Paper 6

Exploration Targeting

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ABSTRACT

Exploration success has declined in modern time with fewer quality discoveries and increasing costs on a per unit metal basis. This to some extent reflects the greater maturity of brownfields districts and a reluctance of many companies to conduct greenfields exploration. Increasingly the minerals industry is focused on mature districts or areas which are remote, covered or have high political risk. Exploration is becoming increasingly technically challenging and more expensive. Therefore, more effective targeting across a range of scales is essential to increase success rates and potentially reverse or slow the trend of increased discovery costs.

Approaches to exploration targeting generally fall somewhere on a spectrum between empirical and conceptual targeting. Empirical targeting focuses on recognizing patterns in spatial datasets, or known geologic controls and using these criteria as guides to ground selection. Conceptual targeting focuses on understanding the processes controlling the distribution of the commodity of interest and predicting how and where these processes would combine to create an economic deposit within an Earth system. These approaches are complementary and should be employed in tandem.

Exploration is an exercise in scale reduction, and has a number of natural business decision points that map to scale. These can be summarised as:
1. *Regional-scale targeting – what basin/belt/arc district has the potential of hosting a substantial mineral system?*
2. *Camp/Cluster-scale targeting – where within the basin/belt/arc/district could a number of deposits be clustered?*
3. *Prospect/Deposit – where is there an orebody of sufficient quality within the camp or cluster of deposits?*

These decision points integrate a trade-off between the relative inputs of prediction and detection technologies and the concomitant escalation of expenditure with decreasing scale. Although the direct cost of targeting at broad regional scales is relatively low, the opportunity cost of making suboptimal decisions at this scale is extremely high. Target generation and ranking systems must take into account these differences across scale, appropriately capture uncertainty, and separately consider below-ground (geological) factors versus above-ground (access, infrastructure) filters. No matter the approach to targeting taken or the scale at which the work is undertaken, an assessment of the residual endowment of an area for the size of deposit targeted must also be evaluated, i.e. does it remain to be found?

INTRODUCTION

Exploration targeting is undertaken over a range of scales, which focuses finite resources (people, time and money) to increase the probability of exploration success. This process reduces exploration risk and in the process creates value by the discovery of new resources. Despite its importance in the exploration process, there is remarkably little literature on the subject of targeting strategy, with most contributions residing in 'grey' literature not easily accessible to industry or academia. The purpose of this paper is to highlight a current perspective on mineral exploration targeting, draw some comparisons to petroleum exploration targeting, and offer some views as to how mineral exploration targeting may change in the future. To accomplish this, some basic concepts around targeting are also reviewed as background.

TARGETING IS A BUSINESS DECISION

A critical aspect of exploration is to clearly define what you are looking for. This will vary not only by commodity focus, but with size of company or business unit. For example, BHP (the world's largest mining company) has reviewed global copper mines historically, as well as the current copper project pipeline, and defined a threshold quality of deposit that it aims to discover. This has led it to focus largely on porphyry and sediment-hosted copper systems that have a higher probability of delivering projects which will meet the business requirements (Tyler et al., 2017).

Alternatively a small to medium sized gold producer may be focused on projects which can potentially deliver 100,000 oz/year production which would be material to that company and its shareholders.

High quality ('world class' or Tier1 deposits; Schodde and Hronsky, 2006) in all commodities are becoming increasingly harder to find, and with few exceptions the current global pipeline of projects is of marginal quality (Schodde, 2017), leaving little room for successful acquisition paths to growth. A renewed focus for the exploration industry on discovery of new mineral resources is becoming evident (e.g. Tyler et al., 2017).

Exploration for new high quality mineral resources increasingly is focused on mineral districts which are remote or under cover in jurisdictions of low-country risk or in areas which have high country risk. With the transition to under cover exploration, the minerals industry is undergoing a transformation much like the petroleum industry transformed to deep sea exploration some decades ago. Discovery of high quality resources has, therefore, become more technically challenging and more expensive. Area selection (exploration targeting) is crucial as value is created by being first movers into new areas or by having a focus on provinces with substantial residual endowment.

