GEOLOGY AND MINING

Aspects of Mineral Exploration Thinking

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Editor's note: The aim of the Geology and Mining series is to introduce early career professionals and students to various aspects of mineral exploration, development, and mining in order to share the experiences and insight of each author on the myriad of topics involved with the mineral industry and the ways in which geoscientists contribute to each.

Abstract

Successful exploration requires an understanding of ore deposit models, the experience to recognize ore guides in an outcrop, nonlinear thinking, and some intuition. Models, using porphyry Cu deposits as examples, combine magmatic and hydrothermal processes; however, process and the results of process are different. Models provide important understanding of process but are not ore guides and do not drive discoveries; models function as rules that inhibit prediscovery exploration thinking. Results of the genetic process are recorded in descriptive models that do not reflect the considerable geologic variations existing between the hundreds of known porphyry Cu deposits. Discoveries and discovery cycles are driven by nonlinear thinking about ore guides visible in outcrop, not by genetic or descriptive models. Reality in an outcrop typically departs from generalized models. Reinterpretations that lead to drilling prospects rejected by previous exploration groups is what makes many discoveries. Increasingly, field-portable instruments for mineral and chemical analyses will add efficiencies.

The most important product of early exploration work is the geologic map, defined here as a decision-making document. Mapping of ore guides in any ore-forming system invariably leads to sampling of outcrops where high grading can help geologists rig the odds in their favor. However, the objective is a highly profitable mine, not just a high-grade sample. That means the mineralization must be sufficiently continuous to build the inventory of recoverable metal required for a profitable mine, regardless of grade. High grade gets you interested, but continuity gets the mine.

The principal intangible in any discovery is intuition, often described as nothing more or less than recognition, and it invariably involves experience. Perhaps the only tangible expression of intuition is displayed by individuals or teams that are unwilling to abandon a complex prospect, a behavior often described in case histories as tenacity.

Introduction

Mineral exploration is the search for and discovery of new ore deposits—mineral deposits that can be mined profitably. These activities are funded both by investors who buy shares in exploration companies and by cash flow from operating mines. Exploration is seen by many as a business strategy. It is also deeply reliant on the geologic sciences, with activities sufficiently similar to those of research scientists that the term applied science is appropriate. Otherwise, exploration groups would send economics graduates with AB and MBA degrees into the field instead of geologists with B.Sc., M.Sc., and Ph.D. degrees. McKinstry (1948, p. xiii) wrote that "in geology the applied aspects are inseparably identified with geology itself."

It is clear to me that all economic activity in the developed world depends on mining and that mining is entirely compatible with the concept of sustainable development. As noted on page 22 in *Our Common Future* (World Commission on Environment and Development, 1987), "Many essential human needs can be met only through goods and services provided by industry, and the shift to sustainable development must be powered by a continuing flow of wealth from industry." Successful exploration creates that wealth and enables the concept of sustainable development.

The role of exploration and mining geologists is to find ore. Richard (1975, p. 48, 49) defined "explore" as "to search for a needle in a haystack," defined the person who does it an "explorationist," and thought the only better word was "prospector." The 21st-century explorer is now part of a team of geologists who arrive at a project with cell phones, computers, drones, GPS, short-wave infrared (SWIR), and X-ray fluorescence (XRF) units and enough gear and provisions for weeks in the bush. That team has the very considerable responsibility of finding new resources that keep the world running, but that world is largely ignorant of what we do, how we do it, and how we think. We are still seen as iconoclasts from the 19th century who spend a lot of money with only the occasional success.

The purpose of this essay is to provide some experience-based insight into mineral exploration thinking as geologists look deeper in known mining districts and in strongly weathered and remote terranes for signs of mineralization. The use of ore deposit models during exploration is contrasted with the use of ore guides visible in outcrop. I also present some thoughts, tangible and intangible, that might encourage early career professionals to consider how they think and communicate that thinking. This discussion is framed within the context of porphyry Cu deposits, reflecting the importance of copper as a critical component of world economies, but is intended to apply to exploration more broadly.

My thinking and opinions have been influenced by conversations over six decades with many accomplished ore finders, including Kenyon Richard, Harold Courtright, and Phil Jenney in particular. An opinion is a conclusion, often subjective, that has been carefully considered and is firmly held as correct by the advocate while remaining open

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doi:10.5382/Geo-and-Mining-14

to discussion. Like many geologists who hold firmly to their opinions, absent facts to the contrary, I am not reluctant to share them, consistent with the title of David Brinkley's 1997 book, *Everyone Is Entitled to My Opinion*. Right, wrong, or debatable, opinions provide diverse experience-based perspective and tend to generate wide-ranging discussions. Diverse opinions on aspects of ore finding are common among explorationists, and this is extremely important *because discovery may result from a contrarian opinion*. As cited in Lasky (1947, p. 82), "What the evidence prevails on the mind to believe, depends upon the mind as well as upon the evidence."

Discovery Philosophy

A discovery is any mineral deposit that may or may not be ore, at the moment. Discovery is a difficult and rare event that, in hindsight, appears to be simple. Principal factors that usually influence a discovery are its size, grade, depth, geology and degree of concealment, and location. A majority of discoveries are made by prospecting regions with known mineralization using geologic mapping and geochemical sampling techniques, and all require drilling. Many discoveries are actually reinterpretations of prospects previously examined and then discarded by others or small mines abandoned in some past decade. Large deposits, and those exposed at the surface, are usually discovered earlier in a discovery cycle. As a result, discovery rates may rise early in the cycle but decline over time.

A submarginal discovery is not a failure, since it demonstrates that a program is working. These discoveries may be sold, joint ventured, leased, traded, or inventoried for later review when metal prices are higher or new technologies appear. What are small or submarginal deposits for larger companies may be acquisition opportunities for junior exploration groups. Numerous advanced prospects and small ore deposits previously inventoried or discarded by the discoverers have become successful mines and subsequently grown much larger.

Exploration objectives should be based on whether a deposit exists, whether it can be found, and whether it will be ore. Exploration decisions are often required in limited time, with limited funding, based on limited data of uncertain quality. Partly as a result, it is estimated that at least 90–95% of all drilling projects fail, at least initially. This makes mineral exploration the highest-risk activity in the mining industry.

Bailly (1972, p. 32) termed exploration philosophy as "the body of principles which guide the explorer…toward discoveries," although his suggested principles did not deal with decisions made by explorationists in the field. Durant (1962) noted that philosophy deals with inexact subjects such as good versus evil, ethics, beauty, and mathematics, not easily studied by the scientific method. Given my view that mineral exploration is the highest-risk activity in the mining industry, ore finding could be considered an inexact subject; if so, might there be useful nonscientific ways of thinking about exploration and the discovery process? Might an applied philosophy yield principles to guide field work and decision-making? These are some of the questions addressed below.

Porphyry Cu Deposits and Models

A porphyry Cu deposit is a large volume of pyrite and copper sulfide minerals formed by epigenetic magmatic-hydrothermal processes that are genetically associated with felsic to intermediate-composition porphyritic intrusions. These deposits exhibit strong zoning of alteration minerals and metals—a feature of considerable use during exploration (Lowell and Guilbert, 1970; Sillitoe, 2010). Many contain more than 1 billion tonnes (Gt) of mineralized rock and, collectively, they are the world's largest source of copper along with gold, molybdenum, and numerous other recoverable metals. Regionally, porphyry Cu deposits are associated with magmatic belts developed over convergent plate margins.

