Glenmalure	2	335	III
Ballycorus	1	244	IV
Connaught Coalfield	7	189	IV
Gortdrum	1	157	IV
Leinster Coalfield	7	133	IV
Slieve Ardagh Coalfield	10	118	IV
Clements (Connemara Pb)	1	97	V
Kilbricken (Clare Pb)	1	89	V
Allihies	6	76	V
Abbeytown	1	70	V
Tassan (Monaghan Pb)	1	44	V
Ballyvergin (Clare Pb)	1	43	V
Ballyhickey (Clare Pb)	1	19	V
Keeldrum (Donegal Pb)	1	18	V
West Cork Cu-Ba	8	17	V
Doolin (Clare Phosphate)	1	15	V
Bunmahon	1	14	V
Hope (Monaghan Pb)	1	13	V
Clontibret (Monaghan Pb)	1	12	V
Glentogher (Donegal Pb)	1	6	V
Benbulbin	1	5	V
Hollyford (Tipperary)	1	4	V

## Metallogeny of the gold-enriched Cambro-Ordovician rocks in the Annidale area, south-central New Brunswick, Canada

Kathleen G. Thorne<sup>1</sup>, Susan C. Johnson<sup>2</sup>,  
Malcolm J. McLeod<sup>2</sup>, & Leslie R. Fyffe<sup>1</sup>

<sup>1</sup>New Brunswick Department of Natural Resources, Geological Surveys Branch, PO Box 6000, Fredericton, NB E3B 5H1 CANADA (e-mail: [kay.thorne@gnb.ca](mailto:kay.thorne@gnb.ca))

<sup>2</sup>New Brunswick Department of Natural Resources, Geological Surveys Branch, PO Box 5040, 207 Picadilly Road, Sussex, NB E4E 5L2 CANADA

**ABSTRACT:** Gold occurrences are prolific throughout the Cambro-Ordovician volcanic, sedimentary, and intrusive rocks of the Annidale area in south-central New Brunswick. The majority of gold occurrences are structurally controlled by regional northeast-trending thrusts related to telescoping of the stratigraphic succession, subsequent strike-slip faulting (and associated shear zones), and late, north- to northwest-trending normal faults that generated relatively minor displacements along the northeast-trending structures. A spatial association with rhyolite dome complexes is established for some of the gold occurrences. The characteristics of gold mineralization vary, depending on the host rocks, structural setting, and proximity to felsic intrusions. Stable isotope studies (O, Pb, S) indicate that the majority of occurrences have features typical of orogenic gold systems derived from metamorphic fluids whereas others are clearly derived from magmatic fluids, which is consistent with field observations. Timing of these mineralizing events has been constrained to Late Cambrian to Middle Ordovician time, with possible remobilization into the later north- to northwest-trending structures.

**KEYWORDS:** *gold, Annidale, New Brunswick, Ganderia, stable isotopes*

### INTRODUCTION

In the Annidale area in south-central New Brunswick, 37 metallic mineral occurrences/prospects are concentrated within a 50 km long northeast-trending belt of Early Cambrian to Middle Ordovician volcano-sedimentary and intrusive rocks. The majority of these occurrences contain gold, in some cases significant quantities, in addition to base-metals, antimony, and/or silver. Mineralization spans the entire length of the belt and is primarily located along major structural features and/or situated peripheral to felsic dome complexes or intrusions within the Annidale Group. We propose that gold-enriched fluids were focussed into favourable depositional environments during mineralizing events associated with episodic tectonic and magmatic activity throughout the belt. This paper will provide a brief overview of the geological setting of the Annidale area, the various styles of gold mineralization present, and provide

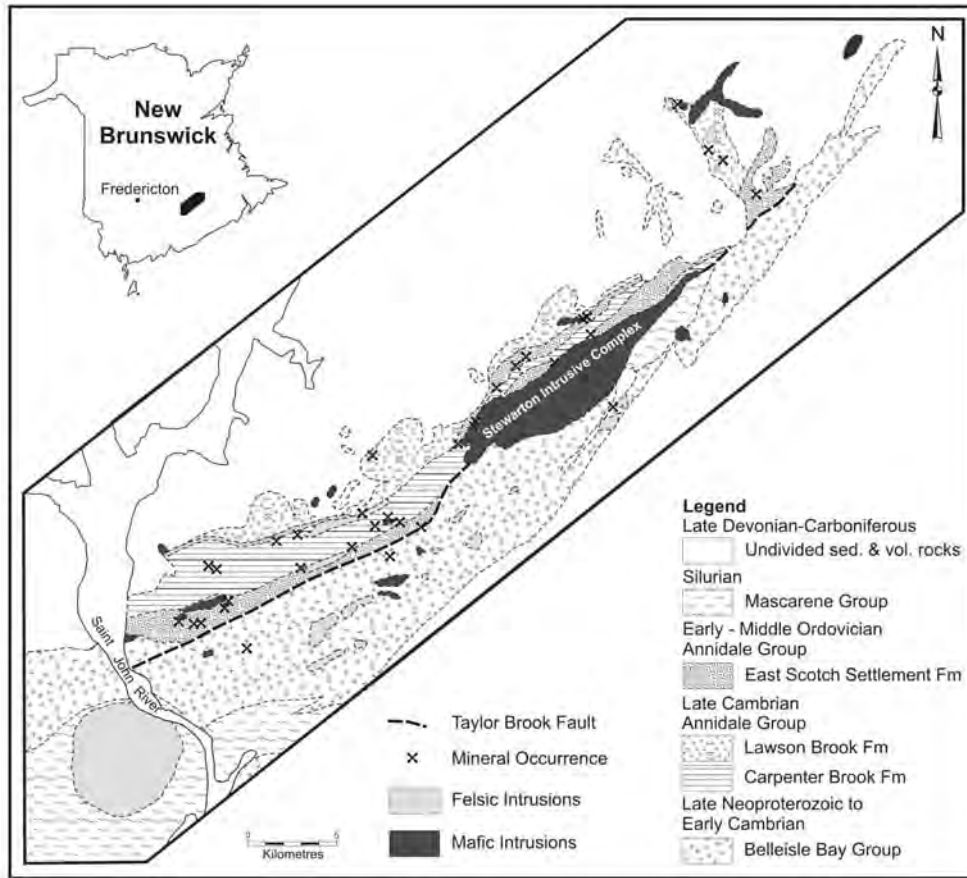
isotopic constraints on the mineralizing conditions and source(s) of the fluids.

