

Application of 3D Geochemistry to Mineral Exploration

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ABSTRACT

The development of sophisticated 3D visualization software has made it possible to fully integrate geological, geochemical, and geophysical data in three dimensional space creating new opportunities to explore data relationships. The advent of inexpensive, multi-element ICP-MS (inductively coupled plasma-mass spectrometry) analysis techniques with low detection limits has led to the identification of zoned element associations and their spatial relations to ore with great efficiency and clarity. Geochemical modeling of down-hole data has advantages in pattern recognition by facilitating the creation of 3D volumes. This is achieved by producing individual element block models using a gridding algorithm to interpolate concentrations between drill holes. The block models provide an effective means of exploring relationships in the down-hole data and integrating this information with other subsurface data (geologic lithology logs, geophysical inversions) and surface data (geochemistry, geology, and geophysics). A key prerequisite for geochemical modeling is the acquisition of down-hole data distributed in a generally systematic fashion along each hole. Some inconsistencies in a geochemical database that need to be addressed prior to modeling include: 1) relative accuracy shifts over time in data reported from a single laboratory or between different laboratories; 2) variable detection limits amongst datasets; 3) mixed partial and total extraction data; 4) special values or zeros representing data below detection limit or missing data; and 5) mixed reporting units. Some applications of 3D geochemistry include: 1) stratigraphic correlation using elements not introduced or significantly redistributed during the mineralizing event; 2) development of a conceptual zonation model of a mineral system; 3) identification of vector criteria for locating high grade mineralization based on zonation relationships; 4) distinguishing proximal from distal signatures; 5) improving vectoring by integrating surface and sub-surface data; 6) improving interpretation of surface data by understanding the effects of surface weathering; 7) locating the bedrock source of anomalies in 3D overburden data; and 8) increasing the understanding of mineral systems and dispersion phenomena. Most of these applications are illustrated using a schematic zonation model for Carlin-type sediment-hosted gold systems in Nevada, U.S.A., a 3D model of the Sleeper low sulphidation gold system in Nevada, and a 3D model of mobile ion dispersion in glacial overburden over the Shoot gold zone, Ontario, Canada.

INTRODUCTION

The development of sophisticated 3D visualization software over the last 10-15 years has made it possible to fully integrate geological, geochemical, and geophysical data in three dimensional space. This has created new opportunities to identify data relationships that were not easily recognized or illustrated using 2D map presentations.

Previously, 3D data relationships have been explored using a surface plan map in conjunction with sets of cross sections and long sections. Each map view, whether plan or section, consisted of a set of maps with each containing certain types of information. A compilation of data relationships was achieved by overlaying the various maps. The integration of surface data has advanced with the development of GIS (Geological Information System) software. This has the advantage of being able to explore data relationships in 2D digital space. Some GIS software has introduced a 3D component for viewing data in the third dimension but it remains essentially a 2D map making tool.

Geochemical exploration methods are based on an understanding of the dispersion behaviour of elements in the

vicinity of an ore body (Rose, Hawkes, and Webb, 1979). This has a primary component related to rock and ore forming processes and a secondary component related to near-surface weathering processes. In the primary environment of hydrothermal systems, the distributions of commodity and pathfinder elements relative to a lithologic background composition define the locations where elements were deposited along the dispersion pathways of ore-forming fluids. Groups of elements are commonly zoned in relation to one another and to geological controls on ore deposition. The zonation sequence may provide a vector to the location of high grade mineralization within the system. The topographic surface slices through the 3D zoned system in an arbitrary fashion. The resulting geochemical patterns observed in surface data may be difficult to interpret without at least a conceptual understanding of the 3D zonation relationships.

In the secondary environment, weathering redistributes elements either chemically or physically. This affects the distribution of elements in the weathered bedrock zone above the redox boundary and for some distance below it. Subsequent processes at the surface may disperse elements into unconsolidated overburden. A good example is the mechanical

dispersion of elements in glacial deposits (Bradshaw, 1975; Nichol and Bjorklund, 1973). The elements are displaced down-ice in a three dimensional configuration. Surface anomalies may be displaced from source in complex ways particularly when multiple till sheets are present reflecting different ice advances and dispersion directions.

All these relationships can be better understood by displaying and exploring data distribution patterns in 3D space. Some of the objectives of 3D geochemistry applications are: 1) stratigraphic correlation using elements not introduced or significantly redistributed during the mineralizing event; 2) development of a conceptual zonation model of a mineral system; 3) identification of vector criteria for locating high grade mineralization based on zonation relationships; 4) distinguishing proximal from distal signatures; 5) improving vectoring by integrating surface and sub-surface data; 6) improving interpretation of surface data by understanding the effects of surface weathering; 7) locating the bedrock source of anomalies in 3D overburden data; and 8) increasing the understanding of mineral systems and dispersion phenomena. All these approaches contribute to the development of more effective targeting criteria and higher quality drill targets.

SCHEMATIC DISPERSION MODELS

Success in mineral exploration has been advanced with the development of schematic geological models for various deposit types (e.g., Bliss, 1992; Cox and Singer, 1986; Kirkham et al, 1993). These models describe common features for a particular class of deposit focusing on the relationship of the distribution of mineralization to stratigraphy, structure, and system expression (alteration, geochemistry, geophysics).

The application of geochemistry has also benefited from the development of schematic models. Some of these describe secondary dispersion phenomena in a 3D context (Bradshaw, 1975; Butt and Smith, 1980). However, with respect to the 3D expression of primary dispersion, the level of our understanding varies considerably depending on the deposit type. Mineralogical models are quite common in the literature (e.g., Bettles, 2002; Galley, 1993). Unfortunately, the corresponding geochemical expression of alteration facies is not as well documented although there are some exceptions (Clarke and Govett, 1990; Herrera et al, 1993; Jones, 1992; Kizis et al, 1997; Large and McGoldrick, 1998; Large et al, 2000; Shaver, 1986). The literature is, however, full of orientation-type data consisting of one or more drill holes that cut orthogonally through a zone of mineralization (example: Eilu and Groves, 2001). These generally document anomalous element associations, the width of the halo along drill holes, and alteration indices that increase the width of the halo. Unfortunately, often little information is provided on district-scale zonation to put the local scale halo into context. Relatively fully developed geochemical zonation models exist only for some deposit types, most notably VMS and SEDEX systems (example: Large et al, 2000). Even these are usually lacking information regarding zonation relationships amongst the pathfinder elements.

Key goals of 3D geochemistry are the identification and application of zonation vectors to locating high grade mineralization within a system. Some of these vectors may already be known or inferred from the literature. However, it is more likely that they will have to be developed from data collected on a specific property with known mineralization. The observed relationships can then be applied to targeting on the property using both surface and subsurface data.

ZONATION VECTORING

Most mineral systems are zoned mineralogically and geochemically but what are the important features in these systems that can be applied to zonation vectoring? With respect to geochemistry, these systems exhibit one or more of the following components: 1) various element associations that define different zonation facies; 2) district-scale layers or shells of anomalous geochemistry (sub-horizontal to vertical in orientation); 3) plume-like zones of anomalous geochemistry; 4) a proximal to distal zonation sequence; 5) a geologic context to the zonation sequence relative to intrusions, host lithologies, structure, and weathered surfaces; and 6) an effect of scale that may be fractal in nature. Key vectors to the location of high grade mineralization in the system include: 1) lateral zonation sequences; 2) vertical zonation sequences; 3) vertical plumes; and 4) plunge alignments.

Lateral zonation sequences or halos may exist on a local or regional scale reflecting some primary control on element deposition such as temperature/pressure or a fluid mixing boundary. These sequences are developed in a variety of configurations: 1) in the plane of structures; 2) along ore-controlling lithologic boundaries; 3) along blanket-like layers or shells of anomalous geochemistry cross-cutting stratigraphy and structure; 4) in relation to intrusive centres; and 5) in the plane of the redox boundary.

Vertical zonation sequences may also be present. In some systems, ore deposits are located in some preferred position within the vertically zoned sequence due to geological or geochemical controls on ore deposition. This relationship helps define a favourable depth interval for the location of ore.

Vertical plumes are another vector to ore. They are common in many zoned systems that form from ore fluids ascending toward the surface along open structures. The plumes define areas of focused fluid flow where there was a sufficient volume of fluid to deposit the quantities of the commodity elements required to produce an economic ore deposit. Deposits occur at some position within the plume due to the influence of some vertical control on ore deposition. The portion below the level of the deposit is referred to as a feeder plume and the portion above is called an exit plume.