APPROACHES TO TARGETING

Approaches to exploration targeting generally fall somewhere on a spectrum between empirical and conceptual targeting (Figure 1; Woodall, 1994; Lewis, 2001; Hronsky and Groves, 2008). Empirical targeting focuses on recognising patterns in spatial datasets, or known geologic controls on mineralization and using these criteria as guides to area selection.
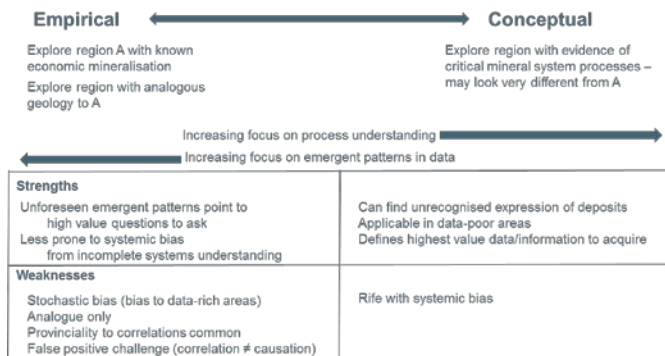
Figure 1: Diagram summarizing the spectrum between empirical and conceptual targeting approaches.

Conceptual targeting focuses on understanding the processes controlling the distribution of the commodity of interest in Earth systems and predicting how and where these processes would combine to create an economic deposit.

Empirical targeting approaches have several strengths—they are data-driven and therefore less prone to systemic or conceptual bias. These approaches allow recognition of the unforeseen patterns or correlations, which pose fundamental research questions around the underlying processes that control the patterns recognized.

The weakness of an empirical approach is that it tends to be most effective in data-rich areas with a high number of known deposits or occurrences. These approaches struggle with non-uniform data coverage and are much less effective in covered terranes or terranes with lower quantities of exploration or geoscience data. Empirical approaches to targeting are only likely to find analogues of the deposit styles already known and will not find the previously unknown expression of ore (Woodall, 1994).

Empirical correlations often exhibit provinciality on the camp or terrane scale, and correlations in one region often do not hold in other camps or terranes. Moreover, empirical correlations with mineralization are plagued by false positives where correlation is not necessarily causation.

Conceptual targeting, on the other hand, has the advantage of being applicable without the requirement of known mineralization 'training' data and can deal with incomplete or partial datasets. It involves breaking down the understanding of the mineral systems to targeting elements that can be mapped directly or by proxy in geoscience datasets (Hronsky and Groves, 2008; McCuaig et al., 2010). Being based on fundamental processes controlling element mobility in Earth systems, conceptual targeting has the potential to find the previously unknown expression of ore. Applied correctly, it highlights the gaps in understanding the mineral systems and identifies the critical research questions that will increase the understanding of the mineral systems and correspondingly the efficiency of exploration targeting. Moreover, conceptual targeting identifies the highest value datasets to acquire at various scales to test for the elements of the mineral system.

The challenge with conceptual targeting is that it is rife with systemic bias, due to our imperfect understanding of the mineralizing systems as well as our imperfect ability to interpret geoscience datasets.

Exploration for orogenic gold deposits in the Abitibi is an example of empirical targeting. These deposits are located along regional scale "breaks" with associated sedimentary and volcanic rocks and common carbonate alteration (Figure 2). Exploration tends to focus on acquiring a land position along these breaks and focusing drilling on favourable lithologies and alteration; typically as extensions to previously discovered prospects. Our geologic understanding of the mineral system approach that formed the orogenic deposits is poor which minimizes the effectiveness of a conceptual approach for these deposit types.

