

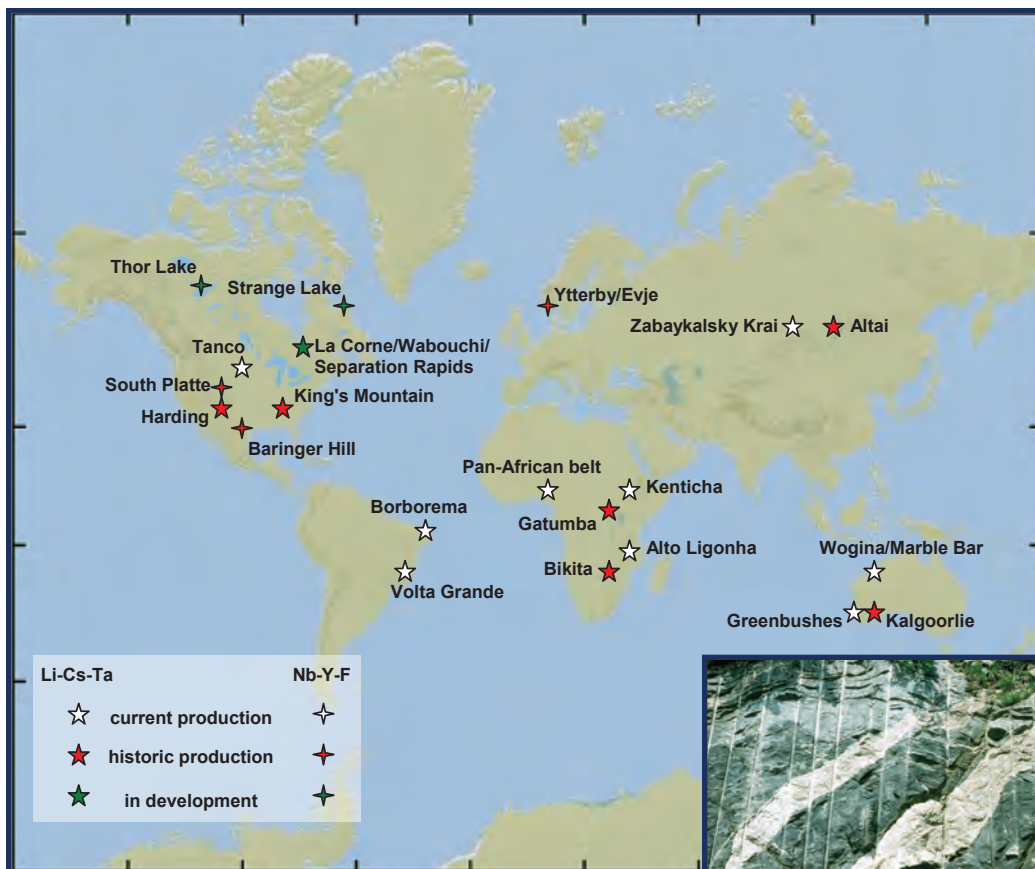


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REVIEWS IN ECONOMIC GEOLOGY

Volume 18

RARE EARTH AND CRITICAL ELEMENTS IN ORE DEPOSITS



Editors

P.L. Verplanck and M.W. Hitzman

SOCIETY OF ECONOMIC GEOLOGISTS, INC.



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RARE EARTH AND CRITICAL ELEMENTS IN ORE DEPOSITS

Volume Editors

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On the cover: The global distribution of some historically important, current, and potential future sources of rare elements from pegmatites. *Inset:* A set of common, unzoned pegmatite dikes that cut amphibolite and gneiss, Haddam, Connecticut, USA. Both images from the paper by D. London in this volume.