The plunge alignment of drill intercepts is another type of vector. It usually is the result of intersecting structures or the noses of folds that control fluid flow and ore deposition. Knowledge of the plunge direction enables effective targeting of ore extensions. The same concept can be applied to testing for high grade mineralization along the plunge of an exit plume.

All of these types of zonation vectors have a three dimensional character. Interpretation of surface data,

particularly zonation relationships, needs to take into account the arbitrary and sometimes irregular manner in which the topographic surface slices through the zoned system. This can produce some unusual patterns that only make sense in a 3D context.

Geochemical modeling of down-hole data is a way of creating 3D volumes by interpolating concentrations between drill holes. This provides an effective means of exploring relationships in the down-hole data and integrating this information with other subsurface data (geology, geophysical inversions) and surface geochemistry, geology, and geophysics.

DEVELOPING GEOCHEMICAL MODELS

A geochemical model, as distinct from a schematic model, is a term to describe the block models that result from gridding data derived from drill-holes (core, cuttings, auger samples). Concentration values are interpolated at points in 3D space based on the analyses of down-hole samples located within some user-defined search radius of the point being interpolated. The result is a 3D block model for each element with interpolated values assigned to each cell of the model. In this form, data trends and relationships can be explored in a variety of ways in 3D space.

A key prerequisite for geochemical modeling is the acquisition of down-hole data distributed in a generally systematic fashion along each hole. The sampling strategies employed to assay core or RC chips for the commodity elements may not be optimum for trace element determinations. Commonly, sampling for this purpose is selective to drill-hole sections that contain visible mineralization or alteration. Sample widths may not be even, varying in relation to the width of zones or conforming to contacts.

In these cases, additional sampling must be carried out in the unsampled portions of the holes in a manner that makes sense given the style of mineralization and is affordable within budget limitations. For example, structurally controlled deposits likely have a geochemical expression on many minor structures such that the collection of representative samples of a constant width and sample spacing would be sufficient to define broad scale zonation patterns. This might consist of collecting a 1 m sample every 5 m down-hole. Pulp samples from previous sampling should be composited to the same sample width or simply analyzed as is. The resulting data may need to be normalized with respect to width if there is a significant variation in the width of samples. The optimum sample width and interval can be determined by detailed sampling of selected holes as an orientation test.

For some deposit types, it is standard practice to sample holes from top to bottom, as for example in Carlin-type sediment-hosted gold systems. Both stratigraphy and structure exert controls on the distribution of this type of mineralization. A core or chip interval of 1.5 m (5 ft) for assay is common practice. For trace element determinations, pulps that have been composited to something in the range of 6-9 m (20-30 ft) have proven to effectively define the broad expression of geochemical signatures in these systems.

Most historic drill-hole databases build up over time in a series of exploration programs often carried out by different

companies. Inconsistencies in the database arise due to the use of different laboratories and analytical methods. Even with respect to one lab, analytical methods for a particular element may change over time.

These inconsistencies need to be addressed prior to geochemical modeling in order to avoid misleading or erratic patterns in the model. Some common problems in a geochemical database are: 1) relative accuracy shifts over time in data reported from a single laboratory or between different laboratories; 2) variable detection limits amongst datasets; 3) mixed partial and total extraction data; 4) special values or zeros representing data below detection limit or missing data; and 5) mixed reporting units. Problems with the collar and survey files for the drillhole traces also need to be resolved.

Data suffering from relative accuracy shifts need to be leveled to the best degree possible. Various approaches to leveling data have been proposed (Agnew, 1999; Daneshfar and Cameron, 1998). Oftentimes, one dataset is shifted by a consistent percentage amount relative to another making this leveling task fairly easy to accomplish. A simple comparison of population modes derived from histograms may help determine what the percentage shift is provided the data overlap spatially. Display of the assay points in 3D space can be used to assure that the analytical bias has been eliminated. If leveling is not possible, then the sets of data should be gridded separately.

Two digestions in common use for down-hole geochemistry are aqua regia ($\text{HNO}_3\text{-HCl}$) and a 4-acid digest ($\text{HF-HCl}_2\text{O}_4\text{-HNO}_3\text{-HCl}$). Opinions vary with respect to which digestion to employ. At first glance, the 4-acid digest would seem to be the best choice. It is near total for most elements in relation to aqua regia but it suffers from: 1) volatile loss of As, Hg, and Sb; 2) higher detection limits for key pathfinder elements; 3) higher level of analytical noise due to matrix effects; and 4) higher cost of analyses.

Aqua regia is referred to as a partial digestion. It is effective in dissolving sulphides, clays, micas, carbonates, and most secondary oxides resulting from weathering. These minerals commonly make up a significant component of mineralization and alteration in mineral systems. Aqua regia is not effective in totally dissolving common rock forming minerals (quartz and aluminosilicates). Oftentimes, however, many elements are extracted in some consistent proportion to their abundance, as illustrated by a comparison of P concentrations in aqua regia and 4-acid digests (Figure 1). This makes it possible to use aqua regia extractable P data in stratigraphic correlation applications and to level and combine it with total digest data. Elements that are generally extracted proportionally in aqua regia to 4-acid digest include Ag, As, Co, Cr, Cu, Fe, Mn, Mo, Ni, P, S, Sb, Se, Sn, U, and Zn.

In a way, aqua regia behaves as a selective digestion to extract elements from mineral forms introduced or altered during the mineralizing event. At the same time, it can provide important lithologic information. Its relatively low cost makes routine down-hole multi-element geochemistry affordable and easy to justify in most exploration programs.

There are some situations where a total digestion or some non-destructive analytical method that measures total concentrations (XRF, INAA) are advantageous and worth the additional cost. The use of these analytical methods is commonly referred to as whole rock geochemistry. An example

is when it is critical to obtain accurate determinations of the major cations (Ca, Fe, Mg, Na), rare earth element's, and 'conserved' elements such as Y and Zr as a basis for determining the addition or loss of the major cations during alteration. This situation arises in VMS exploration (Barrett et al, 1993; MacLean and Barrett, 1993). If the major alteration signature is a silicate like albite or K-feldspar, this too might warrant a total digestion or XRF method. However, even in these cases, there may be enough vectoring information contained in aqua regia data to enable the effective use of this digest and take advantage of its lower cost acquisition. An orientation test study may be needed to determine the optimum digestion for a particular mineral system.

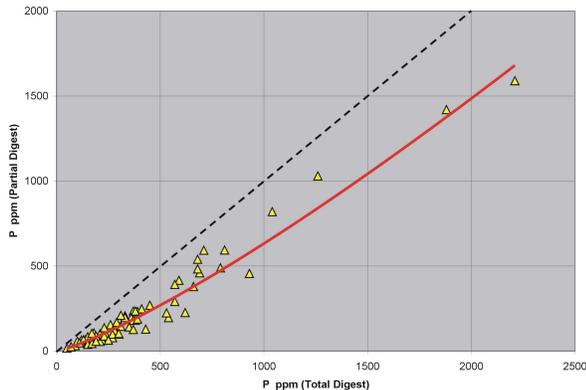


Figure 1: Comparison of P concentration between a partial aqua regia digest and a near total 4-acid digest.

Variable detection limits result in data gaps and noisy patterns at the low end of the data range. This is particularly vexing if the data overlaps spatially. It is inevitable that this problem will creep into a database that is acquired over a relatively long time period as detection limits have dropped significantly with the advent of ICP-MS analytical technology. The effect of variable detection limits in the database is not easily resolved. Setting all data below the detection limit to the value of the highest detection limit is probably the most realistic solution to view all data but then important information may be lost. Or alternatively, data with poor detection limits can be removed from the model. Assigning arbitrary values below the detection limit (example: half the detection limit) is usually not a good solution. If the data are separated spatially, then no action needs to be taken at least in the short term.

With respect to the remaining database issues, special values representing missing data should be replaced by blanks unless the gridding software ignores the special values. Special values or zeros indicating data below the detection limit are best set to the value of the detection limit. One reporting unit should be selected as standard and all other units converted accordingly. Zeros should be eliminated from the database. Errors in collar and survey tables for the drillholes should be identified and corrected.

