EXPLORATION GEOCHEMISTRY: EXPANDING CONTRIBUTIONS TO MINERAL RESOURCE DEVELOPMENT

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ABSTRACT

Geochemistry is an essential component in most modern integrated mineral exploration programs. It constitutes 10 to 25% of exploration budgets. Advances in the field include progressive improvements in mineral deposit models, conceptual models, ICP-ES and ICP-MS instrumentation and capabilities, partial extraction analysis, and computer-based data analysis and visualization techniques.

New and rediscovered developments include formulation of preliminary geoenvironmental mineral deposit models, and renewed interest in field-based, in situ geochemical analysis via soil gas, x-ray fluorescence and near-infrared spectrometric instruments.

Geochemistry has the potential to make additional contributions to the mineral supply process through initial baseline and subsequent monitoring studies for environmental purposes and to the ore reserve estimation process.

With the increasing use of geochemistry in all aspects of mineral resource development, there is concern that insufficient numbers of qualified people will be available to meet these needs.

INTRODUCTION

Geochemistry is an essential component in most modern integrated mineral exploration programs. It has taken on an increasingly significant role in recent years. Two principal factors account for this trend. First, gold has remained the commodity of industry focus; economic deposits are commonly characterized by their low grade and large tonnage, and their discovery, assessment and development are highly dependent upon geochemical methods and analyses. Second, exploration activity is being increasingly directed to tropical and subtropical environments where chemical weathering has predominated and where geochemical prospecting techniques have proven most effective. Recent estimates suggest that between 10 and 25% of exploration budgets are allocated to geochemistry. If drilling costs are allocated to sampling for assaying (geochemistry) purposes, this figure could be in excess of 50%! Clearly, effective use of geochemistry in mineral exploration deserves our full attention.

Hawkes (1957) provided a working definition of geochemical prospecting or exploration geochemistry which is appropriate to this day:

> Geochemical prospecting for minerals…includes any method of mineral exploration based upon systematic measurement of one or more chemical properties of a naturally occurring material.…The purpose of the measurements is the discovery of a geochemical "anomaly" or area where the chemical pattern indicated the presence of ore in the vicinity.

The focus is on applying geochemistry to ore discovery.

Exploration is but one step in what Mackenzie refers to as "the mineral supply process" that provides mineral products to society (Mackenzie and Woodall, 1988). This process has both technical and economic dimensions. Exploration itself consists of a series of stages that, if successful, move from concept to profitably operating mine (Eimon, 1988). It is a high-risk activity. The objective is discovery. Science and technology are used in exploration in an effort to reduce this risk (Muessig, 1979). Adams (1985) reminds us to focus on developments that will provide our organizations with competitive advantages. Woodall (1984) provides insight into the mix of technical and human inputs necessary to exploration success. The objective of each exploration tool is then to provide specific discovery information upon which meaningful exploration decisions can be made, at minimum cost (Bailly, 1972). Geochemistry provides a selection of such tools.

The charge for this paper was to review important advances in the field of exploration geochemistry since Exploration '87 (Garland, 1989) to reflect on how these advances will evolve in the next decade, and to offer perceptions of what will be the exciting new developments in the

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future. Although influenced by discussions with numerous fellow exploration geochemists, this overview does represent an individual viewpoint. It will be structured in the following manner: a) natural progression or evolution of concepts and technology, b) new developments, c) new roles, d) education and research, and e) expanding horizons. Detailed reviews of subdisciplines within the field of exploration geochemistry and their integration into the overall exploration process are provided by specialty experts elsewhere in this volume. Govett (1986) and Coope (1992) also offer overviews of the field.

NATURAL PROGRESSION OR EVOLUTION OF CONCEPTS AND TECHNOLOGY

After conception of an idea or development of an instrument, improvements and advancements commonly occur incrementally over time. Important advancements of this type are considered under the headings of the five major components of a geochemical program: a) design and planning; b) field sampling; c) sample preparation; d) chemical analysis; and e) data presentation and interpretation.

