

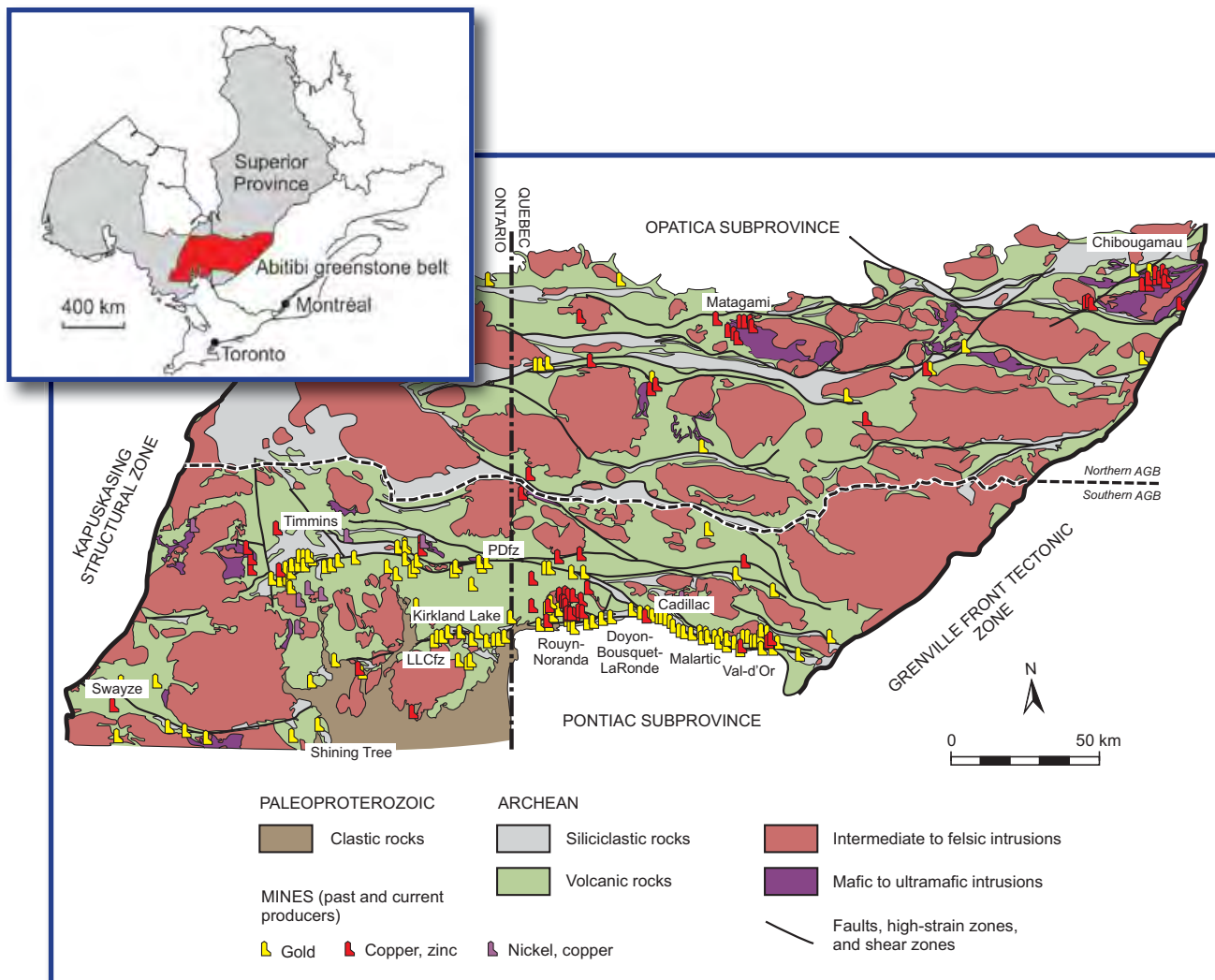


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# REVIEWS IN ECONOMIC GEOLOGY

Volume 19

## ARCHEAN BASE AND PRECIOUS METAL DEPOSITS, SOUTHERN ABITIBI GREENSTONE BELT, CANADA



Editors

Thomas Monecke, Patrick Mercier-Langevin, and Benoît Dubé

SOCIETY OF ECONOMIC GEOLOGISTS, INC.



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### **Volume Editors**

Thomas Monecke  
Colorado School of Mines

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Published by the Society of Economic Geologists, Inc.  
7811 Shaffer Parkway  
Littleton, CO 80127, USA

Website: [segweb.org](http://segweb.org)  
E-mail: [seg@segweb.org](mailto:seg@segweb.org)

ISSN  
0741-0123 (Print)  
1933-1495 (Disc)  
2374-443X (PDF)

ISBN  
978-1-629492-20-9 (Print)  
978-1-629492-21-6 (Disc)  
978-1-629495-77-4 (PDF)

*Reviews in Economic Geology* is a series publication of the Society of Economic Geologists designed to accompany the Society's Short Course series. Like the Short Courses, each volume provides comprehensive updates on various applied and academic topics for practicing economic geologists and geochemists in exploration, development, research, and teaching. Volumes are produced in conjunction with each new Short Course, first serving as a textbook for that course, and subsequently made available to SEG members and others at a modest cost.

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*On the cover:* Geologic map of the Abitibi greenstone belt showing the distribution of supracrustal rocks and intervening domes of intrusive rocks (modified from Thurston et al., 2008). LLCfz = Larder Lake-Cadillac fault zone, PDFz = Porcupine-Destor fault. Inset map shows location of the belt.