### GEOLOGICAL SETTING

#### Regional Geology

Neoproterozoic to Early Paleozoic rocks of the Annidale area are interpreted to mark the southeastern margin of Ganderia in the New Brunswick segment of the northern Appalachians (Johnson *et al.* 2009). The area is underlain by Late Cambrian to Early Ordovician rocks of the Annidale Group and Late Neoproterozoic to Early Cambrian rocks of the Belleisle Bay Group, which are juxtaposed along a major tectonic boundary marked by the Taylor Brook Fault (Fig. 1).

Volcanic rocks of the Annidale Group are mostly arc type but an unusual group of high-Mg, high-Cr basalts with geochemical characteristics typical of normal mid-ocean ridge basalts (MORB) and within-plate types are also



**Fig. 1.** Geology of the Annidale area showing the distribution of mineral occurrences throughout the belt (Johnson *et al.* 2009).

present (McLeod *et al.* 1994; Johnson *et al.* 2009). The mixed MORB and arc signature is consistent with deposition in a back-arc basin tectonic setting, with the MORB rocks indicating possible closure of a small ocean basin (McLeod *et al.* 1994; Johnson *et al.* 2009). The volcanic rocks of the Belleisle Bay Group primarily exhibit within-plate characteristics (Johnson & Barr 2004).

**Local Geology**

Bedrock in the Annidale area is dismembered into several northwesterly transported thrust panels that contain stratigraphic packages, which differ in lithology, age, and intensity and style of deformation. Three formations comprise the Annidale Group (from oldest to youngest): the Carpenter Brook, Lawson

Brook, and East Scotch Settlement formations (Johnson *et al.* 2009). The Carpenter Brook Formation consists of sedimentary and volcanoclastic rocks intercalated with felsic flows and lapilli tuffs, and associated microgranite. The Lawson Brook Formation comprises mafic volcanic rocks, felsic flows and tuffs, and associated microgranite with subordinate black shale and siltstone. The East Scotch Settlement Formation consists of mafic volcanic rocks and black shales. Telescoping of the stratigraphic succession produced an imbricated assemblage consisting of numerous thrust faults, many of which have been later reactivated into steeply dipping strike slip faults. A number of felsic and mafic intrusions were emplaced into the sequence between Late Cambrian to

Silurian time, the largest of which is the Stewarton Gabbro (Fig. 1). A latest Arenig (Ordovician) age for the Stewarton Gabbro constrains the timing of tectonic interleaving of the Annidale Group and its juxtaposition with the Belleisle Bay Group to the Early Ordovician.

#### **METALLOGENY**

Mining activity in the Annidale area has been restricted to limited copper and silver extraction from the Annidale Mine in the early 1900's. Exploration was sporadic until the late 1980's-early 1990's when several mining companies were actively exploring for gold and base-metals. Several significant gold discoveries were encountered during that time, the most notable being a grab sample that yielded >200 g/t Au at the Devil Pike Brook occurrence (PGE Resources Corporation 1993). Chip and grab samples from the East Scotch Settlement - BP (BP Resources 1991) and Grant Brook West (Brunswick Mining and Smelting 1992) occurrences also contained >1 oz/t Au. Subsequent trenching and drilling programs were implemented throughout the belt; however, falling metal prices shortly thereafter hampered further exploration efforts in the area.

The composition and competence of the host rocks, structural setting, and in some cases, proximity to felsic intrusions appear to be the main factors controlling gold mineralization. The majority are structurally controlled by northeast-trending thrust and strike-slip faults within the highly deformed panels containing the East Scotch Settlement and Carpenter Brook formations (i.e., Taylors Brook, East Scotch Settlement - BP, and Grant Brook West). To a lesser degree, occurrences are associated with later north- to northwest-trending normal faults (i.e., Sheba Pit and Devil Pike Brook) that locally offset the northeast-trending faults. A few select occurrences are situated peripheral to (and appear to be associated with) felsic dome complexes (i.e., Jones Creek and Grant Brook Central).

Gold mineralization manifests itself as shear zone-hosted quartz ( $\pm$ carbonate)

veins and/or disseminated mineralization mainly within altered wall rocks. Pyrite and arsenopyrite are commonly associated with the mineralized zones but base-metal sulfides, stibnite, and silver-bearing minerals may be present as well. Alteration assemblages broadly consist of some combination of quartz, carbonate, sericite, fuchsite, and/or leucoxene.

The gold occurrences can generally be classified into two different categories based on their mode of occurrence: those with characteristics typical of orogenic mesothermal lode gold systems and those that have an obvious genetic association with felsic dome complexes. However the alteration assemblages for either deposit type are not diagnostic because of the complexity of the hosting bedrock geology, which ultimately controls the resulting alteration assemblage.

#### **ISOTOPE STUDIES**

In an attempt to establish the fluid and metal sources and to help constrain a genetic model, stable isotope studies (O, Pb, S) were conducted on selected occurrences. Oxygen isotope analysis of quartz vein material from eight separate occurrences yielded  $\delta^{18}\text{O}$  values of 10.9-16.0‰. Assuming equilibrium between quartz and the hydrothermal fluid, the  $\delta^{18}\text{O}$  values calculated for the mineralizing fluids, at temperatures between 300-400°C, range between 4.0 and 11.9‰. This overlaps accepted values for both magmatic and metamorphic fluids.

Based on contrasting common lead isotope signatures from five Pb-bearing occurrences (East Scotch Settlement - BP, Scotch Mountain, South Fuchsite Zone, Grant Brook West, and Taylors Brook), it is apparent that the mineralized fluids are compositionally distinct for each occurrence. For the most part, the sources of lead appear to be derived from a variety of reservoirs, which is likely a reflection of the heterogeneity amongst the hosting lithologies for each occurrence.

