

VIEWS

Mineral Resource Discovery — Science, Art & Business

(These columns are the opinion of the author, and do not necessarily reflect the view of the SEG.)

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INTRODUCTION

I believe that mineral exploration is an art informed by science and that the discovery process is enhanced when approached as a business, albeit not the sort of business taught in contemporary management courses. The business of exploration is to manufacture discovery.

Over the years, many mining company CEOs and exploration managers will have pondered why only some exploration geologists and mining companies make discoveries. After 42 years in mineral exploration and despite having been associated with several discoveries, I do not know the answer. However, I can identify some factors which I believe enhance discovery capability.

As with scientific discovery in general, many mineral resource discoveries appear to be simple with the benefit of hindsight, and one could reasonably ask why they took so long to be made. Similarly, most of the points made herein are simple. They evolved during a career working with teams that defined the following deposits: the Archean Mount Marion Au deposit in Western Australia; the Proterozoic Coronation Hill Au-Pd deposit in the Northern Territory; the Ordovician Cadia Hill, Ridgeway, Cadia East/Far East, and Marsden porphyry Au-Cu deposits in New South Wales; the Permian Crinum coking coal deposit in Queensland; the Permian epithermal Au-Ag Royal, Crown, Sovereign and other veins at Cracow in Queensland; the Jurassic Chinchilla steaming coal deposit in Queensland; the Tertiary Rio Blanco porphyry Mo deposit in Peru; and the Pliocene bonanza Toguraci and Kencana epithermal Au-Ag deposits at Gosowong in Indonesia. Collectively, these deposits have an in-ground commodity value of ~$100 billion at today's prices.

Dan Wood's career includes 24 years with BHP and 18 years with Newcrest Mining. During this time he explored for a diverse range of commodities in Australia and worldwide that ranged from coal and oil shale to copper and gold. From the mid-1990s, he led Newcrest's exploration team that Metals Economics Group judged as the world's most successful gold explorer in the period 1992–2005. He retired in late 2008.

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Time constraint

When I started my exploration career in Australia in the 1960s, I was employed by a large mining company and thought little about the time available in which to make a discovery. Twenty years between discoveries was occasionally mentioned and as large mining companies needed large deposits, this seemed a reasonable timeframe to work within.

Probably starting about 1980, the discovery timeframe changed. Mine lives became shorter, particularly in the gold industry and even 10 years between discoveries was thought of as being too long. The market and the analysts who prod mining company executives want a steady stream of good news with relatively frequent discovery announcements. As a result, exploration geologists came under increasing pressure to make discoveries, irrespective of mineral commodity, but they have failed to deliver these at the rate the market and mining industry believes is required. I suggest that this failure is partly due to the commercial environment within which exploration is conducted and partly because of how mining companies approach the discovery task.

A reason often cited for the reduced discovery rate in many of the traditional exploration terrains is that all of the easy discoveries have been made. Generally these discoveries were of the prospecting type. Mineralization either cropped out, or sub-cropping mineralization was located using geology, geochemistry, or geophysics. I expect that future discoveries in these terrains will rely increasingly on geological inference to identify areas to explore for deep or buried deposits. This may bear heavily on where future exploration is better conducted and has strongly influenced my exploration philosophy.

DISCOVERY-ENHANCING INGREDIENTS

I believe that there are 10 ingredients which can enhance the chance of discovery. They are (not necessarily in order of importance): people, good science (geology), experience, intuition, creativity, perseverance, visualization, serendipity, a systems approach, and drilling.

Only one of these (drilling) is a measurable quantity. Satisfying some numerical target, however, does not foreshadow discovery, although circumstantial evidence links success and drilling expenditure. All of the other ingredients are subjective and open to differing opinions and conjecture. Nevertheless, these criteria have guided my exploration philosophy over the years and have worked for me. Good luck cannot be discounted completely but it is unlikely that chance would have delivered so many discoveries.

REASONS FOR SUCCESS

Good science

Although there are instances where a gifted or not-so-gifted amateur has discovered a mineral deposit, most significant discoveries over the past 50 years have been made by technically sound geologists. Without the capacity for conducting good science the chance of making a major discovery is probably fairly slim. Good science and technical soundness do not require a geologist to be an expert on a deposit type. Expert knowledge may even be a disadvantage, particularly if it results in too much being expected of the available evidence and a reduced willingness to follow one's instincts.