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## PREFACE

Due to the economic importance, accumulated geological knowledge, the outstanding degree of preservation of primary geological relationship, and generally easy access to excellent exposures, the southern Abitibi greenstone belt of Ontario and Quebec, Canada, represents one of the most important field trip destinations for industry professionals and geology students worldwide. Gaining field experience in the classic mining camps of the southern Abitibi greenstone belt is particularly important for industry geologists exploring for base and precious metal deposits.

The purpose of the present volume is to provide a comprehensive review of the geology of the major mining camps of the southern Abitibi greenstone belt. An overview of recent advances in the understanding of Neoproterozoic geology and metallogeny is provided. The papers collected here also give an update on current deposit models and camp-scale geological factors controlling the location of the world-class deposits of the southern Abitibi greenstone belt, and they emphasize implications for deep exploration in Neoproterozoic greenstone terranes.

This volume was initially compiled as a guidebook for a field trip held in conjunction with the Society of Economic Geologists 2010 Conference in Keystone on October 6–11, 2010. Subsequent modifications and updates were made for the Society of Economic Geologist Foundation Student Field

Trip, held September 3–11, 2014. As travel distances between adjacent mining camps are not large in the southern Abitibi greenstone belt, it is possible to visit the most important mines and key outcrops within a few days. Both field trips commenced in Timmins, Ontario, and ended in Rouyn-Noranda, Quebec. Road logs and descriptions of outcrops visited during both field trips are given in the appendices to the respective chapters of this *Reviews in Economic Geology* volume.

We express our gratitude to the mine geologists and company representatives who assisted in the set-up of the field trips, especially B. Atkinson, E. Barr, F. Blanchet, P. Calloway, B. Drolet, R. Dubuc, D. Gamble, D. Gervais, and D. Pitre. We are indebted to R. Goldfarb for constructive review. Some of the contributions forming part of this volume resulted from the collaborative Targeted Geoscientific Initiative of Natural Resources Canada and the Plan Cuivre project of the Ministère des Ressources naturelles et de la Faune du Québec. The production of this volume was financially supported by Natural Resources Canada and the Colorado School of Mines.

Thomas Monecke  
Patrick Mercier-Langevin  
Benoît Dubé  
May 8, 2017



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The Society of Economic Geologists Publications Board  
thanks Natural Resources Canada and the Colorado School of Mines  
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## AUTHOR BIOGRAPHIES

**Brian Atkinson** graduated in 1977 from McMaster University. He has worked as a professional geoscientist for more than 30 years. The first five years of his career were in Cordilleran exploration, starting in Yukon with subsequent work throughout Yukon and British Columbia. His most notable accomplishment was the first North American discovery of the mineral malayaite while exploring for tin-tungsten skarns in southern Yukon. Following that western experience, Brian worked briefly in northern Ontario exploration before joining the Ontario Geological Survey, working in Quaternary geology for a year in southern Ontario. He was appointed resource geologist and advanced to resident geologist in Red Lake, where he spent 13 years learning about Archean greenstone geology and completing township- and regional-scale mapping. In 1997, he moved to Timmins as regional resident geologist and retired from this position in December 2014. Brian's expertise is in Archean greenstone belts, with interests in mineral deposits and economic geology.

**John Ayer** received B.Sc. (1976) and M.Sc. (1979) degrees from Carleton University and a Ph.D. degree from Ottawa University (1999). He worked five years in mineral exploration across Canada before joining the Ontario Geological Survey (OGS) in 1984, where he continued until retirement in 2011. His work with the OGS included extensive bedrock mapping in the Wabigoon and Abitibi subprovinces of the Superior Province. He led the Precambrian Mapping Program in northeastern Ontario and was OGS representative on the Discover Abitibi Initiative and Targeted Geoscience Initiative-3 Abitibi projects. John has been the lead and co-author on numerous government and journal publications and was co-editor of a 2008 *Economic Geology* special issue devoted to base metal and gold metallogeny in the Abitibi greenstone belt. He was corecipient of the Canadian Institute of Mining and Metallurgy Barlow Medal awarded for best geological paper for the 2012 paper in *Exploration and Mining Geology*, entitled "Structure, Stratigraphy, U-Pb Geochronology and Alteration Characteristics of Gold Mineralization at the Detour Lake Gold Deposit, Ontario, Canada." He has been associate director of the Mineral Exploration Research Centre within the Earth Sciences Department at Laurentian University in Sudbury since 2013.

**François Blanchet** earned a B.Eng. degree in geological engineering from Université Laval in 1995. He has more than 20 years with the industry, mainly in gold and VMS exploration and mining operations. From 1995 to 2004, he was successively production geologist, exploration geologist, senior geologist, and then chief geologist at Cambior's Géant Dormant gold mine in northwestern Quebec. From 2005 to 2015, he was in charge of exploration and geology in two major mining operations in the Doyon-Bousquet-LaRonde mining camp in the southern Abitibi greenstone belt. From 2005 to 2006, he served as chief of the geology department at Cambior's Doyon mine and from 2006 to August 2015 as geology superintendent at Agnico Eagle Mines Ltd. LaRonde Division. In 2015 he joined Agnico Eagle Mines Project Evaluation Department as manager of the

Technical Evaluations Group, looking for external growth opportunities.

**Jocelyn Côté** received a B.Sc. degree from Université Laval in 1986. He has worked in the industry for more than 30 years, mainly in the mining industry as exploration geologist for Barrick Gold at the former Bousquet and Bousquet 2 gold mines from 1993 to 2002 and as senior exploration geologist for Agnico Eagle Mines Ltd. at the LaRonde Penna mine from 2002 to 2003, at the Regional Division from 2004 to 2006, and at the Lapa gold mine from 2006 to present.

