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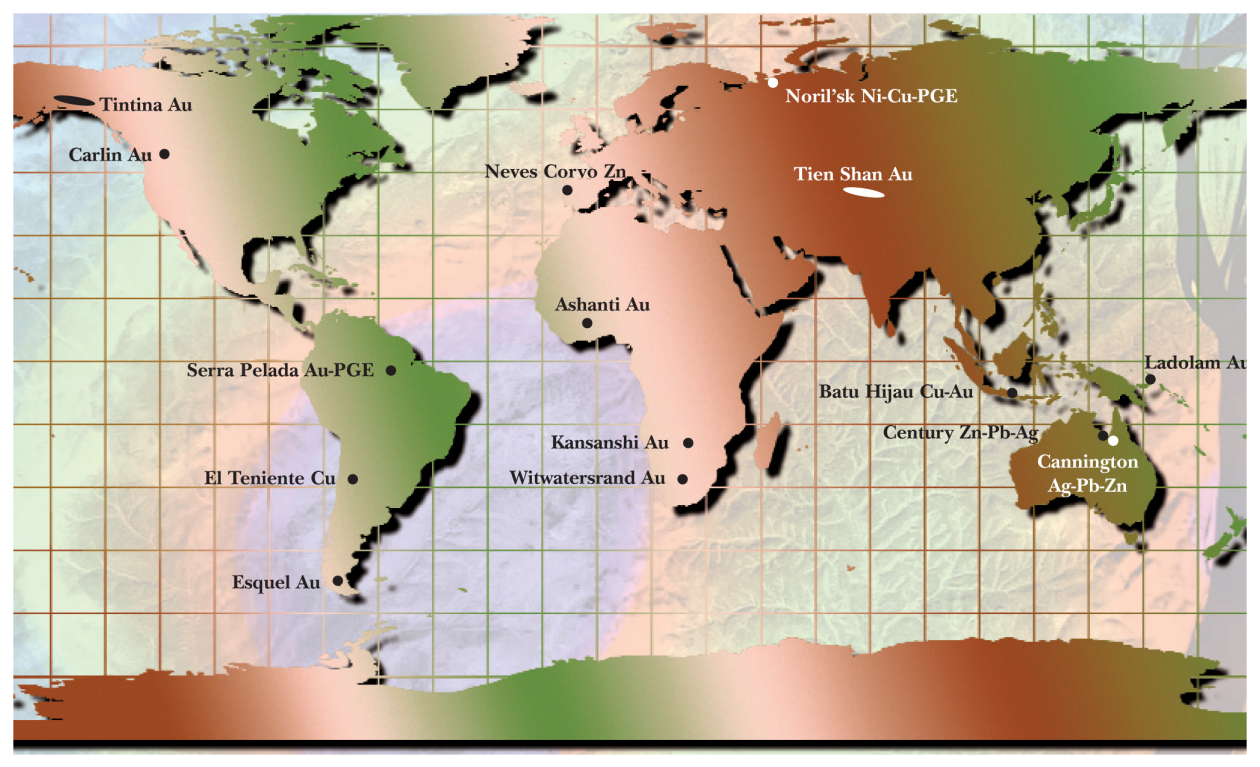
Global Exploration in the Twenty-First Century



Editors
R.J. Goldfarb and R.L. Nielsen

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Integrated Methods for Discovery: Global Exploration in the Twenty-First Century