To be successful in discovery requires a solid foundation in geology and a broad experience in mineral resource geology. Arising from this training and experience should be a good working knowledge of mining and of what is required for mineralization to be economic, including nongeological factors and mining and treatment methods. Most discoveries need a champion to turn mineralization into ore and the exploration geologist is best qualified to fill this role.

So-called technical successes, where nongeological factors render the discovered mineralization uneconomic, are of no present value and it is incumbent on the exploration geologist to consider the potential constraints on development in deciding the exploration target. It is important to not finesse these constraints too much, however. One cannot second-guess what mineralization Nature might have deposited and it is crucially important to approach the discovery challenge with optimism.

Experience, intuition, and perseverance

Unlike most other sciences, for which one's best work is usually done early in the scientist's career, ability in geology and the art of discovery seem to improve with experience. Mineral exploration generally requires a lengthy apprenticeship before one is able to add real value. Apprenticeship time varies but for most it can take upwards of 10 years before sufficient experience is gained for one to be competent.

Experience gives insights based on past history which sometimes can be of considerable importance and, given the general lack of evidence guiding the discovery process, it is not surprising that intuitive thinking plays an important role in some, if not many, scientific discoveries. However, intuitive thinking must be accompanied by complementary action if it is to be of real value. Discovery of the high-grade Ridgeway Au-Cu porphyry-breccia deposit in Australia is a potent example of the reward that can follow from persevering and acting on the basis of intuitive thinking, albeit intuitive thinking developed from considerable experience with the target deposit style.

For whatever reason, only a few geologists have the good fortune to be in the right place at the right time, with the right conditions to make a discovery, and the Ridgeway discovery probably demonstrates this aspect. Undoubtedly, the sequence of events and actions that led to its discovery are not what one would expect to find in a text on prudent mineral exploration management; instead, it might be described as high-risk gambling. However, there was nothing particularly unusual about the sequence of events at Ridgeway, which was consistent with the discovery culture that had been developed within the exploration team at the time.

Are discoverers of orebodies born with discovery ability, in much the same way as a talented artist has a gift that others cannot match? I suspect they are; but there does not appear to be any certain way of identifying individuals with this gift. They tend only to be recognizable after the event. However, given the likelihood that some will go on to make additional discoveries, I suggest that a prudent mining company will employ at least a few of these geologists. I would go even further and propose that it is prudent to employ as an exploration manager a geologist who has made at least one discovery as well.

Discovery culture

Unfortunately, more is required to enhance the chance of success than just employing geologists and exploration managers with a discovery history. Establishing a discovery culture within the mining company is important. This is where many companies fail and is possibly one reason for the decline in discoveries over recent times. Surprisingly, a fertile discovery culture can be at odds with mining company culture, particularly when the latter focus is strongly on production and the commercial aspects of the business. In these companies there is grave risk that the bureaucratic processes attending this focus will hamper the exploration effort.

A simple way to improve the chance of success is by separating exploration as much as possible from the mainstream of corporate activity. Exploration is the R & D arm of a mining company and if this fact is understood by the company board and CEO, and the exploration team is treated accordingly, the chance of it making a discovery is assisted.

Responsibility for developing a discovery culture within an exploration team and mining company rests with the exploration manager. It is best achieved by involving the company chairman and board, CEO, and senior management in technical sessions, appropriately modified to present ideas, concepts, and exploration information in plain language. Hand-in-hand with this involvement there needs to be

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CASE STUDY:

Ridgeway, New South Wales

The Ridgeway deposit is completely blind, with the top of the orebody at a depth of about 500 m (Holliday et al., 1999). The top 20–80 m of cover are made up of postmineralization Miocene basalt lavas. The deposit was not directly detectable in the underlying Ordovician volcanic host rocks by any available geological, geochemical, or geophysical technique at the time of discovery. Ridgeway was discovered because of a willingness to persist with deep drilling in the search of geochemical and hydrothermal alteration vectors to porphyry-style Au-Cu mineralization. This was based on the belief that other porphyry-style Au-Cu deposits, including breccia pipes, should be present in the district in addition to the ore found at Cadia Hill and Cadia East, 3+ km to the southeast of Ridgeway. The sequence of events leading to the eventual discovery intersection at Ridgeway is worth recounting as it illustrates the important roles that intuition and persistence can play in the discovery process.