**Robert A. Creaser** holds B.Sc. (Honors, 1984) and Ph.D. (1990) degrees from the Australian National University and La Trobe University, Australia. He held the position of research fellow in geochemistry at the California Institute of Technology from 1990 to 1992, where he developed efficient mass spectrometry methods for isotopic analysis of osmium, rhenium, and other platinum group elements. He was appointed at the University of Alberta in 1992 and is currently professor and holds the Canada Research Chair in Isotope Geochemistry in the Department of Earth and Atmospheric Sciences. His primary research interest lies in the application of isotope techniques to further the understanding of fundamental processes that control the origin and evolution of Earth's crustal rocks. In particular, his current research focus involves continued development and application of the rhenium-osmium (Re-Os) radioactive isotope system for geochronology of sulfide minerals. He has been awarded the Geological Association of Canada's W.W. Hutchinson Medal (1997), is a Fellow of the Royal Society of Canada (2008), and a Distinguished Member of the Geological Association of Canada (2007).

**Réal Daigneault** received a B.Sc. degree in 1980 from University of Montréal and an M.Sc.A. in 1983 from Polytechnique School in Montréal. Working with the Ministère de l'Énergie et des Ressources naturelles du Québec, he has been in charge of the camp-scale mapping of the Chibougamau mining district from 1982 to 1987. He completed a Ph.D. degree at Université Laval in 1991. Since 1988, he has been professor in structural geology at Université du Québec à Chicoutimi, conducting numerous research projects involving many graduate students, focusing on the major deformation corridors of the Abitibi greenstone belt and their relationship to gold and base metal deposits. Réal is currently director of the Centre d'Études sur les Ressources Minérales (CERM), a research unit of Université du Québec à Chicoutimi. Since 2000, he is also director of CONSOREM, a mineral exploration research consortium that primarily develops innovative, applied exploration tools and concepts for the industry.

**Stéphane De Souza** graduated from Université du Québec à Montréal in 2004, where he also obtained M.Sc. (2007) and Ph.D. (2011) degrees. His doctoral research on mountain building processes, plus a keen interest in economic geology, led him to undertake postdoctoral research (2012–2015) on the genesis of the Canadian Malartic Archean low-grade, bulk-tonnage gold deposit with the Geological Survey of



## BIOGRAPHIES (continued)

Canada as part of the Targeted Geoscience Initiative-4, a multidisciplinary research program on major Canadian ore systems. He also worked in the mineral exploration industry and contributed to mapping projects for the Ministère de l'Énergie et des Ressources naturelles du Québec. He is now professor of geology and tectonics at Université du Québec à Montréal, developing and conducting several research and mapping projects aimed at better understanding the genesis of precious and base metal ore deposits and at providing the industry with improved mineral exploration models.

**Pierre Doucet** received a B.Sc. degree (1981) from Queen's University in Kingston and an M.Sc. degree (1983) in metamorphic petrology from Dalhousie University in Halifax. He has more than 20 years of professional experience. From 1987 to 1989 he worked as a project geologist with Noramco Explorations, exploring for base metal and gold deposits. He has worked for over 18 years with the Ministère de l'Énergie et des Ressources naturelles du Québec as a project and then district geologist. He is the author/co-author of four scientific papers and more than 50 government publications.

**Benoît Dubé** received B.Eng. (1982) and M.Sc. (1985) degrees from Université Laval and a Ph.D. degree from Université du Québec à Chicoutimi in 1990. He has worked in the industry for more than 25 years, mainly with the Geological Survey of Canada as senior research scientist conducting studies on various types of gold and gold-rich massive sulfide deposits in ancient metamorphosed terranes. He has also studied ancient epithermal gold deposits in Newfoundland and Patagonia. In recent years, he has led multidisciplinary and multiagency projects designed to study gold deposits in the Superior and Churchill provinces, Canada. Benoît is an adjunct professor at Université Laval, Laurentian University, and Institut National de la Recherche Scientifique—Centre Eau, Terre et Environnement. He is the author or co-author of more than 50 journal papers and 150 government publications. Benoît was awarded the Geological Association of Canada Julian Boldy Medal in Economic Geology and Robinson Lecturer Medal in 1997 and 1998, respectively, the Association de l'Exploration Minière du Québec Jean-Descarreaux Award in 2006, the SEG Brian J. Skinner award for best paper published in *Economic Geology* in 2007, the Geological Association of Canada Duncan Derry Medal for contributions in the field of economic geology in Canada in 2011, and the Canadian Institute of Mining and Metallurgy Barlow Medal, as co-author, for best geological paper in *Exploration and Mining Geology* journal in 2014.

**Richard Dubuc** obtained his B.Sc. degree from Université du Québec à Montréal in 1991. He was hired by Aurizon Mines as exploration geologist from 1991 to 1993, and then as a production geologist from 1993 to 1997 with TVX (Casa Berardi mine), Cambior (Géant Dormant mine), and Placer Dome (Sigma mine). He was administrative and technical director at Franc Or Resources Cayenne project in French Guyana from 1997 to 1999, where he was in charge of exploration, including soil geochemistry in Amazonian laterites

and saprolites. Richard moved back to Canada in 2000 and worked both as exploration and production geologist at various sites in northern Quebec, including the Sigma and Kiena gold mines in Val-d'Or, the Joe Mann gold mine in Chibougamau, the Raglan nickel mine in Cape Smith, the Croinor project near Val-d'Or, and the Géant Dormant mine in the northern Abitibi greenstone belt. He became senior production geologist (2004) and then chief geologist (2006–2010) with Mines Richmond at the Beaufoir gold mine in Val-d'Or, where he contributed to the discovery of new gold zones that helped extend the mine life. In 2010 he joined Agnico Eagle Mines Ltd. Lapa Division as senior production geologist, and he was soon after promoted to geology superintendent, a role that he still holds today. He is also assistant superintendent at the LaRonde Penna mine.

