METAMORPHOSED AND METAMORPHOGENIC ORE DEPOSITS

CONTENTS

Ores and Metamorphism: Introduction and Historical Perspectives
F. M. Vokes

Regional Metamorphic Remobilization: Upgrading and Formation of Ores Deposits
B. Marshall, F. M. Vokes, and A. C. L. Laroque

Discriminating Between Regional Metamorphic Remobilization and Syntectonic Emplacement in the Genesis of Massive Sulfide Ores
B. Marshall and P. G. Spry

Metamorphic Fluids and Their Relationship to the Formation of Metamorphosed and Metamorphogenic Ore Deposits
I. Cartwright and N. H. S. Oliver

Regional Metamorphism and Ore Formation: Evidence from Stable Isotopes and Other Fluid Tracers
C. A. Heinrich, A. S. Andreux, and M. D. Kull

Fluid Inclusions in Metamorphosed and Synmetamorphic (Including Metamorphogenic) Base and Precious Metal Deposits: Indicators of Ore-Forming Conditions and/or Ore-Modifying Histories?
R. Marshall, A. D. Giles, and S. G. Hagemann

Sulfidation and Oxidation Haloes as Guides in the Exploration for Metamorphosed Massive Sulfide Ores
P. G. Spry

Meta-Exhalites as Exploration Guides to Ores
P. G. Spry, J. M. Peter, and J. F. Slack

Metamorphism of Komatiite-Hosted Nickel Sulfide Deposits
S. J. Barnes and R. F. Hill

Metamorphism of Ni-Cu Sulfides in Mafic-Ultramafic Intrusions: The Svecofennian Saaksjarvi Complex, Southern Finland
F. Mancini and H. Papunen

Tungsten Mineralization and Metamorphic Remobilization in the Felbertal Scheelite Deposit, Central Alps, Austria
B. Höll and R. Eichhorn

Gold Deposits in Amphibolite and Granulite Facies Terranes of the Archean Yilgarn Craton, Western Australia: Evidence and Implications of Synmetamorphic Mineralization
J. Ridley, D. I. Groves, and J. T. Knight

Subduction-Related Diamond Deposits? Constraints, Possibilities, and New Data from Eastern Australia
W. L. Griffin, S. Y. O'Reilly, and R. M. Davies

Editors
F. M. Vokes, B. Marshall, and P. G. Spry
PREFACE

Many of the world's largest deposits of base and precious metal ores are located in metamorphic terranes. Deformation, metamorphism, and the accompanying fluid-flow regimes have tremendous capacity to both form and modify such deposits. Nevertheless, ideas regarding the relationships of specific deposits to metamorphic and deformational processes affecting their host rocks have varied over the years; once again, these relationships and associated concepts are being scrutinized and intensely questioned. It is, therefore, an appropriate time to review knowledge and beliefs pertaining to several aspects of these ores. Not only is such a review of academic interest (important and exciting as this may be), but also, a better understanding of the timing of mineralization relative to deformation, metamorphism, and regional and local fluid flow is essential to more effective exploration for, and exploitation of, these types of ore.

It has not been practical to cover all aspects of ores in metamorphic terranes in this volume. The individual papers are authoritative, being based on the original research of well-recognized experts in their respective fields, and in many cases they present new data. While a degree of balance has been sought, it is recognized that some important ore types and related processes lack consideration. This is undoubtedly the case for some nonsulfidic ore types, and with one exception, most nonmetallic mineral deposits in metamorphic terranes. Furthermore, contact metamorphic ores have received no attention because their ore-generating events are predominantly magmatic-hydrothermal (rather than regional metamorphic), and in any case, such ores would warrant a whole volume to do them justice.

The distinction between metamorphosed, metamorphic, and metamorphogenic mineral deposits is addressed, and the terms defined, in an introductory chapter by Vokes that also reviews the historical development of ideas on ores in metamorphic terranes. Aspects of this terminology have also been developed in several other papers (e.g., Marshall, Vokes, and Larocque; Marshall and Spry; and Heinrich, Andrew, and Knill). It is apparent that some see metamorphogenic as a subset of syntectonic-synmetamorphic, whereas others apply it to any deposit formed during metamorphism, irrespective of the nature of the transporting fluid.