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Dwight Bradley received his bachelor's degree in 1978 from the University of Vermont and a Ph.D. in 1984 from the State University of New York at Albany. He recently retired after a career as a research geologist with the U.S. Geological Survey in Alaska. He spent 26 summers in the field in Alaska, and has also worked in the Canadian Arctic, New England, Maritime Canada, and Mauritania. Bradley's field experience spans a range of tectonic settings, including collisional orogens, magmatic arcs, accretionary complexes, passive margins, foreland basins, and pull-apart basins. His research interests include earth history, plate tectonic interpretations of orogenic belts, geochronology, and tectonic aspects of ore-deposit genesis. He is currently studying the geochronology and tectonics of lithium-cesium-tantalum (LCT) pegmatites, both to elucidate the origins of these remarkable ore deposits, and, possibly, to develop LCT pegmatites as a tool in tectonic interpretations of orogenic belts.

George N. Breit earned a B.S. degree in geological sciences from Pennsylvania State University (1977) and M.S. (1980) and Ph.D. (1986) degrees in geochemistry from the Colorado School of Mines. He worked for the U.S. Geological Survey from 1978 to 2013, holding positions of increasing responsibility, from field assistant to project chief. George's initial work with the USGS focused on the geochemistry of formation of sandstone-hosted uranium deposits. He was also the vanadium resource specialist for 20 years. Later assignments included a range of investigations of low-temperature water-rock interaction, including rock alteration on active volcanoes, mobility of trace elements in the vadose zone in desert environments, natural trace element degradation of groundwater quality (south and southeast Asia and the United States), and controls on trace element distribution in sedimentary systems from deposition to weathering. He currently is conducting investigations of ore and environmental geochemical systems as a consultant.

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Jaroslav Dostal received a B.Sc. degree in geology from Charles University, Prague, where he subsequently worked as a lecturer at the Department of Mineral Deposits. After graduating from McMaster University, in Hamilton, Ontario, with a Ph.D. degree, he pursued postdoctoral studies at the Dalhousie University. He then became a professor of geology at Saint Mary's University, where he is currently professor emeritus. He is also an honorary professor at the Mongolian University of Science and Technology in Ulaanbaatar and an adjunct professor at the Department of Earth Sciences of Dalhousie University. At Saint Mary's, Dr. Dostal established a regional geochemical center and applied its analytical facilities to a variety of questions in earth sciences. His research has been recognized by scientific awards, including the Distinguished Scientist Award of the Atlantic Geoscience Society (Gesner Medal) and the Career Achievement Award of the Volcanology and Igneous Petrology Division of the Geological Association of Canada. Currently, he is a director of Ucore Rare Metals Ltd. His research interests are in geochemistry, mineral resources, igneous petrology, and geodynamics.

Edward A. Du Bray is a research geologist working as part of the U.S. Geological Survey Mineral Resources Program in Denver, Colorado, having obtained an M.S. degree in geology from Stanford University in 1977. He combines geologic mapping with petrologic and geochemical studies of igneous rocks throughout the western United States to understand the processes that govern the evolution of magmatic systems and their associated ore deposits. Recent studies of the 45–3 Ma ancestral Cascades arc along western North America characterize protracted continental arc magmatism and define the time-space-compositional variations that have controlled the evolution of subduction-related magmatism in this area. Currently, he is engaged in a study of voluminous ~1.4 Ga magmatism in the United States and evaluating relationships between the petrogenesis of these rocks and associated REE deposits.

Poul Emsbo is a research geologist with the U.S. Geological Survey in Denver, Colorado. He received his B.S. degree from Union College (1986) and earned his M.Sc. (1993) and Ph.D. (1999) degrees in economic geology-geochemistry from the Colorado School of Mines. Since arriving at the USGS in 1989, Poul has investigated the genesis of Carlin Au, MVT, sedex, sedimentary copper deposits, and high salinity brines. For the past several years he has explored the interplay between ocean chemistry, sea-floor hydrothermal deposits, marine sediment-hosted deposits, and metalliferous black shales.

