MAGMATIC Ni-Cu AND PGE DEPOSITS: GEOLOGY, GEOCHEMISTRY, AND GENESIS

Editors
C. Li and E.M. Ripley

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CONTENTS

Preface
Chusi Li and Edward M. Ripley v

Sponsors vii

Biographies ix

Chapter 1: Fundamentals of Magmatic Sulfide Deposits
A. J. Naldrett 1

Chapter 2: The Perseverance and Mount Keith Nickel Deposits
of the Agnew-Wiluna Belt, Yilgarn Craton, Western Australia
Stephen J. Barnes, Marco L. Fiorentini, Paul Duuring, Ben A. Grguric, and Caroline S. Perring 51

Chapter 3: Komatiite-Associated Ni-Cu-(PGE) Deposits,
Abitibi Greenstone Belt, Superior Province, Canada
M. G. Houlé and C. M. Lesher 89

Chapter 4: Mineralogy, Geochemistry, and Genesis of
Komatiite-Associated Ni-Cu-PGE Mineralization in the
Thompson Nickel Belt, Manitoba
D. Layton-Matthews, C. M. Lesher, J. Liwanag, N. Halden,
O. M. Burnham, L. Hulbert, D. C. Peck, and R. R. Keays 123

Chapter 5: The Pechenga Ni-Cu Sulfide Deposits,
Northwestern Russia: A Review with New Constraints
from the Feeder Dikes
Eero J. Hanski, Zhen-Yu Luo, Harry Oduro, and Richard J. Walker 145

Chapter 6: The Giant Jinchuan Ni-Cu-(PGE) Deposit:
Tectonic Setting, Magma Evolution, Ore Genesis,
and Exploration Implications
Chusi Li and Edward M. Ripley 163

Chapter 7: A Review of Conduit-Related Ni-Cu-(PGE)
Sulfide Mineralization at the Voiseys Bay Deposit, Labrador,
and the Eagle Deposit, Northern Michigan
Edward M. Ripley and Chusi Li 181

Chapter 8: Insights into the Geologic Setting and
Origin of Ni-Cu-PGE Sulfide Deposits of the
Norilsk-Talnakh Region, Siberia
Nicholas T. Arndt 199

Chapter 9: The Kabanga Ni Sulfide Deposits, Tanzania:
A Review of Ore-Forming Processes
W. D. Maier, S.-J. Barnes, and E. M. Ripley 217
Chapter 10: Genesis of the PGE-Enriched Merensky Reef and Chromitite Seams of the Bushveld Complex
Anthony Naldrett, Judith Kinnaird, Allan Wilson, Marina Yudovskaya, and Gordon Chunnett 235

Chapter 11: Geology of the Northern Bushveld Complex and the Setting and Genesis of the Platreef Ni-Cu-PGE Deposit
Iain McDonald and David A. Holwell 297

Chapter 12: Platinum-Group Element Mineralization of the Main Sulfide Zone, Great Dyke, Zimbabwe
Thomas Oberthür 329

Chapter 13: The Pd Deposits of the Lac des Iles Complex, Northwestern Ontario
Sarah-Jane Barnes and T. S. Gomwe 351
Preface

As the world continues to develop and advance with new technologies, the need for natural resources increases in concert. Nickel, copper, and platinum-group elements (PGEs) are but a few of the critical materials that are in demand worldwide. We hope that this review of the genesis of several types of magmatic ore deposits will be of benefit to those involved in the research of and exploration for nickel, copper, and PGE resources.

We dedicate this collection of papers to Professor Tony Naldrett, whose pioneering efforts laid the groundwork for so much of our current understanding regarding the genesis of magmatic Ni-Cu-PGE deposits. Tony’s students are involved in virtually every aspect of the Ni and PGE industries. He has served as mentor to many of the authors of the chapters contained in this book, and his willingness and desire to share his vast knowledge of magmatic ore deposits is a mark of the educator and the gentleman that Tony is. He has had a deservedly celebrated career and has been awarded both the Society of Economic Geologists’ Silver Medal and Penrose Gold Medal. Tony continues to be actively involved in both research and consulting; his enthusiasm and zest for life are inspirational to us all.

