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TECHNIQUES IN HYDROTHERMAL ORE DEPOSITS GEOLOGY

CONTENTS

Editors
J.P. Richards and P.B. Larson

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Techniques in Hydrothermal Ore Deposits Geology

J.P. Richards and P.B. Larson, Editors

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PREFACE

One of the best things about being an "economic geologist" is the fact that the term almost defies definition. The only requirements are that one should be a geologist (preferably a good one!), and have an interest in the economic applications of that science to the minerals industry. Consequently, we can be mineralogists, geochemists, geophysicists, exploration geologists, mine geologists, paleontologists, geochronologists, geomorphologists, sedimentologists, structural geologists—the list could go on, but we are all unified by that interest in mineral deposits. To be fully conversant with this broad science, however, it is not sufficient for us to operate exclusively within our own specialization: the isotope geochemist cannot afford to ignore the paragenetic information available from petrography and mineralogy; the fluid inclusionist can eke far more information out of microthermometric or analytical data by fitting them to thermodynamic models. This requirement can be both a blessing and a curse, however. On the one hand, it encourages us to be geologists in the broadest sense, with a full appreciation of the mechanics of our planet and how they affect ore formation. On the other hand, we cannot possibly hope to be experts in all of these fields in the space of one lifetime.

The solution, therefore, must be interdisciplinary collaboration, combined with more effective communication, so that, although we may not become experts, we at least have a working knowledge of the full range of disciplines at our disposal.

The impetus for this volume arises from the editors' own feelings of inadequacy when confronted with certain aspects of our science, and also our experiences in trying to communicate this subject to our students and colleagues. We all know that the easiest lectures to give are those based on our own specializations and research; however, these are not necessarily the easiest lectures to give *well*, particularly if the target audience is non-expert in our field. Likewise in our writings: as professionals we are expected to write succinct papers focusing solely on our new results and interpretations, with no room for background explanations, and lots of unspoken pressure to impress our peers. However, such writings are opaque to a broader readership, and do little to help expose our science to other scientists, let alone the general public.

In an attempt to address these problems, at least within the broader circle of economic geologists, we have sought contributions from user-friendly expert authors on specific aspects of geochemical data collection and modeling as applied to hydrothermal ore deposits. Our intention was not to compete with Hubert Barnes' milestone volumes (Geochemistry of Hydrothermal Ore Deposits). Rather, we wished to insert a stepping stone in front of these volumes, to enable a wider audience to access and appreciate their wealth of information. Thus, our target audience is very broad, and includes everyone from final-year undergraduate students to industry geologists and academics with specializations in other fields.

Each chapter is self-contained, but the reader may find that he or she needs to read an earlier chapter to brush up on some background theory. However, a specialist's knowledge is not required at any point. The chapters aim to provide the basic principles of the topic, and then to explore the practical applications of the techniques in the study of ore deposits. The volume is thus both a reference book and a handbook, with practical information ranging from the construction and interpretation of commonly used geochemical diagrams, to the size and type of samples required for geochronological analyses.

The volume editors would like to thank all of the authors for their efforts in taming their science, the reviewers for providing an excellent test of our successes and failures and thereby significantly improving the volume, and Mike Lesher, who as former Series Editor provided the lift and encouragement required to turn an idea into a reality.

Finally, we remember and thank Werner Giggenbach, who was preparing a manuscript for this volume at the time of his death in November 1997.

Jeremy P. Richards
Peter B. Larson

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PHILIP E. BROWN received a B.A. degree in geology from Carleton College in 1974, and M.S. (1976) and Ph.D. (1980) degrees from the University of Michigan, where he specialized in economic geology, in general, and the Pine Creek, California, tungsten skarn, in particular. After a one-year post-doctoral appointment at the U.S. Geological Survey in Reston, Virginia, he accepted a position at the University of Wisconsin-Madison in 1981 and has been there since. His research interests center around fluids in the Earth's crust and Archean gold deposits, metamorphic and metamorphosed orebodies, fluid inclusions, skarns and the Proterozoic massive sulfide deposits of Wisconsin. A six-month sabbatical in Western Australia in 1991 began a collaborative research program with the then 'Key Centre' at the University of Western Australia — this continues today, with Dr. Brown holding an Adjunct Faculty position in Perth. Recently his interests include exploring the role that computer visualization technology can play in geological education.