Exploration for volcanogenic massive sulphide (VMS) deposits can be much more conceptual in nature. The mineral system that forms these deposits is much better understood at a variety of scales, mainly due to their recognition on the modern sea floor (Figure 3). In VMS systems a mix of conceptual and empirical exploration across geologic scale is commonly utilized and is the most effective.
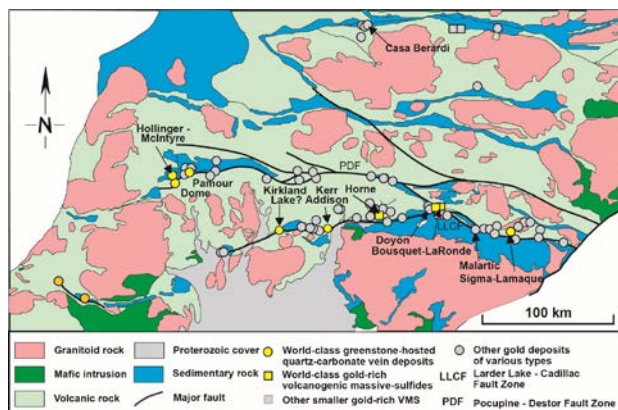
Figure 2: Simplified geological map of the Abitibi greenstone belt showing the distribution of major fault zones and gold deposits. From Poulsen et al. (2000).
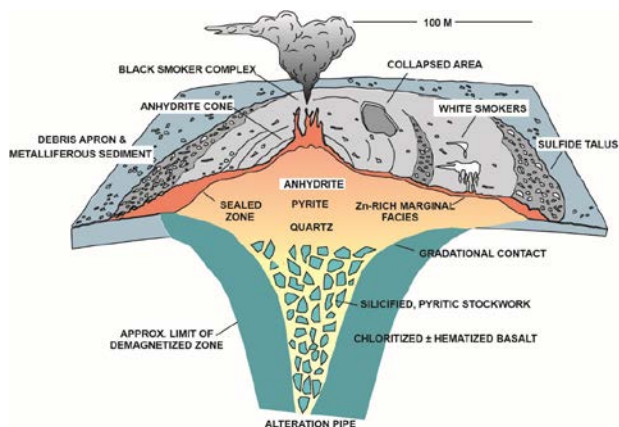
Figure 3: Schematic diagram of the modern TAG sulphide deposit on the Mid-Atlantic Ridge. This represents a classic cross-section of a VMS deposit, with concordant semi-massive to massive sulphide lens underlain by a discordant stockwork vein system and associated alteration halo, or "pipe". From Hannington et al. (1998).

TARGETING ACROSS SCALES

Exploration challenges vary with scale. This is due to three main factors:

- the trade-off between prediction and detection technology with scale,
- the natural business decision points which are scale-dependent,
- the different geological processes and the expression of the mineral systems across scale.

Exploration is an exercise in sequential scale reduction, and has a number of natural decision points that map to scale (Figures 4 and 5). These can be summarized as:

- Regional-scale targeting – what basin/belt/arc/district has the potential to host a substantial mineral system? Activity at this scale is relatively inexpensive and tends to rely upon framework geoscience information.

- Camp/Cluster-scale targeting – where within the basin/belt/arc/district could a number of deposits be clustered? At this scale exploration starts to deploy expensive detection technology.
- Prospect/Deposit – where is there an orebody of sufficient quality within the camp or cluster of deposits? This scale of exploration can be expensive and time consuming. It is at this scale where appropriate decisions to continue to advancing exploration or to exit the project need to be made in a rigorous manner.

Also shown at the top of (Figures 4 and 5) is the trade-off between the relative inputs of prediction and detection technologies, and the concomitant escalation of expenditure with decreasing scale (McCuaig and Hronsky, 2000; Hronsky and Groves, 2008; McCuaig et al., 2010). These figures also highlight that although the direct costs of targeting at broad regional scales are relatively low, the opportunity cost of making suboptimal decisions at this scale is extremely high, and can doom a company to failure from the outset. The 'camp-scale' decision—where social license to explore is secured, prospective ground is captured, and direct costs escalate—is the most critical decision in exploration targeting.
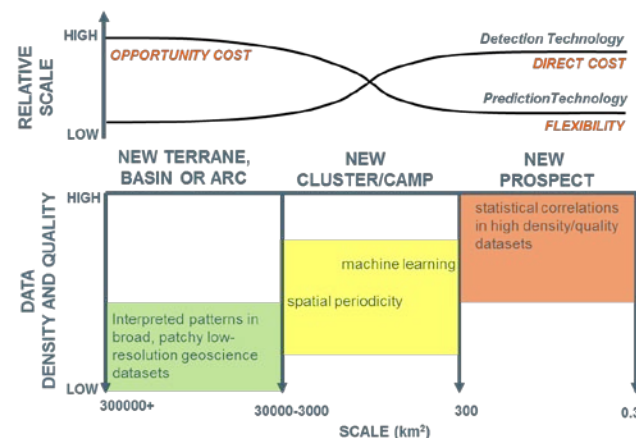