We wish to thank the authors of the chapters in this volume for their contributions and attention to production schedules. We are particularly grateful to the following reviewers of the chapters—without their willingness to serve this volume would not have been possible: James Brenan, Jim Mungall, Rebecca Sproule, Wouter Bleeker, Steve Barnes, Nick Arndt, Andy Tomkins, Peter Lightfoot, Sarah-Jane Barnes, Gerhard Brügmann, Steve Beresford, Tony Naldrett, Jim Miller, Rais Latypov, Andy Saunders, Dave Evans, Iain McDonald, Wolf Maier, Chris Harris, Judith Kinnaird, Martin Prendergast, Marian Tredoux, Dave Good, and Iain Samson. We are grateful to Rich Goldfarb for his suggestion to produce this book and for his support during the process.

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Nicholas Arndt was awarded a Ph.D. from the University of Toronto in Canada in 1975. Following academic positions in the United States, Canada, and Germany, he was a professor at the Université de Rennes from 1990 to 1998, then moved to the Institut des Sciences de la Terre (ISterre) of the Université Joseph Fourier in Grenoble. Professor Arndt’s research interests include petrology and geochemistry of mafic and ultramafic rocks, magmatic ore deposits, and the geodynamics and surface environment of the early Earth. He is a senior member of the Institut Universitaire de France, president of the Geochemistry-Mineralogy-Petrology-Volcanology division of the European Geosciences Union, and director of a project of scientific drilling in the Barberton belt of South Africa, supported by the International Continental Drilling Program.

Sarah-Jane Barnes is the Canada Research Chair in Magmatic Metallogeny at the Université du Québec à Chicoutimi. She studies mafic and ultramafic rocks and ore deposits associated with them; platinum-group element deposits, nickel-copper sulfide deposits, chromite, and Fe-Ti-V-oxide deposits. She also works on developing analytical techniques for analyzing these rocks. She has been a professor at the Université du Québec since 1986. Publications include more than 100 refereed articles, and 25 graduate students and postdoctoral fellows have completed their studies with her. She is currently directing six graduate students and postdoctoral fellows. Dr. Barnes carried out her postdoctoral work, under the direction of Dr. Ron Boyd at the Geological Survey of Norway, on the platinum potential of various mafic intrusions in Norway. Her Ph.D., supervised by Prof. A. Naldrett, was on the fractionation of platinum-group elements in komatiites of the Abitibi greenstone belt, was obtained from the University of Toronto in 1983. Her M.Sc. degree, based on her work for the Geological Survey of South Africa on serpentinites of Namibia, was supervised by Dr. D. Waters and Dr. R. Miller and was awarded by University of Cape Town in 1979. She obtained her B.Sc. (Hons) degree in geology from the University of Witwatersrand in 1975.

Steve Barnes is currently leader of the Geology and Geochemistry Group in CSIRO’s Division of Earth Science and Resource Engineering. He has a B.Sc. degree from Cambridge University (1977), and M.Sc. (1979) and Ph.D. (1983) degrees from the University of Toronto. He has been with CSIRO since 1985, and has also worked as a postdoctoral fellow at the NASA Johnson Space Center in Houston, and in the mining industry in platinum exploration in Australia and the United States. Dr. Barnes has published more than 60 peer-reviewed journal papers on nickel sulfide deposits, komatiites, spinel mineralogy, and chromium geochemistry, and on the geochemistry of the platinum group elements. He was the recipient of the 2011 Gibb Maitland Award from the Geological Society of Australia for services to Western Australian geology.