Once the database has been cleaned up, it is recommended that the geochemical data be log transformed (base 10) prior to gridding. Most geochemical data is geometrically distributed such that the log of concentration defines a single background

population which is symmetrical about the mode/mean of the population. In reality, the data distribution for most datasets is a composite of many overlapping symmetrical populations. By log transforming the data, colour contouring can be used to separate the various population ranges visually to aid interpretation.

Downhole data has been traditionally displayed as points with colour representing concentration or as downhole traces with a histogram-like bar or line along side. However, patterns in the data are better discerned when values are interpolated between the holes based on some mathematical calculation (gridding algorithm) using data from the nearest holes. A voxel or block model must first be defined to contain the interpolated points. The voxel defines the limits of the gridded data and the distance between each interpolated point in the model. The model can be oriented in a direction other than N-S to facilitate exploring data patterns in cross or long sectional views.

The log transformed data can be gridded in a number of ways. The two most common approaches applied to geochemical data are: 1) krigging; and 2) inverse distance squared. The former is used when gridding data that define patterns in principally one preferred orientation in 3D space (strike, dip, plunge). This method is commonly applied to resource and reserve calculations (Olea, 1999). However, when modeling data for exploration purposes on a near-ore or district scale, patterns rarely have a preferred orientation beyond that of the attitude of the rocks. For this reason, the inverse distance squared algorithm is a better approach to represent multiple trends or orientations in the dataset. In gridding the data, it is generally desirable to define a search ellipse (around the interpolation node) within which data will be included in the calculations. The ellipse may be oriented orthogonally in the xyz directions of the voxel or inclined in some preferred direction. It is also usually possible to restrict the number of points included in the calculation to the nearest 'x' number of points.

There is a variety of software available for 3D gridding and the display of 3D objects. Examples of 3D software marketed to the mineral industry include Datamine, FracSIS, Geosoft, Gocad, GemCom, Surpac, Techbase, and Vulcan, among others (Doherty, 2003).

APPLICATION OF MODELS TO EXPLORATION

Lithostratigraphic Mapping

Geochemical models can be used as an aid to stratigraphic mapping if certain lithologic members have a distinctive geochemical signature. This can be helpful in situations where geologists are having difficulty in consistently picking stratigraphic boundaries from one hole to another. Many reasons exist why this might be the case including: 1) existence of transitional facies rather than sharp contacts; 2) presence of an alteration or metamorphic overprint; and 3) limited textural information provided by RC chips as compared to core.

Stratigraphic correlation using contrasting geochemical signatures can, in some cases, overcome many of these problems. Patterns in geochemistry down-hole reflect the composition of several different components: 1) the host rock

stratigraphy; 2) intrusive rocks; and 3) an overprinting mineral system. It is important to recognize which of these contribute to the concentration of any given element. Elements that have been introduced, depleted, or moved around as a result of a mineralizing event are not generally going to be useful for stratigraphic correlation. Also element signatures related to intrusive rocks need to be distinguished from those reflective of compositional changes in the rocks they intrude. For example, felsic dikes may have high Nb and Th contents in sharp contrast to the country rocks. Mafic dikes are generally characterized by high Co, Cr, and Ni concentrations. In carbonate stratigraphy, intrusive rocks typically result in an apparent depletion in Ca, Mg, and Sr in the down-hole profile coupled with an increase in some of the elements mentioned above.

Once these distinctions have been made, compositional changes in the conserved elements can be used to characterize different strata. An example of a characterization plot for a sedimentary sequence is shown in Figure 2. Each geologic contact is defined by either a sharp change in composition or the beginning of an increasing or decreasing gradient. A set of criteria need to be established for identifying each contact consistently from hole to hole. Generally a different suite of elements will apply to different contacts.

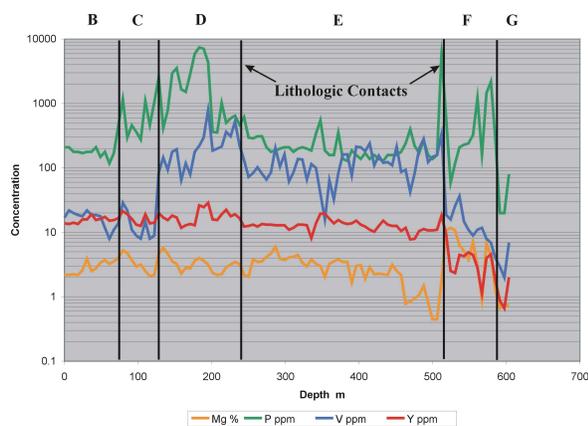


Figure 2: Chemostratigraphic characterization of sedimentary stratigraphy based on partial aqua regia digest data.

In most cases, boundaries defined on the basis of geochemistry will agree well with contacts determined by geologic logging. Where there is a discrepancy, benefits can be derived. The geologist may be prompted to re-examine that portion of the hole and adjust the location of a particular contact. In the process, new or better visual aids to identifying the contact during logging will emerge. This iterative process can only help improve the overall stratigraphic interpretation.

Structural information can usually be obtained once a stratigraphic framework is in place. Normal faults, if intersected in a drill-hole, commonly result in the thinning or loss of section (fault gaps) whereas thrust faults generally result in repeated section. These effects may have an expression in the down-hole geochemistry. In Figure 3, the contact between the 'C' and 'D' units appears twice in the characterization plot. This suggests the presence of a thrust fault at a depth of about 550 m down-hole. Normal faults often exhibit leakage of system elements most commonly foot-wall to the structures but, in some cases,

hanging-wall as well. This may aid identification of feeder faults in the mineral system.

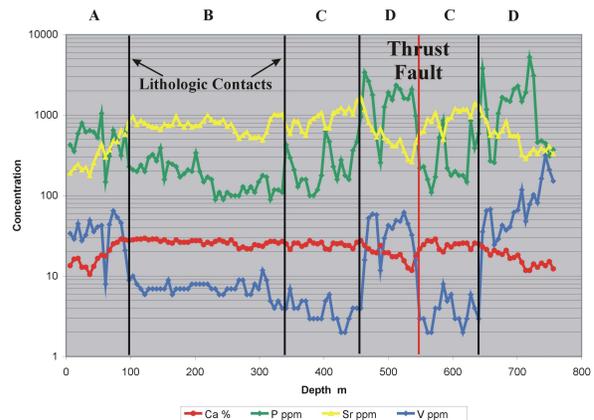


Figure 3: Chemostratigraphic characterization plot illustrating the effect of repeated section due to a thrust fault, based on partial aqua regia digest data.

The result of stratigraphic correlation, whether based on geologic logs or geochemical breaks, is a series of solid surfaces representing lithologic contacts. A complete structural framework is generally best developed from a set of interpreted sections, using the 3D environment to rectify the interpretation from section to section. These surfaces provide a geological context for the interpretation of the system elements.

3D Vectoring based on Geochemical Data

A major challenge in many mature mining camps is the discovery of new deposits that don't outcrop at surface. Zonation vectoring in 3D space can play an important role in the discovery process particularly in these mature districts. The development of ICP-MS analytical technology has made it possible to acquire high quality, low detection, trace element data for a broad spectrum of elements at an affordable cost. This new information can contribute to enhanced insight into the zonation of mineral systems and the development of vectors to the location of high grade mineralization within a system.

An example is the application of zonation vectoring in Carlin-type sediment hosted gold systems. The Carlin Trend in northeastern Nevada, U.S.A., is known to contain in excess of 3,110 metric tonnes of gold amongst over 40 deposits (Teal and Jackson, 1997; Heitt et al, 2000). The mineralization is characterized by sub-micron sized sulphide or arsenide overgrowths on diagenetic or paragenetically early pyrite. The overgrowths usually consist of a solid solution mix of Au, As, Hg, Sb, and Tl. The deposits vary from having a strong stratigraphic control to a dominantly structural control. They are hosted by a sequence of cherts, carbonates, siltstones, and calcareous siltstones of the eastern assemblage Rodeo Creek, Popovich, and Roberts Mountains formations. The deposits occur within 200-300 m of the Roberts Mountains Thrust (RMT), which emplaced siliciclastic sediments of the western assemblage Vinini Formation over top of the eastern assemblage

rocks. Alteration typically consists of silica replacement of carbonate accompanied by argillization.