BIOGRAPHIES (continued)

Richard J. Goldfarb was a research geologist with the Minerals Program of the U.S. Geological Survey for 36 years. He has conducted studies on the distribution of gold deposits throughout the world, compiling comprehensive global descriptions of their spatial-temporal setting and evaluating their controlling factors. His research has been focused on global metallogeny, geology of ore deposits in the North American Cordillera with emphasis on orogenic gold, distribution and geology of lode gold deposits in China and elsewhere in Asia, and fluid inclusion and stable isotope applications to the understanding of ore genesis. Rich has senior-authored and co-authored more than 200 papers on mineral resources, with many recognized as the authoritative research on orogenic gold and on aspects of regional metallogeny. He has served as President of the Society of Economic Geologists, is a past Silver Medalist and lecturer of the Society, has served as chief editor of *Mineralium Deposita*, is currently on the editorial boards of *Economic Geology* and *Gondwana Research*, and was one of the co-editors of the *Economic Geology 100th Anniversary Volume*. He received his B.S. degree in geology from Bucknell University (1975), an M.S. degree in hydrology from MacKay School of Mines (1981), and Ph.D. degree in geology from the University of Colorado (1989). Currently, he is an adjunct professor at Colorado School of Mines and China University of Geosciences Beijing.

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Hannah Grant received an MGeol (International) degree in geological sciences from the University of Leeds in the United Kingdom, followed by an M.Sc. in geological sciences from Queen's University, Canada, where she investigated a silver-rich VMS deposit in the Canadian Arctic. After two years working as a geochemist for Newmont Mining Corporation in the United States, in 2014 she moved to GEOMAR, Helmholtz Centre for Ocean Research Kiel in Germany to pursue Ph.D. research into modern submarine hydrothermal systems. Her research is currently focused on the mineralogical and geochemical characterization of sea-floor massive sulfide deposits—specifically, the rare and critical metal content of these systems.

Mark Hannington is the Goldcorp Chair in Economic Geology at the University of Ottawa and Helmholtz Professor at GEOMAR-Helmholtz Center for Ocean Research Kiel, Germany. Prior to joining the University of Ottawa in 2005 and GEOMAR in 2014, he was a senior research scientist at the Geological Survey of Canada for 15 years. His research combines the study of ancient ore deposits and

active hydrothermal systems on the modern sea floor. He and his students have worked extensively on Precambrian volcanogenic massive sulfide deposits and also have participated on more than 35 research cruises to active volcanic systems in the oceans. From 2001 to 2008, he served as editor of *Economic Geology*. He is the recipient of the Duncan Derry Medal of the Geological Association of Canada and the Silver Medal of the Society of Economic Geologists. He was made a Fellow of the Royal Society of Canada in 2012.

Murray W. Hitzman has B.A. degrees in geology and anthropology from Dartmouth College (1976), an M.S. degree in geology from University of Washington (1978), and a Ph.D. degree in geology from Stanford University (1983). He worked in the petroleum and minerals industries from 1976 to 1993, primarily doing mineral exploration worldwide, and he was largely responsible for Chevron Corporation's Lisheen Zn-Pb-Ag deposit discovery in Ireland (1990). Dr. Hitzman served in Washington, D.C., as a policy analyst in both the U.S. Senate for Senator Joseph Lieberman (1993–1994) and the White House Office of Science and Technology Policy (1994–1996). In 1996 he was named the Fogarty Professor in Economic Geology at the Colorado School of Mines and he served as head of the Department of Geology and Geological Engineering from 2002 to 2007. While his research in economic geology with graduate students has been conducted around the world, for the past 17 years he has focused his attention on the Central African Copperbelt. He served as the President of the Society of Economic Geologists in 2006. He is a member of the National Research Council (of the U.S. National Academy of Sciences) Committee on Geological and Geotechnical Engineering. He has previously served on the boards of a number of junior mineral exploration and mining companies.

