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APPLICATIONS OF MICROANALYTICAL TECHNIQUES TO UNDERSTANDING MINERALIZING PROCESSES

CONTENTS

Editors

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Applications of Microanalytical Techniques to Understanding Mineralizing Processes

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PREFACE

Recent technological advances have made possible the sampling and geochemical analysis of increasingly smaller masses of crystalline material. The application of these new microanalytical techniques to minerals and rocks opens up a level of detailed geological information that was heretofore masked by more primitive bulk sampling techniques. We can now conduct in situ sampling and analysis of individual growth bands within crystals, and of tiny solid and fluid inclusions trapped within crystal lattices, in many cases determining not only their composition but also their time of formation.

Because of these advances and their potential for assisting scientists in attaining a better understanding of mineralizing processes, the Society of Economic Geologists held a short course in October 1996 to highlight the diverse applications of these techniques. Attended by more than 85 people at The Nature Place Resort in Florissant, Colorado, the course brought together scientists from Australia, Europe, North America, and South Africa. It was the largest short course ever held by the SEG in conjunction with a GSA annual meeting.

This volume, like the course, is divided into four topical sections: Geochronology and Radiogenic Isotopes, Stable Isotopes, Elemental Analysis, and Fluid Inclusions. Each chapter represents an overview of the technique utilized and its practical applications to understanding mineral- and rock-forming processes. It is clear that some techniques are further along than others in terms of specific applications, but all of them are promising and have high potential for making important contributions to geologic knowledge. We hope that the volume makes members of the geologic community more aware of the microanalytical techniques and the potential applications to their own specific geologic research problems.

The conveners and editors are indebted to all of the authors for their timely efforts in the production of the short course and the resulting volume.

Michael A. McKibben
W.C. (Pat) Shanks, III
W. Ian Ridley

BIOGRAPHIES

LOUIS J. CABRI is principal scientist at Canada Centre for Mineral and Energy Technology, Ottawa, and has performed research in mineralogy applied to ores and characterization of various industrial wastes over the past 34 years. He has been involved in the development of new microanalytical techniques for surface analysis and trace-element analyses of minerals, especially for precious metals. Cabri has also been a consultant on trace-element analytical techniques and mineralogical balances, for base metals, gold, silver, and platinum-group element ores, to industry, governments, and universities, on an international level. His work has been published in 145 peer-reviewed journals, and he is the winner of SEG Lindgren award in1965, the Mineralogical Association of Canada's Past-Presidents' Medal, and the Leonard G. Berry Medal. Cabri is a fellow of the Royal Society of Canada, Academy of Sciences.

J. L. (IAIN) CAMPBELL is a professor of physics at the University of Guelph in Canada. His Ph.D. was earned in nuclear physics in 1967 at the University of Glasgow, which awarded him the D.Sc. in 1982; he received an honorary D. Tech. degree from the University of Lund in 1997. His research deals with inner-shell atomic processes and application of X-ray spectroscopy to chemical analysis. Campbell is one of the principal developers of the PIXE technique, focusing mainly on trace element analysis and imaging in the geochemical and mineralogical context, in which he has collaborated with a wide range of Earth scientists. He is co-author of the text *PIXE: A novel technique for elemental analysis and Particle-Induced X-ray Emission Spectrometry,* as well as over 150 journal publications.

GERRY CZAMANSKE was an undergraduate at the University of Chicago and received his Ph.D. from Stanford University in 1960. After two years of post-doctoral study and three years as an Assistant Professor at the University of Washington, he was recruited by the U.S. Geological Survey and hired full-time in 1965 as a Geologist GS-12, attaining grade GS-15 in 1978. During his 31-year career with the USGS, he carried out a broad range of field and laboratory research activities. Major areas of active research included study of the processes of magmatic evolution and ore formation trough use of comprehensive chemical analyses and application of the electron microprobe to characterize silicate and sulfide mineral phases; utilization of new techniques to better analyze geologic materials; and, in later years, studies of the ore deposits, flood volcanism, and geologic framework of the Noril'sk-Talnakh region of north-central Siberia.

ALEX N. HALLIDAY studied geology and then geophysics at the University of Newcastle-upon-Tyne, U.K. In 1976 he moved to the Scottish Universities Research and Reactor Centre where he was a post-doctoral fellow, then a lecturer. A professor at the University of Michigan from 1986 to 1998, Halliday was recently appointed as a professor at ETH Zurich, Switzerland. For many years Halliday worked in three distinct areas of isotope and trace element geochemistry—studies of silicic magmas, crustal fluid flow, and the mantle. In particular, he has developed several new approaches to the isotopic dating of diagenetic assemblages and hydrothermal mineralization. Most of his recent work involves the new technique of multiple collector inductively coupled plasma mass spectrometry and its application to the origin and early history of the solar system, studies of crustal fluid flow, and paleoceanography.