Initial reverse-circulation percussion drilling in the Ridgeway area to investigate a shallow induced-polarization (IP) chargeability anomaly recorded a narrow (8 m) mineralized interval grading 0.42 g/t Au and 0.53 wt% Cu from 182 m down hole depth, in the first (RGRC1) of nine, 200 m-deep inclined holes drilled on two fences across the chargeability anomaly. Subsequent investigation showed that this mineralization is part of the outer pyritic-halo quartz vein alteration assemblage above the Ridgeway deposit, to which it is genetically related. The results from the reverse-circulation drilling were interpreted as a coherent hydrothermal alteration-mineralization anomaly that might relate to better grade Au-Cu mineralization at depth.

On the basis of this speculative interpretation, an inclined core hole (NC371) located behind hole RGRC1 was drilled to a depth downhole of 513.6 m. Analytical results showed the presence of increasingly anomalous Cu mineralization, grading 0.10 wt % Cu over the final 118 m of the hole. The mineralized section contained several narrow intervals grading better than 1.0 g/t Au, including 1 m of 5.7 g/t Au and 2 m of ~10 g/t Au. The presence of these higher Au-grade intervals was given great significance at the time and led to the deepening of the hole to 858.4 m. The deepened hole intersected chalcopyrite-bearing sheeted-quartz vein mineralization from 610 to 711 m depth, with the 102-m interval from 610 m averaging 0.13 g/t Au and 0.40 wt. % Cu. A fault truncated the mineralized vein zone, below which several narrow, higher grade Au and Cu intersections were recorded, with results of 1 m of 2.4 g/t Au and 3 m of 4.5 g/t Au.

For many geologists, these intersections at this depth would probably be insufficient to encourage further drilling to even greater depth; but this is what was deemed necessary at Ridgeway, based on experience and intuition. Unknown at the time, hole NC371 had penetrated the low-grade mineralized halo to the Ridgeway deposit. Four more inclined core holes were drilled, with the fourth hole (NC498) intersecting the Ridgeway deposit and recording two relatively high grade intervals of Au-Cu mineralization; 145 m grading 4.3 g/t Au and 1.2 wt.% Cu from 598 m downhole, and 84 m grading 7.4 g/t Au and 1.3 wt.% Cu from 821 m downhole. Hole NC498 was stopped at a depth of 1026 m.

frankness in discussions with the board and senior management about discovery risk. The board and senior management need to accept that exploration success generally requires faith in the exploration team.

Serendipity and people

The New Shorter Oxford English Dictionary (1993 ed.) defines serendipity as "the making of happy and unexpected discoveries by accident or when looking for something else," whereas, luck is "the imagined tendency of chance to bring a succession of (favourable or unfavourable) events."

I believe that serendipity plays a role in many mineral deposit discoveries, as it does in scientific discovery in general, whereas I do not place any store in luck, except insofar as one makes one's own luck if serendipity happens to smile. I also believe that the chance of serendipity acting may be assisted by the simple expediency of employing geologists who have made previous discoveries. For whatever reason, there are some geologists who, after making one discovery, go on to make several discoveries over their careers; as do discoverers in other fields of science.

People are the key to discovery and whereas teamwork is important, inevitably it is the individual flash of genius that sparks discovery. Discovery is not a consensus outcome; someone has to lead the way. Geologists are better prepared for discovery if they have been exposed early in their careers to as much geology and as many orebodies as possible, with a focus on the surrounding rocks and geological setting. It is generally not difficult to recognize mineralization when it is exposed. However, it is exceedingly difficult to recognize proximity to the top or side of an orebody. As Louis Pasteur noted, "in the fields of observation chance favours only the prepared mind."