**Céline Dupuis** earned a B.Sc. degree in earth sciences in 1999 from University of Ottawa, an M.Sc. degree in geophysics in 2001 from University of Western Ontario, and a Ph.D. degree in earth sciences in 2005 from Université Laval. She held a professional researcher position in the Department of Geology and Geological Engineering of Université Laval from 2006 to 2013, working on the chemical signatures of iron oxides and their use as exploration tools. From 2013 to 2015, she was research scientist at the Geological Survey of Canada studying the Archean low-grade, bulk-tonnage stockwork-disseminated Canadian Malartic gold deposit in the Abitibi greenstone belt, and the banded iron formation-hosted Meadowbank deposit in Nunavut. Céline is author or co-author of more than 10 scientific journal papers and 10 government publications.

**Ben M. Frieman** is currently a Ph.D. candidate at Colorado School of Mines, where his research is focused on constraining the formation and evolution of the southern Abitibi greenstone belt using new and compiled structural and geochronological data. Prior to arriving at the Colorado School of Mines, he obtained an M.Sc. degree in earth sciences from the University of Maine in 2012, where his work focused on the kinematics and rheology of porphyroblastic schists. Ben also obtained B.Sc. degrees in geology and geophysics from the University of Minnesota in 2010. His research aims to elucidate how the Earth deforms at various scales and how these processes affect the distribution and endowment of orogenic gold deposits in both ancient and modern terrains.

**Damien Gaboury** is professor at Université du Québec à Chicoutimi, where he teaches economic geology and metallogeny. He received a B.Sc. degree from Université du Québec à Chicoutimi in 1989, an M.Sc. degree from Université Laval in 1991, and a Ph.D. degree from the Université du Québec à Chicoutimi in 1999. He spent four years as research scientist at CONSOREM (Consortium de Recherche en Exploration Minérale), studying volcanogenic massive sulfide and gold deposits, and he has been professor since 2004. He is the author/co-author of more than 20 journal papers and 30 industrial reports. He was visiting professor at Otago University in 2010. In 2012, he spent six months in Burkina

## BIOGRAPHIES (continued)

Faso doing field mapping for SEMAFO, helping define the geological framework of the gold systems of the region and training local geologists. He conducted research field projects in collaboration with the industry in Quebec, Peru, Niger, Burkina Faso, Guinea, Sudan, and Gabon. He is founder and director of the LAMEQ (Laboratoire de Métallogénie Expérimentale et Quantitative), for which he developed a unique apparatus for analyzing gas from decrepitating fluid inclusions by mass spectrometry under direct vacuum. He is cofounder and director of the newly established Professional Master in Mineral Exploration program at Université du Québec à Chicoutimi, a one-year program specially designed for exploration geologists wishing to improve their knowledge of ore systems and working skills through courses and projects in industry.

**Thomas Gemmell** earned a B.Sc. degree in earth sciences from Carleton University in 2009 and an M.Sc. degree in economic geology from the University of Ottawa in 2013. He has worked with both industry and the Geological Survey of Canada as a student and has subsequently gained four years of work experience in industry from 2011 to 2014 as a project geologist with Xstrata Copper–Glencore, exploring for volcanogenic massive sulfide and porphyry deposits and conducting geochemical/metallurgical studies on the Kidd Creek deep orebodies. He joined the Ontario Geological Survey in 2015. He currently is a Precambrian geoscientist with the Earth Resources and Geoscience Mapping Section working in the Swayze greenstone belt. He presented his preliminary M.Sc. findings at the 2010 SEG conference in Keystone.

**Harold L. Gibson** received his B.Sc. degree (1976) from Queen's University and his M.Sc. (1979) and Ph.D. (1989) degrees from Carleton University. After a successful 12-year career in exploration with the Falconbridge Group of companies he joined Laurentian University in 1990 as director of the Mineral Exploration Research Centre. His research focus is the metallogeny of ancient volcanic ore systems, particularly volcanogenic massive sulfide (VMS) deposits with emphasis on volcanology, tectonics, and hydrothermal alteration. He and his students have conducted extensive, mapping-based research on Archean, Proterozoic, and Cretaceous VMS deposits globally. Harold was awarded the Geological Association of Canada William Harvey Gross Medal in 1992, the Duncan Derry Medal in 2012, the Julian Boldy Award in 2003, the Canadian Institute of Mining and Metallurgy Julian Boldy Memorial Award in 1996, and the Barlow Memorial Medal in 1998 for his contributions to economic geology.

**Jean Goutier** received his B.Sc. (1986) and M.Sc. (1989) degrees from Université de Montréal. He has been with Géologie Québec (Ministère de l'Énergie et des Ressources naturelles) for more than 25 years as senior geologist in charge of mapping at various scales in a number of areas in the Archean Superior Province. He also led and contributed to numerous thematic studies on the stratigraphy and structure of the Abitibi greenstone belt and the Blake River Group, which represents the world's best volcanogenic

massive sulfide-endowed Archean volcanic succession. He is the author/co-author of 13 journal papers and 160 government publications (reports and maps). Jean was awarded the Marteau d'Or Award from Géologie Québec in 2003 and 2007 for his work in the Abitibi greenstone belt, the Mérite Géoscientifique-Ressources Minérales Award from the Ordre des Géologues du Québec in 2007, and the Jean Descarreaux Award of the Association de l'Exploration Minière du Québec in 2008 for his contributions to mineral exploration. Jean is also heavily involved in promoting Quebec's geological heritage and in training the next generation of geoscientists.

