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Future Research Directions in Exploration Geochemistry: Is There A Future?

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ABSTRACT

Although there have been some major breakthroughs in the field of exploration geochemistry over the past ten years, there is still much work to be done to advance the understanding of geochemical processes in different environments and proper application of exploration geochemistry in mineral exploration. Some future research directions in exploration geochemistry will include: 1) detailed mechanistic studies of processes affecting the mobilization, transport and fixation of metals that result in patterns of soil geochemistry, gas compositions and other indicators of concealed mineral deposits; 2) further developments in heavy mineral indicator techniques, starting with cheaper and more effective separation methodologies, to evaluate both their distribution and, in particular, their mineral chemistry to determine elemental signatures for an expanded range of deposit types; 3) assessment of survival rates of minerals, in particular sulphide minerals, dispersed through various types of surficial materials associated with a variety of mineral deposit types in differing geological, surficial and climatic regimes globally; 4) evaluate the usefulness of the isotopes of various elements such as Pb, Se, Cu and Hg which could potentially help determine the transport mechanisms for elements released from bedrock to sites of surface accumulation; 5) further examination of the application of groundwater, and other types of water, to determine geochemical signatures for different mineral deposit types in order to establish the potential, the limitations, and the workable protocols for these methods; 6) development of field portable instrumentation for multielement and multispecies analysis of waters and soil gases; and, 7) further refinement and development of visualization and interpretation techniques, particularly within a GIS context. There also needs to be a return to the application of fundamental regional reconnaissance scale geochemical surveys and an increasing awareness of the role that geochemical data can play as environmental baseline data. The biggest problem in the immediate future however, will be the survival of "exploration geochemists" due to the aging of the small population of existing geochemists and the global decline in opportunities for the education, development and training of young exploration geochemists.

INTRODUCTION

In this article, a few key recent references are reviewed as a basis for indicating the status and direction of the science and to give some context to the author's comments on potential future research directions. This paper builds on a recent paper by Kelley et. al. (2006), which examines a variety of far field features of different ore deposit types and considers applications, including geochemical techniques, to their exploration and discovery; and, the paper by Cohen et. al. (this volume), which summarizes significant advances through the past decade in the field of exploration geochemistry. As exploration moves to areas of increasingly thicker cover, geochemistry must focus on understanding the mechanisms that: **control the release and speciation** of metals from ore buried beneath this thick cover; **mobilize and facilitate transport** of the resultant metal species from depth to the surface environment; and, result in the accumulation of metals in various surficial media. Understanding these mechanisms will greatly improve our understanding of and ability to effectively develop and apply

techniques such as selective extractions, gas geochemistry and groundwater geochemistry as well as to correctly interpret and dynamically present the results of such techniques in our search for concealed ore bodies.

There is also a definite need for a return to the "basics" of exploration geochemistry including the proper application of geochemical techniques throughout the various stages of exploration from reconnaissance to detailed follow-up. The role that geochemical data can play as environmental baseline data will become increasingly important in the future. But, of greatest concern to the mineral exploration industry must be the survival of "exploration geochemists"!

PROCESSES CONTROLLING METAL MOBILIZATION, TRANSPORT AND ACCUMULATION IN THE SURFICIAL ENVIRONMENT

In recent years, there has been a concerted effort towards examining: the processes of metal mobilization associated with concealed mineral deposits; the mechanisms of metal transport

through the overburden cover; and, the resultant accumulation of these vertically transported metals in surficial media as pertains to exploring for mineral deposits under cover. And although the presence of secondary geochemical anomalies in transported overburden above buried mineral deposits has been well documented (e.g. Cameron et al. 2004, Kelley et al. 2003, Wang et al. 1999, Smee 1983,1998; Mann et al. 1998, 2005), there is still much debate regarding the factors that control the formation of these anomalies. Research conducted in the past ten years has examined some of the most likely processes involved.

Electrochemical Dispersion

A recent model developed by Hamilton (1998, 2000) proposes that the upward propagation of reduced species to the water table forms a reduced column over the mineralized zone and the development of geochemical anomalies in the overlying surficial overburden. The oxidation of Fe²⁺ and its precipitation in ferric oxy-hydroxides causes acid production and dissolution of carbonate, which precipitates at the edge of the reduced column where the pH is higher. Theoretical ion migration rates in electrochemical fields are much faster than diffusion rates and are consistent with the formation of geochemical anomalies at surface in young (~8,000 yr) thick glacial sediments overlying mineral deposits (Hamilton, 1998; Hall et al., 2004). Given that H⁺ is the most mobile and one of the most reactive aqueous species, sustaining its presence over the reduced column in a high-rainfall, high-carbonate environment requires a continuous process (Hamilton et al, 2004b).