A 3D geochemical model of the Deep Star deposit, located in the northern portion of the Carlin Trend, revealed that a broad suite of elements have been introduced or redistributed during the mineralizing event and that groups of elements are zoned in relation to the location of the deposit (Heitt et al, 2003). This model was derived from data determined on 6.1 m (20 ft) composites of the originally assayed 1.5 m (5 ft) pulps. The composite samples were analyzed for trace elements using an aqua regia digestion and combined ICP-ES/ICP-MS determination methods.

Geochemical characterizations of the Deep Star deposit and other Carlin-type deposits throughout Nevada exhibit many common zonation relationships as depicted in a generalized 3D zonation model for a Carlin-type system (Figure 4). Some approaches to vectoring using this zonation model are described below.

On a district scale, the system is expressed as a regional scale blanket of anomalous geochemistry cross-cut by a series of vertical plumes. The regional-scale blanket of anomalous geochemistry is vertically zoned. Termed the reaction zone, it consists of at least two distinct but overlapping element associations: the epithermal and oxic facies. The epithermal facies is defined by elements commonly associated with Carlin systems: Au, As, Sb, Hg, and Tl. The oxic facies consists of elements not normally associated with these types of deposits: Cd, Mo, Re, Se, U, V, and Zn. This zonation sequence is interpreted to have formed at a fluid mixing boundary between an ascending fluid (mixed magmatic and circulating basinal

sources) and the base of a relatively more oxidizing groundwater aquifer. Changes in redox state during mixing resulted in the epithermal elements being deposited from the ascending fluid and the oxic suite elements from the groundwater.

The epithermal and oxic facies anomalies are vertically extensive for hundreds of metres with generally a sharp gradient at their base. Deposits are located within the epithermal facies just below the bottom of the oxic facies. Thus the 3D distribution and geometry of the oxic facies provides some key information about the optimum depth for ore formation.

The reaction zone has the appearance of being stratabound on a local scale. However, on a district-scale, it inflects across major structural boundaries, sometimes changing its stratigraphic position. Deposits are commonly located foot-wall to these major offsetting structures.

The position and geometry of the reaction zone is controlled by a vertical or lateral lithologic boundary, referred to as the boundary condition. On the Carlin Trend, the boundary condition is predominantly the contact between the deep ocean siliciclastic rocks (western assemblage) and the continental margin sedimentary rocks (eastern assemblage). This contact is a structural boundary that is a combination of a thrust (Roberts Mountains Thrust) and high angle normal faults. Where the boundary condition is sub-horizontal, deposits tend to have a stratiform geometry, sometimes referred to as a passive-style of mineralization. Where the boundary is vertical, breccia bodies are common and a large vertical interval is mineralized, often cross-cutting stratigraphy. The contacts of intrusive bodies like the Goldstrike Intrusion also influence the geometry of the reaction zone.

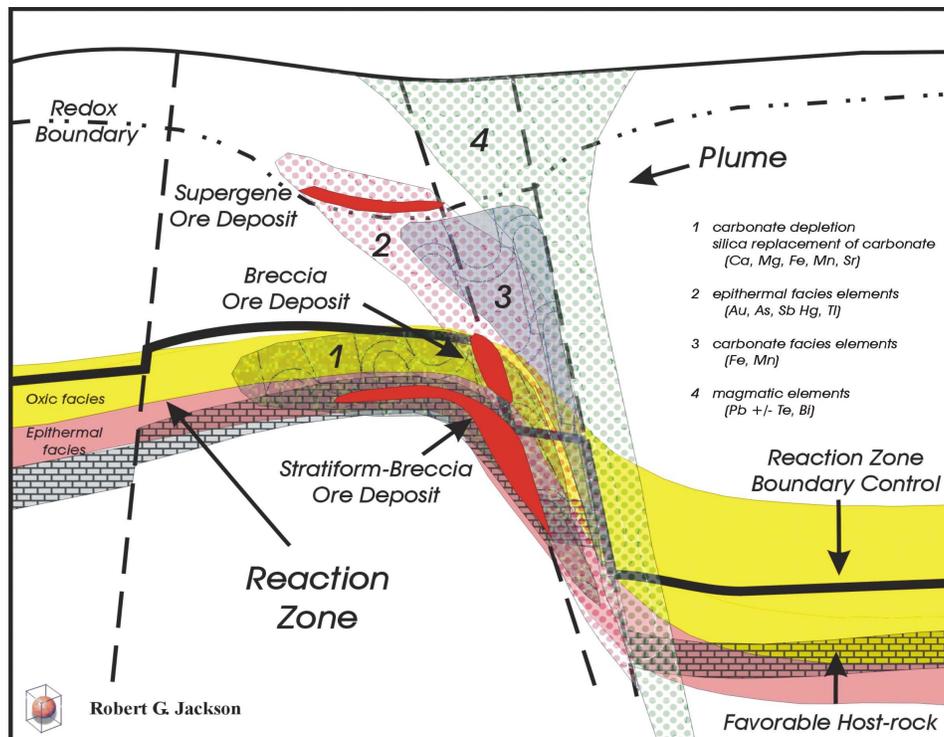


Figure 4: Schematic geochemical zonation model for Carlin-type sediment-hosted gold systems.

Most deposits occur in association with vertical plumes of anomalous geochemistry. These typically have a feeder component below the level of the deposit and an exit component vertically above the deposit. Their conical geometry suggests their location is controlled by intersecting high angle faults. They are commonly zoned laterally providing a distal to proximal vector to locating high grade mineralization. Plume-like geometries of the epithermal elements are present footwall to the major off-setting structures in a proximal position relative to mineralization (Figure 4). Plumes of Pb, Bi, Te, and occasionally W are located more distally in relation to mineralization, often in the hanging-wall of these structures. This group of elements is referred to as the magmatic suite. Clearly, these are very important features to identify in the vectoring process as their recognition in soil data or shallow drill results suggest potential for blind mineralization at depth.

The fractal nature of the zoning is manifested on a district scale by the presence of large magmatic suite plumes marginal to the Au system. These plumes are several km² in area and consist of a mix of epithermal and magmatic suite elements hosted by veins and structures. The base metals may attain percentage levels in concentration whereas, in the plumes associated directly with the deposits, they are present generally at levels in the low ppm range. These regional-scale plumes are interpreted to be located above the intrusive centre that is the heat engine to circulating fluids in the mineral district.

From an exploration viewpoint, a complicating factor on the Carlin Trend is that supergene weathering processes have redistributed elements to varying degrees in the near-surface bedrock. Nevada experienced a supergene weathering event prior to the mid-Miocene period as evidenced by the preservation of an oxidation profile beneath the Miocene-aged Carlin Fm at depths exceeding 300 m (Norby and Orobona, 2002). Age dates of alunite from the Gold Quarry pit also support the age of this oxidation event (Branham, 1994; Bawden et al, 2003).

There are a variety of ways by which the position of the redox boundary can be defined. It is typically mapped geologically by the observed change from iron oxide minerals to sulphide minerals in core or cuttings. However, a single logged pick on the boundary can be oversimplified as the contact is usually gradational. The change in mineralogy at the redox boundary can be quantified chemically by certain types of metallurgical tests (e.g., ratios of cyanide digest Au assays to total Au fire assays; sulphate/sulphide ratios).

The redox boundary also has a distinct expression in aqua regia extractable trace element geochemistry (Figure 5). The boundary is reflected in a decrease in the S content toward the surface and a corresponding increase in Ba content. The sulphur profile reflects the fact that, in an aqua regia digestion, sulphur from sulphide minerals is easily dissolved and retained in solution in contrast to that of sulphate minerals. The high near surface Ba enrichment is interpreted to result from the precipitation of secondary barite from the groundwater as Ba combines with SO₄ released during oxidation. Sometimes, the boundary is sharp and other times, gradational, as it appears to be in Figure 5.

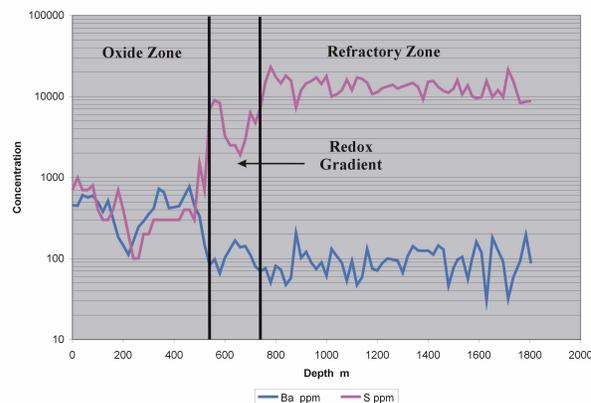


Figure 5: Expression of the redox boundary based on aqua regia extractable Ba and S.