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**Michel G. Houlié** obtained B.Sc. (1997) and M.Sc. (2000) degrees from Université Laval, and a Ph.D. (2008) from the University of Ottawa. Since graduation, he has over 10 years of experience as a senior geoscientist with the Ontario Geological Survey and as a research scientist with the Geological Survey of Canada. He conducted regional bedrock mapping and mineral assessments for Ni-Cu-(PGE) sulfide deposits in the Abitibi greenstone belt with the Ontario Geological Survey from 2003 to 2009. He joined the Geological Survey of Canada in 2009 and is conducting collaborative research on Ni-Cu-PGE, Cr-PGE, and Fe-Ti-V deposits associated with mafic and ultramafic rocks across Canada. Michel is leading major research activities in the “Ring of Fire” emerging mining camp of northern Ontario (i.e., McFaulds Lake greenstone belt) under the Ni-Cu-Cr-PGE project of the Targeted Geoscience Initiative of Natural Resources Canada. His expertise is also on physical volcanology of komatiites and metallogenesis of komatiite-associated Ni-Cu-(PGE) deposits. He is adjunct professor at Laurentian University in Sudbury (2009-present), at University of Manitoba in Winnipeg (2011-present), and at the Institut National de la Recherche scientifique—Centre Eau, Terre et Environnement in Quebec City (2009-present). Michel was awarded the William Harvey Gross Medal of the Geological Association of Canada Mineral Deposits Division in 2013 and has been on the board of directors for the Division since then.

**Ingrid Kjarsgaard** studied geology and mineralogy in Germany, first in Bochum, later in Freiburg, where she earned her

## BIOGRAPHIES (continued)

degrees of Diplom Mineraloge (1984) and Doctor of Science (1988). She completed postdoctoral research in Mainz, Germany. Since moving to Canada in 1991, she has been working as a consulting mineralogist/petrologist for various research scientists and projects of the Geological Survey of Canada, as well as for provincial and territorial governments and industry clients. Her expertise ranges from kimberlite indicator minerals and rare metals in alkaline rocks and carbonatites to the ore and alteration mineralogy of massive Cu-Ni-PGE deposits, volcanogenic massive sulfide, sedimentary exhalative, banded iron formations, chromite, and orogenic gold deposits. She has co-authored 20 scientific journal papers, more than 40 government publications, and several unpublished internal reports. Since 2006 she has been teaching courses in mineralogy, gemology, and mineral deposits at Ottawa and Carleton universities, where she is an adjunct professor. Over the past years, she has supervised a large number of students in their B.Sc. thesis research.

**Annie Laberge** received B.Sc. (1999) and M.Sc. (2003) degrees from Université du Québec à Montréal. She has worked more than 14 years in industry, as geologist and senior geologist, with Cambior Inc. from 2001 to 2005 and with Agnico Eagle Mines Ltd. since 2005. Annie is currently in charge of planning and coordinating definition and exploration programs at Agnico Eagle Mines Ltd. LaRonde Penna mine in northwestern Quebec. She is a member of the Ordre des Géologues du Québec.

**Michael Leshner** received B.Sc. (1974) and M.A. (1976) degrees from Indiana University and a Ph.D. degree from University of Western Australia (1984). He was mineralogist for Iron Ore Company of Canada (1976–1979), a postdoctoral research fellow at University of Toronto (1982–1984), and professor of economic geology at University of Alabama (1984–1997). Since 1997 he has been professor of economic geology and Research Chair in Mineral Exploration at Laurentian University, serving as founding director of the Mineral Exploration Research Centre (1997–2004), department chair (2004–2007), and Director of Mining Initiatives (2010–2011), designing and founding the School of Mines. He has worked on the physical volcanology of komatiites and Ni-Cu-(PGE) mineralization in Brazil, China, Manitoba, Nunavik, Ontario, Quebec, and Western Australia, Cr deposits in northern Ontario, and volcanogenic massive sulfides, lithogeochemistry, and gold deposits in Alabama and Western Australia. He has authored or co-authored over 80 journal articles/book chapters and over 325 technical reports, scientific communications, extended abstracts, and abstracts. He was leader of International Geoscience Program (IGCP) Project 427: Dynamic Processes in Ore-Forming Magmatic Systems (1997–2002), and he currently is principal investigator and director of the \$13M Natural Sciences and Engineering Research Council–Canadian Mining Innovation Council (NSERC-CMIC)-funded pan-Canadian Mineral Exploration Footprints Network (2013–present). He is an elected Fellow of the Society of Economic Geologists, the Geological Association of Canada, and the Geological Society of America, has

been awarded the Geological Association of Canada Mineral Deposits Division Duncan R. Derry Medal and Julian Boldy Award, was co-awarded the Australasian Institute of Mining and Metallurgy Wardell Armstrong Prize, and has been a Society of Economic Geologists Thayer Lindsley Lecturer and a Canadian Institute of Mining and Metallurgy University Visiting Lecturer.

**Patrick Mercier-Langevin** earned B.Eng. (1998) and M.Sc. (2000) degrees from the Université du Québec à Chicoutimi and a Ph.D. degree in 2005 from the Institut National de la Recherche Scientifique—Centre Eau, Terre et Environnement. Since graduation, he has worked two years in industry as project geologist at Agnico Eagle Mines Ltd. Exploration Division (2004–2006) and 11 years with the Geological Survey of Canada (2006–present) as a research scientist conducting collaborative research on gold and volcanogenic massive sulfide deposits. Patrick currently champions the Gold Project of Natural Resources Canada 2015–2020 Targeted Geoscience Initiative. He served as adjunct professor at Université du Québec en Abitibi-Témiscamingue (2006–2009), at Université du Québec à Chicoutimi (2007–2010), and at Institut National de la Recherche Scientifique—Centre Eau, Terre et Environnement (2006–present). He was Visiting Professor at Akita University in Japan in 2010. He has authored and co-authored more than 20 scientific papers and over 300 technical and government reports, extended abstracts, and oral communications. Patrick was awarded the SEG Brian J. Skinner Award in 2007 as co-author of the best paper published in *Economic Geology*, the Geological Association of Canada Mineral Deposits Division William Harvey Gross Medal in 2009, and the Society of Economic Geologists Waldemar Lindgren Award in 2011. Patrick is chair of the Society of Economic Geologists Foundation Graduate Student Fellowship Committee and a member of the Society of Economic Geologists Publications Board.