Design and planning

Effective design and planning of geochemical surveys are based, to a large extent, on a clear definition of the target and a full appreciation of the landscape in which exploration will be carried out. Geochemistry both contributes to and draws from improvements in mineral deposit models. Recent compilations by Bliss (1992), Kirkham *et al.* (1993), and Eckstrand *et al.* (1995) provide updates on those by Eckstrand (1984) and Cox and Singer (1986). These models provide mineralogical, geochemical, and geometrical characteristics of deposits that are essential in proper survey design. As an example, White and Hedenquist (1995) first provide the general characteristics of each of the major styles of epithermal gold mineralization: low-sulfidation style and high-sulfidation style. Secondly, they emphasize the distinctions between these styles that must be appreciated to appropriately apply geology and exploration technologies, such as geochemistry, in the evaluation of such targets.

The conceptual models or landscape geochemistry framework was introduced as a means for explorationists to synthesize, by physiographic domain, extensive data from surficial geochemical exploration (Bradshaw, 1975; Fortescue, 1992). These conceptual models are as significant to surficial exploration geochemistry as mineral deposit models are to the economic geologist. Since the Exploration ’87 meeting, two additional conceptual models volumes have been published. Kauranne, *et al.* (1992) provide coverage of Fennoscandian perspectives to exploration geochemistry in Arctic and temperate terrains. Butt and Zeegers (1992) describe regolith exploration geochemistry in tropical and subtropical terrains. This latter volume was both most timely, in that exploration effort was shifting into these terrains, and very significant, in providing documentation of the occurrence of lateritic and supergene mineralization formed within the regolith during weathering. The evolving development and application of these models are central to progress in exploration geochemistry.

Access to information in the exploration literature is fundamental to effective survey design and implementation. The Association of Exploration Geochemists now has its bibliography available in an electronic format to assist in this task (Grunsky *et al.*, 1995).

Sampling

Field sampling involves both “what” and “how” considerations. Selection of appropriate sample media is dependent upon an understanding of geochemical dispersion mechanisms and responses to mineralization operative under the specific landscape conditions of the search area. Recognition of these materials in surface or drill programs can be a non-trivial task. Failure to correctly identify appropriate sample material can lead to misinterpretation and lost or wasted opportunities. Training of sampling teams under the direction of experienced personnel will go a long way to minimizing these risks.

Hale and Plant (1994) have recently edited a volume on drainage geochemistry. Basic principles and techniques are reviewed and information is provided on the application of drainage surveys to the search for a variety of types of mineralization in different environments worldwide. This volume will be the definitive reference in this aspect of exploration geochemistry and will serve as the departure point in designing effective surveys.

A major problem for gold exploration at the time of Exploration ’87 was sample representativity and analytical reproducibility related to the nugget effect (Nichol *et al.*, 1989). Consideration of sampling theory suggested that the problem could be addressed by collecting larger samples. While technically sound, this solution was, in most instances, impractical. More recently Xie and Wang (1991) have demonstrated that by using a sensitive method for gold (detection limit 0.2 ppb) and an “ultrafine” gold (< 5 μm) fraction, conventional samples of 5 to 20 g were sufficient to provide reproducible regional anomalies for subsequent follow-up. Particle size distribution studies of potential sampling media will establish if sufficient fine fraction material is available and, coupled with the improved gold analytical procedure, will provide effective areal assessment (Fletcher and Day, 1988; Nuchanong *et al.*, 1991). Under such conditions, a vexing problem has been resolved.

Sample preparation

The nugget effect issue related to gold exploration drew attention to the wealth of techniques and expertise available in the allied mineral processing field. Saheur *et al.* (1993) provided a comprehensive review of the principles, practices, and sampling representativity considerations involved in the application of sample preparation to exploration geochemistry. These techniques also have application in addressing sampling representativity problems in diamond exploration and evaluation (Griffin, 1995).