Figure 4: Diagram summarizing use of empirical targeting approaches across scale. Top of diagram illustrates trade-off between availability and effectiveness of detection technology versus prediction technology (after McCuaig et al., 2010). Also shown is relative trends in flexibility of exploration program, and direct costs versus opportunity costs. Bottom diagram shows potential use of empirical targeting across scales. The effectiveness of empirical targeting increases with reducing scale, due to the concomitant increase of internally consistent, high density and high quality geoscience datasets, and the tendency for empirical correlations to be more consistent within than between terranes.

Conceptual Targeting Across Scale

The approach of mineral systems has been increasingly adopted in the resources industry over the past 40+ years, starting with the petroleum industry (Magoon and Beaumont, 1991), and followed slowly by the minerals industry; although adoption of the concept is increasingly commonplace (Wyborn et al., 1994; McCuaig and Hronsky, 2014). The term mineral systems has

been bandied about in academia and industry often with different meanings to different audiences. To some, a mineral system encapsulates all of the processes leading to the formation of a single deposit. To others, it is the processes leading to a cluster of deposits. In reality, the mineral system is linked to the entire Earth system: the coupled evolution of Earth's hydrosphere-biosphere-atmosphere-lithosphere-mantle-core. However, practical subdivisions of this system need to be made. A proposed subdivision of the mineral system tied to natural business decision points is given in Figure 5.
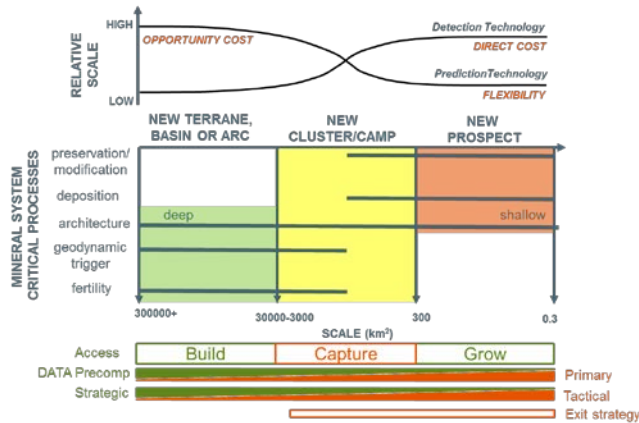
Figure 5: Diagram summarizing the application of conceptual targeting across scales with respect to the critical processes of mineral systems. Key point is that at different scales, different processes are more or less relevant, such that separate targeting exercises must be done across this scale hierarchy, each giving different weights to the respective critical processes.

Consideration of core-mantle evolution has little value to add when making decisions to target prospects within a camp. Yet by the same token, the processes of metal deposition has little to do with where, on a continental scale, a company should focus exploration for a new giant copper system. The boundaries put on the mineral system need to correlate with the natural scales of exploration decisions as noted above. These 'decision point' boundaries of the mineral system must be incorporated into prospectively analysis exercises and the prioritizing of activities across scales to which companies commit their limited people, time and money.

The Petroleum System Across Scale

The petroleum system is well understood in terms of its place within the whole Earth system. For example, it is accepted that to generate a high quality petroleum deposit, a number of critical factors must align: the presence of an organic-rich source rock, the evolution of that source rock through a specific pressure-temperature window, a reservoir rock mass that can hold a large volume of fluid, a trap that can accumulate a large volume of petroleum in that reservoir, a connectivity between the source and reservoir/trap, and a critical geodynamic moment that triggers oil migration from source to trap (e.g. Magoon and Beaumont, 1991). Each of these critical factors are well understood from a geoscience process perspective. Also, because each factor is critical to the genesis of an oil deposit, if

any of these factors are not present in a region, there will be no significant oil accumulation.