O. Marcus Burnham obtained his bachelor’s degree from Cambridge University in 1988. After a brief spell in mineral exploration in Australia, he returned to his studies and, in 1995, obtained a Ph.D. degree from the Open University, studying the Re-Os geochemistry of ultramafic rocks from the Northeastern Pyrenees and Massif Central, France. Between 1996 and 2001, he held two postdoctoral research positions at Laurentian University, Sudbury, where he worked on the geochemistry and petrogenesis of mafic and ultramafic rocks associated with the Raglan and Thompson Ni-Cu-PGE deposits, and he oversaw the geochemical component of the follow-up multidisciplinary study of the geology, stratigraphy, petrogenesis, and metallogenesis of the Thompson nickel belt, Manitoba. From 2001 to 2009, he was a senior scientist at the laboratories of the Ontario Geological Survey in Sudbury, where he oversaw the routine analysis of trace elements and low-level precious metals in geologic and environmental samples in support of the survey’s mapping activities and developed new methods for the analysis of precious metals and hydride-generating elements. Since 2009, Dr. Burnham has been the OGS laboratory’s chief scientist, with responsibility for all technical activities within the laboratories.

Gordon Chunnett is in private practice as a consultant in PGE after a career of 31 years with Anglo American group of companies, 28 years of which were with Anglo Platinum. Working for Anglo American, he had extensive mining and exploration experience and was head of geology before leaving to start his practice.

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Marco Fiorentini is an associate professor at The University of Western Australia (UWA), where he is also deputy director of at the Centre for Exploration Targeting (CET). Since completing his Ph.D. degree in economic geology at UWA in 2005, Marco has successfully led numerous industry-funded research initiatives through federal and state funding agencies and has also liaised and worked efficiently with key national and international academic and governmental institutions. His studies on the genesis of Ni-Cu-PGE systems, evolution of the early Earth’s mantle, lithosphere, and hydrosphere-atmosphere have been published in international journals. In 2005, Marco was awarded the highly prestigious Australian Postdoctoral Industry fellowship.

Tafadzwa Sharon Gomwe works for InnovExplo as a consultant geologist in the Abitibi region. She worked as a geologist on Ni-Cu sulfide deposits at Raglan, Quebec, and Kabanga,
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**Ben Grguric** is currently geoscience manager for Nordisk Nickel Australia, focused on exploration for nickel sulfides and development of sulfide and laterite nickel assets in Western Australia. He has a BSc (Hons) degree from Adelaide University (1992) and a Ph.D. from Cambridge University (1998). He has previously worked for WMC Resources and BHP Billiton in both production and exploration geoscience roles, and he currently specializes in mineralogy of ore deposits, geometallurgy, and economic geology. Outside of Australia, he has worked on gold and base metal exploration projects in Tanzania, Canada, the United States, Wales, and Peru. He is an adjunct fellow at the Centre for Exploration Targeting (UWA) and a Research Associate of the Western Australian Museum.

**Eero J. Hanski** received his MSc. degree in geology and mineralogy in 1980 and a Ph.D. in 1993, both from the University of Oulu, Finland. Ph.D. work was on the genesis of the Pechenga Ni-Cu deposits in NW Russia. After a 20-year career as a geologist at the Geological Survey of Finland, he moved in 2004 to the Department of Geosciences, University of Oulu, where he holds a position of professorship in geochemistry. His has carried out geologic mapping in northern Finland, and his research has focused on ore deposits related to mafic-ultramafic intrusions, highly magnesian volcanic rocks in Archean and Paleoproterozoic greenstone belts and younger flood basalts provinces, and the stratigraphy, geochronology, and evolution of Precambrian successions. Currently, he is involved in the ICDP FAR-DEEP project, studying the geological evolution of the Archean-Paleoproterozoic boundary in the eastern part of the Fennoscandian Shield.