The currently most contentious aspect of ores in metamorphic terranes is the distinction between metamorphosed-remobilized preexisting deposits and those thought to have been formed by metamorphic-deformational events. Marshall, Vokes, and Larocque review the possible roles of metamorphic remobilization in the upgrading of existing deposits and the formation of new ones, while Marshall and Spry thoroughly review the problem of metamorphosed versus metamorphogenic ores, present guidelines to aid in discriminating between these ores, and apply their guidelines to a range of major ore deposits.

The generation of metamorphic fluids, the magnitude and complexity of fluid-flow regimes, and the all-important role of these fluids in modifying existing ores and forming new ones are covered by Cartwright and Oliver. These authors are followed by Heinrich, Andrew, and Knill, who use mass-balance and metal-solubility arguments to constrain metamorphogenesis, before discussing the contributions of stable isotopes and other fluid tracers in studies of metamorphic ore formation. Marshall, Giles, and Hagemann close the section on fluids by focusing on the application of fluid-inclusion studies to determine the genesis and fluid history of metamorphosed-metamorphogenic deposits.

Exploring for and assessing ore deposits in metamorphic terranes are facilitated by the recognition of a range of lithologic-mineralogic guides that result from metamorphism of preexisting ores and their associated host rocks. These ore indicators have district-wide and more local significance for exploration. Spry reviews exploration guides provided by the mineralogical changes produced by sulfidation and oxidation processes in the vicinity of sulfide ores; Spry, Peter, and Slack evaluate the use of characteristic horizons of metamorphosed exhalites as guides to the presence of possible economic, exhalative ores.

The remaining five papers are devoted to aspects of a selected number of ore types found in metamorphic terranes. Two papers deal with the metamorphism of Ni-(Cu) ores of magmatic affiliation found in Precambrian rocks: Barnes and Hill review the metamorphism of komatiitic volcanic-hosted Ni ores in Archean terranes, and Mancini and Papunen consider Ni-Cu ores associated with Proterozoic mafic-ultramafic intrusions in the Fennoscandian shield. Höll and Eichhorn present a reassessment of the metamorphic development of the Felbertal scheelite deposits in the central Alps of Austria. Evidence for the metamorphic (synmetamorphic) origin of important Au deposits in high-grade metamorphic terranes in the Archean Yilgarn craton of Australia is discussed by Ridley, Groves, and Knight. The final paper, by Griffin, O’Reilly, and Davies, deals with the possibility of subduction-related diamond deposits, this being the only nonmetallic ore type considered in the volume.

Throughout the volume, the spelling “terrane” has been used, regardless of whether it relates to, for example, a region of high-grade metamorphism or a geotectonic entity. Where the use is not obvious from the context, clarification is provided by way of a footnote.

Reviews in Economic Geology volumes have in the past, with one exception, been produced in connection with a Society of Economic Geologists Short Course devoted to the theme of each volume. This is not the case with the present volume, principally because of the difficulty in bringing together such a widely distributed set of authors. We nevertheless hope that the volume will provide an up-to-date and relatively comprehensive coverage of the relationships between metamorphism-deformation and fluid flow, and the formation and modification of metallic mineral deposits.

Frank M. Vokes
Brian Marshall
Paul G. Spry
BIographies

ANITA S. ANDREW received her B.Sc. (Hons.) and Ph.D. degrees from the University of Sydney, with thesis study addressing the scale of fluid movement during metamorphism. After holding a postdoctoral position at Virginia Polytechnic Institute and State University, she joined Commonwealth Scientific and Industrial Research Organisation (CSIRO) as a Research Scientist in 1982. There she applied isotopic techniques to problems of ore genesis and mineral exploration. In 1993, she moved to the newly formed Division of Petroleum Resources at CSIRO, researching problems related to petroleum exploration; in particular, she worked on developing new isotopic techniques for inter- and intrabasinal correlations. Currently, Andrew leads the CSIRO Petroleum Exploration and Appraisal research program. She is an author of more than 90 scientific and technical publications.