**Vicki McNicoll** is a geochronologist in the Geochronology Laboratory at the Geological Survey of Canada. She obtained B.Sc. (1987) and M.Sc. (1990) degrees from Carleton University. Vicki has over 25 years of experience, working extensively in the field of U-Pb geochronology on both lab- and field-based research studies. She has authored or co-authored more than 65 journal papers and over 50 government publications, maps, and technical reports. She is the lab manager of the U-Pb ID-TIMS facility and clean lab at the Geological Survey of Canada.

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## BIOGRAPHIES (continued)

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## Introduction

# Archean Base and Precious Metal Deposits, Southern Abitibi Greenstone Belt, Canada

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The Abitibi greenstone belt of eastern Canada represents the world's largest Neoproterozoic terrane of supracrustal rocks. Straddling the border between the provinces of Ontario and Quebec, the belt covers an area that is approximately 700 km from southeast to northwest and 350 km from north to south. The belt is comprised of several major east-trending successions of folded volcanic and sedimentary rocks, with intervening intrusions. The supracrustal rocks of the Abitibi greenstone belt are uniquely well preserved and have mostly been overprinted only at a low metamorphic grade, allowing the study of primary geological relationships.

The Abitibi greenstone belt is of outstanding economic importance as it contains some of the most important gold and base metal mining camps in Canada, with a total endowment of over 800 million metric tonnes (Mt) of polymetallic massive sulfide ore (Mercier-Langevin et al., 2011) contained in volcanogenic massive sulfide (VMS) deposits and over 4,500 t of gold (Dubé and Gosselin, 2007) largely hosted by orogenic, Au-rich VMS, and intrusion-centered gold deposits. World-class deposits in the Abitibi greenstone belt include the Hollinger-McIntyre and Dome orogenic gold deposits in the Timmins-Porcupine gold camp (Rogers, 1982; Moritz and Crocket, 1991; Burrows et al., 1993; Poulsen et al., 2000; Bateman et al., 2008; Dubé et al., 2017); the giant Kidd Creek VMS deposit near Timmins (Bleeker, 1999; Hannington et al., 1999a, b); the Detour Lake orogenic gold deposit northeast of Cochrane (Oliver et al., 2012); the Kirkland Lake orogenic gold or syenite-associated gold deposit (Cameron and Hattori, 1987; Hicks and Hattori, 1988; Poulsen et al., 2000; Ispolatov et al., 2008); the Kerr-Addison orogenic gold deposit in the Larder Lake camp (Kishida and Kerrich, 1987; Smith et al., 1993; Ispolatov et al., 2008); the Home gold-rich VMS deposit in the Noranda camp (e.g., Kerr and Mason, 1990; Barrett et al., 1991; MacLean and Hoy, 1991; Kerr and Gibson, 1993; Gibson et al., 2000; Monecke et al., 2008); the Doyon and Westwood intrusion-centered gold deposits as well as the Bousquet 2-Dumagami and LaRonde Penna gold-rich VMS deposits in the Doyon-Bousquet-LaRonde camp (Savoie et al., 1986; Marquis et al., 1990; Tourigny et al., 1993; Dubé et al., 2007, 2014; Mercier-Langevin et al., 2007a, b, c; Galley and Lafrance, 2014; Yergeau et al., 2015); the low-grade, bulk-tonnage orogenic and/or intrusion-centered Canadian Malartic deposit in the Malartic camp (Helt et al., 2014; De Souza et al., 2015, 2017); and the Sigma-Lamaque orogenic gold system in Val-d'Or (Robert and Brown, 1986a, b; Gaboury et

al., 2001; Olivo et al., 2006). In addition to these deposit types, Chibougamau-type Cu-Au vein deposits, komatiite-hosted Ni-Cu-(PGE) sulfide deposits, silver vein deposits, banded iron ore deposits, as well as molybdenum and lithium deposits have been exploited in the Abitibi greenstone belt.

Since the discovery of the first ore deposits in the Abitibi greenstone belt over 100 years ago (Poulsen, 2017, and references therein), extensive mapping and geoscientific research has been carried out at various scales to constrain the geologic characteristics and genesis of known deposits and their regional stratigraphic, plutonic, structural, and metamorphic context. These studies and resulting peer-reviewed publications, graduate theses, and reports have contributed significantly to the development of ore deposit models, in particular those for VMS deposits (e.g., Franklin et al., 1981, 2005; Galley et al., 2007) and orogenic gold deposits (e.g., Goldfarb et al., 2005; Robert et al., 2005; Dubé and Gosselin, 2007), as well as to models of greenstone belt development and crustal evolution during the Neoproterozoic (e.g., Goodwin, 1977; Dimroth et al., 1983; Ludden et al., 1986; Desrochers et al., 1993; Jackson et al., 1994; Mueller et al., 1996; Ayer et al., 2002; Daigneault et al., 2002; Wyman et al., 2002; Thurston et al., 2008; Bleeker, 2012). With over 500 U-Pb zircon age dates (e.g., Corfu, 1993; Mortensen, 1993a, b; Ayer et al., 2002; David et al., 2006, 2010; McNicoll et al., 2014; Ross et al., 2014), a firm geochronological framework is available for most areas. The Abitibi greenstone belt is arguably the most fertile and best studied Neoproterozoic terrane in the world.