As geologists, we mostly work with a two-dimensional earth, irrespective of how much we try to think in three dimensions. We collect a large amount of information about the earth's surface, but we know relatively little by comparison about the geology of the next 100 or 1000 m beneath our feet. Orebodies that crop out are, in a sense, accidents of the present erosion level. Ore is an economic term and orebodies have a top and a bottom as well as sides. In places, the top, bottom, or side of a deposit that may host an orebody that is intersected by an erosion surface, or by a drill hole, and the ability to sense this possibility is a major asset.

CASE STUDY:

Gosowong, Halmahera Island

A good example of the role that serendipity can play in discovery is the sequence of events that led to the discovery of the bonanza-grade Kencana epithermal Au-Ag deposit at Gosowong, Indonesia (Richards et al., 2005). Good science identified the target, but the need to relocate the first investigatory hole 50 m south because of access difficulties resulted in this hole intersecting 10.5 m of 20 g/t Au and 22 g/t Ag, the first of several large gold shoots discovered at Kencana. The originally planned hole, when drilled, recorded a narrow intersection of 0.5 m grading 0.13 g/t Au, and missed the margin of the gold deposit by about 5 m. Eventually, the gold result in this second hole may have been investigated further and almost certainly would have led to the discovery of one of the several gold shoots at Kencana, but this result is not one to stir emotions and it may have been some time before a follow-up hole was drilled. The Kencana gold deposit is one of the largest high grade epithermal gold deposits discovered in the past 100 years, and without the intercession of serendipity it may not have been discovered, at least in a timely manner.

STRATEGY IS IMPORTANT

In developing an exploration strategy, it is important to remember that the process of exploration is only the means of discovery, and that the only justification for exploration is discovery. Failure to discover is not an acceptable outcome for an exploration team and the first real decision to be made when developing an exploration strategy is how much risk it is prudent to take, given the time available to make a discovery. An effective discovery strategy has three characteristics: it is simple, flexible, and responsive.

Selecting projects and risk management

Area selection is undoubtedly the most crucial component of an exploration program. Good geology, i.e., prospectivity, is important in setting the framework for area selection, but scientific brilliance does not necessarily lead to good area selection and ultimately to discovery; indeed, it may be a hindrance if one gets consumed by the "why" rather than by the "where" in the search for an orebody.

A crucial determinant of which area is selected to be explored may be the company board and senior management. Irrespective of what we as explorers would like to do, our enthusiasm is tempered to some extent by the risk that the company is prepared to accept. Exploration is not a business for the faint hearted or cautious. It is a high-risk endeavor and even for those companies that are successful and make a discovery there is no certainty that the reward will properly satisfy the capital expended and the risk taken.

Few company boards and CEOs appear to truly understand the discovery process and place sufficient confidence in the company's exploration team to provide it with the freedom and tolerance that is needed to enhance its chance of success. Occasionally, there are companies for which the board and CEO are sufficiently knowledgeable and enlightened about the discovery process. When this rare coincidence occurs there is potential for an exploration team to excel, but experience demonstrates that these situations are transitory, as boards and CEOs change.

As noted in a preceding section, determining the level of acceptable risk is a crucial decision and essentially determines the search terrane. In my lexicon, exploration risk progresses from moderate through high and very high, to extreme.

Seeking an extension to a known deposit is moderate risk—with a chance of success of possibly of 1 in 5 to 10, and a short (1–2 years) lead time to discovery or failure. Searching for a subcropping or blind deposit near a known deposit is high risk. The chance of success depends on the type of deposit being sought and may be as good as 1 in 10; lead times may be relatively short (3–5 years).

Very high risk is typical of much exploration and is where a discovery is sought in a mineralized district, containing examples of the target type. The chance of success is typically no better than 1 in 100 and lead times are long (5–>10 years). Extremely high risk exploration is carried out in unconventional areas where the reward can be substantial (Olympic Dam is an example) if a discovery is made, but the chance of success is extremely low.

During my career, I sought whenever possible to work with projects that fell towards the moderate end of the moderate to very high risk range. As a business, exploration needs to be working with odds that offer an obvious and acceptable chance of success; otherwise, it is little better than rolling dice and is more than likely to fail.

The objective of an exploration program is to efficiently and effectively increase the chance of success in the shortest possible time. Time is money, and both time and money are usually in short supply for exploration geologists. Consequently, exploration programs need to be planned and conducted with the aim of reducing risk as quickly as possible.