Sulfide minerals occur largely in quartz veins varying in width down to microcracks a few tenths of a millimeter wide and as disseminated grains. Hypogene ore zone symmetry varies from dome-like configurations to elongated vertical columns. Boundaries between ore and waste are gradational and are determined by assay. Hypogene grades are controlled by position within the system, the degree of fracturing, and wall-rock lithologies. Singer et al. (2008) compiled data on 422 well-explored porphyry Cu deposits and on 250 additional deposits for which data are limited. Numerous discoveries have been reported since then (author's files).

Weathering and oxidation of hypogene sulfide minerals, where pyrite is abundant, generates acidic groundwater that dissolves copper oxide minerals and transports copper in solution down to the water table where it replaces preexisting sulfide minerals. This forms near-surface, horizontal blanket-shaped zones of supergene chalcocite. Supergene enrichment increases hypogene grades by up to several times or more, forming enormously profitable orebodies for open-pit mines. Where the total sulfide content is low, oxide copper minerals remain at the surface and may be recovered by heap and in situ leaching. Most supergene chalcocite blankets and exposed oxide copper deposits developed in the last century are nearing depletion; 21st-century copper exploration and mining is increasingly focused on hypogene deposits. Exotic copper deposits, where copper is transported out of the system by supergene processes and then concentrated, are less common, but may be large.

The term "porphyry copper deposit" was first used by Emmons in 1918 (Titley, 1997) and later by Parsons (1933). It was formalized in ore deposit literature in the first volume dedicated to porphyry Cu geology edited by Titley and Hicks (1966). This volume contained a paper by Jerome (1966) on the exploration aspects of porphyry Cu deposits, which was the first published exploration model. These efforts led to a Penrose Conference in 1969 at the University of Arizona, the first descriptive/genetic model by Lowell and Guilbert (1970), a second volume by Titley (1982), and two Canadian Institute of Mining and Metallurgy special volumes (Sutherland Brown, 1976; Schroeter, 1995), all on porphyry Cu deposits. These efforts initiated several decades of intense research with additional compilations by Cox and Singer (1987), Seedorff et al. (2005), John et al. (2010), and Sillitoe (2010) adding new data and refinements to the original model.

Reality departs from the model

Before models became popular, Spence Titley (Titley and Hicks, 1966) observed that studies of porphyry Cu deposits involve both process and results of the process. The process is a series of dynamic changes that include complex arrays of crosscutting and multiple intrusive, hydrothermal, and structural events occurring over significant time intervals as the mineralizing system cools. These collectively define the genetic porphyry Cu deposit model, and hundreds of studies indicate that the genesis of these deposits is relatively similar.

The results of the genetic process characterize the descriptive (or empirical) model. Descriptions of individual porphyry Cu deposits reveal large differences caused by the complexity of the local lithologic and structural settings in which deposits formed; these variations lead to significant distortions and discontinuities both in hypogene alteration-mineralization zoning patterns and in supergene geometries. Gustafson (1978) thought that a descriptive model failed to describe accurately any real deposit and oversimplified reality. In his Jackling Award Lecture, Titley (1997, p. 61) wrote that "more important than the model is the understanding of how the model may depart from reality."

Models are rules

A model summarizes the essential field and genetic characteristics of a group of deposits and provides a broad understanding of their features. This is important because of the vast amount of published research on mineral deposits. Further, models may be useful broadly as exploration groups review various metallogenetic provinces for new opportunities. A particularly useful model is Emmons's (1933) diagram of metal zoning above a granitic intrusion (Fig. 1). Perhaps due to its vintage and lack of a scale, it is largely ignored, but it communicates district metal zoning patterns that will become increasingly important as geologists look for far-field signs of centers of mineralization. Nevertheless, generalized diagrams risk oversimplifying the numerous important details that guide geologists in the field and give a misleading impression that ore deposits are geologically simple. Models illustrate the typical aspects of ore deposits, but as observed by Titley (1966) and Gustafson (1978) individual ore deposits are rarely typical.

The difficulty of using generalized models during field work relates largely to scale, the varying aspects of their geology, the erosion level, and effects of weathering. Descriptive models of porphyry Cu deposits encompass several km^3. By contrast, a field geologist deals with specific geologic features in weathered outcrops, commonly only a few meters across, that are too small to depict on a diagram of a deposit model. These features are termed ore guides and are essential for successful exploration because they provide the hard data from outcrops that may indicate the presence of an ore deposit.

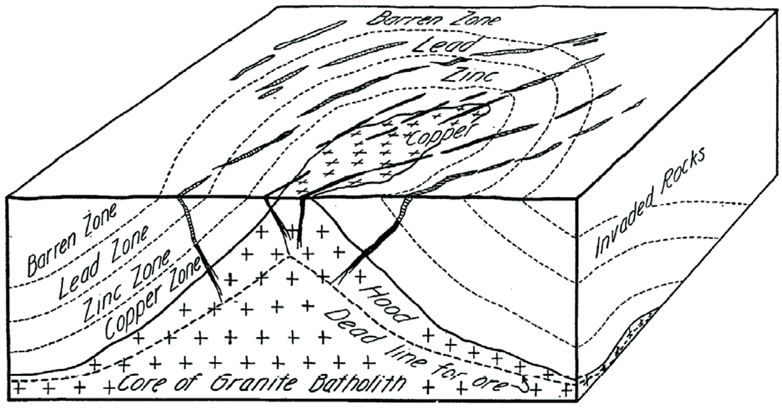

Fig. 1. A district-scale example of a porphyry Cu system, from Emmons (1933). Zonal arrangement of metals, with copper ores deposited as lodes in and near the cupola of a granite intrusion, zinc ore farther out and above copper ores, and lead ores above zinc and farther from the cupola. Reproduced with permission from the American Institute of Mining and Metallurgical Engineers (AIME).

Models may function as rules, implied or stated, as illustrated by the discovery of the giant Escondida deposit in Chile, more than a decade after publication of the Jerome (1966) and Lowell and Guilbert (1970) models. By the mid-1960s, Escondida had been recognized as part of a large zone of strong alteration where several exploration groups had acquired, then relinquished, their mineral rights without any drilling (Sillitoe, 1995). Prominent among the reasons was that copper and molybdenum values in rock samples, although anomalous for porphyry Cu deposits in general, were low for deposits in that region. In 1979, a Utah International-Getty Minerals joint venture led by David Lowell (Lowell, 1991), using an exploration model similar to that illustrated in Figure 1, drilled five unsuccessful holes on a stream sediment anomaly near Escondida. In 1981 four additional holes were drilled by Utah-Getty in areas identified in a separate leached capping study by Harold Courtright. These holes intersected the chalcocite blanket and discovered the deposit (Ortiz, 1995).

If a geochemical anomaly exists, drill it. If the anomaly is "not good enough," is it really an anomaly?