R.J. Goldfarb and R.L. Nielsen, Editors

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Dedication

Bruce A. Bouley, 1947–2001

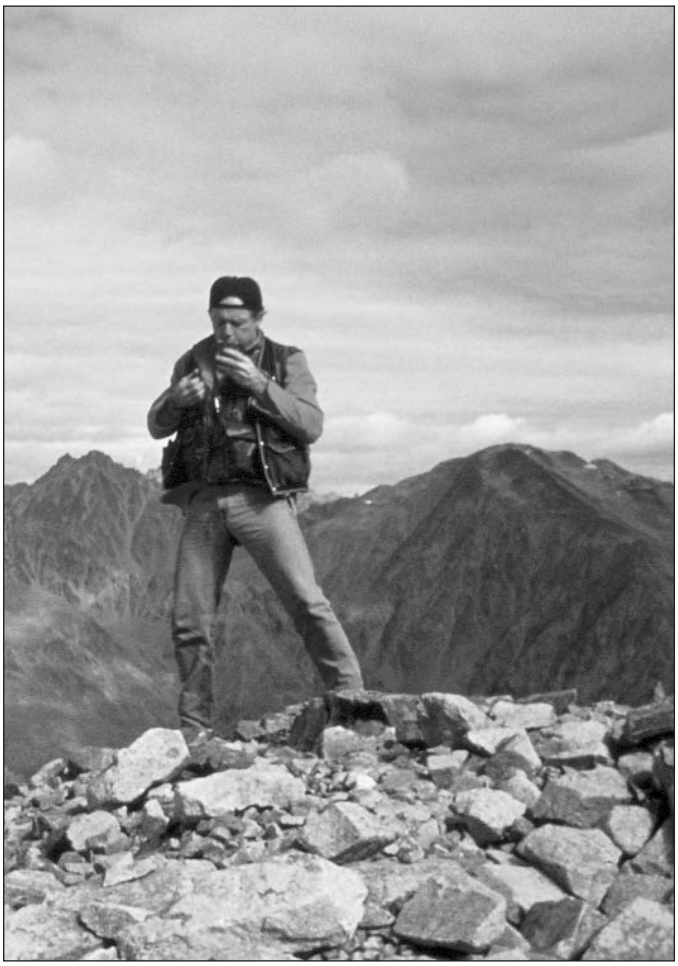
This volume memorializes and honors Bruce A. Bouley, who lost his tenacious, 15-month battle with cancer on August 26, 2001. Bruce was the chief architect of the landmark SEG Meeting, *Global Exploration 2002: Integrated Methods for Discovery*, held in Denver, Colorado, April 14–16, 2002. One product of that international meeting is this volume itself. Beginning with the initial conception of the meeting some four years ago, Bruce served as its General Chairman. For more than three years—indeed, until a few days before his death—he oversaw all aspects of its organization and planning, which included programming, location, financing, administration, and content.

Bruce was born in Worcester, Massachusetts, to Ernest and Rosemary (Finacom) Bouley. A Boy Scout who achieved the organization's highest rank, Eagle Scout, he graduated from Auburn (Mass.) High School in 1965, earned a B.Sc. degree from Bates College in 1969, a master's degree from Wesleyan University, Connecticut, in 1971, and a Ph.D.degree from University of Western Ontario in 1978. He was a "top" student. Bruce's work as a doctoral candidate involved detailed field mapping in a geologically complex and contentious area of coastal Maine, supported by innovative laboratory research. The results of that study remained controversial but, gratifyingly, most recent data corroborate his interpretation.

During his 15-year membership in the Society of Economic Geologists, Bruce served all three SEG entities—the Society itself, the Economic Geology Publishing Company, and the SEG Foundation, a breadth of service matched by very few. He sat on the SEG Program Policy Committee for three years in the mid-1980s and in 1988 chaired the joint winter meeting of SEG-SME in Phoenix, Arizona. He co-organized and led field trips to Arizona's copper porphyry deposits and districts, and to Michigan's Upper Peninsula for the 1988 and 1989 meetings, and was subsequently named as an SEG Thayer Lindsley Lecturer (1994–1995). He was a member of Council and chaired the Membership Committee in the early 1990s. His service was not only technical; in cooperation with the SEG Treasurer, Bruce drafted the description and job functions of the Audit Committee and served on the Finance Committee for three years.

Bruce was a Trustee of the SEG Foundation from 1994 to 1999 and its President for the 1996–1997 term. In the latter capacity he was also a member of the SEG Executive Committee. Through personal and business contacts he was instrumental in organizing and funding the Foundation's Hickok-Radford Grant; he also helped found the Foreign Membership Subsidy Program and the popular and successful Student Grants Program. He served as a Director of the publishing company in 1999.

Bruce's enthusiasm for all aspects of economic geology was unfailingly infectious. His knowledge of its diverse concerns—scientific, technical, financial and administrative—was encyclopedic. He was excellent and at home in the field, yet fully knowledgeable about current technical and scientific understanding. His prime interest was exploration, to which he applied all these skills, progressing through years of increasing experience and responsibility with Midwest Oil Corp., Phelps Dodge, Callahan Mining, Cominco, BHP, and North Star to become an outstanding exploration manager.