STEVEN BARNES is a research scientist at the CSIRO Division of Exploration and Mining in Perth, Western Australia. He completed his B.A. degree in Mineralogy and Petrology at Cambridge University in 1977. Afterward, he earned M.Sc. (1979) and Ph.D. (1983) degrees from the University of Toronto, with master’s work focusing on the Katinq nickel sulfide deposit, and doctoral work on platinum reef mineralization in the Stillwater Complex. He then spent two years as a postdoctoral fellow in experimental petrology at the NASA-Johnson Space Center in Houston. Barnes has been a member of the CSIRO Magmatic Ore Deposits team since 1985, with an intervening spell as platinum exploration geologist for Hunter Resources Ltd., from 1988 to 1990. His research interests include genesis of magmatic sulfide ore deposits, petrogenesis of komatites, petrogenesis and tectonic setting of Archean greenstone terranes, geochemistry of chromium and chromeite, geochemistry and metallogenesis of platinum group elements, and fluid-rock interactions in ultramafic rocks.

IAN CARTWRIGHT is currently Senior Lecturer in crustal fluid flow at the Department of Earth Sciences, Monash University, Australia. He received his B.S. degree from the University College of Wales, U.K., in 1982, and his Ph.D. from the same institution in 1986. Prior to arriving at Monash in 1990, he was a research fellow at the University of Wisconsin, Madison. His research interests encompass fluid flow in a range of geologic environments, including metamorphic, ore-forming, and hydrogeologic systems. Most of his research involves the application of petrology, stable isotopes, and other geochemical tracers to constrain conditions of fluid-rock interaction, pathways of fluid flow, fluid volumes, and the timing and duration of fluid-flow events.

RONDI M. DAVIES is now completing a Ph.D. study on the diamonds of eastern Australia, which has included detailed studies of morphology, internal structure, inclusion chemistry, N aggregation and isotopic composition of diamonds from a number of localities. She also has carried out similar studies of diamonds from Myanmar, Thailand, and the Slave craton of Canada.

ROLAND EICHHORN is a graduate of Ludwig-Maximilians University of Munich, Germany, where he obtained a Diplom degree in geology in 1991 and a Ph.D. degree in 1995. He was guest scientist at several renowned isotope laboratories, such as the Max-Planck Institut for Chemistry in Mainz (Germany), the Institute de Physique de Globe in Paris (France) and the SHRIMP II laboratory of Curtin University (Western Australia). Research interests have focused on isotopic and geochronologic aspects of ore-forming processes of tungsten deposits, especially in areas of multistage metamorphosed complexes. He is now employed by the Geological Survey of Bavaria (Germany), currently working on a statewide geotopo mapping, evaluation, and protection program and as a specialist for geologic GIS map publications via internet and on CD-ROMs.

ALAN D. GILES is the Senior Technical Officer in the Department of Applied Geology, University of Technology, Sydney. He received the degree of B.App.Sc. (Hons.) from the New South Wales Institute of Technology (NSWIT), in 1983. Following a short period in metalliferous exploration, he joined the University of Technology (formerly the NSWIT), where he has particularly concentrated on technology pertinent to deformed and metamorphosed ore deposits. His research publications and nearly completed Ph.D. involve fluid-inclusion studies on massive-sulfide ore deposits in metamorphic terranes. However, he also has undertaken consulting work for industry on inclusion systems in topaz, sapphire, opal, petroleum, epithermal gold, and porphyry style deposits.

WILLIAM L. GRIFFIN is a Chief Research Scientist of the CSIRO and an adjunct professor at Macquarie University. He has spent most of his research career studying high-pressure metamorphic rocks in both the crust and mantle, using petrology, major and trace element geochemistry, and isotopic techniques. Since 1986, a large part of this effort has been directed toward all aspects of the distribution of diamond in the lithosphere, including both diamond genesis and diamond exploration.

DAVID GROVES is Professor of Economic Geology and Director of the Centre for Strategic Mineral Deposits within the Department of Geology and Geophysics, University of Western Australia. He received his Ph.D. degree from the University of Tasmania, with study focused on cassiterite-sulfide deposits, under the supervision of Mike Solomon, and has since researched tin, nickel, zinc-copper, PGE, and gold deposits. Currently, he leads an integrated research team that is studying the genesis of ore deposits, with special emphasis on orogenic lode gold deposits, and assisting in the development of exploration models based on deposit and genetic models. His recent
BIOGRAPHIES (continued)

research has been on the global characteristics of lode gold deposits and the generation of world-class deposits within the deposit style.