Results of  $\delta^{34}\text{S}$  analyses obtained for 12 sulfide separates ranged between -3.90‰ and +12.00‰. Samples with  $\delta^{34}\text{S}$  values that clustered around 0‰ are presumed to

contain S from an igneous source (i.e., a direct magmatic source or the leaching of S from preexisting igneous rocks). Those with more enriched  $\delta^{34}\text{S}$  values are inferred to have S leached from the local sedimentary country rocks by metamorphic fluids. For the most part, the S isotope results thus broadly delineate two groupings, which confirms the presence of two gold deposit types (intrusion-related and mesothermal orogenic).

### DISCUSSION

The Taylor Brook Fault is thought to have played a major role in focusing fluids into subsidiary structures during stacking and dehydration of the stratigraphic sequences thus generating the various orogenic gold systems. Overprinting of these systems by younger intrusion-related gold systems is possible to some extent. Because of the complexity of alteration and sulfide assemblages observed in the field, isotope studies combined with mode of occurrence are key to distinguishing between the two deposit types. Gold mineralization located along late northwest-trending faults may represent younger mineralizing systems or possible remobilization of older deposits.

### CONCLUSIONS

Gold occurrences within the Annidale area:

- (1) were deposited along structural features during episodic orogenic and magmatic activity between 490 and 478 Ma;
- (2) are characterized by quartz-carbonate veining and/or replacement styles of mineralization;
- (3) can be categorized as mesothermal orogenic or intrusion-related gold systems

based on mode of occurrence and isotopic signature.

### ACKNOWLEDGEMENTS

We thank Greg Dunning (Memorial University of Newfoundland.) and Jonathan LaFontaine (student) for their assistance.

### REFERENCES

- BP RESOURCES 1991. Report on prospecting, trenching, channel and soil sampling for the Stewarton claims. New Brunswick Department of Natural Resources Assessment File 474057.
- BRUNSWICK MINING AND SMELTING 1992. Report of Work, Annidale Property – Project 4247, Queens County, New Brunswick. New Brunswick Department of Natural Resources Assessment File 474233.
- JOHNSON, S.C., MCLEOD, M.J., FYFFE, L.R., & DUNNING, G.R. 2009. A Penobscottian arc system along the margin of Ganderia: evidence from geochemistry and U-Pb zircon dating of the Annidale Group in southern New Brunswick. *Atlantic Geoscience Society 35<sup>th</sup> Colloquium, Program and Abstracts*, 18.
- JOHNSON, S.C. & BARR, S.M. 2004. New geochemical data from Neoproterozoic-Cambrian igneous rocks in the Long Reach area, southern New Brunswick. New Brunswick Department of Natural Resources, MRR 2004-4, p. 75-94.
- MCLEOD, M.J., WINCHESTER, J.A., & RUITENBERG, A.A. 1994. Geochemistry of the Annidale Group: implications for the tectonic setting of Lower Ordovician volcanism in southwestern New Brunswick. *Atlantic Geology*, **30**, 87-95.
- PGE RESOURCES CORPORATION 1993. Report of work Devil Pike property Kings County, New Brunswick. New Brunswick Department of Natural Resources, Assessment File 474299.

## Early Devonian felsic volcanic rocks and associated Zn–Pb mineralization, Tobique–Chaleurs Zone, New Brunswick, Canada

James A. Walker<sup>1</sup>

<sup>1</sup>New Brunswick Department of Natural Resources, Geological Surveys Branch,  
P.O. Box 50, Bathurst, New Brunswick, E2A 3Z1 CANADA (e-mail: [jim.walker@qnb.ca](mailto:jim.walker@qnb.ca))

**ABSTRACT:** Early Devonian felsic volcanic rocks of the Tobique–Chaleurs Zone (TCZ) are host to several syngenetic to epigenetic Zn–Pb ± Cu and Ag deposits that span a wide range of size and grade. The largest deposit is Nash Creek (3.2 Mt grading 4.67% Zn, 0.80% Pb, and 27.8 g/t Ag), whereas the smallest and highest grade deposit is at Sewell Brook (≈ 0.5 Mt with grades locally >40 wt.% Zn+Pb). With the exception of Sewell Brook, which has a small Cu-rich zone, these deposits have Zn/Pb ratios ≥ 4 and have low Cu. All of the deposits are spatially associated with high SiO<sub>2</sub> (≥ 70 wt.%) aphyric to sparsely feldspar-phyric rhyolite flows or domes, and at least two are spatially associated with rocks of more intermediate (rhyodacite) composition.

The rocks of the TCZ are interpreted to have erupted in a transtensional continental rifting environment in the Late Silurian to Middle Devonian. In this tectonic environment A-type granites are expected, and indeed the relatively high Zr, Nb, and Y content in these rocks support this. However, many other geochemical aspects of these rocks, i.e., high Ba, Rb, Th and K, are more typical of the I-type magmas that commonly occur in collisional settings.

**KEYWORDS:** Zn-Pb sulfide, VMS, I-type granites, New Brunswick

### INTRODUCTION

The Siluro-Devonian Tobique–Chaleurs Zone (TCZ) of New Brunswick is host to several relatively small Zn–Pb ± Cu–Ag sulfide deposits and occurrences that are all spatially associated with Early Devonian felsic volcanic and related sedimentary rocks (Fig. 1). The sulfide mineralization occurs as veins, veinlets and replacements of rock units that had high primary permeability (e.g., flow top breccias). Massive bedded sulfides that are typical of many modern and ancient VMS deposits are not present; however, their absence is not surprising given the relatively shallow oxidizing marine conditions at that time; therefore, the TCZ deposits belong to that part of the VMS family formed beneath the seafloor. This study was undertaken to assess the nature of the felsic volcanic host rocks and their control on mineralization.

### GEOLOGICAL SETTING

The TCZ extends from the Gaspé Peninsula of Québec in the northeast to the State of Maine (USA) in the

southwest, and is dominated by bimodal volcanic and interlayered fine- to coarse-grained sedimentary rocks. In New Brunswick the TCZ is divided into northern and southern parts by the Rocky Brook–Millstream Fault (Fig. 1).