Bruce at Mount Estelle, Alaska. Photo courtesy of Madelyn Millholland.

His sparklingly unique sense of humor captivated innumerable friends and colleagues with whom he liberally exchanged wry jokes and "bon mots," to the great enjoyment of all. He readily recognized the humorous side of daily incidents; when he first saw an old photo showing himself with long hair, Bruce immediately said he'd have to "doctor it" on his computer—on which he was truly expert—because he'd told son Brad that he never "went

hippie." He was, simply, a "fun guy," always upbeat and positive, a joy to know and a pleasure to be with. A fitness addict, he jogged daily for many years, loved the outdoors, bow hunting, and skiing. His family and many friends will miss him.

Within the very broad field of earth science and our own specialized subdiscipline of economic geology, the vital minerals industry had, in Bruce Bouley, a gifted and diligent disciple. The Society owes him much for his long interest in all its affairs, his dedicated service to its aims and purposes, for his final huge contribution to the success of *Global Exploration 2002: Integrated Methods for Discovery*, and for this volume. Thanks, Bruce, from all of us who were fortunate enough to know and work with you, and from many who did not, but who will benefit from your dedication.

R.W. Hutchinson

Preface

This volume presents 16 important papers that are mainly concerned with recent exploration successes in some of the world's most significant known mining districts or in areas where important new world-class metallic resources have been defined. Additionally, some papers are technical updates on important world-class deposits or districts. These papers were originally introduced orally in Denver, Colorado, on April 14–16, 2002, at the meeting of the Society of Economic Geologists, co-sponsored by the Society for Geology Applied to Mineral Deposits, the Association of Exploration Geochemists, and the Society of Exploration Geophysicists. The international meeting, entitled *Global Exploration 2002: Integrated Methods for Discovery*, brought together economic geologists from academia, government, and industry to examine—on regional and more local scale—how advances in exploration geology, geochemistry, and geophysics have been combined to successfully define important new resources throughout the globe. The papers in this volume focus on that theme and show how novel technology, when intelligently applied, can lead to success in exploration.

The idea for this volume, as well for the meeting itself, was championed by Bruce Bouley, to whom this volume is dedicated. Under Bruce's steady leadership and with recommendations from members of his Global Exploration 2002 SEG Committee, contributors to this volume were selected in January 2000. We would specifically like to acknowledge Odin Christensen, Bill Gee, and Jim Lincoln, as well as Bruce, for their help in organizing the initial program, which eventually led to the resulting excellent papers included here. Although a few papers needed to be replaced or were lost during the peer review process, the broad global aim remains, with 15 papers representing specific exploration successes across six continents. In addition, an introductory paper by Snow and Juhas (2002) examines the state of our mining industry at the start of the current century. These authors conclude that the metal mining industry has suffered severe contraction, but is too important to society to disappear. Future mining companies likely will be opportunistic and entrepreneurial and will anticipate and profit from the changing needs of society.

This Special Publication not only covers some of the most prospective exploration targets throughout the world; it also describes exploration histories from more than a dozen different types of deposits with resources of Ag, Au, Cu, Ni, Pb, PGEs, Ni, and/or Zn, and with ages from Archean to Quaternary. Frimmel and Minter (2002) highlight and synthesize many of the new research developments regarding the stratigraphy, tectonic history, geochronology, and geochemistry of the unique, and always controversial, Witwatersrand gold fields. Evidence is presented for the detrital origin of the gold prior to 2.64 Ga. Tectonic forces deformed and metamorphosed the gold-bearing sediments from 2.83 to 2.05 Ga, prior to a meteoritic impact at 2.02 Ga. Iron oxide-gold-copper provinces are currently among the most desired targets of our industry and the Carajas province in the Amazon region is among the most prospective of these. Grainger et al. (2002) attempt to determine the possible relationship of the enigmatic Serra Pelada Au-PGE deposit, the site of one of the most spectacular gold rushes of the last few decades, to the other Carajas area ores. In an integrated approach to understanding ore controls at the giant Paleoproterozoic Ashanti deposit in the great gold fields of western Africa, Allibone et al. (2002) describe how understanding of the structural geology is particularly critical for definition of future new resources.