Most elements contained in sulphides are mobilized into the groundwater during oxidation. Sometimes, the elements re-precipitate virtually in place as oxide minerals. However, commonly, they are deposited in sub-horizontal layers that mimic the geometry of the redox boundary (Norby and Orobona, 2002).

Supergene weathering processes and their effects on mineral zoning are well documented for the commodity elements in porphyry copper systems (Chavez, 2000). Less well described are their effects on trace element distribution in these settings and in other types of mineral systems. Based on relationships observed on the Carlin Trend, a model of supergene weathering effects is illustrated for oxidation overprinting a vertical plume signature (Figure 6).

Elements such as Au, As, Ba, Bi, Pb, Te, W, and sometimes Sb form oxide minerals above the redox boundary whereas Ag, Cd, Hg, Fe, Mn, Mo, Ni, Se, Tl, U, Zn, and sometimes Sb are leached from the oxide zone and deposited as supergene sulphides or hydrous oxides below the redox boundary. Supergene processes sometimes result in the formation of a flat-lying supergene Au deposit, derived from low grade Au mineralization within a plume. Characteristic features of this type of mineralization are: 1) its flat-lying geometry positioned just above the redox boundary; 2) high fineness of Au; and 3) weak correlation coefficients with As, Sb, and Hg.

The redox boundary often deepens on plumes and along major ore-controlling structures with the result that the exposed surface rocks may appear to be leached of plume elements relative to stronger signatures observed marginal to these areas. This can complicate the identification of plume signatures in surface data. The magmatic suite element plume signatures, however, are retained in the oxide zone and often even enriched in concentration. These elements can more reliably be used in surface data to identify areas with potential plumes.

While the redox effects may complicate the interpretation of surface data, they create an opportunity for identifying plume signatures in down-hole data. Many elements are enriched in the supergene sulphide zone located immediately beneath the redox boundary. Display of data in the plane of the redox boundary may well provide lateral vectors to plumes due to the relative enrichment of elements within the plume as compared to areas outside the plumes.

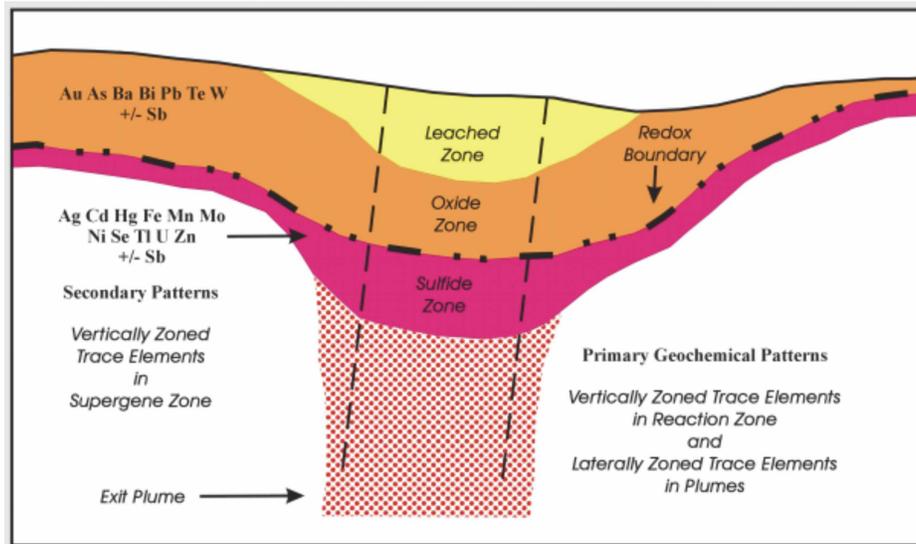


Figure 6: Schematic model of geochemical zonation related to supergene weathering on the Carlin Trend, Nevada.

3D Vectoring based on Mineralogical Data

The development of relatively low cost instruments for determining the occurrence and abundance of alteration minerals in down-hole data has created opportunities to develop 3D vectors to mineralization based on mineral zoning. Infrared spectrometers such as the PIMA and ASD (analytical spectral device), which measure the reflectance spectra of samples, are now widely used. Interpretation of the spectra can determine whether certain minerals are present or absent. In some cases, the relative abundance can be estimated based on the strength of peaks in the spectra.

If this type of data is collected systematically down-hole, it can be gridded so that spatial relationships amongst the various mineral distributions can be assessed and related to other types of data (geology, geochemistry, geophysics). The data can be treated as categorical variables (present/absent) or as semi-quantitative parameters where the relative abundance of a mineral is assigned numerical values (nil=0, weak=1, strong=2).

Approaches to vectoring using mineralogical zoning is illustrated with data from the Sleeper low sulphidation Au system located 26 miles northwest of Winnemucca, Nevada, U.S.A. The property is currently being explored by X-Cal Resources Ltd.

Approximately 1.7 M oz of Au were extracted from the Sleeper deposit (1986-1996) from low grade silica-sulphide breccias and high grade banded quartz-carbonate veins (Nash et al, 1995). The mineralization is predominantly hosted in the Sleeper rhyolite just above the contact with an underlying basalt sequence. One set of structural controls on the distribution of mineralization are N-S to NE range-bounding faults that down-drop the volcanic stratigraphy steeply to the west. The deposit also lies along a corridor of NW trending faults the role of which may have been to channel ascending magmatic fluids at their intersection with the NE faults. The rhyolite has been strongly

silicified in the vicinity of ore. Clay alteration extends into the underlying basalt.

X-Cal Resources Ltd and joint venture partner, New Sleeper Gold Corporation, initiated a down-hole geochemical program to develop a geochemical model and vector criteria that would assist exploration of the remaining property. The holes had been sampled from top to bottom for Au assaying. Individual samples or pulp composites of selected holes were analyzed for a broad range of trace elements using a combination of ICP-ES and ICP-MS determinations on a 4-acid near total digest.

Concurrently, the presence and relative abundance of alteration minerals were interpreted from ASD spectra on selected samples. The minerals identified included: alunite, beidellite, buddingtonite, buddingtonite (NH₄), carbonate-bearing minerals, chalcedony, chlorite, dickite, goethite, gypsum, quartz, smectite, smectite (NH₄), and wairakite. The mineralogical data was converted to numeric values that reflected relative abundance and then gridded using an inverse distance algorithm in a similar fashion to the trace element data.

One of the zonation sequences evident in this data was an east to west progression from illite → kaolinite-buddingtonite-illite (NH₄) → montmorillonite → nontronite (Figure 7). This view of the zoning is of a slice through the block model that parallels the bedrock surface at a depth of 50 m below the surface. In 3D, the alteration zones have vertical to steeply dipping boundaries which cross-cut the stratigraphy. The exception is the illite zone which is only expressed in the basalt underlying or adjacent to the deposit although the most intense development of illite has a vertical geometry. The Sleeper deposit occurs within the kaolinite halo proximal to the boundary with the illite zone. The distribution of jarosite also envelops the ore zones and extends to the east in linear tongues that presumably reflect a cross-structural control on fluid flow.

Some aspects of this zoning sequence are also expressed geochemically. The illite zone corresponds to intense Na depletion in the basalt. The jarosite zone is coincident with an area of Ca-Mg depletion and anomalous Ag, As, S, Se, Te, and Tl. The kaolinite zone is expressed as K-Rb enrichment and

anomalous Sb, Mo, Re, and W. With respect to the geochemistry, the deposit is spatially associated with: 1) the western limit of the Na depletion zone and Ag-As anomalies; 2) the Ca-Mg depletion zone centred on the high grade veins; and 3) coincident or peripheral anomalous K-Rb-Sb-Mo that extends to the west and south of the deposit.

Some of the signatures are plume-like, in particular the distributions of Au, Ag, and As. Plume signatures are also defined by the distributions of buddingtonite and illite (NH₄). In sectional view, the plumes have a southerly plunge that flattens out into a saucer shape enclosing the high grade veins at higher elevations (Figure 8).