In the northern part of the TCZ, the Chaleurs Group comprises subaerially deposited, Late Silurian bimodal volcanic rocks that overlie early Silurian shallow marine fine- to coarse-grained clastic and carbonate sedimentary rocks. The Chaleurs Group is overlain disconformably by bimodal volcanic rocks and interlayered sandstones and siltstones of the Dalhousie Group.

In the southern TCZ only Early Devonian rocks are exposed, and all of them are assigned to the Tobique Group. The Tobique and Dalhousie groups are in part coeval and are similar in terms of rock types. The depositional environment for the Tobique Group is, for the most part, thought to be outer shelf or slope based on sedimentary bed forms and ichnofauna and the presence of abundant pillow lava and hyaloclastite in mafic volcanic units. In

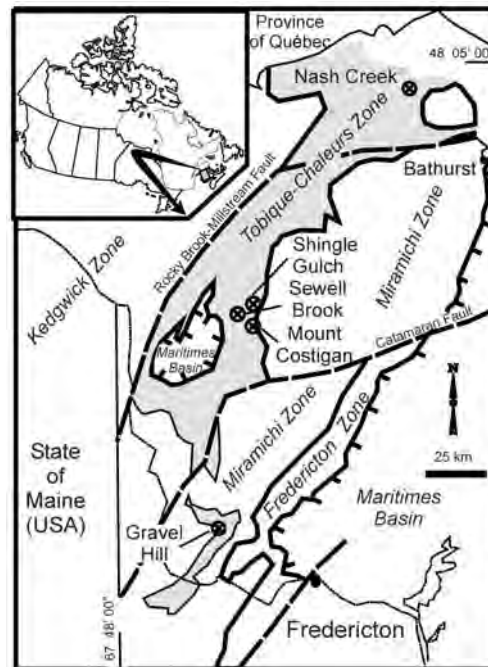
contrast, the Dalhousie Group was deposited in a shallow marine to locally subaerial setting.

There are three common Acadian structural elements in the TCZ; 1) north-northeast trending, doubly-plunging shallow folds of km-scale amplitude, which control the distribution of rock units; 2) east-west striking, normal to oblique faults at high angles to regional stratigraphy; and 3) north-northeast striking, belt-parallel faults. Throughout the TCZ the level of erosion is generally shallow, an interpretation that is supported by the low metamorphic grade (zeolite facies) and absence of coeval plutons; however, limited vitrinite reflectance data from the northern TCZ suggests variable degrees of thermal alteration.

The volcanic rocks of the TCZ are interpreted to have erupted in a continental rift setting. Rifting was triggered by transpression resulting from oblique collision of the Miramichi Zone (Ganderia), with the North American Plate (Laurentia), during the final stages of closure of the Iapetus Ocean, including the Tetagouche–Exploits back-arc basin (Dostal *et al.* 1989).

### MINERALIZATION

Within the TCZ there are five significant Zn–Pb sulfide deposits/occurrences. These vary greatly in terms of grade and size. The largest is Nash Creek ( $\approx 3.2$  M tonnes grading 4.67% Zn, 0.80% Pb, and 27.8 g/t Ag), The other deposits are Mount Costigan (7.1% Zn, 2.13% Pb, and 16.32g/t Ag over 7.5 m), Sewell Brook ( $\approx 25,000$  t grading 20% Zn+Pb), Gravel Hill (best assays  $\approx 10\%$  Zn+Pb), and Shingle Gulch East (large tonnage, low grade ( $< 2\%$  Zn+Pb)). Interestingly, all five of these deposits are spatially associated with Lower Devonian felsic volcanic rocks, in particular high SiO<sub>2</sub> ( $>70$  wt.%) rhyolite. At Nash Creek there are also minor volumes of more intermediate lavas (rhyodacite) whereas, the host sequence at Sewell Brook is dominated by rhyodacite.



**Fig. 1.** The Tobique–Chaleurs Zone of New Brunswick with the location of significant Zn–Pb sulfide deposits or occurrences (modified from Walker 2005).

These deposits are generally simple in terms of their mineralogy, with sphalerite dominant over galena with Zn/Pb ranging between 2 and 5. Significant chalcopyrite occurs only at the Sewell Brook deposit. All of the deposits are marked by low (20–50 volume % of sulfide) pyrite, and an absence of pyrrhotite. Marcasite has been identified in the Nash Creek deposit, implying low-pressure conditions, consistent with shallow level of emplacement. Non-sulfide phases occurring in veins are generally subordinate to sulfides and consist of calcite, siderite and minor quartz. Sericite or K-feldspar (adularia) and (or) chlorite vary in abundance adjacent to sulfide accumulations and are attributed to hydrothermal alteration processes.

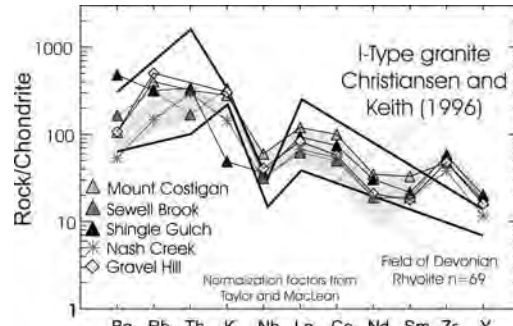
### GEOCHEMISTRY

The submarine depositional setting inferred for most Early Devonian volcanic rocks in part explains the highly variable alkali contents. Specifically, many have generally low Na<sub>2</sub>O ( $< 3$  wt.%) and high

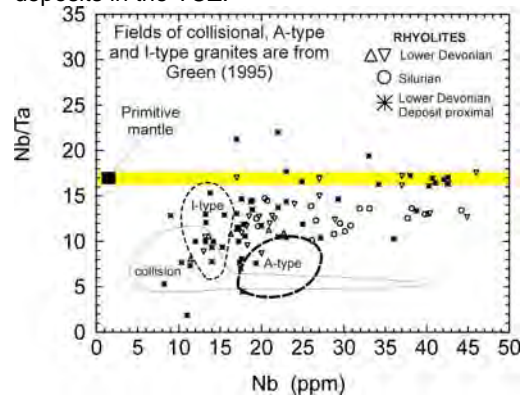
K<sub>2</sub>O (up to 14 wt.%). Such a signature may, in part be explained by low-temperature seawater alteration (Galley 1995); however, unmineralized rocks may also have high K<sub>2</sub>O, implying that some of the K is a function of primary magmatic processes.