Several detailed investigations of surficial geochemical responses over deeply buried sulphide-hosted gold and VMS deposits in northern Ontario have been carried out (Cameron et al., 2004; Hall et al., 2004; Hamilton et al., 2004a, b). Using samples from overburden drilling and trenching, they characterized pH, oxidation-reduction potential and self potential in overburden that covers the mineralized zone and confirmed the presence of a reduced column and other features, including local zones of acidic groundwater, metal deposition, CO₂ enrichments, O₂ depletions, carbonate remobilization, groundwater temperature anomalies, and piezometric highs at the edge of the reduced column (Hamilton et al., 2003, 2004a, b), all of which are supportive of the redox-gradient model of Hamilton (1998, 2000). The piezometric highs may be a previously undocumented form of electro-osmosis, a process where fluid flow is induced by an electrical field (Hamilton et al., 2003). In addition, selective extractions and Pb isotope studies carried out in the VMS example (Hall et al., 2004) strongly suggest that Pb was transported into the exotic overburden from the sulphides below.

Evaporation – Transpiration-Convection

Mann et al. (2005) carried out laboratory experiments that suggest capillary rise and evaporation may play a role in where elements accumulate in the soil profile. Root-zone transpiration may also affect solute deposition and adsorption in the evapo-transpiration zone. In addition, they indicated that perhaps

downward-percolating groundwater after rainfall as well as the upward effects of capillary rise could explain many features of ion emplacement in soils. Their laboratory modeling also suggested that convection from heat produced by deposit oxidation could in some cases be a method for rapid rise of ions below the water table.

Cyclical Dilatancy Pumping

Cameron et al. (2002) proposed that cyclical dilatancy pumping could explain the development of surface geochemical anomalies in areas with a thick vadose zone. Results of soil and groundwater analyses from an integrated study at the Spence porphyry copper deposit in northern Chile, which is buried beneath 50 to 100 m of Miocene gravels, are consistent with the vertical movement of saline metal-rich groundwaters along fractures during earthquakes in this seismically active area (Cameron et al., 2002; Cameron and Leybourne, 2005). Copper in groundwater is restricted to the mineralized area due to the tendency of Cu²⁺ released by the oxidation of sulphides to adsorb to Fe hydroxide colloidal particles and coatings, whereas elements that dissolve as anions as controlled by pH (e.g., As, Mo, Se and Re), are dispersed widely.

Additional evidence for the Cu anomalies in soil being related to cyclical dilatancy pumping comes from the presence of atacamite, a secondary mineral in the oxide zone of many deposits in northern Chile (Cameron and Leybourne, 2006). Atacamite is soluble in low-salinity water and would have been removed from the supergene profile if it had formed as a primary oxidation product during supergene weathering. The composition of saline groundwater at Spence falls within the stability fields of the atacamite-brochantite assemblage and suggests that atacamite is formed by the replacement of original copper oxide minerals by saline basinal fluids being pumped vertically through the deposit.

Despite all of the research and practical application of the resultant geochemical techniques over the past decade, there is still no single process that definitely explains the vertical migration of elements, from a buried mineral deposit to the surface, both above and below the water table; it is most likely that multiple processes occur in any given terrane (i.e. desert versus arctic). There is therefore a critical need to continue research on selective extractions and soil gases to further understand the processes and rates of element / compound dispersion and the resulting formation of anomalous surface responses indicative of buried mineral deposits. The role of the biological compartment in the subsurface and surficial environments and its effect on the aforementioned phenomena is discussed immediately below.

Biogeochemistry / Geomicrobiology / Soil Gases

There are numerous examples in the literature of the utilization of both vegetation and microorganisms in the search for mineral deposits of various types. Dunn (2007, this volume) reviews the use of various plant species and their organs in the exploration for a variety of mineral deposit types over the past several decades. And, although examined to some extent previously

(Pardulum, 1987), the roles of the various types of bacteria (e.g. aerobic, anaerobic, sulphate reducing (SRBs), etc.) in the development of secondary geochemical features associated with a range of ore deposits has received much more focused attention in the past decade. For example, recent work by Goodhue and Southam (2004) demonstrated how the distribution of SRBs highlights the reduced column developed above the concealed Cross Lake VMS mineralization (Hamilton, et. al., 2004a and b). The enrichment of SRBs requires sulphate, which has presumably been transported upwards from the Cross Lake VMS mineralization itself.

