

ECONOMIC GEOLOGY

One Hundredth
Anniversary Volume

1905–2005

Jeffrey W. Hedenquist, John F. H. Thompson, Richard J. Goldfarb,
and Jeremy P. Richards, Editors



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O. Tomurtogoo, G. Badarch, and V. A. Buryak*

[Herrington]

Mineral Deposits of the Urals and Links to
Geodynamic Evolution *Richard J. Herrington, Victor V. Zaykov,
Valery V. Maslennikov, Dennis Brown, and Victor N. Puchkov*



Preface

One hundred years of research and opinion in economic geology have been published in the pages of *Economic Geology* since October 1905. Despite many changes with time, including a large number of deposits discovered worldwide, deposit types unknown a century ago, and new analytical methods employed in the study of deposits, some of the basic questions of 100 years ago remain: how do certain kinds of ore deposits form, what are the ultimate sources, pathways, and depositional mechanisms of the metals, and can we better explore for the resources on which the future of a healthy and sustainable society depends? In addition, how have ore processes changed with the evolving Earth, and how do ore deposits reflect and record this evolution?

During the annual meeting of the Geological Society of America in 2001, Brian Skinner, Chairman of the Publications Board of the Society of Economic Geologists, established an ad hoc committee to discuss plans for the 100th anniversary of the journal. Early the following year this ad hoc group evolved into the Organizing Committee, with members listed below who came from a wide range of backgrounds and locations around the world. The Board approved the three different publications proposed by the Committee: this *One Hundredth Anniversary Volume*, a series of forward-looking Special Papers commissioned for the regular issues of the journal during the centenary period, and a Special Publication to coincide with a meeting in 2006 on the topic of “Wealth Creation in the Minerals Industry.” Papers in the Special Publication will cover a variety of issues related to the business of the minerals industry, from exploration through to mine closure, all to be managed for a sustainable future.

The goal of this Anniversary volume, as it was with the predecessor 50th and 75th Anniversary volumes, is to meet the needs and interests of economic geologists in industry, government, and academia, both professional and student, for concise and up-to-date overview papers that provide a synthesis of important topics in economic geology. The Organizing Committee started with a wide range of material to be considered, and over time the Anniversary volume became focused on the topics covered here.

This volume includes three types of papers: Earth environments and processes, to introduce and summarize many of the other papers; ore deposit types; and regional metallogeny. Authors were asked to review the history of each topic, outline fundamental aspects, synthesize insight on ore genesis, provide observations useful for exploration, and offer an assessment of the questions they perceive will be studied in the century ahead. The editors inserted cross references to other papers in the volume where appropriate, as many of the papers deal with topics that are linked to one another. Some authors have tabulated large compilations of basic information on the deposit types discussed in their papers; this material, together with any additional figures and other supplementary information, is recorded in an electronic Appendix on a CD-ROM at the back of the volume. This was done to aid the reader in searching for data and to keep the printed volume at a manageable length.

We thank members of the Publications Board, chaired successively by Brian Skinner, Samuel Adams, and John Thoms, for their support and direction throughout the four-year process of planning, writing, editing, and production, and Mark Hannington, Editor of *Economic Geology*, and Steve Kesler for their sage advice. We thank all members of the Organizing Committee for their input to the structure and breadth of the volume. Reviewers of the papers, listed below, helped to maintain the quality expected of *Economic Geology*, and we thank them for their timely efforts. We acknowledge Alice Bouley, Managing Editor of SEG Publications, in Littleton, Colorado, and her collaborators, for copyediting and production of the volume, and Bernadette Lancaster, Editorial Assistant, *Economic Geology*, in Ottawa, Canada, for her assistance. Finally, we thank all of the authors for providing papers that we believe will be important to the science of economic geology for many years to come.

In closing, we acknowledge the sponsors of the volume for their generous financial contributions; they are listed below. Their support has allowed the Society to keep the price of this large volume at an affordable level for all.