Because rules were followed, one of the largest and highest-grade porphyry Cu deposits in one of the world's great copper provinces was rejected by at least four previous exploration groups, even though there was limonite after chalcocite in outcrop, rock samples were anomalous in copper, and widely accepted models were available. How can a rock sample anomaly not be good enough? If a geochemical anomaly exists, drill it. If the anomaly is "not good enough," is it really an anomaly? Dave Lowell (pers. commun., 1980s) later commented that the Escondida alteration zone was too large not to be drilled. The Lowell program ignored some rules, reflecting a tenacious approach to the project, and made the discovery.

The Escondida case history illustrates the danger of rules. Where models function as rules in the early stages of exploration, the geologist's decision-making may be inhibited and lead to linear thinking. Geologists must accept that most accessible prospects have already been inspected and rejected. Ore deposits remain to be discovered because clues in their outcrops were unrecognized or ignored or didn't fit a model. *Be aware of the rules and beware of any general rule during the early exploration stage. Following rules can lead to a failure to consider alternatives.*

Ore guides drive discovery

Ore guides are specific geologic features associated with ore. They have been used for centuries, and their importance during exploration can't be overstated. They may be large or small, visible in an outcrop or drill core (copper oxide) or invisible (electrical conductivity or geochemically anomalous). Ore guides are mostly small, very specific aspects of a model that are visible in the field and commonly modified by surface weathering. Initial encounters with ore guides occur when a geologist inspects an outcrop.

Be aware of the rules and beware of any general rule during the early exploration stage. Following rules can lead to a failure to consider alternatives.

Outcrop information may confirm the deposit model, but the drill target and the location of the drill holes are determined by mapping ore guides in outcrop, not the model, and drilling makes the discovery. Drill core provides a continuous sample of sufficient length that the scale of features seen in outcrop transitions to the scale of a mineral deposit, allowing aspects visible in unweathered drill core to be interpreted in the context of the full-scale model. As drilling continues, grade in drill core becomes the principal guide to higher-grade zones of mineralization. Descriptive aspects of the discovery may be used to develop a local model, in order to evaluate nearby targets. It is largely at that point that the model may have some use as a larger-scale ore guide.

As an example, John Kinnison and Art Blucher, while working for American Smelting and Refining Company (Asarco) in Arizona in 1960, located an isolated outcrop of Precambrian granite containing traces of chrysocolla, several narrow and altered porphyry dikes, and disseminated limonite after pyrite and chalcocite. The final exploration hole intersected the edge of what became the Sacaton porphyry Cu deposit (Cummings, 1982). Related fault offsets, containing several billion tonnes of copper mineralization and completely concealed under postmineral alluvial cover, were later discovered, extending over 10 km southwest of the mine (Vikre et al., 2014).

A compilation of ore guides visible in the Sacaton outcrop and other southwest USA porphyry Cu deposits would include (1) copper oxide, (2) limonite after oxidized copper and other sulfide minerals, (3) a felsic porphyritic intrusion, (4) stockwork fracturing or sheeting, (5) hydrothermal alteration, (6) multiple generations of quartz-sulfide veins, (7) exotic copper- and iron-cemented postmineral alluvium, (8) color anomalies from supergene alteration or weathering of sulfides, and (9) prospect pits. One, or a few, of these ore guides would justify aggressive mapping, rock sampling, accelerated field work, and land acquisition. Geophysical surveys may provide support for deeper drilling with justification from early drill results, as discussed by Witherly (2014). However, copper or any metal is still its own best ore guide, a simple concept frequently overlooked.

The importance of ore guides as the principal drivers of discoveries of other ore deposit models is clear. A principal weakness of models during the field phase of mineral exploration is scale. Ore guides are rarely if ever illustrated in publications on individual deposits, even though they provide the initial exploration leads. Further, models rarely, if ever, discuss the effect of weathering. Although it might be implicit that the porphyry Cu ore deposit model incorporates all of the applicable ore guides, the large scale of deposit models is such that small-scale ore guides fall prey to the cliché "out of sight, out of mind."

Descriptive and genetic models provide a general understanding but have the potential to constrain thinking and lead to confusion and premature abandonment of a prospect because "it doesn't fit the model," or results in the mapping of imagined essentials. However, ore guides are what the geologist sees in outcrop, and once identified only then can the geologist determine what the model might be and what the appropriate next steps should be. Simplistically, models and metallogenetic belts get you into the area and focus your mind, but ore guides and field work find the deposit. Not all geologists will agree, but ore guides worked well without models in the 19th and 20th centuries and will work equally well in the 21st century.

Discovery Drives Discovery Cycles

Discovery cycles are intervals of increased discovery rates. The principal drivers of these cycles are ore guides observed in the field. As more discoveries are made, exploration activity may evolve into a "rush" much like the California gold rush in 1849, and following the herd is an effective exploration strategy if one gets in early. Figure 2 shows the porphyry Cu deposit discovery cycle in southwest North America from 1900 to 2000.

Deposits mined prior to World War II in the USA were discovered by prospectors and operated in the mid-late 1800s as small underground mines. Following development of the Bingham Canyon, Utah, open-pit Cu mine in 1906, many other small mines were redeveloped as open pits. Most of the pre-World War II open-pit porphyry Cu deposits exploited near-surface, supergene chalcocite enrichment blankets.

Following World War II, discoveries were increasingly made by managed exploration teams using ore guides that included a leached capping interpretation technique developed initially by Locke (1926). This technique had been used for decades to guide drilling at existing porphyry Cu mines, but not for mineral exploration. The importance of the leached capping technique as a guide to new deposits was recognized and refined in the late 1940s by Kenyon Richard and Harold Courtright, working out of Tucson, Arizona, for Asarco. They applied it with considerable success to identify exploration targets where characteristic limonite after chalcocite indicated potential for supergene chalcocite enrichment. The combined concepts of managed exploration, leached capping interpretation, and other ore guides visible in outcrop sharply accelerated the number of porphyry Cu discoveries (Fig. 2).

Discoveries of porphyry Cu deposits in southwest North America began increasing two decades before the Lowell and Guilbert model was published (Fig. 2). The discovery cycle peaked in 1970, when the model first appeared, and declined to zero 10 years later, demonstrating that neither the Lowell and Guilbert model, nor the earlier Jerome model, drove that cycle. The pattern for and timing of porphyry Cu discoveries in western Canada was similar to that in southwest North America but was more extended in time.