**Norman Halden** is currently dean of the Clayton H. Riddell Faculty of Environment, Earth, and Resources. He has been at the University of Manitoba 27 years. Dr. Halden graduated from Glasgow University with a First Class Honours in geology in 1979 and earned a Ph.D. in 1983 from Glasgow University, while funded as Carnegie Fellow. He has developed and taught a number of courses, principally in geochemistry and petrology and instrumental methods, and has published over 80 refereed journal and book articles. He is heavily involved in the development and use of microbeam analytical techniques for the analysis of minerals. Contributions include using both low and high energy proton-induced X-ray emission, electron microprobe and image analysis, and most recently, laser ablation-inductively coupled-mass spectrometry. He currently operates one of two near infrared femtosecond laser facilities in the world (NIR-fs-LA-ICP-MS). Dr. Halden is also active in nonlinear numerical modeling and fractals of oscillatory zoning patterns in minerals. Most recently, he and his graduate students have been applying these new microanalytical techniques to the analysis of fish otoliths in areas impacted by mine tailings and in the Arctic, where contaminant dispersal has major implications for indigenous subsistence fisheries.

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**Michel G. Houle** obtained B.Sc. and M.Sc. degrees in geology from Laval University (Quebec City) in 1997 and 2000, respectively, and a Ph.D. (earth sciences) from the University of Ottawa in 2008. His studies focused on the Cr-PGE mineralization associated with an ultramafic-mafic layered intrusion (Menarik Igneous Complex) and on the physical volcanology and metallogeny of komatiites in the Abitibi greenstone belt. From 2003 to 2009, as senior geoscientist with the Ontario Geological Survey, he conducted regional bedrock mapping and mineral assessments for Ni-Cu-(PGE) sulfide mineralization in the Abitibi greenstone belt. He is currently a research scientist with the Geological Survey of Canada, since 2009, where his interests are focused on the nature and origin of ultramafic-mafic complexes and/or flows in Canada and especially the understanding of the genesis of nickel-copper, platinum-group elements, and chrome mineralization related to those volcanic and/or igneous rocks.

**Larry J. Hulbert** received his D.Sc. degree from the University of Pretoria, South Africa, in 1983. His doctoral thesis research was on the petrology, geochemistry, and metallogeny of the mafic-ultramafic rocks of the Northern (Potgieterus) Limb of the Bushveld Complex. From 1984 to 2007, he was a research scientist in the Mineral Deposits Division of the Geological Survey of Canada (Ottawa), investigating the metallogeny of mafic-ultramafic rocks. His main interest was in nickel and PGE mineralization associated with both conventional and unconventional geologic environments. He was awarded the Barlow Medal from the Canadian Institute of Mining and Metallurgy in 1993 for his work on nickel and platinum group element mineralization in Devonian black shales—a new deposit type. He is currently a consultant residing in Calgary, Alberta.

**Reid Keays** received a B.Sc. degree in geological engineering from Queen's University in Kingston in 1962. He completed...
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Judith Kinnaird received a BSc (Hons) from the University of London and M.Sc. and Ph.D. degrees from the University of St. Andrews in Scotland. She then taught at University College Cork in Ireland for several years before setting up an independent consultancy company working on various projects in Africa and the UK. She returned to academia in 1999 as a research fellow in the School of Geosciences in the University of the Witwatersrand. In 2002 she joined the Economic Geology Research Unit at Wits, where she is now a professor in economic geology. She is involved in research on metagenesis in southern Africa, including studies on the Bushveld Complex, with emphasis on the Platreef.

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C. Michael Lesher earned a B.Sc. degree in 1974 from Indiana University, an M.A. degree in 1976 from Indiana University, and a Ph.D. degree in 1984 from the University of Western Australia. He is a professor of economic geology—holding the Research Chair in Mineral Exploration—and is director of Mining Initiatives at Laurentian University, Sudbury, Ontario. He has worked on the geology, mineralogy, geochemistry, and genesis of migmatic Ni-Cu-PGE deposits in Brazil and China, and in Western Australia, Manitoba, Ontario, and northern Quebec.