Several studies have also examined the processes going on between concealed orebodies and surficial geochemical anomalies with regard to the linkage between microorganisms and metal mobility and transport. Studies of gold and base metal mines in the Precambrian Shields of Canada and South Africa have shown that gases (methane, ethane, propane, butane and high concentrations of hydrogen) are the products of the long-term water-rock reactions with ore and their host rocks (Sherwood Lollar et. al., 2002). Deep subsurface microbial communities are shown to play an important role in cycling carbon and potentially metals (Sherwood Lollar et. al., 2006). Work on both porous media and aquatic sediments has investigated the processes whereby microbes, gases and charge gradients can cause metals and elements to migrate through various media in the subsurface (Edwards et. al., 2000). For example, a number of microbial associations have been implicated in the generation of gases above buried deposits (sulphur reducing bacteria (SRB)), dissimilatory iron reducing bacteria (DIRB), methanogens, and methanotrophs) have been shown to influence gas generation above a buried deposit. Therefore, beyond electrochemical and diffusive mobilization of metals above economic deposits, it is necessary to begin examining the effect of rising gas bubbles on element mobility (Piotrowicz et. al., 1979).

There is still much more work to be done towards understanding the roles that various microorganisms undoubtedly play in the formation of secondary geochemical features, in both the surficial and subsurface environments, that can be used in exploration to vector towards economic ore deposits. In this context, there needs to be more work focused on geomicrobiology with respect to the mobilization, transport and fixation of metals that result in anomalous surface soil/gas/microbial or bacterial population etc. responses related to concealed mineral deposits. AMIRA P778 - Predictive Geochemistry in Areas of Transported Overburden follows on from past CAMIRO projects on this subject.

HEAVY MINERAL INDICATOR GEOCHEMISTRY

Indicator minerals are heavy mineral grains that can reflect the presence of a specific type of mineralization through their abundance and/or particular mineral chemistry. Indicator minerals have been used for centuries to explore for a wide range of deposit types (McClenaghan, 2005). Over the past couple of decades, advances in analytical technology, particularly microanalytical methods (e.g. laser ablation ICP-MS) applied to individual mineral grains has helped to advance

the understanding of key diagnostic mineral chemistries, particularly for diamond exploration (Gurney, 1984; Gurney et. al., 2005). And even more recently, there have been definitive advances made in the use of heavy indicator minerals in the exploration for magmatic or metamorphosed base metal sulphide deposits (Averill, 2001, 2007a, b).

As well, there needs to be an examination of how heavy mineral indicators can be used more effectively in an exploration program. Cheaper and more efficient separation techniques are important, to better evaluate both their distribution and in particular their mineral chemistry to determine element / compound signatures for an expanded range of deposit types. In this regard, there are a number of current research projects, within CAMIRO and AMIRA, that are investigating the viability of refining and/or developing diagnostic indicator mineral chemical signatures indicative of prospective terrains or which could be used to vector in to Ni-Cu-PGE, porphyry Cu or IOCG deposits.

There is also work to be done to understand the relative survival rates of various heavy mineral grains, as they are dispersed through various types of surficial materials associated with a variety of mineral deposit types in widely differing geological, surficial and climatic regimes around the world. In this context, of particular interest to many explorationists are the survival rates of sulphide mineral grains.

ISOTOPE GEOCHEMISTRY

There is a considerable amount of information and numerous examples available in the literature on the use of stable and/or radioactive isotope signatures as: 1) indicators of permissive conditions for the presence of significant mineralization (sulphur); 2) as distinctive indicators of source materials for geological systems (oxygen, hydrogen and carbon); and, 3) as a means to differentiate, through isotopic differences (i.e. zoning), between mineralized and background zones, as reviewed in Kelley et. al. (2006).

To date, only limited work has been done on the usefulness of isotope signatures for a few elements (Pb, Se, Cu and Hg), which can now be determined with acceptable quality by high resolution and multi-collector ICP-MS techniques (Caughlin, this volume), for fingerprinting the source(s) of the element accumulated in a given sample medium (surface and ground waters or surficial materials) within the surficial environment. An example of the power of this approach are the Pb isotopic studies from selective extractions of surficial soils over a VMS site (Hall et. al., 2004) that strongly suggests that Pb was transported into the exotic glacial overburden from the concealed sulphides beneath.