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ECONOMIC GEOLOGY ONE HUNDREDTH ANNIVERSARY VOLUME



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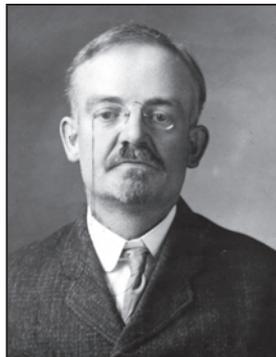


The Founders of *Economic Geology*

Twelve individuals played a major role in founding the journal. Their photos appear below .



H. FOSTER BAIN
1871–1948



ARTHUR H. BROOKS
1871–1924

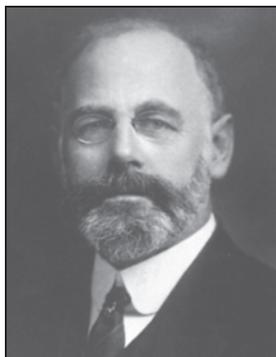
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MARIUS R. CAMPBELL
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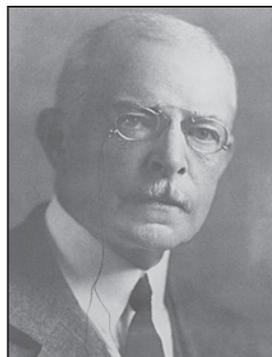
JOHN D. IRVING
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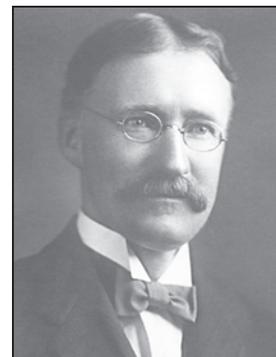
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1875–1956



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HEINRICH RIES
1871–1951

Photo Source: Geological Society of America

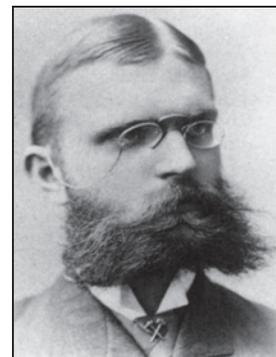


GEORGE O. SMITH
1871–1944

Photo Source: USGS Photo Library



JOSIAH E. SPURR
1870–1950



WALTER H. WEED
1862–1944

Photo Source: Smithsonian Institution (83-1310)

The Editors of *Economic Geology*
1905 – 2005

During the first 100 years of the journal, five individuals have served as its Editor .
Below are their photos with years of service indicated.



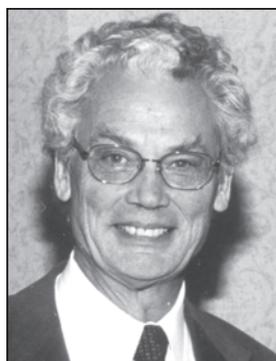
JOHN D. IRVING
1905–1917



ALAN M. BATEMAN
1917–1969



BRIAN J. SKINNER
1969–1995



MARCO T. EINAUDI
1995–2001



MARK D. HANNINGTON
2001–



Introduction: A Century of Excellence

BRIAN J. SKINNER[†]

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From the first issue in 1905 onward, *Economic Geology* has been the main publication for those who study mineral deposits; indeed, it is now difficult to imagine economic geology without *Economic Geology*. It is interesting to ask, therefore, *Who were the farsighted people who founded the journal, and Why did they think a specialized publication devoted to mineral deposits was needed?*

Who Were the Founders?