The petroleum industry also clearly understands how to evaluate these processes across scale (Figure 6). For example, at the scale of identifying new petroleum basins, the fundamental initial question posed is 'is there a world class source rock present'. If negative then no further consideration is given to the site of oil accumulation. In the mineral industry this decision point would equate to the fertility of a region (see below). Conversely, at the scale of production wells, the geoscience targeting becomes much more focused on trap geometry, integrity and capacity—or a focus on what volume and rate of production that can be expected. In the mineral industry this decision point equates to a tonnes, grade and geometallurgy of a mineral deposit.
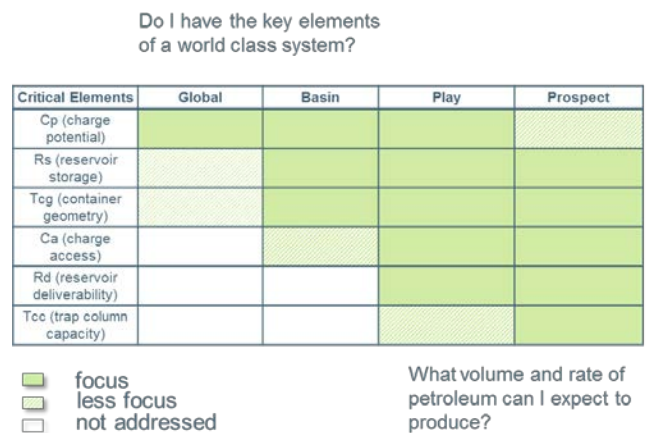
Figure 6: Critical elements of the petroleum system, emphasizing which elements are focused on across scale of exploration decision (BHP).

Definition of Critical Components of the Mineral System Across Scale

Figure 4 shows the critical processes that must coincide to create a high quality mineral system, and the practical subdivision of these processes into the natural exploration decision points of regional terrane, camp and prospect scales. These processes are (after McCuaig and Hronsky, 2014): **fertility** (source of commodity of interest; source of ligands and transporting agent (fluid or magma) to transport the commodity); **transient geodynamic triggers** (major tectonic changes that provide a combination of heat and stress field changes that trigger the moment and emplacement of mineralization—similar to critical moments in oil systems); **whole-lithosphere architecture** that provides pathways for mass and energy transfer across a range of scales to transport and focus the movement of the commodity in the transporting agent; **depositional mechanisms** to concentrate the commodity into a small volume of rock and form a deposit, and **preservation/modification** of the deposit such that it is at a depth amenable to economic extraction and potentially has had appropriate interaction with surficial weathering environments so that is it either upgraded or not destroyed.

Much like petroleum systems, such a view of the mineral system allows focus on the critical processes appropriate to scale (Figure 5): a focus on fertility at the larger scales (with only limited, if any, consideration of depositional site), and a focus on site of deposition at the smaller scales (with limited focus on larger scale fertility). Employed correctly, the mineral system approach identifies (1) significant gaps in understanding the system, which are high value areas for research, and (2) what the highest value datasets to acquire at any scale to progress to the next targeting decision.

APPLICATION OF TARGETING MODELS

Even given a sound empirical or conceptual understanding of the mineral system, adopting a systematic approach to target generation and ranking that is soundly based in science remains a challenge for industry. This stems from two main factors:

- failure to appreciate and capture uncertainty in the targeting process;
- mixing of 'above ground' factors such as land access, infrastructure and socio-political environment with 'below ground' factors involving the geology of the mineralization.

Uncertainty, Heuristics and Biases

Uncertainty in the targeting process can be divided into two main classes: (1) stochastic uncertainty, arising from issues with data support, quality and representativeness (e.g. false positive problem), and (2) systemic uncertainty, arising from human factors—our imperfect ability to interpret data, our imperfect understanding of mineral systems, and heuristics and biases that pervade our decisions (e.g. Bardossy and Fodor, 2001; McCuaig et al, 2009). Both conceptual and empirical targeting are affected by these uncertainties, with empirical targeting very strongly susceptible to stochastic uncertainty, and conceptual targeting strongly susceptible to systemic uncertainty.