Albert H. Hofstra is a research geologist at the U.S. Geological Survey, where he has worked to advance understanding of Carlin-type gold deposits in the Great Basin and Carlin-like gold deposits around the world (e.g., an upcoming *Reviews in Economic Geology* volume). His publications on these deposits address their age and relation to magmatism and tectonics, lithogeochemistry, alteration, mineral paragenesis and chemistry, P-T conditions, composition and source of ore fluids, processes of ore formation, and fluid flow modeling. His career path began with exploration for sediment-hosted gold deposits and a fluid inclusion study of the Jerritt Canyon district that developed into a comprehensive dissertation at the University of Colorado-Boulder. As leader of the Denver Inclusion Analysis Laboratory (<http://minerals.cr.usgs.gov/dial/>), he has recently begun to focus on melt and fluid inclusion studies of a myriad deposit types (IOA-REE, IOCG-Co, REE pegmatite, porphyry Mo, volcanogenic Be, Li brine, mesothermal Sb, epithermal Au-Ag, replacement and vein alunite).

Zengqian Hou has been a research geologist in the Chinese Academy of Geological Sciences (CAGS) for the past 25 years, since obtaining his M.Sc. (1985) and Ph.D. (1988)

BIOGRAPHIES (continued)

degrees in economic geology from the China University of Geosciences (Beijing), China. He conducted postdoctoral research on modern sea-floor hydrothermal processes and mineralization while visiting the Geological Survey of Japan (1993–1994). Subsequently, he has become involved with a major government-funded mineral resources program in southwestern China (1995–2015). Hou's major interests include metallic metallogeny and mineral systems of orogenic belts, with emphasis on temporal-spatial distribution, geology, and geochemistry of porphyry, VMS, MVT, and carbonatite-associated REE deposits. He has supervised students studying a broad range of industry- and government-funded projects, including work in the Chinese Mainland and work on modern sea-floor hydrothermal environments. He is currently the Director of the Institute of Geology, CAGS (2005–2015) and was the Deputy-Director of the Institute of Mineral Resources, CAGS (2000–2005). He was in charge of a State Basic Research Plan of China (973 project) "Metallogenesis of the Tibetan Collisional Orogen (2003–2008)." He is currently a chief scientist for a new 973 project, entitled "Continental Assembly and Related Metallogenesis in Tibet (2011–2015)" and co-chair of an IGCP project on "Metallogenesis of Collisional Orogens in the East Tethyside Domain (2011–2015)."

Scott Hynek earned a B.A. degree in geology from Carleton College in 2001. He earned an M.S. (2003) and Ph.D. (2011) degrees in geology from the University of Utah. During this time he worked on both geochronology and paleo-environmental reconstruction from late Miocene–present in South America. As a postdoctoral scholar at the University of Utah, he applied mineralogy and geochemistry to characterize elemental fluxes associated with dust transport in the western United States. Later, as a postdoctoral scholar at Pennsylvania State University, he worked on chemical weathering and solute transport in the Luquillo Mountains of Puerto Rico. Currently, he is a research assistant at Penn State University where he manages the Metal Isotope Laboratory. The study of Li brine genesis is a primary research interest, and it draws upon his research experience in mineralogy, geochronology, chemical weathering, and elemental and isotopic geochemistry.

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epithermal and porphyry deposits in the western United States. This work includes detailed studies of several Tertiary epithermal gold-silver deposits, hydrothermal systems associated with Quaternary volcanism in the Cascades and Yellowstone, and Cenozoic magmatism and associated hydrothermal systems in the Great Basin, including volcanic fields of the ancestral Cascade arc, the northern Nevada rift, and several large ignimbrite calderas.

Karen Kelley has been a research geologist with the U.S. Geological Survey in Denver for the past 33 years. She earned a B.S. degree at University of Colorado in Boulder, an M.S. degree in geology from the University of Reno (Mackay School of Mines), and a Ph.D. in economic geology from the Colorado School of Mines in 1996. Her dissertation focused on the geochronology and geochemistry of the Cripple Creek Au-Te deposit in Colorado. Other research interests include the genesis of sediment-hosted Pb-Zn massive sulfide deposits and exploration geochemistry, particularly techniques applied to buried deposits such as the giant Pebble porphyry Cu-Au-Mo deposit in Alaska. Karen has been a member of the editorial board for *Economic Geology* and served as guest editor of two special issues. She is currently on the editorial boards of *Mineralium Deposita* and *GEEA (Geochemistry: Exploration, Environment, Analysis)*. Karen was the 2015 SEG Thayer Lindsley Visiting Lecturer, and she has served as Councilor and chaired committees for the Society of Economic Geologists and Society for Geology Applied to Mineral Deposits.