In contrast to southwestern North America, the discovery cycle for Archean volcanogenic massive sulfide (VMS) deposits in eastern Canada was different. It showed an abrupt increase in discoveries in the early 1950s (Fig. 3), Geology and Mining: Aspects of Mineral Exploration Thinking (continued)

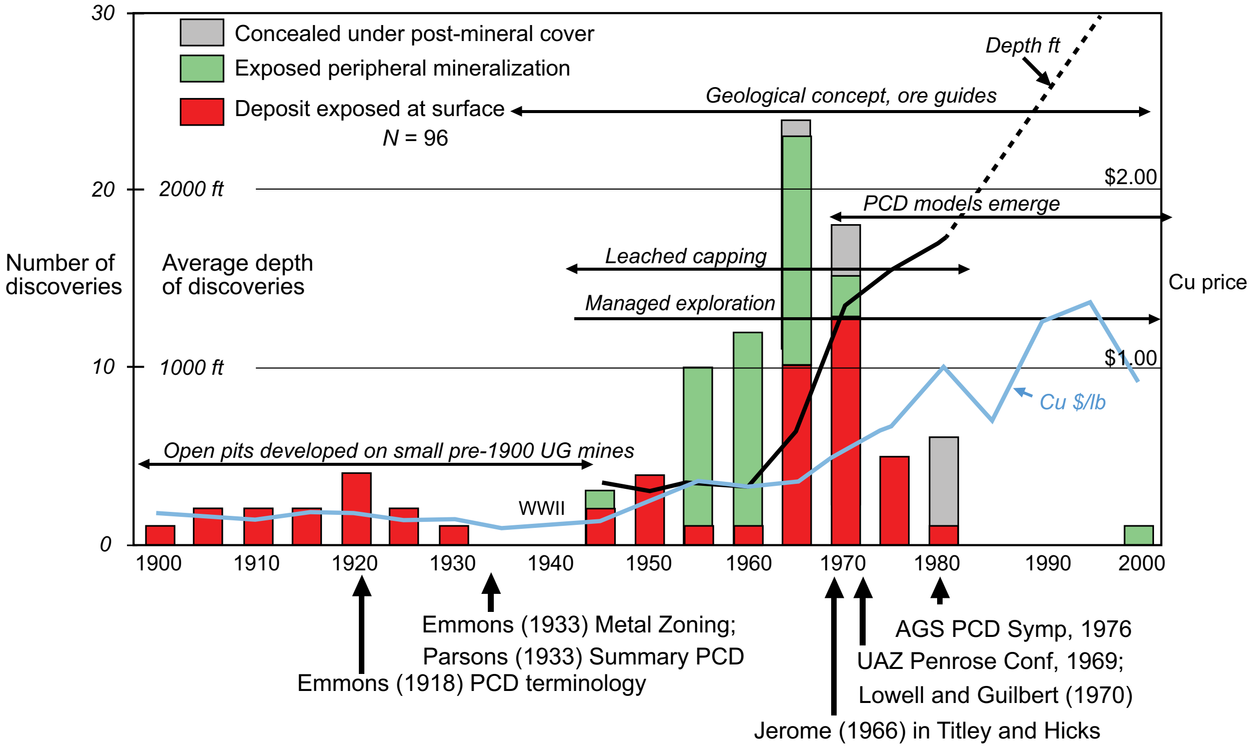

Fig. 2. Discovery frequency for porphyry Cu deposits (PCD) in southwestern North America (Arizona, New Mexico, Utah, Nevada, Montana, and Sonora, Mexico) from 1900–2000 in five-year intervals showing depth, extent of concealment, metal prices, time intervals when principal ore guides were influential, and dates of important publications of porphyry Cu models. The gradual increase in the number of discoveries reflects the time-consuming nature of the field studies. This discovery cycle was geologically driven and ended when depths for open-pit mining were exceeded and gold prices started a rush to Nevada. Data from the author's files. See text for further details.

which resulted from the development of highly successful airborne magnetic and electromagnetic techniques that could rapidly survey large areas. Published VMS models appeared about 10 years later. Airborne geophysical technology, not a model, initiated the VMS rush and drove additional discoveries.

The different shapes of the discovery cycles in Figures 2 and 3 reflect two different exploration techniques. Discoveries of porphyry Cu deposits were driven by ore guides; this was a geologically driven discovery cycle. It included time-consuming leached capping studies, unfamiliar to most geologists, which provided time for latecomers to participate. VMS discoveries were driven by new and rapidly applied airborne geophysical surveys. It was a technology-driven cycle that could cover large areas quickly and required that exploration groups move quickly or miss out, although a few exploration groups working secretly with proprietary models were very successful (Bleeker and Hester, 1999).

The porphyry Cu and VMS discovery cycles demonstrate that recognition of ore guides in outcrop and technological advances were the essential elements driving these two discovery cycles, not ore deposit models. Ore guides lead to discoveries that enable the concept of modeling, not the reverse. Models eventually provided an easily understood visual frame of reference, however, and this new intellectual approach appears

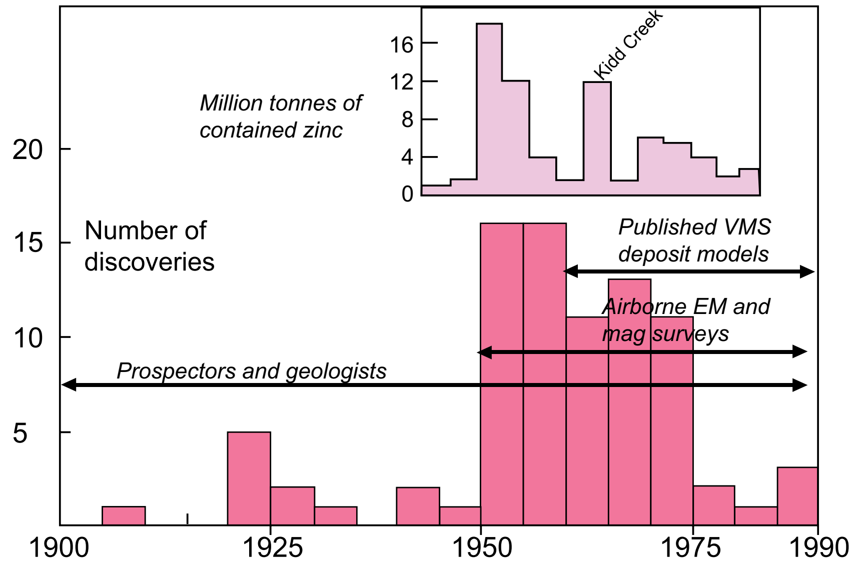

Fig. 3. Discovery frequency of Canadian Archean volcanogenic massive sulfide (VMS) deposits from 1900–1990 in five-year intervals, showing when exploration techniques and published VMS models became influential. The abrupt increase in the VMS discovery rate in 1950 was driven by airborne electromagnetic (EM) geophysical surveys in areas with virtually no outcrop. Data from the author's files.

to have generated enough enthusiasm to sustain longer-term discovery rates. The same may be said for scientific research on porphyry Cu and VMS deposits. It did not initiate discovery cycles, but likely extended those cycles as new concepts reenergized the profession and investor interest in exploration.

Discovery Thinking Must Be Nonlinear

Mitcham (1967, p. 421) wrote, "In seeking concise mechanical solutions and procedures, our attentions are easily focused away from reasoning toward methodology." Although the term "linear thinking" had barely entered the literature in 1967, it appears that this was what Mitcham had in mind by "mechanical solutions" and "methodology." Linear thinking follows well-defined step-by-step progressions, or rules, starting with the completion of a specific task before moving to the next one (Charles, 2009). The starting point and outcome are fixed in advance. An example is developing a mine. Engineers must be linear thinkers because of the financial risk involved in changing the plan during an expensive construction project.