Chemical analysis

Hall (1996) reviewed the field of geoanalysis for the period 1970–1995. Second generation inductively coupled plasma mass spectrometers (ICP-MS) and inductively coupled plasma emission spectrometers (ICP-ES) now constitute core instrumentation in geochemical laboratories. Increases in automation, productivity, and range of elements determined are coupled with decreases in detection limits and analytical costs. These lower detection limits have given new life to hydrogeochemistry.

Earlier workers recognized the significance of sorption and the potential of partial extraction procedures to aid in discrimination of true versus false anomalies (for example, Horsnail and Elliott, 1971). There has been a rebirth of interest in partial, selective, and sequential extraction analysis in exploration geochemistry. Attention has been focused on metal associated with organic complexes, manganese oxides, and amorphous iron oxyhydroxides (Hall *et al.*, 1996a,b). Substantial interest and support for these studies has come from the environmental community. In addition, bulk leachable gold determinations have been employed to address sampling representativity problems (Radford, 1996).

Major oxide and immobile element analyses have been used to establish petrogenetic trends and thereby assess bedrock favorability to host specific mineral deposit types. Major and trace element analyses provide the basis for assessing depletion and enrichment zonation. Examples of these developments include magmatic sulfide deposits (Naldrett *et al.*, 1984), epithermal gold deposits (Clarke and Govett, 1990), porphyry copper deposits (Jones, 1992), and massive sulfide deposits (Wyman, 1996).

Data presentation and interpretation

Exploration geochemistry has, as with all sciences, benefited greatly from the expanded capabilities and reduced costs of personal computers. Many activities, from report writing to data reduction and analysis, are carried out on laptop computers in the field. Geographic information systems (GIS) and image processing capabilities provide means of visualizing, analyzing, integrating, and presenting all forms of geoscience data.

Several specific developments are noteworthy. Garnett (1993) reminds us that to obtain stable solutions from the use of multivariate statistical procedures, there must be at least three times the number of samples as the number of variables (elements) included for analysis. Second, there is a trend to move from threshold determination to pattern recognition analysis to identify anomalous situations. This approach is particularly applicable in the cases of soil gas geochemistry and electrogeochemical surveys. Lastly, the facility of dissecting data populations on the basis of statistical and/or spatial criteria, in real time, on the computer screen provides geochemists much greater insight into their data.

These represent but a few of the numerous developments that have occurred in an evolutionary manner over the last 10 years. Many continue to undergo development and improvement.

NEW DEVELOPMENTS

New development can here refer to brand new or, more commonly, newly rediscovered after a period of inactivity. Many of these rediscovered techniques are dependent upon improvements in instrument technology. Of particular interest is the fact that a number of these approaches provide in situ data and provide the opportunity for faster data turnaround and greater integration of field condition assessment and targeted sampling. Examples include soil gas geochemistry (Klusman, 1993), portable x-ray fluorescence (Glanzman and Closs, 1993), and portable near-infrared spectrometer (Hauff *et al.*, 1989) surveys. While there is a great attraction to being able to conduct in situ, real time geochemical surveys, it must be appreciated that these instruments are sophisticated and require a professional who appreciates both mineral prospect evaluation and the principles and operational aspects of the instruments used. These tools offer great potential but it is unlikely they will be used effectively in the near future by untrained "dirt baggers"!

As noted earlier, there is renewed interest in partial, selective, and sequential chemical analysis as a means of isolating that form of metal in the sample most closely associated with dispersion from mineralization. Smee (this volume) emphasizes that these techniques may be most helpful in areas covered by exotic overburden. Initial results are encouraging; however, our present understanding of the nature of metal migration from bedrock to the surface is limited. Two commercially available partial extraction procedures, enzyme leach (Clark and Cohen, 1995) and mobile metal ion (Mann *et al.*, 1995; Birrell, 1996) are currently undergoing extensive application and field testing and show considerable promise.