Keith A. Labay is a physical scientist at the U.S. Geological Survey in Anchorage, where he performs geographic information system (GIS) work in the Alaska Science Center Geology Office. He received a B.S. degree in natural science from the University of Alaska Anchorage (1999). He has created spatial databases to accompany numerous new geologic maps and other publications within Alaska. Recently he has been applying spatial analysis techniques to a collaborative project, looking at mineral potential throughout Alaska.

David Leach received his B.S. degree at the Virginia Polytechnic Institute and his M.S. and Ph.D. (1973) degrees from the University of Missouri. He worked for the Lawrence Livermore National Laboratory for 5 years as a project scientist on uranium geochemistry, hydrothermal alteration experiments on porphyry ores, and exploration geochemistry. He joined the U.S. Geological Survey in 1978, where he worked for more than 34 years. He is currently an affiliated professor at the Colorado School of Mines and consultant to the minerals industry. He has authored or co-authored more than 200 papers on the geology and geochemistry of ore deposits and is a recognized expert on sediment-hosted base metal deposits. His career focused on hydrothermal mineral-rock interactions with special interest in Mississippi Valley-type and CD (SEDEX) Pb-Zn deposits, ore formation in metamorphic environments, global metallogeny, and deposit targeting using global geodynamics and secular distribution of ore deposits.

BIOGRAPHIES (continued)

David London is a Stubbman-Drace Presidential Professor and Norman R. Gelpman Professor of Geology, and director of the University's electron microprobe laboratory at the University of Oklahoma. He obtained his B.A. degree in geology (1975) at Wesleyan University, Connecticut, and M.S. (1979) and Ph.D. (1981) degrees from Arizona State University. London joined the faculty at OU following a postdoctoral research fellowship (1981–1982, sponsored by Hatten S. Yoder, Jr.) at the Geophysical Laboratory of the Carnegie Institution of Washington. London's research pertains to the chemical evolution of silicic magmas, but with an emphasis on and application to the origins and internal evolution of granitic pegmatites. This work relies heavily on experimental studies and on the chemical attributes of common and rare minerals in granites and pegmatites. He is the author of the book *Pegmatites*, which was published in 2008 as Canadian Mineralogist Special Publication 10, and he is the chair and managing editor of the "Pegmatite Interest Group" of the Mineralogical Society of America. The mineral londonite, isometric $\text{CsAl}_4\text{Be}_4[\text{B}_{11}\text{Be}]_2\text{O}_{28}$ (Can. Mineral. 39: 747–755), is named after him.

Anthony N. Mariano and **Anthony Mariano Jr.** are mineral exploration geologists. They work as a team and specialize in the geology and mineralogy of rare elements on a world level. They have worked extensively in the field and in the laboratory for more than 50 years and in more than 50 countries. Their emphasis is on the economic evaluation and ranking of REE and other specialty metals deposits, which are often associated with carbonatites and alkaline complexes.

Erin Marsh is a research geologist with the Minerals Program at the U.S. Geological Survey in Denver, Colorado. She earned her B.S. (1998) and M.S. (2001) degrees from the University of Colorado, Boulder. She runs the fluid inclusion microthermometry and LA-ICP-MS labs at the Denver Federal Center. Generally, she is interested in the geochemistry of ore deposits. Her research emphasis is on the integrated application of multiple microanalytical techniques along with traditional field and laboratory work on understanding the formation of orogenic gold, placer gold, Te-rich Au deposits, Ni-Co laterite, and sedimentary rock-hosted base-metal deposits.