To mitigate against such uncertainties, computerized methods are increasingly being adopted to marry human intuition with the power of the computer to quickly, systematically and 'objectively' query datasets. Ideally, targeting should involve manual targeting by individuals or teams, augmented by GIS-driven empirical targeting where appropriate (e.g. weights of evidence), and GIS-assisted conceptual targeting (e.g. fuzzy logic). In such a way, multiple approaches can investigate multiple scenarios, and produce a range of decision aids for final targeting decisions (e.g. Joly et al., 2012).

Above Ground Versus Below Ground Inputs to Targeting

It is clear that no value can be extracted from in ground resources if above ground factors do not align. For example, if one cannot obtain social license to mine in an area, or if insufficient power, transport or water infrastructure is in place. Distance to infrastructure is often viewed as a scalable variable, essentially adding to the required size of the target with distance from infrastructure.

Whilst above ground factors are essential to consider for final prioritization of targets, it is important that they are not mixed with the geological factors controlling the genesis and preservation of the deposit. Targeting exercises should ideally consider below ground factors first, with above ground factors as an essential filter for prioritization of opportunities (e.g. Kreuzer et al., 2010).

RANKING

Targets, once generated, also need to be ranked and prioritized. The rank or priority of a target is a function of the geologic attributes which underpin, or are thought to underpin, the target from a conceptual or empirical standpoint.

Challenges in ranking arise from: (1) combining geological criteria in a way that truly reflects the relative probability of the presence of a deposit; (2) avoiding a bias to areas with more data (and therefore more criteria defined), as opposed to potential value, and (3) effectively combining above- and below-ground factors mentioned previously.

Many targeting exercises combine empirical criteria in multiplicative or additive fashion to achieve a relative ranking of targets. However, this often leads to a bias towards areas with more information being ranked higher than less-sampled, higher-quality targets. Such exercises often mix criteria that are critical to formation of a deposit with those that are merely desirable, and some criteria (e.g. details of alteration in covered targets, or at larger scales) can often not be fully assessed at early stages of exploration. Mineral systems approaches can mitigate against this bias by ranking only criteria critical to ore formation (Kreuzer et al., 2008; McCuaig et al., 2010). Such approaches also identify the highest value information to acquire to advance or reject the target.

The maturity of a target is dependent on the amount of geoscience knowledge that underpins that target, or how well the target is understood. For example, an immature target may be interpreted to have a high rank based on geologic attributes, many of which may be inferred from indirect evidence. Similarly, a mature target may have a high rank based on its geologic attributes which are well understood and defined.

Targets which are more conceptual in nature (high rank, low maturity) can be attractive as they are often largely unconstrained and poorly defined, however they are also higher uncertainty. These targets tend to be in a greenfields environment. Correspondingly targets which are more mature (high rank, high maturity), are well understood in terms of their geologic attributes, and have lower uncertainty. These tend to be in a brownfields environment. The latter will usually continue to attract exploration expenditure, even if they are fully defined or will only add incremental value. The challenge is ranking these different styles of target according to expected value (e.g. Kreuzer et al., 2008).

Whilst above ground and below ground factors are both critical to assess in ranking and prioritizing targets, it is important that they are kept as distinct filters, with below ground factors ranked first, followed by above ground filters (e.g. Kreuzer et al., 2010).