The highly variable Zr/Ti and Zr/Hf ratios of felsic rocks along the belt are not likely a function of crystal fractionation in large magma chambers. Rather, these variations are interpreted to reflect differences in small-batch felsic melts that erupted along the belt at the same time. These data also show elevated Ba, Rb, and Th (Fig. 2) and anomalously low Nb, Sr, Ti, and Eu. The chondrite-normalized major element and REE diagram (Fig. 2) shows that these rocks have profiles that, in many respects, are similar to I-type granites. This is problematic as I-type intrusions are not normally associated with rift-settings; rather, they tend to occur in subduction settings (Christiansen & Keith 1996). The negative Nb anomalies in these rocks (Fig. 2) are consistent with a subduction-related setting, as Nb tends to be sequestered in the down-going slab rather than passing into the overlying mantle wedge via metasomatic fluids (Green 1995). However, absolute values of Nb and to a lesser degree the Nb/Ta ratio, are somewhat higher than the upper limit of I-type granite (Fig. 3). The higher Nb+Y of these rocks was interpreted by Lentz (1998) to represent an A-type affinity.

The rhyolites hosting the deposits in the TCZ are aphyric to very sparsely feldspar-phyric. Most have high SiO<sub>2</sub> (commonly ≥ 70 wt. %), and negative Eu anomalies that are indicative of feldspar fractionation in the source magma. These characteristics are typical of relatively highly fractionated magmas. Locally, the rhyolites can be divided into low-Zr (250 to 350 ppm) and high-Zr (400 to ≥ 900 ppm) types; with maximum Zr contents in excess of 1100 ppm have been recorded. In some areas, e.g. Nash Creek, relatively low Zr/Hf indicate extensive fractionation. A few of the very high Zr samples collected by previous workers have been classified as



**Fig. 2.** Chondrite-normalized major and REE data for host felsic volcanic rocks from various deposits in the TCZ.



**Fig. 3.** Nb vs. Nb/Ta discrimination diagram with TCZ rhyolites plotted with respect to fields for A-, I-, and collision-type granites.

peralkaline (R. Wilson pers. comm. 2008). The relatively high Ga and Ga/Al of many of these rocks suggest an affinity with A-type granites.

Volcanic rocks of more intermediate composition are rare in the TCZ but are present at both the Nash Creek and Sewell Brook deposits. At Nash Creek, feldspar-phyric rhyodacite containing 500 ppm Zr immediately overlies low-Zr rhyolite and likely reflects draw-down in a small, zoned magma chamber. At Sewell Brook, most of the volcanic rocks in the immediate vicinity of the deposit are rhyodacitic in composition.

### CONCLUSIONS

The volcanic rocks of the TCZ were erupted in a shallow marine basin developed during trans-tensional rifting (Dostal *et. al* 1989). These lavas exhibit some of the geochemical characteristics typical of magmas generated in rift

settings, e.g., the bimodal nature of the magmatism. With respect to the felsic volcanic rocks, elevated K, Zr, Y, Ga, and Ga/Al ratios are consistent with A-type felsic rocks. However, these felsic rocks also display characteristics typical of I-type (subduction-related) magmas, such as high Ba and Nb.

Undoubtedly, the source material for the melts that generated these rhyolites and related sulfide mineralization developed from a heterogeneous mantle source (Dostal *et al.* 1989) with a complex history including subduction, and mantle heterogeneity. At higher crustal levels contamination, magma segregation (magma chamber zoning), and crystal fractionation process probably added additional complications.

In terms of exploration vectoring, the following physicochemical criteria are most likely to lead to successful targeting of Zn-Pb mineralization in the TCZ.

(1) High K<sub>2</sub>O, low Na<sub>2</sub>O compositions indicate zones of deposit-related hydrothermal alteration.

(2) Rocks of more intermediate (rhyodacite) composition, as based on Zr/TiO<sub>2</sub>, may indicate proximity to intrusions that have undergone crystal-fractionation and subsequent development of metal-laden hydrothermal fluids.

(3) Rocks with high primary permeability (flow-top breccia, etc.) are the preferred traps for sulfide minerals.

#### ACKNOWLEDGEMENTS

Thanks to Reg Wilson for supplying some unpublished geochemical data, and to S.R. McCutcheon for editorial comments.

#### REFERENCES

- CHRISTIANSEN E.H. & KEITH, J.D. 1996. Trace element systematics in silicic magmas: A metallogenic perspective. In: Wyman, D.A. (ed), Trace Element Geochemistry of Volcanic Rocks: Applications for Massive Sulphide Exploration: *Geological Association of Canada, Short Course Notes*, **12**, 115–151.
- DOSTAL, J., WILSON, R.A., & KEPPIE, J.D. 1989. Geochemistry of Siluro-Devonian Tobique belt in northern and central New Brunswick (Canada): Tectonic Implications. *Canadian Journal of Earth Sciences*, **26**, 1282–1296.
- GALLEY, A.G. 1995. Target vectoring using lithochemochemistry: Applications to the exploration for volcanic hosted massive sulphide deposits. *CIM Bulletin*, **88**, 15-27.
- GREEN, T.H. 1995. Significance of Nb/Ta as an indicator of geochemical processes in the crust-mantle system. *Chemical Geology*, **120**, 347–359.
- LENTZ, D.R. 1998. Petrogenetic evolution of felsic volcanic sequences associated with Phanerozoic volcanic-hosted massive sulphide systems: the role of extensional geodynamics. *Ore Geology Reviews*, **12**, 289–327.
- WALKER, J.A. 2005. *Petrogenesis and tectonic setting of Devonian volcanic and related rocks and their control on mineralization at the Shingle Gulch East Zn–Pb–Ag sulfide deposit, northwest New Brunswick*. Unpublished PhD thesis, University of New Brunswick, Fredericton, NB, Canada, 430 p.