Patrick I. McLaughlin is a research geologist with the Indiana Geological Survey (Indiana University). He obtained his B.Sc. degree from Illinois State University (1999) and completed his M.Sc. (2002) and Ph.D. (2006) work at the University of Cincinnati, where he studied sequence and event stratigraphy as a doctoral fellow. As an associate professor with the Wisconsin Geological Survey (2007–2015) he directed efforts in bedrock mapping. Pat's interest in high-resolution chronostratigraphy and sedimentary ore deposits has led him to develop new approaches to C-isotope and handheld XRF analysis of marine rocks and time-specific facies concepts. His field-based studies span the Proterozoic to Pliocene on three continents, with an emphasis on the lower Paleozoic of eastern North America.

Thomas Monecke obtained his Ph.D. degree at the TU Bergakademie Freiberg, Germany, in 2003. He subsequently spent five years as a postdoctoral fellow at the University of Ottawa and the Geological Survey of Canada. In 2006, he received the Waldemar Lindgren Award of the Society of Economic Geologists for his early career contributions to economic geology. He joined the Colorado School of Mines in 2008. His research focuses on the metallogeny of modern and ancient volcanic arcs and related extensional settings. He and his students have conducted extensive research on shallow marine hydrothermal systems and the volcanic setting, alteration mineralogy and geochemistry, and ore mineralogy of volcanogenic massive sulfide deposits.

Sven Petersen is currently a senior researcher at GEOMAR-Helmholtz Centre for Ocean Research Kiel, Germany. He received an M.Sc. degree in economic geology from the RWTH Aachen in Germany, investigating gold-rich sea-floor massive sulfide deposits in the Lau Basin. After almost 2 years at the Geological Survey of Canada, he moved to the TU Bergakademie Freiberg, Germany, where he obtained a Ph.D. degree for work on the TAG deposits in the central Atlantic. Since 2004 he has been working at GEOMAR, where his research focuses on understanding the processes that form and change sea-floor hydrothermal systems and associated mineral deposits. He participated in more than 30 research cruises to submarine hydrothermal systems in the Pacific, Atlantic, and Indian Ocean. The major aim of his research is to understand their chemical and mineralogical variability and the geological processes that affect them. He uses mobile drilling techniques and geophysical methods to investigate their resource potential and seafloor processes as well as autonomous underwater vehicles for their exploration.

Lee Ann Munk is a professor of geochemistry in the Department of Geological Sciences at the University of Alaska Anchorage. Professor Munk received her B.S. degree in geology from St. Norbert College in 1995 and her M.S. degree from the Department of Geological Sciences at Michigan State University in 1997, followed by a Ph.D. degree in geochemistry in 2001 from The Ohio State University. Dr. Munk's research is focused primarily on investigating water-rock interactions across a spectrum of environments in order to understand sources, transport, and fate of trace elements. Major focus areas are acid-rock drainage, novel trace elements as tools for geochemical exploration, and origin of continental lithium brines. She has managed federal and private research grants and projects in Alaska, Chile, and the United States, and has worked on other collaborative research projects in Antarctica and the Caribbean. She is recognized as a global leader on the development of a lithium-brine resource model.

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BIOGRAPHIES (continued)

deposits, intrusion-related W-Sn-Mo, Cu, PGE-Cu, and rare-element deposits, diagenetic systems, and fluid inclusions. He is currently a professor, and former Head, in the Department of Earth and Environmental Sciences at the University of Windsor, and was President of the Mineralogical Association of Canada from 2010 to 2012.

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Debashish Sengupta is an applied geophysicist and professor at IIT Kharagpur. He has supervised 31 M.Sc. project dissertations, 12 M. Tech. project dissertations, and 11 doctoral dissertations. He has undertaken significant research work on rare earth and other economic deposits along the eastern coast of India for the past two decades. He has 90 papers published in journals of international repute and more than 50 publications in Conference Proceedings. He has collaborated with many national and international institutes, including Variable Energy Cyclotron Centre, Kolkata; Environmental Assessment Division, Bhabha Atomic Research Centre, Trombay, Mumbai; Research Reactor Institute, Kyoto University, Osaka, Japan; Department of Civil and Environmental Engineering, University of West Indies; Institute of Physics, University of São Paulo, Brazil; and Institute of Experimental Mineralogy, Moscow, Russia. He authored *Handbook on Radioactive Methods and Geochronology* and has edited a book titled *Recent Trends in Modelling of Environmental Contaminants*, published by Springer in 2014. In 2003, he was awarded the Society of Geoscientists and Applied Technologists (SGAT's) Award of Excellence in Earth Sciences.