Exploration histories and strategies are thoroughly documented for some of the most important recent Mesoproterozoic and Paleozoic base metal discoveries. Broadbent et al. (2002) describe the discovery of a large, economic, shale-hosted Zn-Pb-Ag resource at Century, northeastern Australia. Persistence and development of innovative exploration models paid off and led to Century's recognition in a previously well-prospected region, partly overlain by postmineral cover. Similarly, intensive study of the Broken Hill district, Australia, led to development of a model that applied novel exploration technologies in the Mt. Isa region, as described by Walters et al. (2002). Application of this integrated model resulted in discovery of the world's largest silver producer, in high-grade metamorphic rocks at Cannington, northeastern Australia. Recent recognition of a massive new Pan-African copper resource at Kansanshi, hundreds of millions of years younger than the stratiform copper-cobalt ores of the Zambian copper belt that occurs about 150 km to the east, is indicated in Broughton et al. (2002). Strong structural control and a distinctly different age compared to the copper belt ores serve to focus attention on a second type of economically significant copper mineralization in central Africa. Relvas et al. (2002) discuss what we have learned from 25 years of geological study at the Neves Corvo deposit, in the Iberian pyrite belt, which remains the most important massive sulfide deposit discovered during the last quarter of the twentieth century.

Two relatively newly recognized, world-class regional gold provinces are described by Hart et al. (2002) and Yakubchuk et al. (2002). Hart et al. (2002) review features of a variety of intrusion-related gold deposits of mid-Cretaceous age in the Tintina gold belt in central Alaska and Yukon. These varied deposits are encompassed within an overall exploration model that should provide effective and efficient exploration strategies. Yakubchuk et al. (2002) focus on plate reconstruction approaches in central Asia and demonstrate how gold mineralization is related to tectonic evolution. Favorable tracts for late Paleozoic gold resources are defined along the length of the Tien Shan Mountains, which extend from Uzbekistan into western China. Geologic studies of the exceptional Permian Noril'sk Ni-Cu-PGE system, described

by Diakov et al. (2002), led to recognition that structure, form, and geometry of magma chambers and conduits can define ore targets. Geophysical techniques and geochemical guides serve to locate drill targets. Steps leading to the very recent discovery of the Esquel gold deposit, and the features of this deposit, which are provided by Sillitoe et al. (2002), indicate that the Mesozoic Patagonian Andes of southern Argentina are a notable new target for giant, low-sulfidation epithermal deposits.

Some of the most important ore deposits and exploration targets are recognized in the Oligocene and younger settings of the North American Basin and Range, the Andes, and the southwest Pacific. Bettles (2002) presents a detailed history of the exploration and a geologic evolution of some of the highest tonnage gold deposits in the Carlin trend in Nevada, which have then been incorporated into the present working model for understanding the distribution of ores. Multiple episodes of Mississippian to Eocene deformation helped to develop a complex structural architecture that controls the orebodies. Skewes at al. (2002) describe the giant El Teniente copper deposit in central Chile, focusing on new information from deep mine levels, and interpreting geological and mineralogical attributes of the magmatic-hydrothermal system. Mineralization is present in and surrounding multiple magmatic-hydrothermal breccias, forming a massive breccia pipe, with some features not typical of more classic porphyry deposits. The first detailed description of the Batu Hijau porphyry copper-gold deposit in Indonesia, submitted by Garwin (2002), integrates district-scale geologic mapping, drill core logging, geochemistry, geophysics, and igneous petrology into a model that will be useful for exploration geologists throughout this region. Mineralization is located in a Miocene volcaniclastic complex cut by several intrusions of intermediate to felsic compositions. At the nearby Ladolam gold deposit in New Guinea, Müller et al. (2002) present a study of gold-associated alkaline igneous rocks that can be used to help understand origin of the ore-forming hydrothermal system.

It is evident from many of these papers that exploration has continued to be successful throughout the world in recent years and some of the most significant discoveries have resulted from well-integrated technologies. It is hoped that this group of papers, which provides numerous examples of such integration, will prove useful in aiding future exploration strategies.

Richard J. Goldfarb
Richard L. Nielsen

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REFERENCES

Allibone, A.H., McCuaig, T.C., Harris, D., Etheridge, M., Munroe, S., Byrne, D., Amanor, J., and Gyapong, W., 2002, Structural controls on gold mineralization at the Ashanti gold deposit, Obuasi, Ghana: Society of Economic Geologists, Special Publication 9, p. 65–93.