To have an acceptable chance of delivering a discovery in a timely manner one should seek to have a project portfolio where the chance of success is better than 1 in 100 and preferably closer to 1 in 10. In practice this means carefully selecting projects and exploring them with sufficient vigor to reasonably gauge discovery potential after completing only a few properly targeted and directed programs of work.

Investigations should be staged with a decision point at the end of each stage; to assess whether the results advance the project, neither advance nor retard it, or diminish the chance of success and the project probably should be abandoned. Clearly, opinions will differ on what constitutes progress and this is possibly why a discovery can still be made where fairly exhaustive investigations have been conducted by competent exploration geologists, including those who have come from previous companies.

EXPLORATION PHILOSOPHY

Two basic tenets of my discovery philosophy are the belief that orebodies can be made and that mineralization can be changed into ore if one has the good fortune to be in the right place at the right time, with the skill to recognize what needs to be done to bring about this transformation. In this philosophy, ideas, concepts, and actions are more important than techniques, which are only tools for getting the job done.

Look beyond the obvious

The economist John Maynard Keynes once observed that "the difficulty lies not so much in developing new ideas as in escaping from old ones." Keynes was dealing with economics, but the comment applies equally to mineral exploration. The difficulty for many geologists is that they can be captive to what they expect to see.

When a discovery is made in a much-explored area, it is invariably because the successful explorer was able to see something in the available information that either escaped the attention of previous explorers, or was given more credence by the discoverer. This ability to see something in the information that turns out to be crucially important in the discovery process is one of those skills that separate exploration geologists who make discoveries from those who do not.

Encourage risk-taking

No one would doubt that mineral exploration is a risky undertaking. Caution and conservatism are not appropriate if one is seeking to make a discovery. Bold, adventurous, and daring are more common descriptors for the types of actions required.

The challenge for exploration geologists is to walk the fine line between being bold, adventurous, and daring, and being reckless, irresponsible, and imprudent. It is not an easy distinction to make and it is something that needs to weigh on the minds of all exploration geologists. Failure to find the correct balance in this can have a disastrous effect on the exploration team and on the chance of success.

To foster discovery, risk-taking needs to be encouraged. However, it is important to distinguish between responsible and less-than-responsible risk-taking. Achieving the former is the goal, but not at the expense of becoming overly cautious. The discovery history of the Ridgeway Au-Cu deposit provided a sense of the type of risk-taking required.

I place great store on the ability to visualize the target deposit when planning and conducting discovery exploration. This enables an easier choice between responsible and less-than-responsible risk-taking. Discovery drilling, for example, can be conducted with relatively widely spaced holes if there is an appreciation of the possible shape and size of the undiscovered mineral deposit. Orebodies have barren parts to them and it will be anticipated that widely spaced discovery drilling within a deposit will confirm this condition.

Most importantly, this ability encourages boldness in risk-taking, particularly in deciding how best to follow up a mineralized intersection. Some geologists will be cautious with the spacing between follow-up drill holes and the initial pay-hole, and seek to slowly build the deposit. Other geologists will step out boldly from the initial intersection with widely spaced holes, seeking as quickly as possible to broadly define the deposit. This is the approach I favor, even though it introduces a greater level of risk into the delineation process. It has the advantage of fairly quickly determining if the deposit is small and the exploration expenditure might be better applied elsewhere.

Creativity and visualization

As indicated, I believe that the ability to visualize in three dimensions is fundamental to discovery. It goes beyond what one might possibly expect and includes the capacity to assemble in one's mind disparate and spatially unconnected pieces of geological and discovery-related information, and build from these an image of what might be. In doing this, it is essential to continually ask "what if?" and develop ideas for investigating the possibilities that this questioning throws up.