Stuart Simmons is a consulting and research geoscientist. His work for clients is directed at finding mineral and energy resources, and his research is focused on geothermal energy and understanding precious metal transport and deposition and hydrothermal fluid flow in epithermal environments. He earned M.Sc. and Ph.D. degrees in economic geology (University of Minnesota), and he spent much of his professional career in New Zealand, at the Geothermal Institute, University of Auckland. He is currently a research professor at EGI, University of Utah.

Paul Spry is professor of geology at Iowa State University, where he has been since 1983. He earned B.S. (Honors) and M.S. degrees in geology at the University of Adelaide (Australia), and a Ph.D. degree in economic geology at the University of Toronto in 1984. Paul has focused his research efforts on the geology, mineralogy, and geochemistry of epizonal and

mesozonal gold-silver telluride deposits, the effects of metamorphism on ore deposits, and the mineralogy of ore deposits, in general. He has also conducted research on Mississippi Valley-type, porphyry-style Cu and Mo, high-temperature carbonate replacement Pb-Zn-Ag, and intrusion-related gold deposits. Paul is currently on the editorial board of *Economic Geology* (on which he has served the last four editors), and he has also been a member of the editorial boards for *Ore Geology Reviews*, *Canadian Mineralogist*, and *Mineralogy and Petrology*. He was the SEG Thayer Lindsley Visiting Lecturer for 2012, and has served on or chaired several committees for the Society of Economic Geologists.

Ryan D. Taylor is a research geologist with the Minerals Program of the U.S. Geological Survey, a Ph.D. candidate at Colorado School of Mines, and the SEG student field trip guidebook editor. He obtained his B.S. (2006) and M.S. (2008) degrees in geology from Northern Arizona University. His general research interests include geochronology and geochemistry of ore deposits. Much of his work is focused on lode gold deposits and porphyry deposits of the western cordillera of North America, from California to Alaska. This includes correlating the timing of formation of these deposits with the tectonic evolution of the region and the processes that result in ore deposition in a regional framework. New research includes mineralogical studies of REE-bearing iron oxide-apatite deposits and mineral chemistry of alteration products of lode gold deposits.

Thijs R.A. Vandenbroucke received his Ph.D. degree in geology from Ghent University (Belgium) in 2005. His dissertation research focused on the chitinozoan biostratigraphy from the historical type area of the Upper Ordovician in the UK, compared to that of the series' new GSSPs. Following postdocs at the universities of Durham (UK), Leicester (UK), and Ghent, he held a research position at the French CNRS from 2009 to mid-2015. Vandenbroucke returned to Ghent University in 2015, where he is an assistant professor, lecturing on paleobiology, stratigraphy, and paleo-environments. His research has evolved into the application of integrated bio-chemo-stratigraphy to better understand the dynamic paleoclimate and paleo-oceanography of the early to middle Paleozoic.

Bradley Van Gosen received his B.A. degree in geology from the University of Colorado and his M.S. degree in geology from the Colorado School of Mines. He has been a research geologist for the U.S. Geological Survey in Denver for more than 30 years. His research career began with studies of uranium deposits hosted by solution-collapse breccia pipes in the Grand Canyon region. A recent withdrawal of about 1 million acres of public lands surrounding the Grand Canyon, enacted by the Secretary of the Interior, brought him back to these U deposits as the geologic consultant. Midcareer he studied a variety of deposit types for USGS assessments of mineral resources in public lands. In the last 15 years, he has focused more on industrial minerals— asbestos, talc, rare earth elements (REEs), and heavy-minerals sands. He has worked

BIOGRAPHIES (continued)

extensively on the geology and distribution of natural occurrences of asbestos in the United States, providing insights that can be used to limit human exposures to asbestos. Currently, he serves as a project chief for a USGS project studying the mineral resources (Ti, Zr, REEs) of heavy mineral sands in the coastal plain of the southeastern United States. Brad serves as a U.S. delegate and Vice Chair for the United Nations Economic Commission for Europe (UNECE) Expert Group on Resource Classification. He also is the U.S. member of a collaborative uranium-thorium working group of the International Atomic Energy Agency (IAEA).