ANDREW R. CAMPBELL received a B.S. in geology from Indiana University in 1977 and a Ph.D. in geology from Harvard University in 1983. Since then, he has been teaching at New Mexico Tech in Socorro, N.M., where he is currently Professor of Geology. He has served the Society as an Associate Editor for Economic Geology and as Editor of the Newsletter. Dr. Campbell's research interests include fluid inclusion and stable isotope studies of ore deposits as well as application of stable isotope geochemistry to other topics. He pioneered the use of infrared microscopy to study fluid inclusions in opaque ore minerals.

PHILIP A. CANDELA received his Ph.D. from Harvard University in 1982. Since then he has been at the University of Maryland, where he is now Professor of Geology and co-director of the Laboratory for Mineral Deposits Research. He has also been a Visiting Fellow at the Department of Geology at the Australian National University, and is a Fellow of the Geological Society of America, the Mineralogical Society of America, and the Society of Economic Geologists. His research involves: the study of element partitioning in melt-vapor-brine-crystal systems, with special reference to the behavior of ore metals, including Au and Cu; field and theoretical studies of the mass transfer dynamics in devolatilizing magma chambers; textural studies in igneous rocks; experimental studies of wall-rock alteration in ore deposits and geothermal systems; experimental studies of sulfides in magmatic-hydrothermal environments; and ore deposits and tectonics of the Appalachian Orogen. At the University of Maryland, he teaches graduate level classes in thermodynamics, advanced economic geology, and igneous petrology; he is also the director the undergraduate senior thesis program in Geology.

JEFFREY W. HEDENQUIST is a geologist with the Geological Survey of Japan, in the Department of Mineral and Fuel Resources. He began graduate studies on an Archean gold deposit, and at the same time worked for the U.S. Geological Survey on coastal sedimentology, granites, and lunar petrology. He completed his graduate study on gold mineralization of an active geothermal system while at the University of Auckland, New Zealand, on a Fulbright fellowship. He joined Chemistry Division, DSIR New Zealand, in 1982, and while based at Wairakei was involved in geothermal energy development and epithermal gold exploration in the western Pacific. He moved to Japan in 1989 to expand his epithermal research to the porphyry environment, and also to study metals in volcanic discharges.

PETER B. LARSON is Chair of the Geology Department at Washington State University, where he has served on the faculty since earning his Ph.D. from Caltech in 1983. His primary research interests are water-rock interaction in hydrothermal environments, and igneous petrogenesis, to which he applies stable isotope analyses. He was born and raised in the midst of the Michigan native copper district, and received his B.Sc. in geology from Michigan Tech in 1973.

STEPHEN R. NOBLE received a B.Sc. (geological engineering) in 1980 and an M.Sc. (geology) in 1992 from the University of Toronto. During this time he was involved in research associated with porphyry Mo-W and related skarn deposits in the Yukon and Northwest Territories. Noble received a Ph.D. in geochemistry in 1989 from the University of Toronto, where his work involved investigating the U-Pb geochronology, and geochemical and Sm-Nd isotope characteristics of Archean granite-greenstone terranes in northwest Ontario. Since then he has been a research geologist, responsible for establishing the U-Pb geochronology laboratory at the Natural Environment Research Council Isotope Geosciences Laboratory, now part of the British Geological Survey. Current research focuses on high precision U-Pb geochronology in the Himalayas and Scottish Highlands, Lu-Hf isotope systematics, and the development of ICP-MS and laser ablation geochronology techniques.

PHILIP M. PICCOLI is a Research Scientist at the Laboratory for Mineral Deposits Research, University of Maryland. His interests include field studies of silicic volcanic and plutonic rocks; the use of accessory phases in the determination of magmatic, hydrothermal, and ore-forming

processes; chemical modeling of ore-forming processes; microanalysis of minerals; and experimental simulation of magmatic-ore systems involving Au, Cu, etc. Piccoli employs a multidimensional approach involving field observations, modeling, and experimentation to solve problems in ore-genesis.

ANDY H. RANKIN received his B.Sc. in chemistry and his Ph.D. in geology from the University of Leicester, UK. Prior to his current appointment in 1991 as Professor of Applied Geology and Head of the School of Geological Sciences at Kingston University, UK, he held various faculty positions in the Royal School of Mines, Imperial College, London, over the period 1974-1991, first as lecturer in Mining Geology, then as Reader in Applied Mineralogy and Head of the Fluid Process Research Group. His main research interests are in hydrothermal and magmatic processes in ore genesis and in the development and application of fluid inclusion methods to a range of problems in the Geosciences. He has published widely on these topics and has organized and participated in a number of successful short courses in fluid inclusion in the UK, USA, and South America. Until recently he was president of the Mineralogical Society of Great Britain and Ireland.