Let us first address the question, *Who were the founders?* They were the 12 men who collectively decided a new publication was needed, who then planned the financial structure to support the venture, and who served as the original editorial group. All were employed by, or associated with, the U.S. Geological Survey. Josiah Edward Spurr suggested the need for a journal sometime in November or December 1904. After informal discussions, nine of the founders met in the office of Waldemar Lindgren in the headquarters of the U.S. Geological Survey in Washington, D.C., on May 16, 1905, and founded the Economic Geology Publishing Company. The sole purpose of the company was the publication of a journal "...devoted primarily to the broad application of geologic principles to mineral deposits of economic value, and to the scientific description of such deposits, and particularly to the chemical, physical, and structural problems bearing on their genesis." Initial financing for the new company was raised by the sale of 80 shares at a cost of \$25 per share.

Eight of the men at the founding meeting formed the first board of directors; Spurr was president, Frederick L. Ransome, secretary, and George O. Smith, treasurer. Other members were Arthur H. Brooks, Marius R. Campbell, Walter H. Weed, Waldemar Lindgren, and a young academic from Lehigh University in Pennsylvania, John D. Irving. The ninth man at the meeting was H. Foster Bain. Irving was appointed editor. Lindgren, Ransome, and Campbell from the U.S. Geological Survey, together with three academics, James F. Kemp of Columbia University, Heinrich Ries of Cornell University, and Charles K. Leith of the University of Wisconsin, were appointed associate editors. The initial board members, the editor, and associate editors are the people we now recognize as the founders of *Economic Geology*. Two others, Frank D. Adams, of McGill University in Canada, and John W. Gregory, of Glasgow University in Scotland, were subsequently added as associate editors, and a third person, W. S. Bayley of the University of Illinois, was appointed as business editor, but they are not known to have played any role in founding the journal. It is interesting to note the ages of the founders in 1905. Marius Campbell, at 47, was the eldest, followed by Kemp, aged 46, Lindgren, aged 45, and Weed, aged 43. All the rest were in their 30's. The launching of *Economic Geology* was a venture by a group of young men near the peaks of their productive careers.

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Why a Journal?

Now to the second question, *Why a journal devoted to mineral deposits?* The answer lies in the science of mineral deposits at the dawn of the twentieth century. Although rich mineral deposits had been discovered around the world, throughout the nineteenth century, critical thinking concerning the genesis of deposits came mainly from Europe. Late in the nineteenth century, after a few young North American geologists had studied at European mining schools, things began to change. European ideas and European ways of thinking about the origins of deposits came westward across the ocean. Three of the founders—Kemp, Ries, and Lindgren—had studied in Europe and were bearers of European ideas.

An important player in the events leading to the founding of the journal, though not himself a founder, was Samuel Franklin Emmons. Emmons had trained in Europe and, as leader of the Metals Division of the U.S. Geological Survey, was the supervisor of the founders who worked for the Survey. Emmons, who was 65 years old in 1905, had studied with Gabriel Auguste Daubrée and Élie de Beaumont at the École des Mines in Paris and with Carl Bernhardt von Cotta at the Bergakademie in Freiberg, Saxony. On his return, he was employed by the Geological Exploration of the Fortieth Parallel under the leadership of Clarence King. When the U.S. Geological Survey was founded in 1879, King, the first director, appointed Emmons as Geologist in Charge of the Rocky Mountain Division. In this position, Emmons completed a classic study of the Leadville district in 1886 that was published as Monograph 12 of the Survey. This work became the standard against which subsequent Survey monographs and professional papers on mineral deposits were measured. When Emmons delivered his presidential address to the Geological Society of America in 1904, he explained why the U.S. Geological Survey considered monographic studies to be so important: "It was the expectation of those who planned this work that when all the important mining districts of the United States had been thus exhaustively studied, a sufficient store of well ascertained facts regarding ore deposits would have been accumulated to admit of the formulation of a new theory more firmly grounded on a basis of well established fact than any that had yet been presented."

All of the founders published Survey monographs or professional papers and most of them are now recognized as classics. In addition, Kemp published *The Ore Deposits of the United States and Canada*, a lengthy volume that ran through several editions and provided the first comprehensive summary of mineralization in the continent, and Ries published the first detailed economic geology text in North America.