Increasing research on stable isotope systematics (i.e. Cu, Se, etc.) in surficial materials will help us understand and identify the possible isotopic fractionations that occur and document the ranges of values associated with the various surficial environments (Leybourne and Cameron, this volume). Research is also required to develop cheaper and faster sample preparation and analytical methods for isotope analyses. All of this could go a long way towards helping to determine the transport mechanisms for elements released from bedrock to

their accumulation within surficial media (i.e. contribute to understanding of processes).

GROUNDWATER GEOCHEMISTRY

As reviewed and summarized by Leybourne and Cameron (this volume), groundwater geochemistry has the potential to be a powerful mineral exploration tool as exploration moves to searching for deeply buried deposits under thicker cover. There are several reasons for this, as detailed by Leybourne and Cameron (this volume) including the following: advances in analytical technology enabling rapid and sensitive multielement determinations; the potential to explore in the third dimension using groundwaters; groundwaters are chemically reactive with mineralized zones and host rocks; groundwaters flow away from the site of reaction with mineralization, providing a potentially broader exploration target than litho-geochemistry; the sample preparation required is minimal; and, background concentrations are low for many species of interest, thereby enhancing anomaly contrast.

Even though there are many examples documenting the use of water geochemistry in mineral exploration, applications of detailed groundwater studies are limited. Groundwater must come into contact with the mineralization being sought in order for a geochemical response to actually occur. Several examples of the nature of groundwater responses associated with a variety of ore deposit types are summarized in Leybourne and Cameron (this volume).

Unfortunately, the application of groundwater geochemistry for mineral exploration does not meet its potential when explorationists fail to interpret the geochemical data in context. Understanding mineral saturation indices and metal speciation, which require good quality and complete physicochemical data (including pH and some form of oxidation-reduction potential), is paramount to the successful application of groundwater geochemistry for mineral exploration. Thus, further evaluation of the application of groundwater, as well as other types of water chemistry, to determine element / compound signatures for different mineral deposit types is necessary. This will help to establish the potential, limitations, and workable protocols for these aqueous geochemical methods and thereby definitely advance their use in mineral exploration as it moves to areas of thicker cover around the globe.

FIELD PORTABLE INSTRUMENTATION FOR WATER AND GAS ANALYSES

It may be possible to adapt sampling procedures and portable field equipment used in the environmental industry for use in the mineral exploration industry for water and gas analyses. In particular analytical instrumentation such as portable instrumentation for water (Hach, Sencore, etc.) and gas (e.g. Leybold-Inficon Hapsite GC-MS, etc.) (Meuzelaar, et al., 2000) analyses, could be used in mineral exploration.

As discussed by Glanzman and Closs (this volume) there is increasing use of field portable instrumentation in mineral exploration. Usage is driven by the immediacy of results

enabling rapid assessment in the field of the direction of the exploration program. Compact field portable XRF devices can deliver good quality analytical data when used by qualified personnel, eliminating longer turnaround for data from the laboratory. Together with field portable infrared instruments (PIMA, ASD) for mapping alteration mineralogy, it allows rapid and effective reconnaissance of prospective mineralized zones. Visualization and Interpretation Techniques for Geochemical Data

As summarized in Grunsky (this volume), developments in software over the past ten years, in terms of the increase of data capacity, improvements in visualization and statistical methods have made enormous contributions to the way that exploration geochemists can evaluate and integrate all types of geoscience data. There has also been extensive growth in the field of multivariate data analysis and statistics during the past decade. Integrating spatially referenced data, in a geographical information system (GIS) framework, with multivariate geochemical analyses and field observations is an area that is undergoing many interesting developments. Increased integration of multivariate methods together with spatial analysis will provide a comprehensive approach to assessing all spatially reference multivariate data.

There is definite need to continue the research and development on geochemical visualization and interpretation techniques, particularly within a GIS context. (i.e. to allow the integration and assessment of geochemical data within the context of all the other spatially referenced geoscientific data available). It is also important to remember that while there are statistical / mathematical multi-element geochemical patterns and associations there are also spatial / areal geochemical associations that exist and should not be overlooked. Newly developed geochemical data exploratory software, such as ioGas (www.ioglobal.net), is a powerful tool for looking at inter-relationships amongst geochemical, field observational and spatial data. There is also a need to develop better 3D capabilities for the examination and display of integrated geoscientific datasets that are more and more common in mineral exploration.