SEARCH SPACE AND RESIDUAL ENDOWMENT

No matter the approach to targeting taken, an assessment of the residual endowment of an area for the size of deposit targeted must be undertaken, i.e. does it remain to be found? Approaches such as the percentage of metal discovered with proportion of drilling (e.g. petroleum 'creaming curves'; Meisner and Demirmen, 1981) or size-rank distributions (e.g. Guj et al., 2011) have commonly been employed in petroleum to estimate the residual endowment and therefore the maturity of basins, but have had only sporadic uptake in minerals. Nevertheless, some uptake of spatial metal/km^2 estimates based on analogue geological terranes and deposit types (e.g. USGS three-part assessments used by US government; Singer, 1993) and size-rank distributions (e.g. Figure 7) are gaining in popularity in the minerals industry. Such methods are very useful tools, with the caveat that they need to be geologically interpreted in terms of the search space being explored (a multi-parameter space including geology, commodity, detection technology, political environment, market, etc.; Hronsky, 2009). The question that needs to be repeatedly asked across all scales is "can the footprint of a mineralizing system of the required size realistically be concealed throughout the exploration history of the search space?"
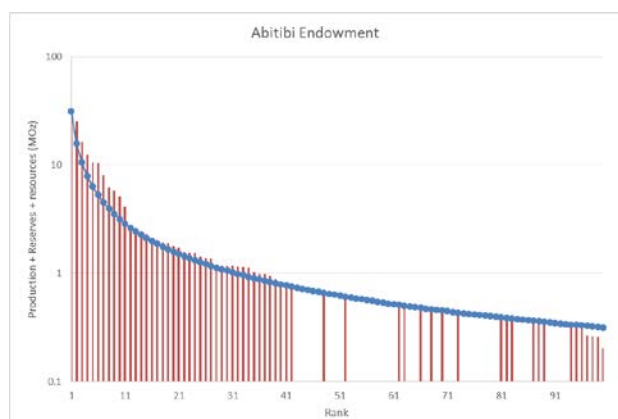
Figure 7: Size-rank distribution of gold deposits in the southern Abitibi belt of Canada. Blue line shows the predicted endowment if the deposits follow a power law relationship with an exponent of -1. Red bars show the known endowment (pre-mining) for known gold deposits. Constructed using the database of Gosselin and Dubé (2005), and methodology of Guj et al. (2011).

An exploration strategy that does not systematically evaluate maturity of the exploration search space and consider residual endowment versus required quality of discovery is high risk.

The highest value comes from opening up a new search space, as early movers into new search spaces capture a disproportionate amount of wealth compared to late entrants (Hronsky, 2009). It is on opening these new search spaces that exploration technology development and mineral systems concepts should focus.

WHERE TO FROM HERE?

Considering the preceding discussion, a systematic approach using empirical and conceptual targeting clearly has highest merit.

In terms of empirical targeting, technology advances in geophysical methods, geochemical analysis and data integration and visualization allows geoscientists to collect unprecedented amounts of data at an increasing rate. Field portable, XRF, XRD, SWIR instruments now allows rapid real time collection of mineralogical and geochemical data. However, the bulk of the data collected remains under-utilized. Wide spread public geoscience data, archival exploration data and the rapid, inexpensive collection of quality geochemical and geophysical data provides massive complex datasets which require methodologies to effectively utilize this data and empirically target. The minerals industry is increasingly data rich and knowledge poor. It is here that ever-increasing computational power and evolving artificial intelligence (AI) algorithms (supervised and unsupervised), will provide opportunity to improve our ability to empirically target across a range of scales. Emergent patterns in these large datasets will not only point us to possible targets, but to fundamental science questions to ask about the system itself to improve our conceptual targeting.

In conceptual targeting, the biggest barrier at present is our narrow-focused commitment to different system models, or styles of mineralization. The next big breakthrough is to understand element systems within the Earth system (e.g. the full copper system through time, rather than porphyry, sediment hosted copper, IOCG, etc.). A key difference between petroleum and minerals exploration is the relative confidence in understanding the respective systems and their translation to proxies in geoscience datasets. The petroleum system is well understood across a range of spatial and temporal scales, such that the industry is willing to risk capital based on conceptual targets. In the minerals industry, the mineralizing systems are often more complex than petroleum and have not had the same level of systems thinking applied to them. The mineral industry lags far behind the petroleum industry in terms of a comprehensive understanding of the processes that source, transport and deposit large accumulations of metal. As a result, conceptual targeting in the minerals industry is much less effective, and most of the minerals industry is much less confident in applying it.

There is hope in this space however. The understanding of self-organized critical systems (SOCS) has changed our way of looking at Earth and mineral systems (Bak, 1996; Hronsky, 2011; McCuaig and Hronsky, 2014). This recognition puts science behind some of the patterns we see that are fractal in nature (Bak, 1996) with a power law size distributions (Robert et al., 2005; Guj et al., 2011), and which exhibits spatial periodicity (Doutre et al., 2015). Earth itself is a SOCS; posing the questions of what are the processes that operate across a range of scales that change a geological system to a mineralizing system and ore system? This is a high-value area in which to focus fundamental geoscience research efforts.

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