Some of the information provided by the mineralogical data is not evident in the geochemistry and vice versa. For example, a number of elements exhibit relatively flat-lying, vertical zonation that is sub-parallel to the present redox boundary positioned at a slightly shallower elevation. The distribution of Zn illustrates the saucer-shaped geometry of this feature (Figure 9). Elevated Ba is present within the Zn depletion zone and high S forms a layer below it. This has some, but not all, of the characteristics of supergene weathering effects described previously for the Carlin Trend. A supergene component has been recognized in the ore zones but for the most part, sulphides have survived within the lower portion of the Zn depletion zone. By cause and effect or coincidence, the bottom limit to the depletion zone corresponds closely to the depth limitation presently observed for high grade Au concentrations associated with boiling zone textures (bladed calcite veins). If the two are related, this feature would be a vector to the favourable depth interval for high grade veins.

The Zn depletion zone is also a regional vector (Figure 10). On a plane 50 m below the bedrock surface, the zone of Zn depletion encloses the high grade veins. The geometry of this feature is slightly more proximal than the kaolinite alteration or absence of nontronite. However, on a plane 50 m below the rhyolite/basalt contact, the Zn depletion is restricted to the area of illite alteration and Na depletion.

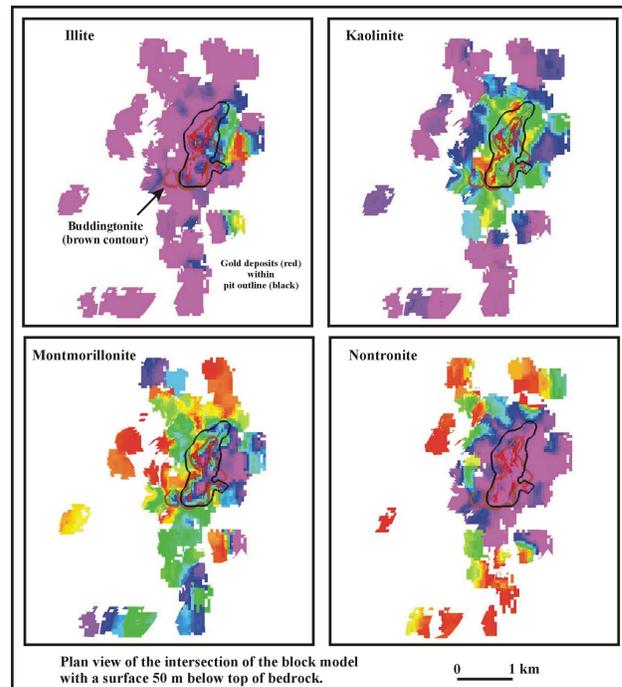


Figure 7: Zonation relationships amongst illite, kaolinite, montmorillonite, and nontronite on a surface parallel to but 50 m below the top of bedrock, Sleeper low sulphidation gold system, Nevada (abundance increases from purple-low to red-high).

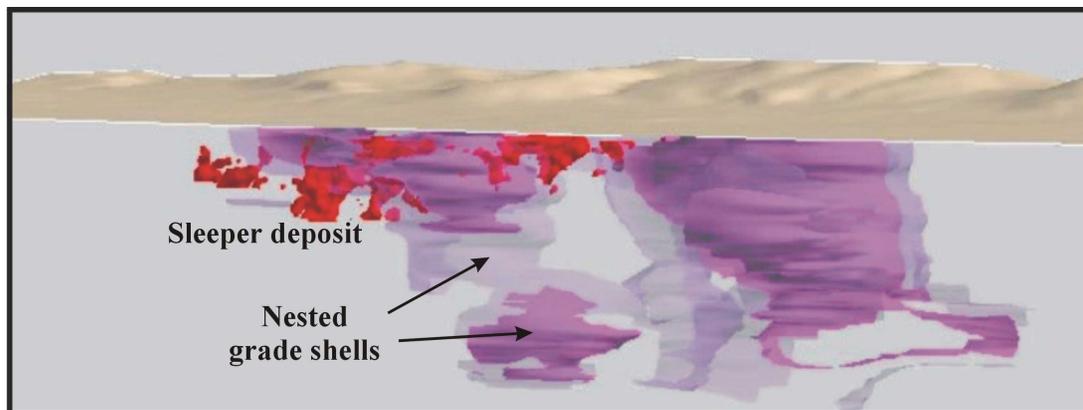


Figure 8: Plume signatures defined by the distribution of buddingtonite (nested grade shells), Sleeper low sulphidation gold system, Nevada.

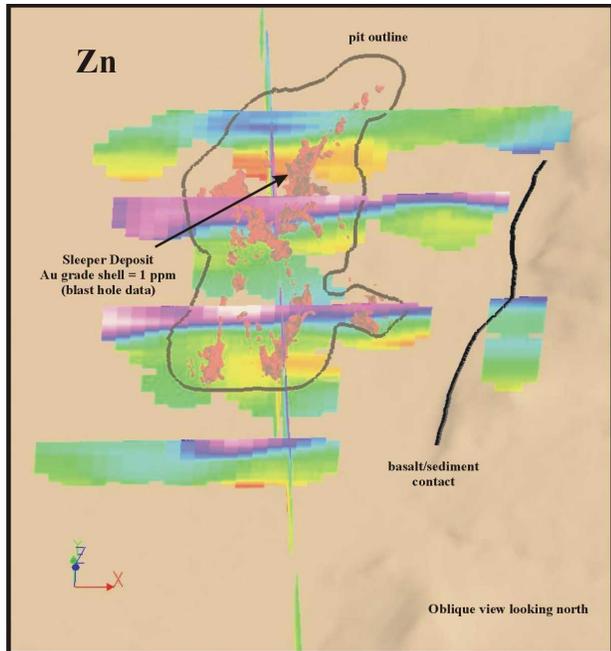


Figure 9: Near surface zinc depletion zone corresponding to the base of the boiling zone that deposited high grade gold veins, Sleeper low sulphidation gold system, Nevada (concentration increases from white-low to red-high).

3D Geochemistry applied to Secondary Dispersion

Many situations arise where a better understanding of secondary dispersion in surficial media can be obtained with 3D visualization. A good example is the interpretation of trace element data in glacial overburden where the glacial stratigraphy is complex, consisting of multiple till sheets and intervening glacio-fluvial or glaciolacustrine deposits. However, any kind of profile data will benefit from a 3D perspective. The following example describes the results of a study carried out to investigate the 3D geometry of mobile ion dispersion anomalies in glacial sediments above a blind deposit, the Shoot gold zone, owned by St Andrews Goldfields Ltd.

The deposit is located 15 km west-northwest of Matheson, Ont, Canada (Jackson, 1995). Reported reserves of 2.1 million tonnes grading 3.84 g/tonne (Bajc, 1998) are contained within altered ultramafic rocks intruded by syenite porphyry dikes. The deposit is approximately 10-15 m wide and 200 m long with a dip of 45 degrees to the south. The bedrock is overlain by 30-40 m of glacial overburden that consists of a vertical sequence of basal till, glacio-fluvial sand, and glaciolacustrine clay. The glacio-fluvial sand is an apron to a N-S trending esker that overlies the eastern half of the deposit. The predominant ice direction is to the south at 120-170 degrees azimuth.

Soil and water samples collected by the Ontario Geological Survey (Jackson, 1995) had indicated the presence of surface trace element anomalies with many of the characteristics of mobile ion signatures such as: 1) twin-peak anomalies with a central low directly above the deposit; 2) water anomalies closely associated with the location of the deposit; and 3)

anomalously low pH in surface waters. This was followed up with 18 sonic drill holes which retrieved in-tact sections of the