### Overview of the Volume

The present volume is structured into nine chapters, reviewing the geology of major mining camps and deposits of the southern Abitibi. Chapter 1 (Monecke et al., 2017a) provides a review of the geological make-up of the Abitibi greenstone belt. The chapter describes the distribution of rock types and discusses the volcanic and sedimentary stratigraphy of this Neoproterozoic terrane. Based on the work of previous authors, the structural and tectonic evolution of the Abitibi greenstone belt is reconstructed. The chapter also provides an introduction to the main deposit types occurring in the Abitibi greenstone belt and their metallogenic significance.

The Timmins-Porcupine gold camp of northeastern Ontario (Fig. 1) represents the largest Archean orogenic greenstone-hosted gold camp worldwide in terms of total gold production. This uniquely endowed gold camp is associated with the Porcupine-Destor fault zone, a first-order, crustal-scale fault that is also associated with a number of other gold deposits

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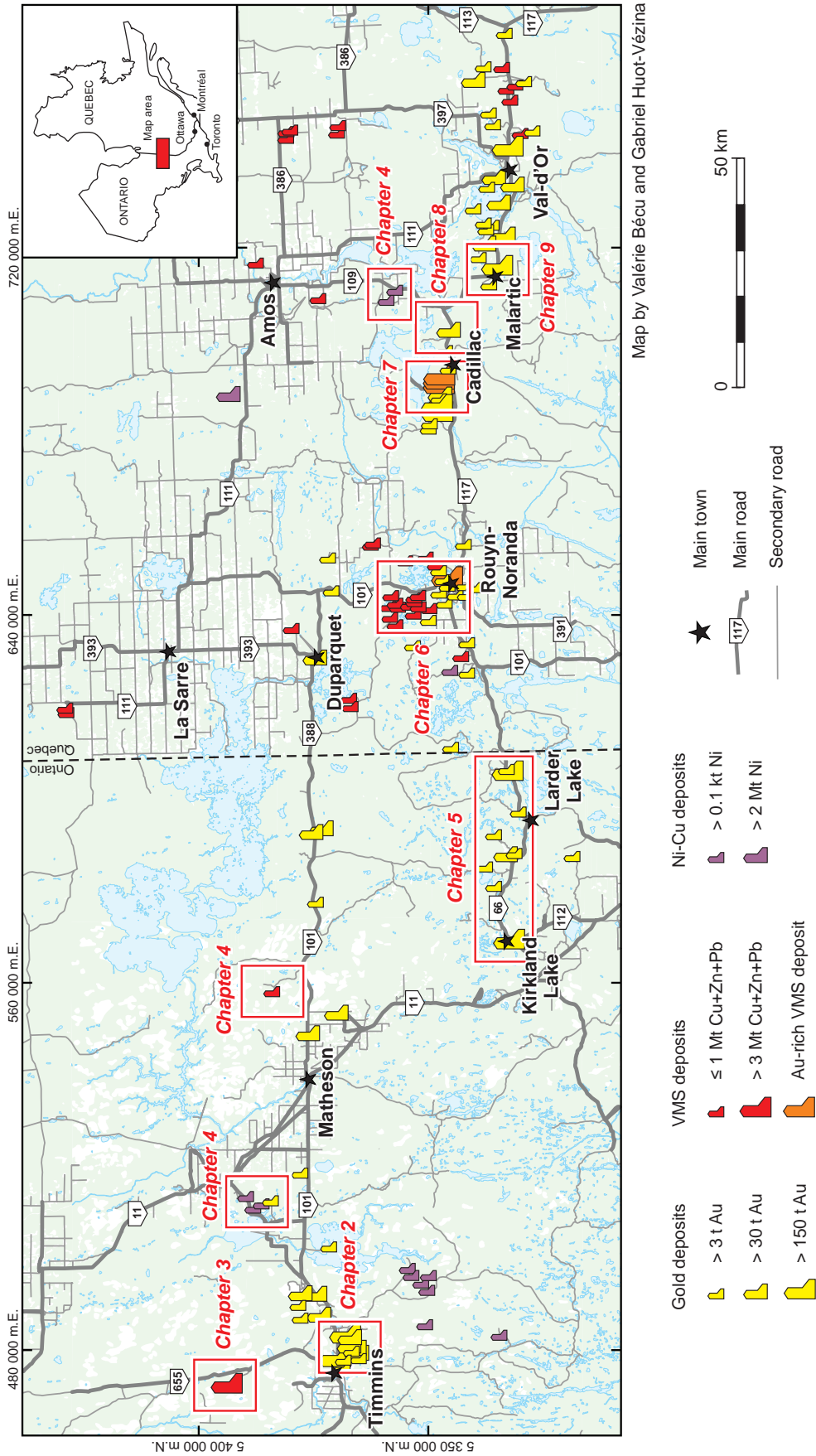


Fig. 1. Topographic map of the area covering the southern Abitibi greenstone belt of Ontario and Quebec. The map shows the location of major mining camps and specific areas discussed in this volume.

and districts further to the east. Chapter 2 (Dubé et al., 2017) presents a review of the stratigraphy and structural setting of this important camp. The characteristics of the two giant deposits in the camp, Hollinger-McIntyre and Dome, are described in detail. The Hollinger-McIntyre deposit represents the largest single concentration of gold in Canada. The deposit yielded approximately 1,000 t of Au from 102 Mt of ore grading on average 9.76 g/t Au. The Dome deposit has been in production since 1910 and to date has produced more than 500 t of Au.