Bettles, K., 2002, Exploration and geology, 1962 to 2002, at the Goldstrike property, Carlin trend, Nevada: Society of Economic Geologists, Special Publication 9, p. 275–298.

Broadbent, G.C., Andrews, S.J., and Kelso, I.J., 2002, A decade of new ideas: Geology and exploration history of the Century Zn-Pb-Ag deposit, northwestern Queensland, Australia: Society of Economic Geologists, Special Publication 9, p. 119–140.

Broughton, D.W., Hitzman, M.W., and Stephens, A.J., 2002, Exploration history and geology of the Kansanshi Cu(-Au) deposit, Zambia: Society of Economic Geologists, Special Publication 9, p. 141–153.

Diakov, S., West, R., Schissel, D., Krivtsov, A., Kochnev-Pervoukhov, V., and Migachev, I., 2002, Recent advances in the Noril'sk model and its application for exploration of Ni-Cu-PGE sulfide deposits: Society of Economic Geologists, Special Publication 9, p. 203–226.

Frimmel, H.E., and Minter, W.E.L., 2002, Recent developments concerning the geological history and genesis of the Witwatersrand gold deposits, South Africa: Society of Economic Geologists, Special Publication 9, p. 17–45.

Garwin, S., 2002, The geologic setting of intrusion-related hydrothermal systems near the Batu Hijau porphyry copper-gold deposit, Sumbawa, Indonesia: Society of Economic Geologists, Special Publication 9, p. 333–366.

Grainger, C.J., Groves, D.I., and Costa, C.H.C. , 2002, The epigenetic sediment-hosted Serra Pelada Au-PGE deposit and its potential genetic

association with Fe Oxide Cu-Au mineralization within the Carajás mineral province, Amazon craton, Brazil: Society of Economic Geologists, Special Publication 9, p. 47–64.

Hart, C.J.R., McCoy, D.T., Goldfarb, R.J., Smith, M., Roberts, P., Hulstein, R., Bakke, A.A., and Bundtzen, T.K., 2002, Geology, exploration, and discovery in the Tintina gold province, Alaska and Yukon: Society of Economic Geologists, Special Publication 9, p. 241–274.

Müller, D., Herzig, P.M., Scholten, J.C., and Hunt, S., 2002, Ladolam gold deposit, Lihir Island, Papua New Guinea: Gold mineralization hosted by alkaline rocks: Society of Economic Geologists, Special Publication 9, p. 367–382.

Relvas, J.M.R.S., Barriga, F.J.A.S., Pinto, A., Ferreira, A., Pacheco, N., Noiva, P., Barriga, G., Baptista, R., de Carvalho, D., Oliveira, V., Munhá, J., and Hutchinson, R.W., 2002, The Neves-Corvo deposit, Iberian pyrite belt, Portugal: Impacts and future, 25 years after the discovery: Society of Economic Geologists, Special Publication 9, p. 155–176.

Sillitoe, R.H., Cooper, C., Sale, M.J., Soechting, W., Echavarria, D., and Gallardo, J.L., 2002, Discovery and geology of the Esquel low-sulfidation epithermal gold deposit, Patagonia, Argentina: Society of Economic Geologists, Special Publication 9, p. 227–241.

Snow, G.G., and Juhas, A.P., 2002, Trends and forces in mining and mineral exploration: Society of Economic Geologists, Special Publication 9, p. 1–16.

Skewes, M.A., Arévalo, A., Floody, R., Zuñiga, P.H., and Stern, C.R., 2002, The giant El Teniente breccia deposit: Hypogene copper distribution and emplacement: Society of Economic Geologists, Special Publication 9, p. 299–332.

Walters, S., Skrzeczynski, R., Whiting, T., Bunting, F., and Arnold, G., 2002, Discovery and geology of the Cannington Ag-Pb-Zn deposit, Mount Isa Eastern Succession, Australia: Development and application of an exploration model for Broken Hill-type deposits: Society of Economic Geologists, Special Publication 9, p. 95–118.

Yakubchuk, A., Cole, A. Seltmann, R., and Shatov, V., 2002, Tectonic setting, characteristics, and regional exploration criteria for gold mineralization in the Altaid orogenic collage: The Tien Shan province as a key example: Society of Economic Geologists, Special Publication 9, p. 177–201.

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