## Sulfide petrology and geochemistry of the Key Anacon Main Zone and East Zone massive sulfide deposits, Bathurst Mining Camp, NB, Canada

Joseph D.S. Zulu<sup>1</sup>, David. R. Lentz<sup>1</sup>, & James A.Walker<sup>2</sup>

<sup>1</sup>Department of Geology, University of New Brunswick, Fredericton, NB, E3B 5A3 CANADA (e-mail: [dlentz@unb.ca](mailto:dlentz@unb.ca))

<sup>2</sup>New Brunswick Department of Natural Resources, Geological Surveys Branch, PO Box 50, Bathurst, New Brunswick E2A 3Z1 CANADA

**ABSTRACT:** The Key Anacon Zn-Pb-Cu-Ag massive sulfide deposits contain more than two Mt of 0.22% Cu, 3.47% Pb, 8.41% Zn, and 111 g/t Ag. These deposits occur in the hinges of parasitic F<sub>2</sub> folds of Middle Ordovician felsic volcanic rocks. Zone refining of massive sulfide deposits (Cu-rich footwall to the Zn-Pb rich hanging wall) is controlled by temperature, pressure, metal ion concentrations, stabilities of soluble complex ions during transport, multiple hydrothermal episodes and mixing, and mineral free energies.

Zinc strongly correlates with Pb ( $r^2=0.97$ ) reflecting similar paragenesis, determined by free energies of sphalerite and galena, and the degree of saturation. In contrast, the absence of correlation between Cu and Ag ( $r^2=0.11$ ) or Zn ( $r^2=0.34$ ) is attributed to non-cogenetic deposition. Silver exhibits strong positive Spearman's Rank correlations with Pb ( $r^2=0.91$ ); associated with tetrahedrite- and galena-rich assemblages), Zn ( $r^2=0.86$ ), Cd ( $r^2=0.86$ ), and Sb ( $r^2=0.63$ ). Mineral growth zoning in arsenopyrite and pyrite support multiple injections of fluids during mineralization and the order of crystallization is deduced from entrapped inclusion trails of other sulfides. The sulfide compositions are influenced by the discharge of hydrothermal elements (Eu, Fe, Mn, Zn, Cu, Pb, Cd, Au, Ag, Sr, Ba, Ca, P, and CO<sub>2</sub>) on the sea floor.

**KEYWORDS:** massive sulfide deposit, silver, Key Anacon, New Brunswick

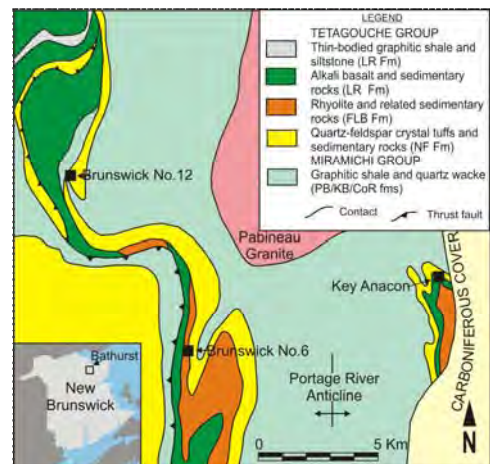
### INTRODUCTION

The calculated reserve for the Key Anacon Main Zone is 1.11 Mt of 0.22% Cu, 3.47% Pb, 8.41% Zn, and 111 g/t Ag (Irrinki 1992). No reserves are reported for the Key Anacon East Zone; however, twelve drill intersections were reported in a Northern Miner press release dated August 11<sup>th</sup>, 1993, with the best intersection of 82.3 m of low- to high-grade massive-sulfide lens at 350 m vertical depth in (DDH KA 93-42). The two zones are approximately 1.5 km apart, and located 20 km south of Bathurst and 11 km east-northeast of the Brunswick No. 6 deposit (Fig. 1).

The Key Anacon deposits lie on the eastern limb of the Portage River Anticline (Fig.1). They are hosted by an autochthonous sequence of Middle Ordovician felsic and mafic volcanic rocks and related sedimentary rocks of the Tetagouche Group, and overlie sedimentary rocks of the Miramichi Group,

which includes the Patrick Brook, Knights Brook and Chain of Rocks formations (van Staal & Williams 1984).

This study documents sulfide petrology and the chemical behaviour of various



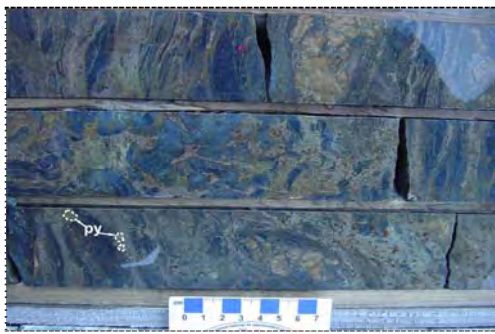
**Fig. 1.** A Geological map with location of the Key Anacon Main Zone deposit, New Brunswick, Canada (modified after van Staal & Williams 1984).

metals within the massive sulfides, with emphasis on Ag and on the factors controlling mineral zonation in this volcanogenic massive sulfides system.

### SULFIDE PETROLOGY

The Key Anacon Main and East zones occur at or near the upper contact of the felsic volcanic rocks of the Nepisiguit Falls Formation (Tetagouche Group). These exhalative deposits formed in a reducing ocean. Three sulfide facies, based on the predominant mineralogy, are recognized: 1) pyrite–chalcopyrite, 2) pyrite–sphalerite–galena, and 3) pyrrhotite–sphalerite–galena (Jambor 1979). These three assemblages have distinct textural and microstructural characteristics, metal grades, and spatial distribution (Jambor 1979; Irrinki 1992).

The pyrite–chalcopyrite–pyrrhotite assemblage contains up to 1% Cu, and consists of disseminated to massive pyrite, pyrrhotite, with subordinate remobilized chalcopyrite filling the intragranular fractures in pyrite and interstitial spaces between highly strained and brecciated Fe-sulfides (Saif 1983; Fig. 2).