MARK H. REED received B.A. degrees in chemistry and geology from Carleton College in 1971, followed by an M.S. in 1974 and a Ph.D. in 1977 from University of California, Berkeley. His Ph.D. research focused on the origin of massive sulfide mineralization in seafloor settings, for which studies he developed original forms of two computer programs for multicomponent, multiphase chemical equilibrium calculations. Reed worked as a staff geologist and project geologist for the Anaconda Company in Butte, Montana, from 1977 through 1979. During that period, he mapped underground exploration crosscuts and underground and surface drill core, focusing on describing the hydrothermal alteration and mineralization in the large porphyry copper-molybdenum system at Butte. From 1980 to the present, Reed has been on the faculty of the Department of Geological Sciences, University of Oregon, specializing in studies of ore deposits and in modeling geochemical processes in geothermal systems, hydrothermal ore systems, volcanic gas fumaroles, and sediment diagenesis.

JEREMY P. RICHARDS received his B.A. (1983) in geology from the University of Cambridge, UK, his M.Sc. (1986) in economic geology from the University of Toronto, Canada, and a Ph.D. (1990) in economic geology from the Australian National University. After a two-year post-doctoral position at the University of Saskatchewan, Canada, he joined the faculty at the University of Leicester, UK, in 1992. He has since recently moved back to Canada, where he is currently an Associate Professor in economic geology at the University of Alberta. His research focuses on the genesis of hydrothermal ore deposits, and previous and ongoing investigations include studies of the Keweenawan basalt-hosted copper deposits in Michigan and Ontario, sediment-hosted stratiform copper deposits in the Democratic Republic of Congo (formerly Zaère), porphyry copper deposits in Chile and Ecuador, and alkalic intrusive-related gold deposits in Papua New Guinea.

IAIN M. SAMSON received a B.Sc. in applied geology in 1979 and Ph.D. in economic geology in 1983 from the University of Strathclyde. From 1983 until 1986 he was a Research Associate with the Mineral Exploration Research Institute (IREM-MERI) at McGill University. In 1986 he joined the faculty of the University of Windsor where he is currently an Associate Professor in the Department of Earth Sciences. His research interests are in the genesis of hydrothermal mineral deposits and the geochemistry of hydrothermal systems. He has published papers on a variety of types of mineral deposits, including SEDEX Pb-Zn, granite-related W, Mo, Sn, and Cu deposits and Precambrian Au-Ag deposits. His current research is focused on the genesis of REE and other rare-element deposits, particularly those associated with alkalic igneous rocks, and on the microbeam analysis of fluid inclusions.

TOM J. SHEPHERD received his B.Sc. and Ph.D. in geology from the University of Durham, UK. Following a two-year period as an exploration geologist working from Cominco's European office he joined the Geochemical Division of the British Geological Survey (Institute of Geological Sciences), where his initial brief was to develop methods for fluid inclusion analysis. He has maintained his current interest in the development and application of fluid inclusion methods, especially in relation to mineral and petroleum exploration and ore genesis, since joining the survey in 1971. He currently holds a Cabinet Office Individual Merit Position at the BGS, Nottingham, UK, which permits him to further develop his research interests in these fields. He has published widely in these and related fields, including a textbook on fluid inclusions, coauthored with Andy Rankin and Dave Alderton.

SCOTT A. WOOD received a B.A. degree in both geology and chemistry from Hamilton College in Clinton, New York, in May 1980. He then went on to obtain an M.A. (1982) and a Ph.D. (1985) in Geochemistry from Princeton University under the supervision of Dr. David Crerar. From January 1985 until December 1991 he was first an Assistant and then Associate Professor at McGill University in Montreal. Since then he has been at the University of Idaho where he is currently Professor of Geochemistry. Starting with his Ph.D., he has been involved in experimental and theoretical research into the solubility of ore minerals and the speciation of ore metals in hydrothermal solutions, and has had particular interests in the platinum-group elements, the rare earth elements, tungsten, gold, beryllium, and zirconium. He has also been involved in field-based geochemical studies of the origin of ore deposits, including hydrothermal REE, epithermal Ag-Au and porphyry Cu mineralization. In recent years he has devoted a significant proportion of his research effort to environmental geochemistry. Since 1989, Dr. Wood has been an Associate Editor of the journal Geochimica et Cosmochimica Acta.

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