Textbooks, monographs, and professional papers are great for summarizing and recording, but they are not convenient for ongoing scientific debates. The answer to "Why a journal?"

lies in those weighty tomes. *Economic Geology* was founded to meet the needs of a community of young geologists who wished to present evidence, summarize ideas, discuss points of view, and sharpen developing hypotheses.

Why 1905?

Why 1905 rather than 1895, or 1915? The time was right in 1905 because by that time many young North American geologists had come to realize that European concepts were not always in agreement with the new evidence being discovered in North America. Two publications served to focus attention on trans-Atlantic disparities between concepts and evidence. The first, “The Genesis of Ore Deposits,” was a paper delivered at the annual meeting of the AIME in 1893 by a famous European economic geologist, Franz Posepny. The second was the 1904 Presidential address to the Geological Society of America, by Emmons, on “Theories of Ore Deposition Historically Considered.” Emmons posited that many mineral deposits formed as a result of meteoric waters circulating extensively in the crust, picking up mineralizing components, and depositing them by reactions in favorable rocks. Posepny, on the other hand, advocated mineralization from below, the source of the metals being the “barysphere,” a poorly defined but metal-rich region, deep in the Earth. The young founders had their own ideas—some rather extreme, such as Spurr’s idea that quartz veins had been injected as ore magmas. *Economic Geology* was to be the medium in which such disparate ideas could be presented and discussed.

After the Founding

The community of economic geologists was small in 1905, and it was centered in government surveys and, to a lesser extent, in academic institutions. Burgeoning demand for mineral supplies in the years immediately following World War I brought a considerable change to the employment structure. In particular, the number of geologists employed by the mining industry began to increase markedly. By 1920 the change in professional demographics led J. E. Spurr—the same man who had been the first president of the Economic Geology Publishing Company—to suggest that the time was right to form a professional society for the growing community. Thus was formed the Society of Economic Geologists. The Economic Geology Publishing Company and the Society continued as separate but closely related and cooperating entities until they were finally merged in 2001. The history of *Economic Geology* from 1920 onward is not just the history of a scientific journal but also the history of a society and a profession.

It is interesting to ask, “*What effect did the founding of Economic Geology have on the field of economic geology?*” First and most obviously, the journal gave the field its name. The term economic geology had been coined in the early years of the nineteenth century but had fallen into disuse and been replaced by names such as “applied geology” and “mining geology.” Indeed, one of the first issues the founders had to settle was the choice of a name for the new journal; some argued for applied geology, others for economic geology. The same argument arose at the time the Society was founded; economic geology won the day on both occasions.

A second effect arising from the founding of the journal was the separation of economic geology from mining engineering.

As a result, economic geology became an essential component in the scientific fabric of geology. Prior to the founding of *Economic Geology* most papers on mineral deposits were published in mining journals. In the first paper of issue number 1 of *Economic Geology*, Ransome addressed the publication problem and argued the need for a journal that

provides a place where the results of investigations of scientific character, recorded in the concise and accurate phraseology of science and addressed to readers who need no concessions to their knowledge or intelligence, may appropriately be assembled, and where questions of interpretation or theory may be freely discussed. If this idea is steadfastly adhered to, there can be little doubt that the journal will not only be a potent means of maintaining the dignity and influence of one of the most important branches of geology but will be of the greatest ultimate service to both mining engineers and to general geologists.

Ransome’s words need no explanations or additions. The journal has served the purposes he outlined. It has more than fulfilled the hopes and visions of the founders. It is still the principal place for the leading scientists to record their original ideas about how, why, and where mineral deposits form.

Growth of the Discipline

The history of the first century of *Economic Geology* is coincident with the history of economic geology in the twentieth century. One period of massive change stands out. Just as World War II caused massive societal changes, so too did it bring major scientific advances to economic geology. The advances were in part due to new techniques and new discoveries from other sciences, but equally they were due to a rapidly growing world population that led to a boom in mineral exploration and a flood of new field observations.