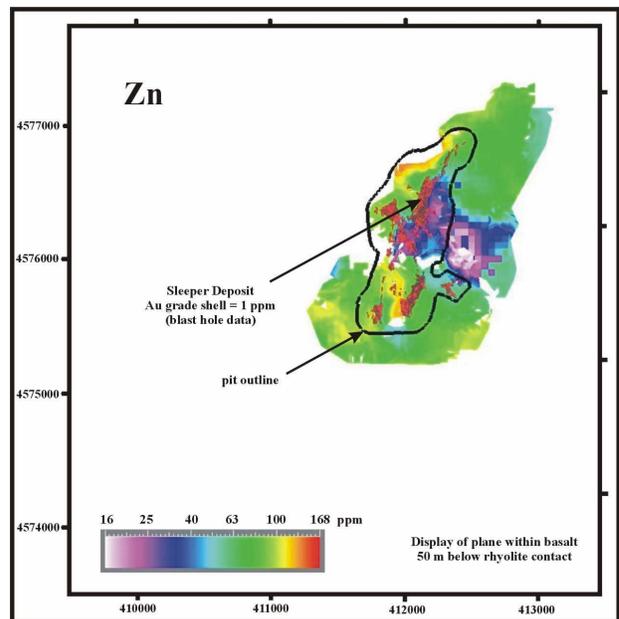
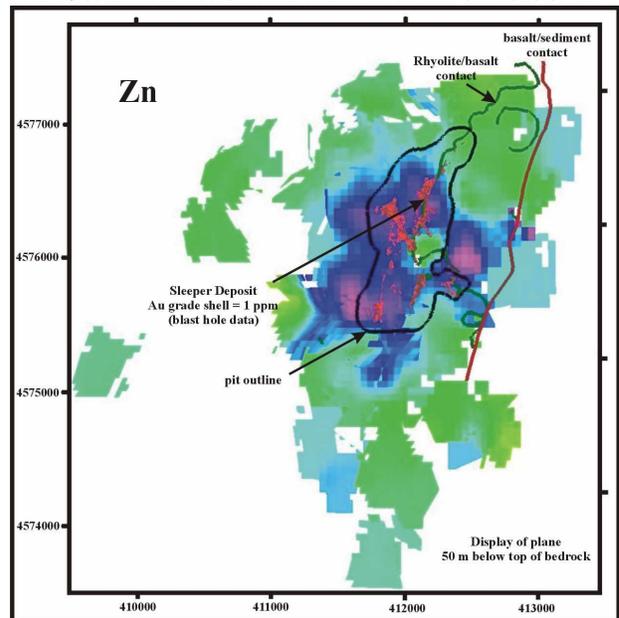


Figure 10: Distribution of Zn in a plane 50 m below the bedrock surface and 50 m below the rhyolite/basalt contact, Sleeper low sulphidation gold system, Nevada.

glacial sediments (Bajc, 1998). Samples of 1.5 m lengths were collected at 3 m intervals and analyzed for trace elements by enzyme leach/ICP-MS (-0.25 mm fraction) and for their clay, silt, and sand content by particle size analysis. In addition, the basal till samples were analyzed for Au, As, Sb, and W by instrumental neutron activation analysis (INAA) and for trace elements by ICP-ES on an aqua regia digest.

Subsequent to this work, the mobile ion dispersion phenomenon was the subject of several research projects funded by the Canadian Mining Research Organization (CAMIRO). Mobile ion dispersion characteristics and dispersion mechanisms resulting from these studies have been summarized in a number of publications (Hamilton, 1998; Hamilton, 2000; Cameron et al, 2004). As part of a 3D Geochemistry CAMIRO Project carried out by Analytical Solutions Ltd, a 3D geochemical model was created for the Shoot Zone area by gridding the sonic drill-hole data (Jackson, 2002). Surfaces were generated for the topography, glacial stratigraphic contacts, and the bedrock surface.

Based on this information, the Shoot Zone did not appear to have a distinctive expression in the basal till in Au or any other element. The deposit is located on the south side of a valley depression developed over the Destor-Porcupine fault zone (DPDZ) located 250 m north of the deposit. This may not have been a favourable geometry for physical entrainment of mineralization into the till.

The concentrations of elements determined by enzyme leach varied in proportion to the amount of silt in the samples. This reflects the fact that the enzyme leach extracts ions loosely bound to the surfaces of mineral grains or to amorphous Mn oxides coating the grains (Hall, 1998). The finer grained silt size fraction has a greater surface area available for adsorption than the coarser sand fraction. To normalize the data, the trace element values were regressed against silt content to identify the residual component derived from secondary dispersion in the vicinity of the deposit. Concentrations between the holes were interpolated by gridding the data using an inverse distance squared algorithm.

Patterns in the resulting block models for the enzyme leach residual variables reveal the presence of stratiform anomalies marginal to the deposit at the interface between the clay unit and the underlying sand aquifer (Figure 11). Anomalies at this interface are absent directly above the deposit. This geometry recalls that of twin peak anomalies observed in surface soils (Jackson, 1995).

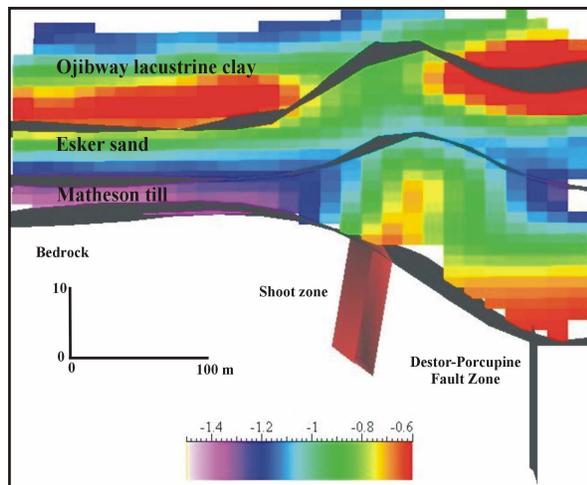


Figure 11: Mobile ion Cd anomaly in section through glacial overburden; based on enzyme leach data normalized to silt content, Shoot gold zone, NE Ontario, Canada (view looking west).

The clay/sand interface appears to be an important depositional site for mobile ions ascending through the water-saturated sand aquifer. This likely represents a redox boundary not unlike the one that exists at the interface between the A-horizon and B-horizon soils where similar signatures are observed.

Patterns in residual Cd and Mo suggest that these twin-peak anomalies at the clay/sand interface are related to plumes of mobile ions dispersing vertically above the deposit (Figure 12). Anomalies are present in the basal till north of the Shoot Zone within the bedrock trough developed on the DPDZ. However, this feature is up-ice of the deposit. Possibly tracing out the path of mobile ion dispersion is the plume in Mo that cross-cuts the sand aquifer above the deposit.

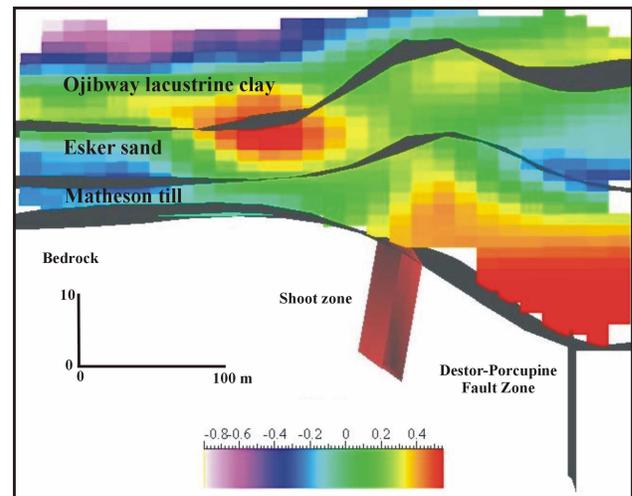


Figure 12: Mobile ion Mo anomaly in section through glacial overburden; enzyme leach data normalized to silt content, Shoot gold zone, NE Ontario, Canada (view looking west).

To visualize the lateral patterns within the sand horizon, the surface representing the contact between the sand and the overlying clay deposits was dropped by 3 m (Figure 13). The image on this plane of view is derived from the intersection of this surface with the block model. The plume-like feature observed in section straddles the mineralization and trends off to the southwest along strike. The highest concentrations define flanking or ring-like anomalies with a central low over the deposit. The spatial distribution of residual Mo at the base of the Ojibway clay reveals an even more pronounced ring-like geometry (Figure 14). This pattern is very similar to that in clay soils collected at a depth of 30-45 cm (Jackson, 1995).

This example serves to illustrate how insight can be derived from 3D data by interrelating geochemical dispersion patterns and geology in a way that is visually easy to understand. It is important to display the data in views that make sense in relation to dispersion pathways and possible controls on element deposition. In this case, stepping through the model in cross-section helped to recognize a plume-like dispersion pathway through the sand aquifer. The overall geometry of the plume was best seen in the plane of ion deposition – the clay/sand interface.