K. V. HODGES is a professor of geology and Dean for Undergraduate Curriculum at the Massachusetts Institute of Technology. He received his B.Sc. from the University of North Carolina in 1978 and his Ph.D. from the Massachusetts Institute
of Technology in 1982. Much of his research focuses on the relationships among thermal, deformational, and erosional processes during the evolution of mountain ranges. In the field of $^{40}Ar/^{39}Ar$ thermochronology, recent projects include exploring the time-temperature histories of metamorphic complexes in the Himalaya, East Greenland Caledonides, Irish Caledonides, and the southwestern United States. He regularly collaborates with industrial and academic scientists conducting research at the MIT Ar isotope laboratory on studies ranging from establishing the provenance of sedimentary basin fill, to high-resolution dating of volcanic rocks, to in situ dating of deformational fabrics in low-grade metamorphic rocks.

JIM J. IRWIN obtained his B.Sc. in geology from McGill University, Montreal, in 1980, and Ph.D. in geology from the University of California, Berkeley, in 1986. Between 1986 and 1992 he was a research fellow in the Department of Physics at Berkeley, developing microstandards and studying fluid inclusions associated with a wide range of ore deposits and geologic settings using the laser microprobe noble gas mass spectrometric approach. He worked as a project scientist at Scripps Institution of Oceanography, San Diego, from 1992 to 1994. Since 1994 he has resided in Vancouver, British Columbia, active as a consultant to and director of companies in the resource exploration industry.

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 in 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 gone on to apply SIMS in other areas of geochemical research. Before taking up her position in Manitoba, Larocque 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.

F. E. LICHTE received his B.A. degree from Wartburg College, Waverly, Iowa in 1963, and his Ph.D. from Colorado State University, Ft. Collins, Colorado in 1973. He has been involved in the development of instrumental methods of analysis for 35 years. During his career, he has worked for Sinclair Oil,

Atlantic Richfield, the Environmental Trace Substances Center at the University of Missouri, and for the U.S. Geological Survey for the past 20 years. During his tenure with the USGS, he has been a key researcher in the development of the inductively coupled plasma for the elemental analysis of geologic materials. He has worked with ICP mass spectrometric technique development for the past 15 years, and laser ablation ICP-MS for the past 8 years. He retired in December of 1997 and is currently enjoying his hobbies.

JOHN MAVROGENES holds a Ph.D. in geology from VPI&S, and is currently a Lecturer/Research Fellow in Economic Geology at the Australian National University in Canberra Australia. His work concentrates on experimental studies of ore-forming processes, particularly the analysis of dissolved metals in synthetic fluid inclusions. He works on a wide range of ore deposits, including porphyry Cu deposits, and experimental studies of sulfide saturation in komatiites and melting relations in high-metamorphic grade sulfide deposits.

MICHAEL A. MCKIBBEN received his Ph.D. in geochemistry and mineralogy from the Pennsylvania State University in 1984. Since then he has been on the faculty at the University of California at Riverside, where he teaches and conducts research in the areas of economic geology and geochemistry. He has published several papers and book chapters on ore-forming processes in the Salton Sea geothermal system, and on using ion microprobe sulfur isotope data to decipher ore-forming processes in sedimentary, geothermal and volcanic systems. McKibben has served on the editorial boards of Economic Geology and Geochimica et Cosmochimica Acta, and as a Councillor for the Society of Economic Geologists. He also serves as a consultant to mining and geothermal companies exploring for metalliferous brines.

JILL DILL PASTERIS received her undergraduate degree in geology from Bryn Mawr College in 1974. She then spent a year studying ore microscopy at the University of Heidelberg, Germany, working under Dr. Paul Ramdohr. In 1980, she completed a Ph.D. at Yale University, doing thesis research on the opaque oxide phases of a kimberlite pipe in South Africa. In the same year, she joined the faculty of the Earth and Planetary Sciences department at Washington University in St. Louis, where she has remained. Her work involves various aspects of fluid-rock interactions as they pertain to igneous and metamorphic rocks and, especially, to the formation of igneous ore deposits. She and her students have focused on Cu-Fe-Ni-sulfide and Fe-Ti-oxide deposits. With colleague Brigitte Wopenka, Pasteris set up a laser Raman microprobe laboratory in 1983, which they have used for the study of natural fluid inclusions, synthetic fluid inclusions and gas mixtures, microsamples of solid phases, and specific types of aqueous fluids.