The years from 1905 to 1955

In recognition of the first 50 years of publication, the Economic Geology Publishing Company commissioned the *Fiftieth Anniversary Volume of Economic Geology* in 1955. This 1,130-page publication summarized the advances and accumulated thinking of the previous 50 years. When the journal was founded in 1905, those involved held very broad views of the field of economic geology. All mineral-based resources save soil were included. The first volume contains papers on petroleum, coal, water, clays, and other resources in addition to metallic mineral deposits. Over the next 50 years the mix slowly shifted toward metallic minerals, but it was still an ecumenical mix in 1955. Reflecting the balance of papers in the journal, the *Fiftieth Anniversary Volume* included papers that summarized advances in petroleum geology, coal geology, properties of calcium and magnesium carbonates, groundwater studies, and clay mineral technology. Metallic minerals were treated in detail. Interestingly, some of the topics are the same as those discussed in papers in volume one, half a century earlier: examples are secondary enrichment, zonation in deposits, and classification of deposits. All papers in the volume record advances, but in many cases the advances were not what we might now, in hindsight, call major.

What, then, were the major advances of the first 50 years?² I suggest that six topic areas in the *Fiftieth Anniversary Volume* cover the main advances of the previous half-century.

1. Metallogenic provinces and epochs, as addressed by F. S. Turneure. Global tectonics was not a concept in 1955, but Turneure perceptively combined a wealth of data on structural patterns, deposit types, and timing of mineralization in ways that, 30 years later, could simply be dropped into place in a plate tectonic framework. The pattern had been recognized but the explanation was wanting.

2. An extraordinary amount of work had been done on the chemistry of hot-spring waters and hot-spring mineralization. The relationship between hot springs and certain kinds of mineralization had been recognized in antiquity, but only in the twentieth century was the concept tested in detail. An intriguing paper by D. E. White pulled a mass of data together and made the case that hydrothermal solutions can have several possible origins; they can evolve from magmatic, meteoric, or even connate saline solutions.

3. Detailed structural analyses of complexly deformed orebodies had been carried out starting in the 1920s. A number of groundbreaking structural studies had been done in places such as Hollinger in Canada, Homestake in the United States, Kalgoorlie and Broken Hill in Australia, leading to the discovery of new orebodies in old fields. An intriguing and beautifully written paper by one of those involved in some of the studies, H. E. McKinstry, describes the advances.

4. The fact that large volumes of altered rock commonly surround cores of mineralization was known in the time of Agricola and probably much earlier. Detailed mineralogical studies of hydrothermal alteration began to advance rapidly in the first half of the twentieth century. Indeed, the first monograph published by the Economic Geology Publishing Company, *Rock Alteration as a Guide to Ore, East Tintic District, Utah*, by T. S. Lovering and others, appeared in 1949. In the *Fiftieth Anniversary Volume*, G. M. Schwartz summarized advances in alteration mineralogy.

5. As a consequence of World War II, a previously minor metal, uranium, rose to major status. Over a 15-year period there was a massive advance in the understanding of uranium geochemistry and in the formative processes of uranium deposits. The work was summarized in an elegant paper by V. E. McKelvey, D.L. Everhart, and R. M. Garrels.

6. The last example is an advance based on improvements in analytical equipment and techniques. Trace element distributions had long been recognized as an indicator of mineral zoning, and also as offering potential clues to the genesis of deposits, but precision of measurement tended to restrict confident use of trace element data. M. Fleischer pulled together the massive body of quantitative spectroscopic data that had been obtained on trace elements in sulfide minerals. Fleischer's compilation was a harbinger of things to come; in the second half of the twentieth century quantitative trace-element studies became important components of studies of compositional zoning of deposits, and also began to play a role in mineral exploration.

The years from 1955 to 1980

Hints that major changes lay ahead began to appear in *Economic Geology* as the first 50 years came to a close.