STEFFEN G. HAGEMANN received a B.Sc. degree from the Johann-Wolfgang Goethe University in Frankfurt, Germany, and an M.Sc. degree from the University of Wisconsin-Milwaukee. Master’s degree work involved courses and research at the UW-Madison, San Diego State University, and Universidade de Brasilia, Brazil. He obtained his Ph.D. in economic geology from the University of Western Australia in 1993, working in the Key Centre for Strategic Mineral Deposits (headed by David I. Groves) within the Department of Geology and Geophysics. Subsequently, Hagemann held a National Science Foundation-sponsored postdoctoral position at the UW-Madison, with brief stints at the University of Toronto and the University of Saskatchewan, before accepting a position as Assistant Professor at the Technical University of Munich. Currently he is a Senior Lecturer at the Centre for Strategic Mineral Deposits at the University of Western Australia. Research interests are the structural-hydrothermal architecture and processes that form orogenic gold, intrusion-hosted (oxidized) gold, volcanic-hosted massive sulfides, high-grade banded-iron formation and emerald deposits, and the relationship between transcrustal tectonic zones and metallic ore deposits.

CHRISTOPH HEINRICH studied geology and petrology at ETH (Zürich), completing a Ph.D. degree on high-pressure metamorphic petrology in the central Alps. He then emigrated to Australia to study economic geology at the CSIRO in Sydney and worked as a research scientist at the Australian Geological Survey in Canberra until 1994, when he was appointed Professor of Mineral Resources at the Swiss Federal Institute of Technology and the University of Zürich. His current research concentrates on the chemical, thermal, and mechanical aspects of fluid transport in the Earth’s interior, to quantify the processes of hydrothermal ore formation. His ore fluids group in Zürich combines field studies with experimental and numeric model simulations, with a particular interest in metamorphic and magmatic-hydrothermal systems. Heinrich is a board member of the Swiss Geotechnical Commission and the Society for Geology Applied to Ore Deposits (SGA). He serves on the SEG Distinguished Lecturer Commission and on the editorial board of Economic Geology.

ROBIN E. T. HILL graduated from the University of Queensland, Australia, in 1964, with the degree of Bachelor of Applied Science. He earned the degree of Ph.D. from Queen’s University, Kingston, in 1968 (experimental geochemistry). Since then, he has completed postdoctoral research, at Pennsylvania State University, on the role of carbon dioxide in mantle-derived silicate melts, was senior nickel research geologist with a mineral exploration company in Canada, and since 1973 has been a research scientist with CSIRO, Perth, Western Australia, working on the genesis of mafic sulfide deposits associated with mafic and ultramafic rocks.

RUDOLF HÖLL is Professor of Geology at the Institute for General and Applied Geology at the University of Munich. He studied economics and geology and received a Diplom-Volkswirt degree in economics and a Diplom-Geologe degree in geology at the University of Munich. He earned his doctoral degree in geology for research of stibnite, cinnabar, and tungsten deposits in Turkey. Projects he has worked on include economic geology, economics in geology, stratigraphy, regional geology, mapping, and supervising of mapping for the state of Bavaria. He discovered the Felbertal scheelite deposit and numerous other scheelite occurrences in central Europe.

JOSEPH T. KNIGHT earned his B.Sc. (Hons.) degree in geology from Nottingham University, and an M.Sc. degree from the Camborne School of Mines. His Ph.D. work, at the University of Western Australia, was on the geology of the Coolgardie Goldfield. Currently, Knight is working for BHP Minerals Discovery as Principal Geologist based in Brisbane, Australia.

MATTHIAS KNILL studied economic geology and petrology at ETH Zürich, Switzerland, and then completed a Ph.D. degree on the Lengenbach deposit in the Swiss Alps at the same University. This was the first modern geochemical study of a small but famous deposit that had previously been mainly the focus of mineralogical interest. Previously a research scientist and information officer associated with the Swiss nuclear waste management program, NAGRA, he is now in charge of corporate communications at the Swiss Industrial Company Holding Ltd.