Developments in other fields can contribute significantly to improving the effectiveness of exploration geochemistry. Reconnaissance lake sediment geochemistry would not have been as economically attractive without the development of the turbojet helicopter. More recently, public access to the United States military global positioning system (GPS) has revolutionized navigational accuracy in all geoscience fields.

NEW ROLES

In addition to the traditional role of geochemistry in mineral exploration (Hawkes, 1957), two other roles offer contributions from geochemistry to mineral resource development. These are: a) environmental geochemistry and b) ore reserve evaluation.

Environmental geochemistry

Environmental issues are an integral part of mineral resource development by both concern and law. As implied here, there is a distinction between environmental and exploration geochemistry. While there are differences in background, tools, and approaches, the central distinction is the nature of the problem being addressed. Both refer to the application of geochemistry to satisfying human needs within a common natural environment. Both have something to gain from a better appreciation of the other.

Regional drainage surveys have proven to be effective reconnaissance exploration tools. In addition to detecting anomalies related to mineralization, it was also recognized that survey results could contribute to regional geological mapping. Over the years these regional surveys were carried out by individual companies and governments. In addition to mineral exploration, geochemical mapping is also relevant to soil fertility assessment, agriculture, human health, land use planning, and the establishment of baselines for both exploration and environmental purposes. The Wolfson geochemical atlas of England and Wales was one of the first multipurpose studies (Webb *et al.*, 1978). The Nordkalott project provided an example of international cooperation in conducting regional geochemial surveys (Bolviken *et al.*, 1986). In 1988 the International Geochemical Mapping project was initiated under the joint sponsorship of the International Union of Geological Sciences and UNESCO (Darnley, 1995). The program is currently in its second phase with the overall objective of establishing a systematic global geochemical database. Much of the early expertise and even data sets came from the mineral resource sector. Government economic constraints worldwide suggest that unified support and participation by all interested parties would be mutually beneficial.

The geological and geochemical characteristics of mineral deposits have both exploration and environmental implications (Plumlee and Logsdon, 1997). Preliminary descriptive geoenvironmental mineral deposit models have been proposed by the U.S. Geological Survey (duBray, 1995). They can be used to recognize and address, at an early stage, the environmental consequences of selecting, exploring for, and exploiting a particular deposit type. For example, sulfide-bearing deposits carry a potential liability associated with their acid rock drainage generation potential.

On a property scale, environmental geochemistry surveys typically must meet strict regulatory guidelines to qualify as bona fide baseline studies. Glanzman and Closs (1993) argue that these requirements actually provide a stimulus to conduct more detailed and comprehensive orientation surveys. This, in turn, benefits both the quality of the exploration geochemistry evaluation of the property and the establishment of a documented baseline condition for use in determining future environmental liability. Claridge and Downing (1993) and Downing and Giroux (1993) describe such a program carried out at the Windy Craggy massive sulfide deposit in British Columbia.

Ore reserve evaluation

An appreciation of the geological and statistical aspects of sampling, the selection of analytical techniques and the evaluation of geochemical data is part of the stock in trade of exploration geochemists. These activities are also essential components of ore reserve estimation (Vallee *et al.*, 1992). Whether it be for preliminary exploration assessment, advanced stage project evaluation or due diligence, an individual with experience in exploration geochemistry would be a valued member of the assessment team.

Environmental geochemistry and ore reserve evaluation would commonly be considered on the fringe of exploration and exploration geochemistry. They are, however, activities that are essential to the overall mineral supply process and additional opportunities for geochemistry to contribute more fully to mineral resource development.

EDUCATION AND RESEARCH

Nielson (1997) has pointed out that there is a worldwide mining exploration boom going on—help wanted! Countering this trend, there is a falloff in students pursuing careers in economic geology, particularly in North America. Furthermore, there is concern that university curricula are de-emphasizing fundamental courses, such as field geology, that are essential to the training of economic geologists. This situation is leading to a shortage of qualified staff for industry.