In this context, it is worth emphasizing the importance of using one's thought processes rather than relying on technology to provide a creative edge. Geology is an observational science and there are some things in exploration

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CASE STUDY:

Cadia Hill, New South Wales

A simple example of visualization skill is demonstrated by the discovery of the Cadia Hill Au-Cu porphyry-style deposit in Australia (Wood and Holliday, 1995). It also illustrates the importance of good science, experience with the target deposit type, and interpreting the available historical exploration data in a simple and creative manner. Previous exploration by a number of companies had essentially discovered the Cadia Hill deposit, but the failure to properly combine the spatially fragmented and disconnected data prevented its recognition. By using the historical data and results from subsequent sampling of residual soils to provide a linking mechanism it was possible to deduce the grade, shape, distribution, and possible size of the potential orebody at Cadia Hill from the soil Au and Cu values, and by overlaying the outline of the soil anomaly on the topography. This enabled discovery drilling to be planned within a hypothetical mining pit and ensured that all holes, from the start of the discovery drilling program, were drilled to optimum depth for mine-planning purposes.

that are better done in a low-tech way, even though the temptation will be to use the latest technology. For example, the geology of an area is often better understood by hand-coloring a geological map, rather than turning to a computer. It is not high-tech but it is effective. Similarly, when seeking to identify anomalies in geochemical data, better interpretation can result from using one's eyes and brain, than from relying on some statistical package to produce an answer.

HOW TO OPERATE

Deposit models and 3-D dartboards

Deposit models are an important adjunct to the discovery task. Used creatively, they can speed up the discovery process; misapplied or used too rigorously, they have the capacity to delay or prevent discovery. They are best used by experienced geologists who are familiar with the target deposit type. Unless a deposit model is applied, irrespective of how rudimentary it might be, the discovery task is reduced to almost aimless wandering; although many of the regional exploration efforts that were in vogue when I started my career were almost of this type, and some were successful. Understanding the limitations of the deposit model is essential.

Hand-in-hand with a properly understood deposit model and the ability to visualize in three dimensions, the discovery process is assisted if one reduces the target in one's mind to a 3-D dartboard, appropriately modified to accommodate the 3-D spatial characteristics of the deposit type being sought. Simplicity is the key to using this approach, with the deposit reduced to four components—ore, mineralized waste, altered waste, and unaltered host rock. The ore is the bull's-eye, with the three encircling rings of the dartboard progressively representing the other three components. The objective of the approach is to develop a vector to potential ore as efficiently and as cost effectively as possible. It requires the ability to recognize the importance of seemingly insignificant results from investigations, and to act reasonably boldly on the basis of these.

Do rather than procrastinate

Some geologists are reluctant to act until an almost watertight case for action has been made. Discovery results from taking risk, whereas procrastinating until the weight of evidence for action is almost overwhelming is an inefficient and ineffective use of scarce resources. It is better to act sooner than to hesitate while unnecessary supporting information is acquired.

TECHNICAL APPROACH

Systems

It is easy in mineral exploration to focus on a part of something rather than on the whole. One sees this often when observing geologists logging core. Some geologists meticulously log meter by meter (or smaller increments) to produce a detailed accounting of the rock types and other observable features present in the core. A summary log is often then prepared to try to understand how all this information relates to the reason the hole was drilled, which was to discover mineralization or, failing this, to identify a vector to ore.

In my experience, formal logging is best left until after the hole is completed. The entire core can then be laid out and more effectively logged by reducing it down to observable component parts; in the same way that, when mapping, one moves from a regional to a detailed scale, rather than vice versa.

Similarly, when exploring, there is great advantage in being able to stand back and see the broad picture, rather than focus on the detail. One of the most useful approaches that one can adopt in this respect is a systems approach. In this, the target deposit is thought of as a dynamic system that has affected the regional and local geology around the orebody, and clues to its possible presence are sought accordingly. By "thinking like an orebody" a more holistic approach to the target can be developed, which will assist in interpreting and understanding the seemingly unconnected and disparate pieces of evidence that are accumulated in the search process.

Drilling

Ultimately, drilling is the key discovery technique, preferably by collecting core rather than drill-cuttings. I strongly believe that a large part of the exploration budget should be applied to drilling (meaningful) holes, and that spending 40–60 percent of the exploration budget on drilling will contribute to a reasonable chance of success over the longer term. I also believe that it is better to err on the side of possibly over-drilling a deposit to gain more knowledge, than to risk the nasty surprises that inevitably appear to haunt the mine geologist when insufficient delineation drilling has been completed. It is a false and ultimately expensive economy to scrimp on resource definition drilling.