Fluid inclusions in minerals had been observed and commented on for more than a century. When Lindgren reported his classic study of the Clifton-Morenci district in Arizona (U.S. Geological Survey Professional Paper 43, 1905), he noted the presence of salt crystals in fluid inclusions in quartz and concluded that hydrothermal solutions must be saline. Despite such intriguing observations, fluid inclusions were not objects of study in *Economic Geology* until a paper by H. S. Scott, involving the determination of inclusion-filling temperatures using the decrepitating method, appeared in volume 43, 1948. Six years later, in volume 49, 1954, F. G. Smith published the first paper dealing quantitatively with the compositions of fluid inclusions. The first paper discussing stable isotopes in ore deposits was published by M. L. Jensen in volume 48, 1953, and three years later, J. L. Kulp and others published the first paper demonstrating the potential uses of fractionations between the isotopes of sulfur. Today almost every issue of the journal carries papers in which data and interpretations are derived from fluid inclusion and stable isotope analyses.

The quarter century beginning in 1955 was a time when startling geochemical discoveries began to change geology, economic geology included. An indication that the long-standing puzzle of the transport of ore minerals in hydrothermal solutions was about to yield came with an important paper by J. J. Hemley on the solubility of galena in saline solutions, published in volume 43, 1948. But the path to understanding hydrothermal chemistry really started to widen with papers by P. B. Barton, Jr., in volume 52, 1957, and by H. D. Holland in volume 54, 1959. Terms such as chemical potential (first used in the journal by McKinstry and Kennedy in 1957) and fugacity (first used by Holland in his 1959 paper) started to appear frequently.

The rapidity of advances in geochemistry exceeded the capacity of *Economic Geology* to publish all papers and to some extent challenged the capacity of the readership to absorb all the new findings. In response, a group of young geologists, all of whom looked to *Economic Geology* as their main vehicle of publication, repeated, in essence, the action taken by the founders 60 years earlier—they founded a new publication. Instead of a new journal, the group, led by H. L. Barnes, published a multi-authored review volume titled *Geochemistry of Hydrothermal Ore Deposits*. Three editions of this seminal publication, each edited by Barnes, have now appeared—in 1967, 1979, and 1997. The influence on the science of economic geology has been immense. Every issue of the journal today shows the impact of the three volumes and the geochemical advances in techniques and interpretations that they chronicled.

Leaving aside the dramatic changes produced by geochemistry in the years 1955 to 1980, *What were the other major advances of the time?*³ This was the question pondered by the Organizing Committee and the editor of the *Seventy-Fifth Anniversary Volume* of *Economic Geology*. Five topics stand out above the others:

1. Through the power of radiometric dating, time bounds of certain deposit-forming processes were determined sufficiently precisely to convince even the staunchest skeptics of their validity. A prescient and explicitly convincing paper by

Charles Meyer laid out the case. Certain kinds of mineralization clearly have evolved through geologic time.

2. The plate tectonics paradigm was changing all of geology by 1980. There is no specific paper on the topic in the *Seventy-Fifth Anniversary Volume*, but evidence of a new way of thinking engendered by plate tectonics is evident throughout. At least half of the papers in the volume relate either deposit types or ore-forming process to tectonic locations controlled or influenced by the motions of tectonic plates.

3. For many years, evidence had been gathering to support the hypothesis that Precambrian climates and atmospheres had differed greatly from climates and atmospheres of the Phanerozoic. Two papers addressed some of the consequences for mineralization: Pretorius discussed gold and uranium in Paleoproterozoic quartz-pebble conglomerates, and Button and Tyler discussed the importance of Precambrian paleoweathering and erosion surfaces in southern Africa.

4. Two classes of mineral deposits had received much attention over the 25-year span. Porphyry coppers were not a new class of deposit, but by 1980 so many had been discovered, explored, and studied, that a detailed understanding of their tectonic locations and internal variations of mineralization and alteration was emerging. A seminal paper by Titley and Beane pulled all the findings together.