Nonlinear thinking involves simultaneous, multiple directions of thought, with multiple starting points, where one can apply the appropriate thinking to an objective (Charles, 2009). An example would be an initial examination of a prospect or large alteration zone. Nonlinear thought increases possible outcomes because the starting point and path to an objective are undefined. It has also been called lateral or right-brain thinking; every alternative is evaluated, and conventional wisdom is marginalized. There are few or no rules in a nonlinear situation, and a nonlinear thinker is likely to ignore them, paying no attention to accepted ore deposit models or head office instructions, and, demonstrating a combination of common sense, intuition, and fearlessness, decide an outcrop is just different enough to be drilled.

A classic example of this fearlessness occurred on Bougainville Island in the southwest Pacific Ocean in the early 1960s when Ken Phillips decided to ignore a head office direction to stop drilling while further exploration was reviewed, since early drill holes hadn't intersected the sought-after copper and gold grades. Phillips then relocated the rig to an obviously copper mineralized outcrop that local Bougainville Island people had shown him and intersected the high-grade core to the Panguna Cu-Au porphyry deposit in Papua New Guinea (pers. commun. from K. Phillips to D. Wood, 1976).

The Escondida and Panguna examples demonstrate that exploration thinking can be quite messy, intellectually. It is not an exercise in perfection. When the opportunity to test an idea arrives or is at risk of being lost, it must be seized. The opportunist is a risk taker trying to identify the connection between diverse and apparently unrelated facts in outcrops that head office staff have never seen. One never knows everything when the first hole is drilled, which is one reason that it's drilled. Adherence to an ore deposit model can lead to costly, time-wasting delays in the search for more data "to fit the model" that simply isn't available. Corporate headquarters staff have very different responsibilities in a very different business culture, and rarely understand the on-site thinking behind a new discovery.

> **It's a common lament of many prospectors that *ore is where you find it*. I would redefine that phrase as the Exploration Uncertainty Principle and reword it to state that *ore is increasingly where you least expect to find it*.**

Evaluate all alternatives

Harold Courtright (pers. commun., 1970s) remarked that overreliance on a single interpretation is the most common reason that ore deposits remain to be discovered. Every 21st-century geologist examining an area with prospect pits or small abandoned mines must understand the likelihood that other geologists have been there previously and concluded that the prospect lacked potential, and one may never know why. Many discoveries might be more appropriately termed rediscoveries. Bristow (2020) commented that "on average, the fifth person that looks at a deposit discovers it." Sillitoe (1995) made a similar estimate. That number could easily be dozens, and many of those geologists likely had a decade or more of field experience.

The next geologist on any property must identify and evaluate all possible alternatives, however unlikely they may seem. It's a common lament of many prospectors that *ore is where you find it*. I would redefine that phrase as the Exploration Uncertainty Principle and reword it to state that *ore is increasingly where you least expect to find it*. Every new prospect evaluation will be different, and, more often than not, geologists will only have one chance to get it right. Those who reject a prospect rarely ever reexamine it in the field.

Geologic maps are decision-making documents

A geologic map is a decision-making document. A reliable map is as important as a resource estimate or financial analysis, and it is probably more accurate. Data gathering in the early stages of exploration should start with the geologic map. That map is far more than an exercise in gathering isolated facts that may be of limited use. It combines facts in a context that provides understanding of the nature and size of the target: whether that target is large enough to justify more work and acquisition of mineral rights, what additional field work is needed to decide where to site the first drill holes, and the locations of outcrops, prospect pits, claim posts, and all geologic details. Field sheets and notes should be retained permanently, however sun-bleached, rained-on, blood-stained, or dirty they may be. All geologic maps must be accompanied by geologic sections.

The importance of a geologic map can't be overemphasized. Outcrop mapping separates facts from interpretation, and, where possible, data should be recorded quantitatively. In an operating mine, the map is a check on the reserve model, as well as on safety issues such as pit-wall stability. Some will say remapping is unnecessary, because the rocks haven't changed, but their interpreted importance frequently does. Kenyon Richard (pers. commun., 1970s) advised that all rock exposures should be observed and reobserved.

Similar thinking should apply to relogging of drill core with visual estimates of the grade recorded as a check against sampling and assay errors. It is not logical to spend large sums for QAQC programs that don't also check the consistency of the geologic database that exerts the primary control on assay continuity in the resource estimate. The first look is not always the last word. I also log quantitatively on paper where the entire log is constantly visible and carry my completed field sheets with me in the field. Eventually all data should be digitized in an easily retrievable format and summarized graphically. It is nice to be unbiased, but as geologic patterns develop, they provide alternatives that influence your thinking about where the first drill site might be, where you might need additional mineral rights, and other early-project concerns such as whether drilling is even justified.

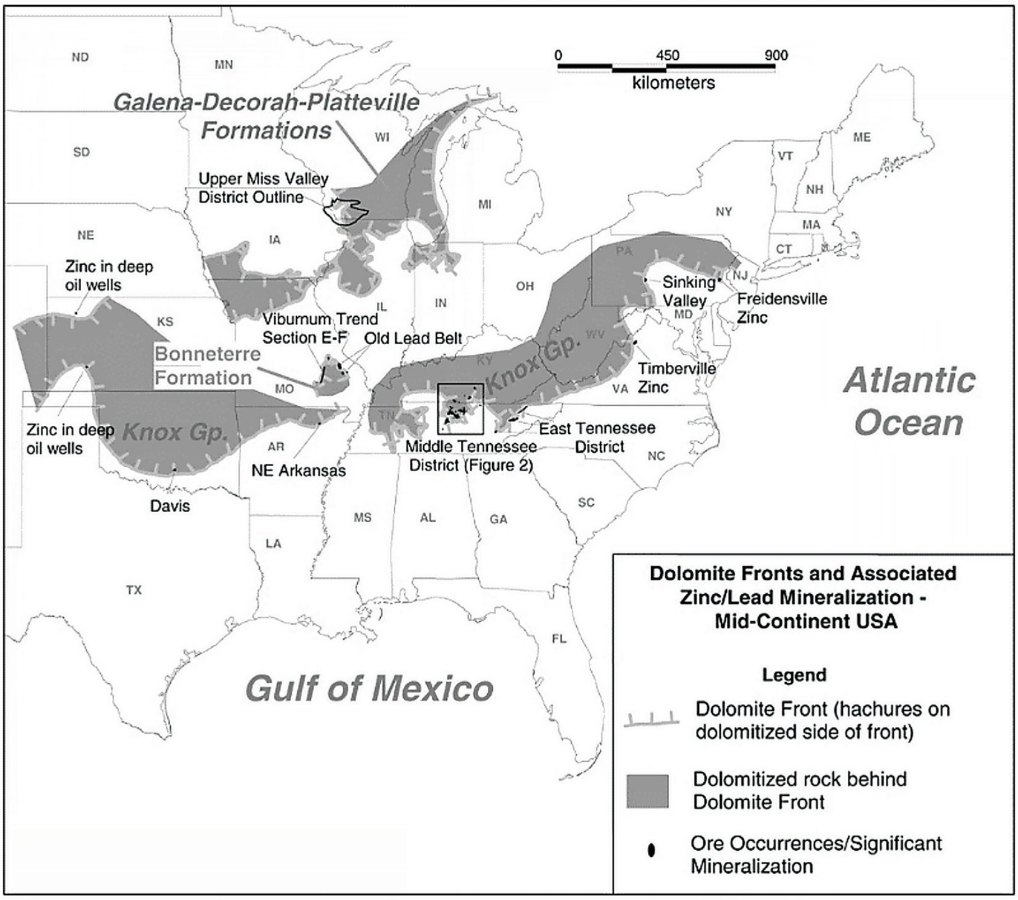

Fig. 4. Map of eastern USA showing linear extent of dolomite fronts and location of associated Mississippi Valley-type zinc-lead districts (Harper and Borrock, 2007).