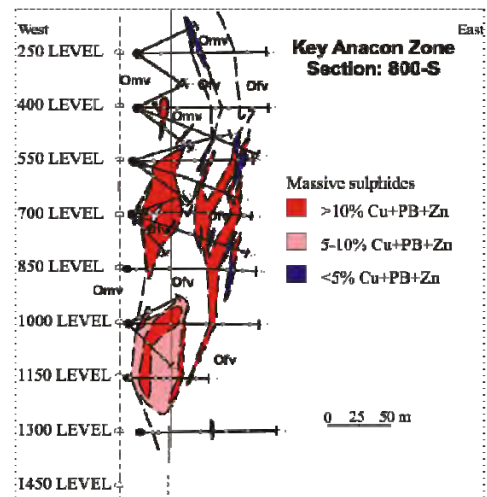
**Fig. 2.** Pyrrhotite-chalcopyrite breccia from footwall of the Key Anacon East zone. Note pyrite porphyroblasts (arrow). Sample from DDH KA61-921m.

The pyrrhotite–sphalerite–galena assemblage occurs mainly as disseminated fine- to medium-grained pyrrhotite and sphalerite, and fine- to coarse-grained pyrite, with arsenopyrite occurring as inclusions in pyrrhotite and sphalerite (consistent with observations made by Lentz 2002). Arsenopyrite occurs mostly as euhedral porphyroblasts enclosed in pyrite.

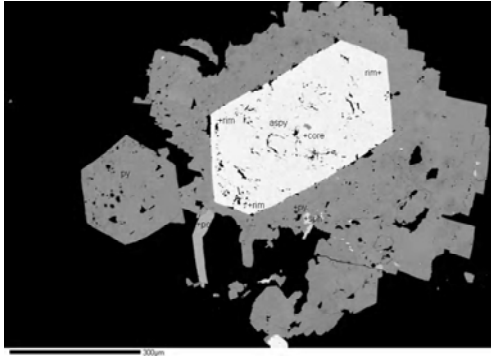
The pyrite–sphalerite–galena facies is typically fine- to medium-grained and consists of disseminated to banded massive sulfides, containing brecciated clasts of pyrite. Locally, minor amounts of chalcopyrite, galena, and pyrrhotite occur as fracture fillings or as inclusions in pyrite.

The distribution of sulfide lenses at the Key Anacon Main Zone is the result of folding with sulfides thickened in the hinge zones of  $F_1/F_2$  folds and attenuated on the limbs (Fig. 3). The  $S_1$  fabric is transposed parallel to  $S_2$  on the fold limbs, resulting in a composite  $S_1/S_2$  fabric. In contrast  $S_1$  is at a high angle to  $S_2$  near the noses of  $F_2$  folds (van Staal & Williams 1984).

Evidence from drill core and microstructure studies indicate that euhedral, zoned arsenopyrite grains tend to be clustered, and mantled by pyrite (Fig. 4), and their distribution is structurally controlled. These textures are interpreted to represent pressure solution as the main deformation mechanism during  $D_1$ . This interpretation is supported by serrated pyrite boundaries (Fig. 4) and pyrite-bearing veins. However, locally unstrained euhedral pyrite porphyroblasts overprint  $D_1$  and  $D_2$  structures, implying a late-stage post- $D_2$  growth (Fig. 4).



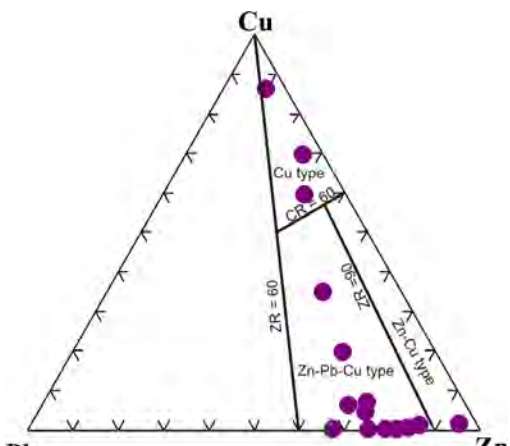
**Fig. 3.** A vertical projection indicating geology and zonal distribution of sulfides in Key Anacon Main No. 2 zone, Section 800 S (from Rennie & Irrinki 1986).



**Fig. 4.** Photomicrograph of a SEM-BSE image showing arsenopyrite enclosed in a serrated pyrite porphyroblast from the Key Anacon Main zone. Note: The euhedral and serrated pyrite contain inclusions of sphalerite and pyrrhotite (DDH KA64-712.8 m).

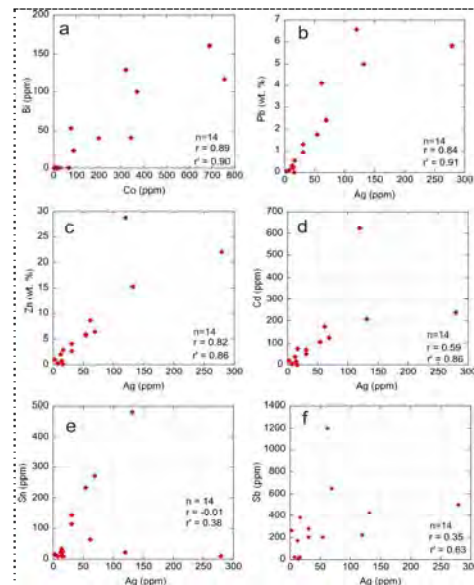
**GEOCHEMISTRY OF MASSIVE SULFIDE**

Metal contents of the sulfide samples collected from the Key Anacon deposits have been classified using the Cu and Zn ratios (Fig. 5). The majority of the massive sulfide samples plot in the Zn–Pb–Cu type (cf. Large 1992; Fig. 5); however, the semi-massive to disseminated sulfides in the footwall are enriched in Cu, Co, and Bi and lower in Zn and Pb, typical of stringer zone mineralization. These plots in the Cu type field and one sample contains enough zinc to be placed in the Zn-Cu group (Fig. 5).



**Fig. 5.** The Pb-Cu-Zn, discrimination diagram for massive sulfide samples collected during this study. Field boundaries are from Large, 1992.  $ZR = (100 \text{ Zn}/(\text{Zn}+\text{Pb}))$ ,  $CR = 100 \text{ Cu}/(\text{Cu}+\text{Zn})$ .