The second class of deposit to be studied in great detail was volcanic-hosted massive sulfide deposits, reviewed exhaustively by Franklin, Sangster, and Lydon. These fascinating deposits had been known and mined from antiquity, but only in the twentieth century did it become apparent they had been formed on ancient sea floors. Oceanographic explorations of the sea floor in the years following World War II had yielded tantalizing hints of mineralization at places along the modern mid-ocean ridge, but few geologists, if any, thought that modern deposits might be discovered forming on the sea floor today. But discovered they were, first on the East Pacific Rise at 21 degrees north in the late spring of 1979, and then at many other places along both spreading and subduction plate edges.

The years from 1980 onward

The papers that accompany this introduction to the *One Hundredth Anniversary Volume* record many of the advances of the last quarter century. It is always dangerous to decide the importance of topics while the issues are still being studied. You, the reader, can decide for yourself. Articulated with the help of Stephen Kesler and Jeffrey Hedenquist, the following are suggestions for the major advances of the past quarter century:

1. The important role of global tectonics in the formation and distribution of mineral deposits has become firmly established. Evidence of the linkage is principally Phanerozoic in age, the time when Pangea was assembled and then fragmented. It is still unclear to what extent Phanerozoic tectonic models can be safely applied to Proterozoic circumstances and even less clear that Phanerozoic models can be used for the Archean. Despite such uncertainties, the recognition and application of global-scale tectonics in explaining the location of mineralization has had a huge impact on the study of mineral deposits.

2. The extraordinary expansion in the number of discovered diamondiferous pipes is an advance of major proportions. Discoveries are still being reported at a remarkable rate. The science behind the discoveries lies in the vast amount of research on the petrology of mafic and ultramafic rocks and the application of that research to the prospecting for new deposits.

3. When the second edition of *Geochemistry of Hydrothermal Ore Deposits* was published in 1979, the point was made that one of the major unanswered questions concerning hydrothermal systems was their magnitude. Historically they had been thought to be rather localized systems. The 11.7-km hole drilled in the Kola peninsula by Soviet scientists was the first clear indication that our thinking was incorrect. It was discovered that fluid pressures in the hole remained hydrostatic, or nearly so, all the way to the bottom—the crust has to be more permeable than previously thought and widespread circulation may well extend to depths of 20 km or more. At the same time computer modeling has shown that fluid flow, especially in sedimentary basins, can cover distances that are continental in scale.

4. Submarine hydrothermal systems and associated mineralization were discovered just as the *Seventy-Fifth Anniversary Volume* was published. The extraordinary intensity of marine research that followed the breathtaking discoveries has rapidly built our understanding of submarine mineralization, both in the present and the past, to such an extent that ore deposition in the submarine environment is arguably now one of the most clearly understood of all mineralizing environments.

5. The search for alternatives to carbon-based energy sources has sparked intensive investigations into land-based geothermal systems, leading to important insights about meteoric and magmatic hydrothermal systems. Direct analyses of fluids in active hydrothermal systems, both terrestrial and submarine, have refined interpretations of fluid inclusion data from ore deposits, and have allowed numerical models of chemical and physical processes to be tested and refined.

6. So many ore deposits have been discovered over the past half century, and collaborations between industrial, academic, and governmental geologists has been so extensive, that realistic deposit models have now been developed for many of the major classes of mineral deposits; a few examples are epithermal gold, porphyry copper, and immiscible sulfide nickel-copper deposits.

The century past has been an extraordinary one for science in general, and economic geology is no exception. One might reasonably ask, *What is the major challenge that economic geology will face in the century ahead?* My answer, which is hardly controversial, is that the accumulated understandings of deposit-forming processes and the wealth of data now being codified into robust deposit models need to be developed into an exploration philosophy by which geologists can prospect the half of the continental crust that is covered by barren rocks. That is where the great mineral deposits of the future await discovery, but so far we are only starting to develop ways to find them.