System-based exploration thinking

A system is a group of related features having a common basis, or source. The first reference to a hydrothermal system may have been Emmons (1933), who called them metalliferous lode systems and provided a diagram (Fig. 1). The earliest successful application of systems-based exploration thinking may have been in 1964 when the New Jersey Zinc Company (NJZ) drilled an ore-grade intersection of Mississippi Valley-type (MVT) zinc mineralization in Tennessee, following a three-year program of continuous regional drilling (Callahan, 1977). The search area covered 3,900 km^2 in size and involved drilling 79 holes with an average hole spacing of 8–10 km. NJZ was following the edge of a 1,900-km-long alteration zone in the eastern USA (Fig. 4), possibly one of the largest hydrothermal systems known (Harper and Borrock, 2007). This program was notable for its continuity of effort, i.e., tenacity.

Publications on individual porphyry Cu deposits rarely discuss the outer limits of visibly related features, such as the edge of pyritic or peripheral alteration zones and small mines or prospects. However, scaling up exploration thinking to the size of a mining district, or hydrothermal system, is a valid search strategy. Metal zoning patterns may extend well beyond the central alteration and pyritic zones in porphyry Cu deposits. Such patterns encompass 152 km^2 at Mineral Park (Wilkinson et al., 1982), 120–140 km^2 at Sunnyside (Graybeal, 1984), and >160 km^2 at Bingham Canyon (Babcock et al., 1997). Shapes are generally elongate with a bilateral symmetry. Bingham Canyon metal zoning is anomalously asymmetric, with the open pit at the southwest end of the district. This asymmetry may indicate additional potential to the southwest, as suggested by geophysical data (Witherly, 2014).

District zoning patterns in porphyry Cu systems are powerful exploration guides. In the 21st century a few insignificant-looking veins of high-grade silver-manganese oxide, or a small massive lead-zinc sulfide replacement of carbonate rock, may hint at an outer zone to a porphyry Cu system several kilometers beyond the distal skarn and other pervasive alteration zones typical of the cores of these systems. The distribution of distal base and precious metal lode deposits has led to discovery of several genetically related porphyry Cu deposits in southwest USA, including the Pima, Mission, Twin Buttes, and Sunnyside deposits in Arizona (Titley, 1982; Graybeal, 1984, and pers. files). The reinterpretation of the origin of the Big Cadia copper-gold-magnetite skarn in New South Wales, which had previously been considered a VMS deposit, was the impetus for Newcrest geologists to look for a porphyry deposit at Cadia, resulting in the discovery of five individual gold-copper deposits (D. Wood, pers. commun., 2021).

Other deposit types may also generate large halos, as discussed by Beinlich et al. (2019) for the Cinco de Mayo Zn-Ag carbonate-replacement deposit in Mexico and by Large et al. (2001) for the dolomitic siltstone-hosted HYC Zn-Pb-Ag deposit in Australia. The importance of these halos as exploration guides is substantial.

Acquire enough ground

Before drilling can begin on a new prospect, mineral rights must be acquired, and this invariably attracts the attention of competitors. Intangible questions must be answered with little more than experience for guidance, such as what kind of a hydrothermal system it is, how big it is, where the center is, and when to start acquiring mineral title. Numerous mineral deposits have been lost to less informed competitors due to failure to acquire enough ground. News concerning new exploration activities and concepts spreads rapidly.

There are no rules for determining how much ground is enough. Almost every explorationist has faced this dilemma, and every situation is different. One is faced with spending too much for moose pasture or missing out on the next Escondida. How much is enough is an inexact question, and science won't help. Thinking philosophically about protecting identified opportunities and adjacent areas of postmineral cover, I suggest that you don't have enough until you have more than enough.

Once mineral rights are acquired and a target has been confirmed, start drilling. There is no need for confirmation overkill, and time is rarely on your side.

Rig the odds

The odds of making a discovery are very low. Slichter (1960, p. 42) wrote, "An attractive feature of [prospecting] is the fact that the players are free to rig the odds as favorably as possible." There were no suggestions for "rigging," but one approach might be high grading the outcrops. A high-grade rock sample from an isolated outcrop hints of a hydrothermal system capable of extracting, transporting, and depositing high concentrations of metal, and this is an important ore guide. High grade is a start and might beat everything at the initial prospecting stage, because that single high-grade sample is often the only thing that the geologist has to keep that project alive. In my experience, geologists are very good at high grading.

A second approach is to explore in a known mining district, if there is ground available. Available means open for staking, or filing permits, or acquiring from an owner amenable to a deal. Any hint of district zoning or isolated prospects may indicate a central, deep heat source, even if the deposit model is unknown.

Third would be to use all of the available data—an obvious, yet widely ignored practice. Too many geochemical programs collect thousands of samples, analyze each for dozens of elements, and then plot one map—or worse, the samples are analyzed for the one element of initial interest and are then discarded. Analyses should include all elements related to the objective, and every element should be plotted on separate maps, along with relevant ratios. Modern multielement analytical methods are accurate and inexpensive (Halley et al., 2015), and, contrary to some, I consider pathfinder elements important ore guides. Useful statistics should be calculated, with the warning that statistical software only provides what the programmer instructed it to provide, and that's not always what is wanted.

Fourth would be to design and fund a multiyear program to bridge short-term issues such as falling metal prices and staff continuity. In the exploration business, one year of funding is simply not enough for a junior company with no cash flow. The program should lead to drilling quickly because investors know a good drill intersection will boost the price of your company's shares, and that is their goal.

A final admonition is to spend wisely—another widely ignored concept. Too often companies continue to explore after a target has been identified. That's OK, but drill when there is a target, and use the drill results to guide further exploration when uncertainty is high and that information is most useful.

As a sidebar to exploration spending, numerous business surveys report that falling discovery rates are destroying wealth because the annual value of metal in the discoveries is exceeded by the total annual expenditures of all exploration programs. These surveys are misleading because the time interval of the expenditures is fixed. In contrast, the value of initial resource estimates will likely increase as operations become more efficient, cutoff grades decrease, and metal prices rise. The ultimate annual value of all resources discovered, including metal sales, capital expenditures, and wages and taxes, won't be known for decades and may far exceed the total of annual expenditures on all projects. Many mines like Silver Bell and Mission in Arizona and Bingham Canyon in Utah have since produced in excess of 10 times the original resource and are still producing.