The binary plots of selected metals along with Spearman Rank coefficients are presented in Figure 6. Cobalt correlates strongly with Bi ( $r'=0.90$ ) and both are concentrated with Cu in basal sulfides or in the stringer zone. Deposition of sulfides belonging to this same class (Susak & Crerar 1982) are determined solely by the free energies of the mineral species (chalcopyrite, bismuthinite, arsenopyrite), corresponding dissolved metal species, and by the degree of saturation.



**Fig. 6.** Binary plots of metal contents of massive sulfides, showing spearman rank correlation coefficients ( $r'$ ) of: **a)** Co vs Bi ( $r'=0.90$ ), **b)** Ag vs Pb ( $r'=0.91$ ), **c)** Ag vs Zn ( $r'=0.86$ ), **d)** Ag vs Cd ( $r'=0.86$ ), **e)** Ag vs Sn ( $r'=0.38$ ), and **f)** Ag vs Sb ( $r'=0.63$ ). Note:  $r'$  is the Pearson's product-moment coefficient of linear correlation.

Silver exhibits a strong Spearman's Rank correlation with Pb ( $r'=0.91$ ) reflecting its original syngenetic substitution for Pb in galena and/or micro-inclusions of other Ag-Pb phases. There is a slightly lower correlation of Ag with Zn ( $r'=0.86$ ), and Cd ( $r'=0.86$ ). In contrast, Ag correlates poorly with Au, and Cu suggesting that the high Ag/Pb ratio is from substituted Ag, and that tetrahedrite has little control on the Ag/Pb ratios. The positive correlation of Ag with Sb ( $r'=0.63$ ) is attributed to

tetrahedrite. Cadmium correlates well with Zn ( $r'=0.99$ ), indicating substitution of Cd for Zn in the sphalerite structure. Tin does not correlate with Ag or with Zn.

### ORE GENESIS DISCUSSION

The Key Anacon deposits are exhalative deposits with metal zonation grading from a pyrite-chalcopyrite-pyrrhotite zone in the footwall, through a pyrite-sphalerite zone in the main parts of the deposits, to pyrite-sphalerite-galena zone in the upper and vent-distal parts of the system (cf. Petruk 2000). At the base, these deposits consist of structurally attenuated and dismembered stockwork veins and disseminations of chalcopyrite and pyrrhotite, in a matrix of chlorite.

The pyrite-sphalerite zone contains mono-mineralic bands of sphalerite- and galena that wrap around brecciated and rotated pyrite. These textures reflect variation in the response to deformation of sulfides of varying ductility. Evidence supporting this metal zonation is evident at microscopic scale where the crystallization sequence of ore minerals is explained by zone refining processes due to progressive changes in the solution chemistry, temperature, and the  $f_{O_2}$  and  $f_{S_2}$  as the rising hydrothermal solution mixed with sea water (Large 1977).

### CONCLUSIONS

This contribution can be summarized in a number of points:

- (1) The  $F_1/F_2$  sheath-like fold structures control the distribution of sulfide mineralization in the noses of the  $F_2$  parasitic folds.
- (2) Ag exhibits a strong Spearman's Rank correlation with Pb, Zn, Cd, and Sb reflecting its cogenetic nature with these elements as they are controlled by free energies, dissolved metal species, and degree of saturation.
- (3) Metal zonation in massive sulfides is controlled by progressive changes in the solution chemistry, temperature, and the  $f_{O_2}$  and  $f_{S_2}$  as ascending hydrothermal solution interacts with the massive sulfide lens and with sea water.

- (4) The sulfide compositions are dictated by hydrothermal elements such as Eu, Fe, Mn, Zn, Cu, Pb, Cd, Au, Ag, Sr, Ba, Ca, P,  $CO_2$ , and S, precipitated on the sea floor from discharged hydrothermal solutions.

### ACKNOWLEDGEMENTS

The Department of Natural Resources, Geologic Surveys Branch, is thanked for the logistical support during field work. Steven R. McCutcheon is thanked for discussions on the petrogenesis of massive sulfides.

### REFERENCES

- JAMBOR, J.L. 1979. Mineralogical Evaluation of Proximal-Distal features in New Brunswick Massive-Sulfide Deposits. *Canadian Mineralogist*, **17**, 649-664.
- IRRINKI, R.R. 1992. Key Anacon sulfide deposit, Gloucester County, New Brunswick. *Exploration Mining Geology*, **1**, 121-129.
- LARGE, R.R. 1992. Australian volcanic-hosted massive sulfide deposits: features, styles and genetic models. *Economic Geology*, **87**, 471-510.
- LARGE, R.R. 1977. Chemical Evolution and Zonation of Massive Sulfide Deposits in Volcanic Terrains. *Economic Geology*, **72**, 549-572.
- LENTZ, D.R. 2002. Sphalerite and Arsenopyrite at the Brunswick No. 12 Massive-Sulfide Deposit, Bathurst Camp, New Brunswick: Constraints on P-T Evolution. *The Canadian Mineralogist*, **40**, 19-31.
- PETRUK, W. 2000. Applied Mineralogy in the Mining Industry. *Elsevier, Netherlands*, 268 p.
- RENNICK, P.M. & IRRINKI, R.R. 1986. Geology and zonal distribution of Sulfides at Key Anacon No. 2 zone. Internal unpublished Report. *New Brunswick, Department of Natural Resources and Energy, Minerals and Energy Division*.
- SAIF, S.I. 1983. Petrographic and geochemical investigation of iron formation and other iron-rich rocks in Bathurst District, New Brunswick. In: *Current Research, Geological Survey of Canada*, **80-1A**, 309-317.
- SUSAK, N.J. & CRERAR, D.A. 1982. Factors Controlling Mineral Zoning in Hydrothermal Ore Deposits. *Economic Geology*, **77**, 476-482.
- VAN STAAL, C.R. & WILLIAMS, P.F. 1984. Structure, origin, and concentration of the Brunswick 12 and 6 orebodies. *Economic Geology*, **79**, 1669-1692.



# Sponsors



## Symposium bags sponsor



## Platinum sponsors



**ANGLO AMERICAN**

## Gold sponsors



## Silver sponsors



## Bronze sponsors