Exploration geochemistry, as a subdiscipline within the field of economic geology, suffers similar concerns. This is occurring at a time when the use, sophistication and cost of geochemistry is increasing. There is a need to raise the level of competency in applying geochemistry in mineral exploration. Education and research are vehicles for achieving these improvements.

Taylor (1997) recently reviewed the Australian universities' education programs and found them wanting. In particular, too little attention was given to understanding the local landscape as a foundation for a career in mineral exploration. His analysis is constructive and a model for other countries to follow.

Bloom (1969) reported on a panel discussion on the topic: The education of the exploration geochemist. It is worth a reread. The practice of having graduate students work on real world problems, supplied and supported by industry, initiated under the direction of Professor John Webb at Imperial College, London, has contributed several generations of exploration geochemists to the mining and environmental industries. More recently, the projects of the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) Laterite Geochemistry group have, and continue to, provide training under a similar strategy (Smith, 1996). Many of these projects address precompetitive research topics and have been partially funded by consortia organized by the Australian Mineral Industry Research Association (AMIRA) (May, 1995). A similar organization was formed in Canada in 1992 to manage and co-ordinate co-operative exploration research: Exploration Division of the Canadian Mining Industry Research Organization (CAMIRO) (Debicki, 1996). Industry has considerable input to the direction of the research. Despite these efforts, there is a shortage of trained exploration geochemists!

EXPANDING HORIZONS

Advances in the following areas are anticipated in the next decade. Several of these areas were suggested by Closs and Nichol (1989) at Exploration '87, again emphasizing that change is ongoing.

1. Fuller utilization of available low-cost multi-element data. Currently, we often still only look at samples having the highest contents of ore and associated pathfinder elements.
2. Computer-based data analysis and visualization techniques will aid in extracting more process-type information from our data.
3. Development of greater analytical capability with geographic information systems (GIS) to permit fuller assessment of all geoscience data.
4. Refinement of mineral deposit and conceptual (surficial) models. As the Canadian Shield, Canadian Cordillera and Basin and Range conceptual models are now 20 years old, they would benefit from formal updates. Further development of geoenvironmental mineral deposit models should be encouraged.
5. Increasing exploration activities in areas of exotic cover will spawn fundamental and applied studies of processes of dispersion such as evapotranspiration, atmospheric pumping, electrochemical migration (CHIM, Smith *et al.*, 1993) and vapor transport.
6. Hawkes and Webb (1962), while acknowledging the need for specialists for each geoexploration subdiscipline, speculated that at some point in the future, it may be necessary to develop a specialized field devoted to co-ordination in mineral exploration. With the increasing diversity and sophistication of all exploration technologies, are we now at that point?

Finally, even with all these new developments to assist us, it often is the fundamental concepts and techniques that trip us up. The following guidelines, prepared by Davis (1986) on the occasion of a tribute to Professor John Webb in 1983 at Imperial College, London, are timeless.

Webb's Evergreen guidelines

1. Attention to detail in design.
2. Importance of orientation studies.
3. Effective communication between industry and research groups.
4. Awareness of advances in related technologies.
5. Power of overlap between pure and applied science.
6. All patterns arising from a geochemical survey should make geological sense.

CONCLUSIONS

The basic principles of exploration geochemistry have been established. As the discipline matures the developments that are forthcoming commonly represent more detailed knowledge of existing techniques and improvements in technology to better execute the techniques. Opportunities for breakthroughs in theory, concept, and technology are ever present.

The five major components of a geochemical program are: a) design and planning; b) field sampling; c) sample preparation; d) chemical analysis; and e) data presentation and interpretation. These are both sequential and interactive. Success is controlled by the weakest link. Attention to detail in both the components and their integration in a given program are still essential.

Mineral exploration is market driven. In the last decade exploration geochemistry has responded to the needs of gold exploration in tropical and subtropical terrains. More professionally trained exploration geochemists are needed to meet the increasing use of geochemistry in mineral resource development, whatever the target and wherever the exploration activity will be conducted.

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