BACK TO BASICS – REGIONAL RECONNAISSANCE GEOCHEMICAL SURVEYS

A return to fundamental regional reconnaissance scale geochemical surveys is critical for the future of exploration. In particular, regional surveys must continue to be an important focus of exploration geochemistry within government geological surveys. However, future surveys must be integrated studies, both at the design, implementation and sampling phases as well as, and very importantly, at the data interpretation phase (i.e. geochemists, geophysicists and geologists working together to plan, implement and interpret). The Tellus Project carried out recently in Northern Ireland is a good example of the type of modern integrated ground geochemical and airborne geophysical surveys that are needed by the mineral exploration industry (Smyth and Johnson, 2007).

There is a definite need by mineral exploration companies to get back to some basic conventional geochemical

methodologies. This needs to be done using “modern day approaches” for sample collection (type of medium/media), preparation (size fraction) and analyses (more elements to lower detection limits – ICP-MS). In addition, newly developed or newly applied techniques should be implemented. These could include, although not necessarily exclusively: 1) regional heavy mineral sampling, for commodities other than diamonds (HMCs from glacial and drainage sediments); 2) regional residual and/or transported surficial material sampling (tills, soils, etc.); 3) regional drainage sampling (stream and lake - sediments and waters); and, 4) regional groundwater sampling (well waters). These aforementioned geochemical approaches in regional geochemical sampling programs are cost effective methods for assessing and prioritizing large areas for their mineral potential. The overriding question that needs addressing is: “Are exploration companies actually utilizing geochemistry efficiently and effectively throughout their exploration programs?” In this context, there are a number of critical issues to be considered: 1) does the company have the personnel capable of organizing and running geochemical programs (design, collection, analyses, QAQC, etc.) and of carrying out an integrated multi-disciplinary interpretation employing the geochemical data obtained; 2) is geochemistry even considered as one of the datasets to use for program / project / target generation, or is it still primarily geophysically driven; 3) is the company even aware of, and if so, does it use the geochemical data available within the targeted region (i.e. from government agencies, JV partners, UN, World Bank, historic data from the company itself); 4) if available for a given region, in what era was the regional geochemical survey carried out (i.e. is there an opportunity to apply “modern” sampling, analytical and interpretive methodologies to the same area); and, 5) does the company really have adequate QAQC protocols in place to properly assess the quality of all of the analytical geochemical data it acquires?

To advance exploration programs / projects, companies need to more effectively utilize geochemical approaches in their exploration programs / projects. In so doing, the company must first assess its internal geochemical expertise and the availability of existing geochemical data for the program / project area.

ENVIRONMENTAL ASPECTS OF GEOCHEMICAL DATA

Going forward, there must be more awareness by mineral exploration companies, and the geoscientists employed by these companies, of the role that geochemical data can play in establishing environmental baselines. However, samples and analytical data pertaining to them must be properly collected under applicable regulatory codes within the mining industry as well as those related to environmental protocols.

EXPLORATION GEOCHEMISTS - WHERE ARE THE FUTURE ONES?

Perhaps the most significant problem that exists today, which is becoming increasingly problematic for the mineral exploration

industry, is the survival of true “exploration geochemists”. This is a result of the aging, fast-retiring and basically small population of existing exploration geochemists coupled with the globally declining opportunities for the education, development and training of young exploration geochemists. This in turn means that there is a lack of university researchers in the field of applied exploration geochemistry to carry out any proposed new research. To rectify this, there is a need to capitalize on the still present applied exploration geochemistry expertise. Establishing “Chairs in Exploration Geochemistry” within selected universities is a good mechanism for preserving this expertise and for teaching applied exploration geochemistry in order to produce the next generation of exploration geochemists.

Concluding Comments

Multidisciplinary exploration teams utilizing all of the available geoscientific data, including geochemical data, in a GIS framework will be where the successful new discoveries will come from in the future. Significant new breakthroughs in exploration geochemistry may likely come from developments outside of the traditional geosciences, such as in the environmental, biological, microbiological, health, aerospace, etc. disciplines, which will be modified and adapted for use in mineral exploration.

Exploration geochemists, and the science of geochemistry, are at a definite critical stage in their history. If the mineral exploration industry does not rise to the challenge and do something immediately to ensure the long-term survival of geochemists and exploration geochemistry they will both disappear as contributors to the successful discovery of new ore deposits in the future.

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