ADRIENNE LAROCQUE is an Assistant Professor in the Department of Geological Sciences at the University of Manitoba. She received her Ph.D. from Queen’s University, Ontario, in 1993. Her thesis on the topic of metamorphic remobilization in a gold-rich Archean VMS deposit was supervised by C. J. Hodgson and Louis Cabri. Adrienne made extensive use of SIMS (secondary ion mass spectrometry) for her doctoral work, and since then has applied SIMS in other areas of geochemical research. Before taking up her position in Manitoba, Adrienne was a Director’s Postdoctoral Fellow at Los Alamos National Laboratory. There she worked with Don Hickmott on ion implantation for standardization of SIMS analyses and studied metal residence and mobility in volcanic systems with Fraser Goff. Larocque continues to use various microbeam techniques to study base and precious metal mobility and accumulation in magmatic and hydrothermal systems.

FRANCO MANCINI received an M.Sc. degree in Earth Sciences in 1989 from the University of Rome, Italy, and a Ph.D. degree in Geology and Mineralogy from the Uni-
BIOGRAPHIES (continued)

University of Turku, Finland, in 1996. He has been involved in various studies of regionally metamorphosed Ni-Cu ore deposits, including the effects of hydrothermal alteration and the remobilization of sulfides. His research interests also include crystal chemistry as a tool to characterize the effects of metamorphism on ore deposits. He is presently a postdoctoral research assistant/scientist at the transmission electron microscope laboratory of the Geological Survey of Japan, where the research centers on the microstructures in a number of minerals from regionally metamorphosed Mn-Fe ores.

BRIAN MARSHALL became adjunct Professor in Geology at the University of Technology, Sydney, Australia, in 1997. He received his B.Sc. (Hons.) degree in Geology (1959) from Imperial College, London University, and his Ph.D. (1966) from Bristol University, U.K. He has variously worked for the Tasmanian Geological Survey (1965–1966), for large and small companies in full-time base and precious metal exploration (1970–1974), and in a range of consulting activities (over some 30 years). Marshall’s intermittent academic career commenced at Melbourne University (1966–1967), continued at the University of New South Wales (1967–1970), and recommenced in 1974 when he joined the New South Wales Institute of Technology (now, University of Technology) as a senior lecturer. Although for many years a structural geologist, he applied the principles of this discipline in the sphere of deformed and metamorphosed base and precious metal deposits. Over the past 15 years, this initial interest in the imposed geometry and mechanical response of deposits has evolved into a more general consideration of fluid-related processes of remobilization of sulfides versus their host rocks, and mobilization and emplacement-site geology in the context of syntectonic deposits.

NICHOLAS OLIVER (B.Sc., Hons., University of Queensland, 1981; Ph.D., Monash University, 1988) has a wealth of field and analytical experience in appraisal of alteration systems in metamorphic rocks and ore deposits, mostly in Australia. These include studies of regional albition, veining and related Cu-Au mineralization in the Mount Isa block, greenstone-hosted Au in the Yilgarn and Pilbara cratons, Cu in the Kambanoo district of South Australia, and iron in the Hamersley province of Western Australia. He has published papers on mechanical constraints on fluid flow in these systems as well as a range of more geochemical-isotopic-petrologic papers. He was appointed as the W.C. Lacy Professor of Economic Geology in the School of Earth Sciences at James Cook University in 1997.

SUZANNE Y. O’REILLY is Professor of Geology at Macquarie University and Director of the ARC National Key Centre for Geochemical Exploration and Metallogeny of Continents (GEMOC), which aims to understand the development of the Earth’s outer 300 km. Her research interests include basalt geochemistry, xenolith petrology and geochemistry, and the composition, evolution, and thermal state of the continental lithosphere.

HEIKKI PAPUNEN received his M.Sc. degree from Helsinki University (1960) and Ph.D. from University of Turku, Finland (1971). He joined the Department of Geology, University of Turku, where he is now Professor and head of the department. He has been involved in ore geology, mineralogy, and exploration-related research, particularly in the fields of ore deposits associated with mafic and ultramafic rocks. He has served on the editorial boards of Economic Geology and Lithos, as leader of the International Geological Correlation Programme (IGCP) Project 161 (Ore deposits related to mafic and ultramafic rocks), and as the chairman of a commission of International Association on the Genesis of Ore Deposits (IAGOD). He has also acted as a chairman of organization committees for several symposia and field courses, including the 5th International Platinum (1989) and 4th Biennial SGA Meeting (1997). He was elected President of SGA for 1999–2000.