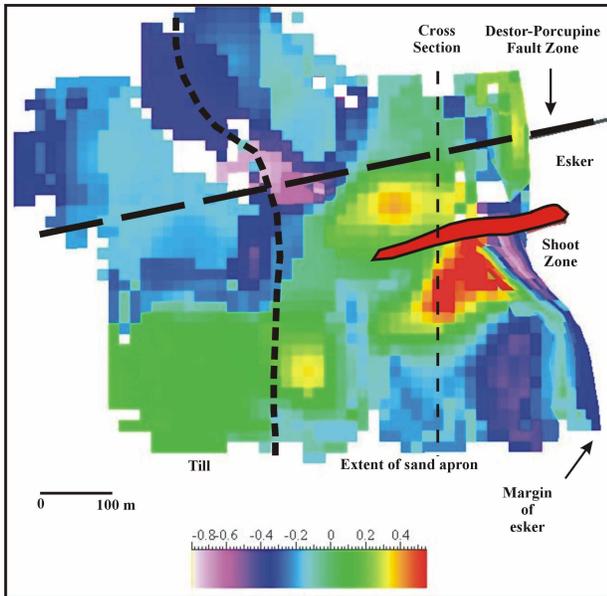


Figure 13: Mobile ion Mo anomaly on a surface parallel to but 3 m below the clay/sand interface; enzyme leach data normalized to silt content, Shoot gold zone, NE Ontario, Canada (plan view).

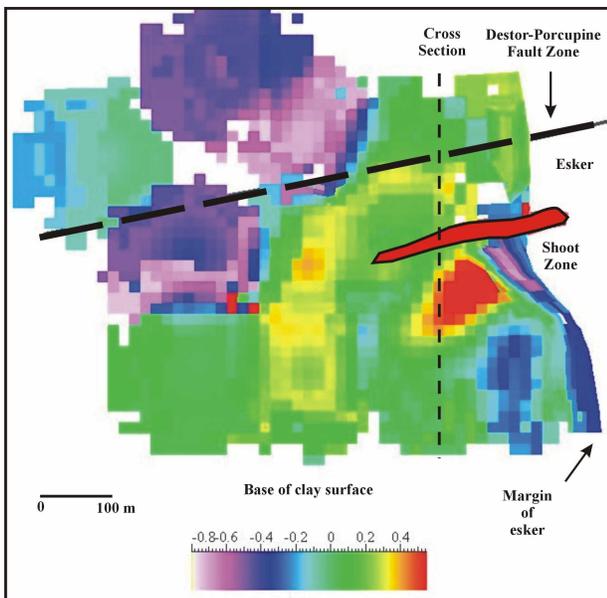


Figure 14: Mobile ion Mo anomaly at the base of the Ojibway clay unit at its contact with the underlying sand aquifer; enzyme leach data normalized to silt content, Shoot gold zone, NE Ontario, Canada (plan view).

FUTURE DIRECTIONS

Some ways in which 3D geochemistry applications will be advanced in the near future are as follows:

1. Application of continuous sampling/analytical strategies to a wide range of deposit types.
2. 3D GIS querying and multivariate analysis.

3. Vectoring using the geochemistry of the redox boundary to locate blind deposits.

4. Application to a broad range of surficial media

The insight provided by 3D modeling of down-hole data on known deposits can be considerable particularly with respect to an understanding of zonation relationships and the development of vectors to high grade mineralization. Current applications of 3D geochemistry have been limited to certain deposit types due to the requirement for reasonably uniform density of data distributed down-hole. For example, it has been used extensively in exploration for gold in Nevada where it is common practice to systematically sample the entire hole as it is difficult to predict which intervals are mineralized. However, in many mineral systems, sampling is restricted to visually altered or mineralized intervals. This is often the case for orogenic Au or VMS systems. Of course, it is always possible to display irregularly distributed down-hole data in relation to other information in 3D space but the ability to interpolate patterns from hole to hole by gridding is limited.

Many companies now routinely analyze drill-hole samples for a broad spectrum of elements by ICP methods in order to maximize the information gained from drill tests given that the incremental cost of this additional data is relatively small. The value of this data would be greatly enhanced if it was supplemented by a program of systematic sampling down-hole. This could be accomplished by collecting a representative sample (1-2 m) at some defined interval – generally in the range of 5-15 m. The precise sampling strategy should be determined by an orientation study whereby several holes, perhaps along a type section, are sampled and analyzed from top to bottom. This would be a good opportunity to compare the relative merits of partial vs total digestions prior to initiating a 3D geochemical sampling and analytical strategy.

A number of statistical and querying methods applied to surface data have been applied to the 3D environment (J. McGaughey, personal communication, 2006). There is further potential to explore the utility of these methods. Statistical methods should be applied to the primary data itself. Any newly derived variables can then be gridded to interpolate features from hole to hole. For example, a combination of factor analysis and regression analysis may provide new insight by identifying a component of data variability that is not clearly evident by absolute concentration alone but is related to mineralization. Querying in 3D space is appropriate if there are known constraints on the distribution of mineralization such as proximity to a stratigraphic contact, fault, intrusive, or zonation relationship. Knowledge of a particular district evolves over time. These types of exercises are intended to prioritize target opportunities, not to eliminate discovery potential.

In areas affected by supergene weathering phenomena, the geochemistry of the redox boundary may provide vectoring information to locate deposits below the level of oxidation. Many hydrothermal deposits have a weak upper level expression on faults or fracture systems. During oxidation, elements are mobilized and re-deposited in flat-lying layers in the oxide zone above the redox boundary or in the supergene sulphide zone below the boundary. In the process, concentrations and thicknesses of anomalies generally increase. Potential exists to search for these redox anomalies in the plane of the redox boundary.

Applications of 3D geochemistry can be extended into any type of sampling that involves systematic sampling along holes. This includes such data sets as groundwater, soil profiles, peat profiles, auger holes through saprolite, and so on. Many environmental data sets could benefit from 3D modeling.

CONCLUSIONS

The full integration of geological, geochemical, and geophysical data in 3D space has created new opportunities to explore data relationships and this has resulted in an increased understanding of mineral systems and dispersion phenomena. Some 3D geochemistry applications include: 1) stratigraphic correlation using elements not introduced or significantly redistributed during the mineralizing event; 2) development of a conceptual zonation model of a mineral system; 3) identification of vector criteria for locating high grade mineralization based on zonation relationships; 4) distinguishing proximal from distal signatures; 5) improving vectoring by integrating surface and sub-surface data; 6) improving interpretation of surface data by understanding the effects of surface weathering; and 7) locating the bedrock source of anomalies in 3D overburden data.

Geochemical models can be used as an aid to stratigraphic mapping if certain lithologic members have a distinctive geochemical signature. This can assist geologists in situations where contacts are difficult to select visually in a consistent fashion due to their gradational nature, metamorphic overprint, or complex geometry related to structural offset.

Zonation vectoring in 3D space can play an important role in the discovery process. The development of ICP-MS analytical technology has made it possible to acquire high quality, low detection, trace element data for a broad spectrum of elements at an affordable cost. This new information has contributed to enhanced insight into the zonation of mineral systems and the development of vectors to the location of high grade mineralization within a system.

Geochemical modeling also makes it possible to observe and interpret the effects of element redistribution due to weathering processes. A better understanding of trace element behaviour under these conditions may lead to vectoring tools for the discovery of blind sulphide ore bodies using lateral geochemical gradients proximal to the plane of the redox boundary.

The development of relatively low cost instruments for determining the occurrence and abundance of alteration minerals in down-hole data (PIMA, ASD) has resulted in data that can be numerically modeled and used to develop 3D vectors to mineralization based on mineral zoning. This type of data is a good complement to geochemical data as some unique features are present in each type. However, many mineralogical zones have a corresponding geochemical signature.

Geochemical modeling can be applied to understanding the effects of secondary dispersion using virtually any type of data collected systematically down drill holes or auger holes. This includes profiles through glacial overburden, peat, or saprolite. It is also amenable to the interpretation of groundwater geochemistry whether for exploration or environmental application.

ACKNOWLEDGEMENTS

The author would like to thank a number of organizations and their staff who have contributed to the development of 3D modeling applications by enthusiastically supporting modeling initiatives. These include Analytical Solutions Ltd, Barrick Exploration Ltd, Canadian Mining Research Organization (CAMIRO), Mira Geoscience, Newmont Mining Corporation, Timginn Exploration Limited, US Gold Corporation, and X-cal Resources Ltd. Particular gratitude is extended to X-Cal Resources Ltd for allowing the use of the Sleeper low sulphidation gold deposit model from Nevada in a live 3D Gocad presentation during Explore '07.

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