CASE STUDY:

Tipton, Queensland

Discovery of a 130 M-tonne (t) steaming coal deposit, Tipton, in the Surat Basin near Chinchilla, Australia, in the early 1980s illustrates how this dart-board technique can be applied, provided that there is a reasonably well-understood geological model for the discovery-target deposit. Coal deposits of the Surat Basin were deposited as thick areally restricted coal accumulations in a meandering river environment. Sedimentation in made up of sandstone lenses superimposed on a siltstone background with the coal grading into carbonaceous shale on the margin of the deposit. The size range of a Surat Basin coal deposit is typically 30–150 Mt, with coal seams that range in thickness from less than 5–30 m and in plan occupy an area that is roughly circular and 1–3 km in diameter.

Previous exploration in the Tipton deposit area had called for regional drilling on a 4-km, spaced, square-grid pattern. This drilling recorded a relatively thin interval of coal in one hole, and shale and carbonaceous material in some of the other holes. In thinking about the geometry of a 100- to 150-Mt target coal deposit, it seemed possible that drilling on a 4-km grid pattern might miss discovering a deposit of this size, although the holes needed to be carefully located to achieve this outcome. Nevertheless, stranger things have happened and it was concluded that it would be possible to conceal a 100-Mt coal deposit within the drilling grid, if one of the holes had intersected part of the deposit.

In thinking about the results of the previous drilling in relation to a 3-D dartboard for a Surat Basin-style coal deposit, the components of the dartboard are the coal bull's-eye, succeeded progressively outward by a carbonaceous material ring as mineralized waste, shale as altered waste, and siltstone or sandstone as unaltered host rock. Follow-up discovery drilling at Tipton consisted of off-setting the hole that had recorded the coal intersection with four holes spaced 4 km apart, effectively infilling with one hole each of the four, 16 km^2 blocks around the coal-bearing hole. One of the holes in this four-hole program intersected 20 m of coal. The other three holes intersected carbonaceous material (the mineralized waste ring of the dartboard) and provided the vectoring to locate follow-up drilling and eventually delineate the deposit.

In addition to being an ardent believer in the worth of using the drilling rig as a tool for acquiring geological information, I also believe strongly that an anomaly (significant within the setting) needs only to be detected once for it to be drilled. There is no point confirming the presence of an anomaly by multiple techniques before resorting to drilling.

The first allocation in an exploration budget should be to drilling. If the targets do not appear to be present in the exploration project portfolio to justify expending at least 40 percent of the budget on drilling, then I suggest that consideration be given to using drilling to generate targets for the next budget. The sooner the exploration team becomes accustomed to regularly drilling holes, the sooner, in my opinion, that the team will begin to make discoveries.

Discovery technique

I have elaborated several skills and methods of operating that I believe are important components of the art of discovery. Combined, they provide a discovery technique that relies on the ability of the geologist rather than on technology to achieve the discovery goal. It is a simple technique that in many ways mirrors the scientific method, as one might expect given the nature of the exercise. The essential steps start with geological observation and interpretation, followed by visualizing the potential, and culminating with investigating the hypothesis by drilling.

CONCLUSION

I do not know why it is that relatively few geologists and mining companies discover mineral deposits. At the risk of sounding elitist, I suggest that it probably does not have a lot to do with how talented and knowledgeable one is as a geologist; rather, it has something to do with how some geologists' brains are wired and the thought processes that then follow as a result. If this is the case, it is unfortunate for mining companies that there is no obvious way to identify these individuals until after the event.

I used to believe that the art of discovery can be taught, but I now believe that some geologists, for whatever reason, have a greater aptitude for discovery than others. Nevertheless, if discovery can be taught then I suggest that this capacity can be enhanced by honing the various skills and approaches that I have briefly outlined. Above all, I encourage all exploration geologists and their exploration managers to develop their visualization skill, as I believe that this is the ultimate key to discovery. One needs to be able to "see" the orebody in order to discover it. After all, as the winner of the 1937 Nobel Prize in medicine, Albert von Szent-Györgyi, observed, "discovery consists of seeing what everybody has seen and thinking what nobody has thought."

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