The Kidd Creek deposit north of Timmins (Fig. 1) is the largest known Archean volcanogenic massive sulfide (VMS) deposit currently in production. With total past production, reserves, and resources of 170.9 Mt grading 2.25% Cu, 5.88% Zn, 0.22% Pb, and 77 g/t Ag, Kidd Creek also represents one of the largest and highest grade deposits of its kind. The orebodies of the deposit are exploited from surface to more than 3 km depth, making Kidd Creek the deepest base metal mine in the world. Chapter 3 (Hannington et al., 2017) provides a comprehensive review of the exploration and development history of the Kidd Creek deposit and the geology of the different orebodies. Emphasis is placed on the geology of Mine D, which accounts for most of the current production.

Chapter 4 (Houlé et al., 2017) gives an overview of the komatiite-hosted Ni-Cu-PGE deposits of the southern Abitibi greenstone belt and their geologic setting. Details on two of the best-preserved spinifex-textured sheet flows in world are given, one of which was originally described by Pyke et al. (1973) and today represents the komatiite-flow archetype. The chapter also describes the geological setting and physical volcanology of the Potter deposit that is located close to Pyke Hill in Munro Township east of Matheson (Fig. 1). The Potter deposit is a comparably small volcanogenic massive sulfide deposit hosted within basaltic volcanoclastic rocks intercalated within a komatiitic flow succession. The volcanoclastic rocks hosting the massive sulfides form part of a vent-proximal submarine fire fountain and spatter rampart deposit.

The Larder Lake-Cadillac fault zone, which represents a first-order, crustal-scale fault that shares analogies with the Porcupine-Destor fault zone to the north, is a steeply dipping zone of deformation that has a curvilinear trace and is marked by a strong and protracted deformation history and hydrothermal carbonate alteration. Conflicting kinematic indicators record a complex structural history. Chapter 5 (Poulsen, 2017) describes the geological characteristics of major gold camps located along the Larder Lake-Cadillac fault zone (Fig. 1). It highlights the importance of this long-lived crustal-scale structure in controlling sedimentation during the late stages of the greenstone evolution, its importance as a conduit for orogenic gold fluids, and role in the preservation of the deposits. The chapter also describes key stratigraphic and structural relationships and highlights the importance of alteration vectoring in the exploration for orogenic greenstone-hosted gold deposits.

The Neoproterozoic Noranda camp in Quebec (Fig. 1) is host to some of the most thoroughly studied volcanogenic massive sulfide deposits in the world and has, together with the Miocene Hokuroku district of Japan, shaped the current understanding of the geology and volcanological setting of this deposit type. Chapter 6 (Monecke et al., 2017b) provides a review of the geology and stratigraphy of the lava-flow-dominated host-rock

succession of the Main Camp, which comprises several Cu-Zn ± Au-Ag massive sulfide deposits that formed as mounds on the ancient sea floor. The chapter compares and contrasts the characteristics of the massive sulfide deposits of the Main Camp with the world-class, gold-rich Horne and Quemont deposits of the South Camp, which formed largely by subseafloor replacement and sulfide infiltration of felsic volcanoclastic strata. The chapter reviews volcanological controls on the location of massive sulfide deposit in ancient volcanic terranes and provides exploration guidelines.

Among the over 90 known massive sulfide deposits of the Abitibi greenstone belt, five deposits are characterized by an unusual gold endowment. These include the LaRonde Penna and Bousquet 2-Dumagami deposits of the Doyon-Bousquet-LaRonde mining camp, east of Rouyn-Noranda (Fig. 1). Chapter 7 (Mercier-Langevin et al., 2017a) reviews the history of exploration and development of this mining camp and briefly describes the camp geology. The chapter also describes the geology of the LaRonde Penna deposit. With a total endowment of 71.3 Mt of ore at 3.91 g/t Au, for approximately 280 t Au, this deposit represents one of the largest Au deposits in Canada. The chapter provides important information on the nature of the hydrothermal alteration halo surrounding the LaRonde Penna deposit, which has undergone intense deformation and a metamorphic overprint at upper greenschist to lower amphibolite facies conditions.

Chapter 8 (Mercier-Langevin et al., 2017b) focuses on the geology of the Cadillac mining camp and the Lapa orogenic gold deposit near Cadillac in Quebec (Fig. 1). The Lapa deposit represents an exceptional example of a deformed quartz-carbonate vein- and replacement-type deposit located within a first-order crustal structure, the Larder Lake-Cadillac fault zone (Simard et al., 2013). The chapter highlights the effects of superimposed hydrothermal alteration and metamorphism at upper greenschist to lower amphibolite grade on the dominantly ultramafic host-rock succession. It also describes the various styles of ore present in the Cadillac camp, which are largely hosted within the Larder Lake-Cadillac fault zone.

The final section of this volume, Chapter 9 (De Souza et al., 2017), describes the geology and geological setting of the orogenic and/or intrusion-centered Canadian Malartic deposit in the town of Malartic in Quebec (Fig. 1). Commercial production of the open pit mining operation began in May 2011, with proven and probable Au reserves of 303 t, contained in 343.7 Mt of ore grading an average of 0.97 g/t Au and calculated on a basis of a 0.34 g/t lower cutoff grade. The operation, which currently is the largest Canadian gold producer (~17.3 t Au in 2014), is centered on three past-producing underground mines that exploited the same auriferous hydrothermal system at an average grade of 3.3 to 4.9 g/t (De Souza et al., 2015). The Canadian Malartic mine has not only made history as it represents the first large-scale bulk-tonnage-low-grade gold deposit to be developed in the Abitibi greenstone belt, but also because it is located south of the Larder Lake-Cadillac fault zone within sedimentary rocks previously regarded to be unlikely hosts for major gold deposits. The chapter provides a detailed account of the deposit geology, its structural setting, the style of mineralization, and the characteristics of the hydrothermal alteration associated with this world-class deposit.

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