Philip L. Verplanck is a research geologist with the Mineral Resources Program of the U.S. Geological Survey. He received his B.S. degree in geology from Tufts University (1981), an M.S. degree in geology from Oregon State University (1986), and a Ph.D. degree in geology from the University of Colorado (1996). He has been with the U.S. Geological Survey since 1997. He has studied rare earth elements (REEs) since 1983, and his REE research includes lunar evolution, igneous petrology, aqueous geochemistry, and ore genesis. His current research focuses on carbonatite and alkaline intrusive-related REE deposits.

Yuling Xie is currently a professor at the University of Science and Technology Beijing (USTB), Beijing, China, and the team leader of the Economic Geology Group in USTB. Xie completed a B.Sc. degree at China University of Geosciences (Wuhan) in 1985 and a Ph.D. degree at China University of Geosciences (Beijing) in 1999. From December of 2008 to June 2009, Xie was a visiting professor in the ARC Centre of Excellence in Ore Deposits (CODES) of the University of Tasmania. As a research geologist, her interests include ore microscopy, fluid and melt inclusions, and metallic metallogeny. She has studied carbonatite-related REE, gold, porphyry Cu-Mo, and epithermal Pb-Zn-Ag deposits in Tibet, Sichuan, Anhui, Inner Mongolia, and Zhejiang.

Lei Wang earned her B.S. degree in mineral processing from Chang'an University (2011) and received her M.S. degree (2014) in mineralogy, petrology, and economic geology from

the University of Science & Technology Beijing. Currently, she is working for the Northwest Bureau of the China Metallurgical Geology Bureau. During undergraduate and graduate studies, she examined mineral deposits in Inner Mongolia, Anhui, and Sichuan provinces. She has conducted research on the geology, fluid inclusion geochemistry, and mineralogy of REE, porphyry Mo, and epithermal Pb-Zn deposits. Currently, her work is focused on mineral deposit exploration design and assessment.

Yasushi Watanabe attended Hokkaido University, from which he received a B.Sc. degree in geology in 1982. He joined the Geological Survey of Japan (GSJ) in 1985 and has worked for the Survey for 29 years. He engaged in a metallogenic study of epithermal and porphyry Cu deposits in the circum-Pacific regions. He served as the leader of Mineral Resources Research Group from 2003 to 2008, and later, as Prime Senior Geologist of the GSJ. Since 2005, he has been involved in the "Rare Earth Exploration and Evaluation Project" of the GSJ, investigating rare earth deposits in the world. In April 2014, he began a new career at Akita University in Japan. He is currently a professor in the Faculty of International Resource Sciences of the university, and is teaching mineralogy and economic geology to undergraduate and graduate students.

Robert A. Zielinski received his B.A. degree in chemistry from Rutgers University and his Ph.D. degree in geochemistry from the Massachusetts Institute of Technology. He has enjoyed a full career as a research chemist with the U.S. Geological Survey in Denver. Areas of specialization include trace element geochemistry, isotope geology, and radiochemistry. Applications have included studies of igneous petrogenesis, trace element mobility during various alterations of volcanic rocks and formation of red beds, U-rich wetlands, and redistribution and environmental mobility of trace elements and radioisotopes during resource production (coal, oil and gas, phosphate, uranium). Most recently, his research has focused on the redistribution of uranium during ISR mining and on the occurrence and environmental mobility of radium in phosphogypsum and in scale deposits in oilfield equipment.