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; experimental simulation of magmatic-ore systems (involving Au, Cu, etc.). He employs a multidimensional approach involving field observations, modeling, and experimentation, to solve problems in ore-genesis.

LEE R. RICIPUTI received a B.S. degree in geology from Carleton College in 1985 and M.S. and Ph.D. degrees in Geology from the University of Wisconsin-Madison in 1987 and 1991. After spending two years in a joint research appointment at Oak Ridge National Laboratory (ORNL) and the University of Tennessee-Knoxville, he joined the research staff at ORNL full-time, and is currently a staff scientist in the Chemical and Analytical Sciences Division. His current research focuses on application of secondary-ion mass spectrometry to investigate microscale stable isotope and trace element distributions in order to better understand mass transport processes in geologic settings using both natural and experimental samples. Riciputi is also interested in improving analytical capabilities through a better understanding of the fundamental sputtering/ionization processes occurring in secondary-ion mass spectrometry.

W. IAN RIDLEY received a B.Sc. in geology in 1964 and a Ph.D. in geology in 1968 from the University of London, following volcanologic studies in the Canary Islands. From 1970 to 1973 he was involved with astronaut training and studies of lunar rocks at the Johnson Space Center, Houston. Until 1980, Ridley was Associate Professor of Geology at Columbia University, with research interests in volcanology, lunar petrology, and analytical techniques. He has organized and supervised several analytical laboratories for XRF, XRD, SEM, EMP, and lately for laser ablation ICP-MS. He is currently a research geologist with the U.S. Geological Survey, Denver.

DOUGLAS RUMBLE is a geologist with the Geophysical Laboratory, Carnegie Institution of Washington. He was educated at Columbia College (B.A., 1964) and Harvard University (Ph.D., 1969). His research interests include designing and building new laser systems for analyzing isotopes in minerals and field, petrologic, geochemical, and tectonic analysis of coesite- and diamond-bearing ultra-high pressure metamorphic rocks in China and Kazakhstan.

W. C. (PAT) SHANKS, III, received his Ph.D. from the University of Southern California, where he worked with Jim Bischoff on the geochemistry of the Red Sea brine pools and associated metalliferous deposits. Shanks was involved in geochemical studies of the initial massive sulfide discovery at 21N on the East Pacific Rise, and has spent many years studying seafloor hydrothermal systems. In 1988, Shanks and Bob Criss of the U.S. Geological Survey organized an international workshop on the use of lasers and ion probes in stable isotopic analyses. The proceedings of this workshop were published as U.S. Geological Survey Bulletin 1890, and set the stage for many of the discoveries presented in this volume.

ZACHARY SHARP received his bachelor's degree from the University of California at Berkeley, and a Ph.D. from the University of Michigan. Sharp joined the Carnegie Institution of Washington as a post-doctoral fellow, working closely with Doug Rumble. He spent eight years as a research scientist

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JOHN W. VALLEY received his A.B. from Dartmouth College, and his M.S. and Ph.D. in geology from the University of Michigan in 1980. From 1989 to 1990, he was a Fulbright Scholar at the University of Edinburgh. He is presently professor and Chair of the Department of Geology and Geophysics, University of Wisconsin-Madison. His research in metamorphic petrology and geochemistry has included many studies of the role of fluids during metamorphism and hydrothermal reaction. Valley co-edited the MSA Reviews in Mineralogy volume, Stable Isotopes in High Temperature Processes and wrote a chapter on metamorphism. Since 1987, he has been active in development and applications of new techniques for microanalysis of stable isotopes by laser probe and by ion microprobe. He is author of over 100 scientific articles and 200 abstracts, has served as Associate Editor for GSA Bulletin, Journal of Geophysical Research, and American Journal of Science. Valley has also served on numerous committees and as a member of Council for MSA. He has been on review panels for NSF, DOE, GSA, and the Geochemical Society, and is a fellow of MSA and GSA.

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GRAHAM C. WILSON holds a part-time post as a research associate of the IsoTrace Laboratory at the University of Toronto. He received a B.A. (Hons.) degree in geology and mineralogy from the University of Oxford and a Ph.D. from Cambridge. His wide-ranging interests in economic geology and petrology are addressed in part through the application of in situ electron, proton, and ion-beam analytical methods, including accelerator mass spectrometry. These methods are used to complement more "traditional" work in field geology, petrography, and geochemistry. Ongoing research interests include the mineralogy of precious- and base-metals deposits and the development of computer databases. Since 1985, Wilson has operated a consulting firm, Turnstone Geological Services Ltd, producing approximately 300 geological and mineralogical reports

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