JAN M. PETER is an economic geologist for the Mineral Resources Division of the Geological Survey of Canada (GSC) in Ottawa. He received his B.Sc. (Hons.) degree in Geology from the University of British Columbia in 1983 and his M.Sc. and Ph.D. degrees from the University of Toronto in 1986 and 1991, respectively. His graduate training focused on sea-floor hydrothermal mineralization and ancient analogues. Prior to joining the staff of the GSC in 1994, he was an Natural Sciences and Engineering Research Council (NSERC) postdoctoral fellow at the GSC. Peter’s research has dealt with the setting and depositional processes of modern sea-floor hydrothermal mineralization at the sedimented Guaymas basin and Middle Valley sites, the genesis of the Windy Craggy deposit, and genesis of hydrothermal sediments (iron formations) related to massive sulfide deposits of the Bathurst lead-zinc mining camp, in New Brunswick, and their application to the exploration for concealed mineralization.

JOHN RIDLEY received his Ph.D. degree (1982) from Edinburgh University, where his work focused on metamorphic and structural geology. After completing a postdoctoral fellowship in Switzerland and a short contract with the Norwegian Geological Survey, he taught at the University of Zimbabwe, the University of Western Australia, and ETH, Zürich. In Western Australia, his major research interest was the gold deposits of the Archean Yilgarn craton, which are hosted in high-grade metamorphic rocks, with emphasis on the tectonic environment of these deposits and their structural, geochemical, and petrological characteristics. He was recently appointed as lecturer in economic geology at Macquarie University, Sydney.

PAUL G. SPRY is Professor and Chairman of the Department of Geological and Atmospheric Sciences at Iowa State University in Ames, Iowa. He completed B.Sc. (Hons.), and
BIOGRAPHIES (continued)

M.Sc. degrees at the University of Adelaide in 1976 and 1978, respectively, and a Ph.D. degree at the University of Toronto in 1984. Paul has conducted research on various metamorphosed massive sulfide deposits in South Africa, Canada, Norway, Australia, and the United States, with a focus on the origin of meta-exhalites, sulfidation halos, and mineralogical anomalies. Other research interests include the petrologic, mineralogic, stable isotope, and fluid inclusion characteristics of epithermal and mesothermal gold-telluride deposits. Paul served on the editorial board of Economic Geology from 1993 to 1998.

JOHN F. SLACK received a B.S. degree in geology from West Virginia University in 1970, an M.S. in geology from Miami (Ohio) University in 1972, and a Ph.D. in economic geology from Stanford University in 1976. Since 1974 he has been employed by the U.S. Geological Survey, first in Menlo Park, California, and since 1976 in Reston, Virginia. His Ph.D. research was on multistage vein ores in southwestern Colorado. Early work for the U.S. Geological Survey involved research on Appalachian massive sulfide deposits, concurrently with mineral-resource assessments of Wilderness areas and the Glens Falls (NY-VT-NH) CUSMAP quadrangle. A significant part of his career has been devoted to the study of tourmaline in hydrothermal ore deposits. Recently he directed a major USGS project on the Bald Mountain massive sulfide deposit in northern Maine. His current research is focused on volcanogenic and sedex-type mineral deposits in Alaska.

FRANK M. VOLES, Emeritus Professor of Ore Geology at the Norwegian University of Science and Technology, Trondheim, received his undergraduate and master's training in mining engineering and geology at Leeds University, England, from 1945 to 1950. After working for several years on the Zambian copper belt, he investigated massive cupriferous sulfide deposits in northern Norway. The resulting publication was the emphasis of his doctoral work at the University of Oslo (Ph.D., 1957). After documenting molybdenum deposits in Canada and massive sulfides on Cyprus, interspersed with teaching and research at Oslo, he moved in 1966 to Trondheim, where he further developed his interests in massive sulfide deposits, especially their metamorphism and deformation. From 1974 to 1984, Vokes was leader of IGCP Project no. 60 on Caledonian strata-bound sulfides and later, chairman of the IAGOD working group on ores and metamorphism. He is a past President of SGA and former Regional Vice-President of SEG.
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Metamorphic Remobilization and Syntectonic
Emplacement in the Genesis of Massive Sulfide Ores
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to the Formation of Metamorphosed and
Metamorphogenic Ore Deposits
I. Cartwright and N. H. S. Oliver

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Precious Metal Deposits: Indicators of Ore-Forming
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Sulfide Ores
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