Continuity beats everything

Conventional wisdom holds that grade beats everything. I disagree with that view. The objective of mineral exploration is to find a highly profitable ore deposit, regardless of the grade. That single thought should be constantly on the mind of every explorationist. Low-grade deposits can be very profitable, and some high-grade deposits are unprofitable.

I rank continuity of grade as the most important of the technical aspects required for a profitable mine, although it is not the only important thing. Continuity of grade is just one of many important aspects of a mineral deposit including access, infrastructure, jurisdiction, permits, reserve estimates, mining and metallurgical methods, cost estimates, and social and environmental setting, and any one of these aspects can doom a mine development.

For a mineral deposit to be ore, there must first be continuous mineralization between adjacent drill holes. Continuity builds tonnes; those tonnes contain the total units of metal (ounces, pounds, kilograms, etc.) that pay for mine development, operating expenses, shareholder dividends, geologists' salaries, and ongoing exploration to replace the ore being mined. One indication of grade continuity between drill holes is the continuity within a single drill hole. Phil Jenney once advised (pers. commun., 1960s) that "when you have an intersection of continuous mineralization like this one there is always more so keep the drill running."

A resource estimate is a geologic characteristic of a mineral deposit that has been quantified using various estimation methods. Jowitt and McNulty (2021) discuss the complex computer software used in these estimates, usually a one-size-fits-all algorithm that follows programmed instructions, regardless of the variability of grade and geology in the deposit. Geologists must keep up-to-date, hand-drawn cross sections as a check against excessive spreading and smoothing of computer-generated versions of continuity; exploration involvement doesn't end until the final estimate is published. Questions regarding continuity of an open-pit resource can be resolved by drilling additional interspaced holes; Stone and Dunn (1994, p. 93) propose less costly alternatives. Continuity of any underground resource is best established by driving workings into the orebody—an effective if expensive exercise.

Many mineral deposits have small, discontinuous pods of high-grade mineralization called nuggets that disproportionally influence resource estimates if used at face value. Failure to reduce these values allows their influence to be spread too far by current software programs, resulting in a false impression of continuity and excessively high estimates of the resource grade.

Continuity may also be implied in news releases that report long drill core intersections of apparent ore grade with a short high-grade interval. Normally, the total and internal high-grade intersections are reported separately. Subtracting a high-grade interval from the entire intersection may reveal the grade of the remainder is below the cutoff grade being used, and the implication of significant continuity disappears; I have found negative residuals. Numbers convey an impression of certainty, but don't be fooled. Think about numbers that don't look quite right and check them carefully.

Continuity should be confirmed by routine geologic mapping in all mines. That is where exposures of ore can be followed visually and deviations from computer models can be revised for more efficient mining. Flawed resource estimates are a principal cause of mine failures and lack of continuity is a principal reason. McGee (2019) provides several examples.

Continuity of effort also keeps an exploration program alive, holding off gamblers ruin, while developing and keeping expertise and further rigging the odds in your favor. Grade gets you interested, but continuity gets you the orebody.

Numbers convey an impression of certainty, but don't be fooled. Think about numbers that don't look quite right and check them carefully.

Discovery is not about luck

Let me be very clear: discovery is not about luck. It is about experienced geologists with limited funding and limited time making decisions based on limited data of variable quality.

Grassroots discoveries are those made on relatively unexplored and undrilled prospects and are relatively infrequent. Brownfield discoveries are those made in active mining districts that can be mined using existing mine infrastructure and are developed as existing mines are depleted. Discoveries made in abandoned mining districts can rapidly turn closed mine sites into ore and might be termed rediscoveries. As one example, the realization around 1980 that the mostly closed underground gold mines in Western Australia could be redeveloped as open pits on the lower-grade envelopes adjacent to the gold veins resulted in many dozens of highly profitable new mines. Occasionally a new deposit model is recognized, such as the Carlin-type extremely fine grained gold deposits in Nevada that are very obscure in outcrop but can be detected by detailed prospecting and rock sampling. Recognition of the Carlin gold model generated a major rush to Nevada driven largely by detailed geochemical sampling that greatly accelerated the discovery rate.

Discoveries result from an awareness of a changing landscape of metal prices, exploration strategies, extractive technologies, a strong streak of opportunism, and the rare new model that generates new discovery cycles; brilliant geologic insights help but are uncommon. The advantage of exploring in known mining districts and metallogenetic provinces and getting in early on a new cycle should be obvious. Thinking about exploration is more than thinking about rocks, minerals, and models.

Failures involving abandoned prospects where a competitor later made a discovery are rarely published. Geologic errors are often traced to tunnel vision and a failure to consider alternatives. Hollister (1985, p. 1051) wrote, "Exploration successes hinge on both management and geologic factors. But many projects employing crack teams of geologists have failed. Thus, the management factor reigns most important." Corporate-level errors often result from poor communication, rigid strategies, decision makers who lack geologic insight, excessive caution, and short-term thinking driven by investors.

Although it's nice to be lucky, no one denies that certain explorationists have superior track records, suggesting (or proving) that skill beats luck. They are ore finders who are simply better at it than others, however intangible their skills and difficult it might be for them to explain their success. The success of ore finders, in particular repeat performers, demonstrates strong components of opportunism, skill, realism, a sixth sense for ore (intuition), a preference for field work, and tenacity that goes far beyond mere luck. As exploration geologists are forced to consider increasingly deep targets in heavily weathered terranes, in addition to the potential for new models and the variability of accepted models, intuition may become an increasingly important exploration attribute. Intuition, as described by Kahneman (2011, p. 237) is "knowing without knowing" how you know. Simon (quoted in Kahneman, 2011, p. 11) concluded, "Intuition is nothing more and nothing less than recognition." Although intuition can't be quantified, it is thought to be enhanced by experience.

Many discoveries result from important, even direct and essential, input from multiple participants who may be unnamed members of the exploration team, mine managers, consultants, and others including CEOs and members of corporate boards of directors. The Newcrest story is a good example (Wood, 2014). Just don't expect to get your name in the newspapers if you are a discoverer. Your peers and supervisors will let you know they know, and there could hardly be a better reward than that.

Some field activities that lead to new discoveries can be taught, like mapping, sampling, and logging. However, ore deposits and their variable weathering environments are so diverse that identifying the point when a team might be close to a discovery is a concept too difficult to teach. Neither, as far as I am aware, can intuition be taught. Recognizing that a discovery may be imminent is an attribute acquired by experience and not by taking notes in a short course.

So how does one acquire or recognize the intuition that might lead to a new discovery? The most obvious move is to get early career professionals into the field where they are exposed to the masking effects of weathering, the uncertainties of exploration decision-making, and the thinking, activities, and experience of senior ore finders, then see what happens. Being part of a field team is important because it helps to generate group discussions about alternatives.

Another would be to study case histories. The perspectives of multiple participants may differ, and any historical narrative may suffer both from unintended revisionist thinking and the absence of comments from those most closely involved in a decades-old discovery. However, case histories by Callahan (1977), Coope (1991), Lowell (1991), Ortiz (1995), Sillitoe (1995), Bleeker and Hester (1999), and Wood (2012) are carefully documented page turners, and the literature has many others.