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**ANTHONY NALDRETT** was born in the UK and received his first degree from the University of Cambridge. He emigrated to Canada in 1957 and worked as a mine geologist in the Falconbridge Nickel Mines at Sudbury. After studying for his M.Sc. and Ph.D. degrees at Queen’s University, and working three postdoctoral years with the Geophysical Laboratory, Carnegie Institution of Washington, he joined the University of Toronto in 1967. While there he taught mineral deposits geology and supervised 45 M.Sc., Ph.D., and postdoctoral students, retiring in 1998. His research has covered Ni-Cu-PGE deposits in Russia, Australia, China, Norway, the United States, and Canada, and southern Africa and South America, and has resulted in over 240 refereed papers and authorship/editorship of six books, the most recent of which is *Magmatic Sulfide Deposits—Geology, Geochemistry and Exploration*, published by Springer Verlag in 2004. He now resides in the UK, although he holds an honorary professorship at the University of the Witwatersrand, South Africa.

**THOMAS OBERTHÜR** studied at the University of Cologne in Germany and obtained a diploma in mineralogy with a thesis on Ni and Cr mineralization in the Finero Complex of the Alps in 1978. Subsequently, he was employed in South Africa working on various Witwatersrand gold mines. His Ph.D. thesis on the gold mineralization of the Carbon Leader Reef, Witwatersrand, was completed at the University of Cologne in 1983. Afterward, as an assistant at the Institute of Mineralogy and Geochemistry, University of Cologne, he worked on BIF-hosted gold deposits in southern Africa. In 1985, he joined the Federal Institute for Geosciences and Natural Resources (BGR) in Hannover, Germany. He headed the project “Metallogenesis of Gold in Africa” with his own emphasis on deposits in Ghana and Zimbabwe. Since 1989, he has been head of the Ore Deposit Research section at the BGR, which currently concentrates on mineral deposits of rare metals, mainly in Africa, and the “fingerprinting” of conflict minerals such as “coltan” (columbite-tantalite). Research activities on platinum-group element mineralization centered on the Great Dyke in Zimbabwe and have lately been focused on placers worldwide and the mineralization (primary and oxidized ores) of the Bushveld Complex in South Africa.

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**DAVE PECK** is a graduate of the University of Windsor and received a Ph.D. in geology from Melbourne University in 1991. His research career has focused on the genesis of Ni-Cu-PGE deposits and the geology and geochemistry of mafic and ultramafic intrusions. In the 1990s he worked in government as a mineral deposits geologist in both Ontario and Manitoba, where he led research projects focused on the geology and metallogeny of the East Bull Lake suite of intrusions, the Thompson nickel belt, and the Fox River belt. Dave joined the Falconbridge Limited exploration team in Winnipeg in 2000; he was responsible for project generation for western North America. He was appointed global commodity leader for Anglo American’s Exploration Division in 2003 and held that role until 2009. He recently joined a Vancouver-based private exploration consulting company and remains active in North America Ni-Cu-PGE exploration projects.

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ALLAN WILSON is professor of geology and director of the Economic Geology Research Institute at the University of the Witwatersrand in Johannesburg, South Africa. He has spent the greater part of his academic career carrying out research into the origin of mafic layered intrusions in southern Africa. Of these, the Great Dyke of Zimbabwe and the Bushveld Complex are the most important. Studies of parental magmas and their origin remain a major research thrust. He has also studied the occurrence of komatiites and the evolution and tectonic setting of Archean volcanic rocks in the southern Kaapvaal craton.

MARINA YUDOVSKAYA obtained her diploma in geology of ore deposits from Moscow State University and graduated from the same school with a Ph.D. degree in 1995. While at Moscow University, she carried out research at the Vernadsky Institute in Moscow. Since 1995, she has been employed by the Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry (IGEM), Russian Academy of Science, conducting research on PGE mineralization in fluid-rich environments. Dr. Yudovskaya worked a number of field seasons in remote areas of Eastern Siberia and the Russian Far East to study unconventional PGE occurrences. From 2007 to 2010, she worked as a postdoctoral fellow at the University of the Witwatersrand (South Africa) on PGE-bearing chromitites of the Platreef. Currently, she continues her research at IGEM and holds a position as a visiting researcher at Wits.