A third clue might be to recognize that when you are on a prospect you can't quite understand, the uncertainty you are experiencing might be your intuition kicking in. Stay with those thoughts and return to or think back about that prospect until you do understand it.

A subtle aspect common in many discovery case histories is that successful teams were conspicuously tenacious, meaning that they did not give up easily. Hutchinson and Grauch (1999, p. 1) call it persistence. I see both terms as tangible evidence of intuition at work, not luck. And don't forget that intuition is recognition of something experienced before, whether or not you can recall or describe it. It's that sixth sense of knowing without knowing how you know. For more on when we can and cannot trust our intuition, I recommend Daniel Kahneman's 2011 book, *Thinking, Fast and Slow*.

The New Normal

The early career professional

Exploration begins with the identification of rocks in weathered outcrops and drill core, often in difficult field conditions; these observations are not possible in classrooms. This is an all-important skill that is often lacking in early career geoscience professionals. Even the experienced geologist may have issues when first arriving at a new prospect. When answers were not clear, I would move to the next exposure, eventually returning to the troublesome exposure to get it right. Debates concerning the nature and importance of a strongly weathered and altered rock are common in the field and are great learning experiences. Familiarity with the broader aspects of mineral exploration will come with time.

For the individual seeking a career in mineral exploration, a field-based graduate thesis opens many doors and might then be followed by a few years as a mine geologist. Mine work is the fastest way to gain insight into what ore and ore controls look like in the real world. You see far more rock in a mine than on a typical field assignment where the rocks may be badly weathered and so concealed that you might only see a few outcrops in an entire day.

What one learns on the job depends on taking some initiative to learn. Graphic and geographic information system (GIS) computer skills will be assumed, as will a desire to get into the field. Field-portable instrumentation capable of chemical and mineral analyses is increasingly sophisticated and should vastly accelerate the speed at which sample analyses are received by field crews. However, field work still begins with a rock hammer, hand lens, and geologic map—the principal tools for geologists of all generations. These will determine where and when the use of more complex instruments will be justified. One of your most important career assets will be your network of professional colleagues. Volunteering time to support scientific and professional organizations will help build that network and should be considered one of your professional responsibilities. Just when a geologist might be considered experienced is an intangible assessment not easily measured and depends on the individual. Ten years of experience is different from one year of experience repeated 10 times.

A less tangible, but important, skill is communicating with those unfamiliar with ore deposits. Although geologists are the front line of the discovery process, we are not the center of the universe inhabited by those who provide our funding. Clear communication is critical, as funding may disappear if senior executives and directors don't understand what you are doing. To communicate, the geologist should know whether the jargon of science or the bottom line of business is more appropriate for the venue. In addition, write one-page memos whenever possible.

New models and technologies

Unrecognized ore deposits and deposit models that deviate importantly from accepted models may exist in plain sight or at modest depths, with features so subtle or unusual that the potential for mineralization has been overlooked. Their recognition may require thinking beyond the conventional wisdom that what is seen is all there is. As an example, the first Carlin-type gold mines developed in the USA were the Getchell and Gold Acres deposits in Nevada. Both started production in the mid-1930s, and the unusually fine grain size of the gold mineralization was later reported by Vanderberg (1939). However, Carlin, the first significant sediment-hosted gold mine in a well-known fine-gold district, was not discovered until 1962, 30 years later; this started a Carlin gold rush in Nevada that continues today (Coope, 1991).

Another example is the NJZ discovery of the MVT deposits in central Tennessee that contain co- and by-product gallium and germanium, which at times had a higher combined dollar value than the zinc. Still another is the Cadia district Au-Cu discoveries in the Macquarie arc of New South Wales, once thought to be a VMS environment but now known to be variations on the porphyry Cu deposit style (Wood, 2012).

The Superior East exotic copper deposit in Arizona (Graybeal and Cook, 2007) is a 500 Mt to 2 Gt, entirely concealed deposit of native copper and cuprite averaging about 0.5% Cu and hosted in a polymictic mid-Tertiary conglomerate. The copper minerals are restricted to coatings on and thin seams in diabase clasts; there are no veins, no sulfide or blue green-copper oxide minerals, and the only visible alteration is a reddish zone from oxidation of mafic minerals that coincides with the native copper zone. The copper was derived from an adjacent porphyry Cu system. Exotic copper deposits may leave little evidence of their presence other than a nearby, moderately eroded porphyry Cu deposit with a deficiency of copper measured as supergene chalcocite relative to the interpreted total amount of eroded copper.

New mining and metallurgical techniques may turn mineral deposits into ore deposits. Oxidized copper deposits concealed under postmineral alluvial cover at depths uneconomic for surface mining are becoming viable exploration targets. The Florence (formerly Poston Butte) and Gunnison (formerly I-10) porphyry Cu deposits in Arizona are currently in the ramp-up stage as in situ copper mines. The possibility of heap leaching chalcopyrite in waste dumps is now being tested at Pinto Valley in Arizona (Williams, 2021) and might open possibilities for in situ leaching of chalcopyrite. In situ mining of sandstone-hosted uranium is already a well-developed technology.

Artificial intelligence and machine learning are becoming useful for developing information from large data sets quickly (Woodhead and Landry, 2021). Regardless, time in front of a computer means less time in the field looking for the next drill target, and any recommendation to drill a hole based on computer output must first be confirmed in the field by a geologist. I agree with the closing comment by Woodhead and Landry (2021, p. 29) that, compared to machine learning as an exploration tool, "intuitive human expertise will remain essential for the foreseeable future."

New normal and half-life of knowledge

The new normal will include systems-based exploration thinking scaled to the type and size of the ore-forming system being explored, modeling subtypes of porphyry Cu and other deposit models, compilations of ore guides visible in outcrop, field-portable chemical and mineralogical instrumentation, and finding new ways to rig the odds in one's favor. The potential for oxide and exotic copper deposits and chalcocite-enrichment blankets under postmineral alluvial cover remains high, although they are difficult targets to generate due to limited ore guides.

The likelihood seems high that the next big discovery will have been rejected numerous times. Reexamining small and/or odd deposits for which there are no known models, such as the recognition of fine gold at Gold Acres in 1935 and the 2008 discovery of the Merlin Mo deposit in Australia (Babo et al., 2017), will require that geologists continuously rethink conventional wisdom and go with their sixth sense where it seems appropriate. Various government survey publications, particularly those that are older, are good sources of this type of information. MVT deposits with high concentrations of elements like gallium, germanium, and indium may be possible targets.

There is a half-life of the knowledge that one needs to succeed in any profession. I estimate that the half-life for metals exploration in 2021 might be 10 years. Half-life means half of what one knows now will be obsolete in 10 years, and half of what one will need to know in 10 years is not yet known. Half-lives decrease with time, so we must stay current with both the science and business of exploration at all stages in our careers.

Acknowledgments

Doug Kirwin, Miguel Ponce, Dick Tosdal, and Peter Vikre clarified opinions and suggested topics that required more detail, and Dan Wood and Jeff Hedenquist provided editorial guidance. I thank these geologists for their collective input, which has improved earlier drafts.

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