

Geological Exploration

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7.1 INTRODUCTION

If there is no mineral exploration, there would be no mining, no processing, no industry, few of the cultural amenities and creature comforts. For the maintenance of any country's economy, it is inevitable to have adequate supply of mineral resources. Mineral exploration has its own characteristics that differ from other resources sector. They are: (1) mineral resources are largely hidden from view. Some part of the earth is well endowed with respect to mineral resources while other parts are poorly endowed. (2) Mineral deposits are "where they are in nature" and cannot be moved out to a desirable location by anybody. (3) After establishing a deposit, a mining camp is developed. Since many deposits are known to occur in cluster, the first developed mine and its infrastructure will facilitate for the development of additional finds, thereby reducing costs for the project. (4) Many a times, use of advanced technology is needed to define an economic mineral resource. Mineral exploration is a time-consuming "high reward, high-risk" event.

Many companies, Government, Private, and Local communities, are involved in mineral exploration worldwide. Although successful exploration yields good rewards/dividends to the participants and local communities, the risks involved are also high. Responsible mining companies can be a driver of economic and private sector development, as well as poverty alleviation at a national level. They can also offer technology transfer to both the local community and to the nation. The ultimate goal of mineral exploration is the extraction, beneficiation, and profitable and beneficial sale of mineral commodities.

7.2 MINERALS ACTIVITY PROJECT

In general, a minerals activity project can be divided into various stages involving the application of successively more discriminating (and more expensive) techniques, to successively smaller land areas, in order to identify, develop, and produce an economic mineral deposit. A "full sequence" of mineral project life cycle, from exploration to development and operation to closure would involve the following stages:

1. Regional appraisal
2. Reconnaissance of the selected region
3. Detailed surface investigation of the target area
4. Detailed three-dimensional physical sampling of the target area
5. Deposit development
6. Mine development and production

7. Mineral processing/mineral beneficiation
8. Mineral/metal extraction; smelting and refining
9. Marketing of mineral/metal produced
10. Mine closure, after the end of mine's life.

Target identification constitutes the first two stages whereas the next two stages are *Target investigation*. Hence, in short, mineral exploration entails the identification and investigation of targets to discover economic mineral resources. Once a mineral resource is discovered, all the associated infrastructural works to bring the deposit to the point of production is called *Development*. Actual mining of ore from the ground is referred as *Production*. *Mineral processing* involves comminution, separation of ore (economic) minerals from gangue (waste), and concentration of ore minerals. *Metal/mineral extraction (smelting and refining)* involves extraction of metals from the mineral concentrate and purifying them, if need be. *Marketing* involves shipping of the mineral product (can be concentrate or metal/refined ore) to market. The final stage is “*mine closure*” (after the end of mine's life) involving significant expenses to clean up and remedial measures of degradation due to mining and smelting sites. This stage will also involve employee retrenchment, social and community implications. The boundaries between these substages mentioned earlier are not precise but arbitrary. It is generally considered as a continuum of activities.

The various stages and activities of mineral deposit life cycle are given in Fig. 7.1. Only a few projects will see the full sequence since a project can be abandoned at

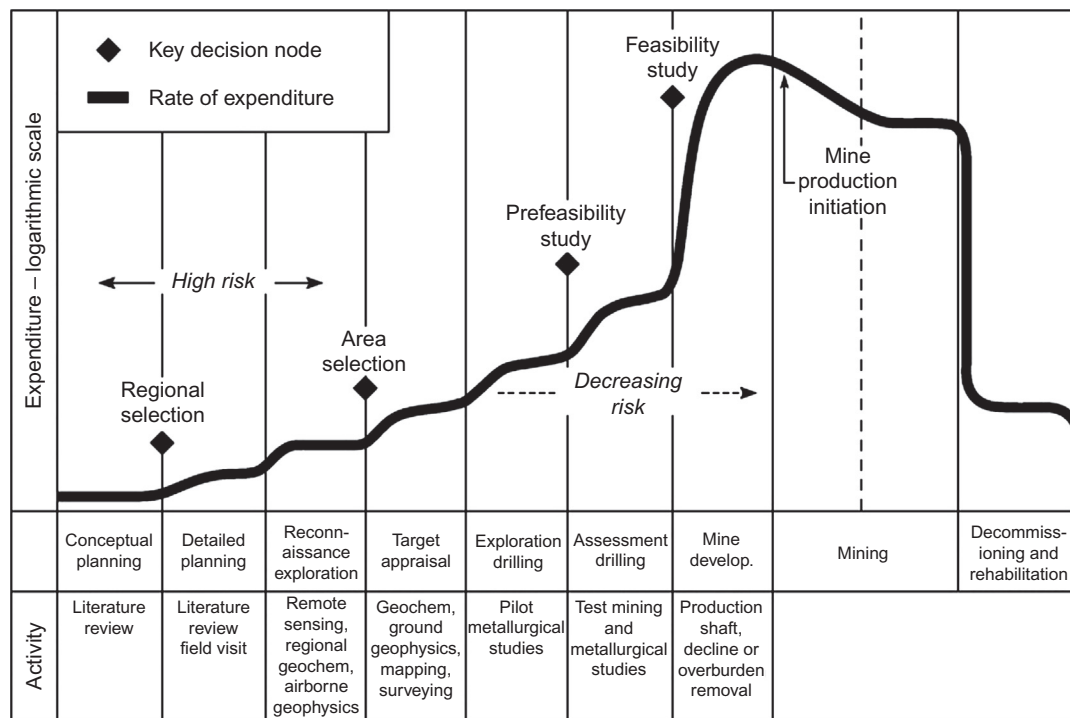


FIGURE 7.1 Various stages and activities of mineral deposit life cycle. Source: From Moon et al. (2006).

any stage, if the results are discouraging. It is possible to skip or abbreviate some of the initial stage activities, if the information is already available to the company either by its own earlier work or work done by other agencies. Only certain types of deposits in certain type of geological environments demand some techniques, owing to cost/physical characteristics.

In the above referred mineral exploration/supply chain, a Company, depending upon its strengths and weaknesses, can enter at any stage with many options. Grassroot exploration can be conducted by a Company and later involve in advanced exploration by joining with a partner to undertake further exploration. It can also opt to develop a known “undeveloped deposit.” Alternatively, a company can invest in R&D work that can make activities at any stage of production more efficient. The scientific/technical inputs of exploration and mining must be fast, efficient, and effective in order to add value to the project (Woodall, 1992).

7.3 MINERAL EXPLORATION

Mineral exploration can be technically defined as “all the activities and evaluation necessary before an intelligent decision can be made establishing size, initial flow sheet, and annual output of new extractive operation.” The purpose of mineral exploration is the discovery and acquisition of new mineral deposit amenable to economic extractive operations now or in future. The prime objective of mineral exploration is to find and acquire a maximum number of such economic mineral deposits at a minimum cost and within minimum time.

Mineral exploration acceleration is due to (1) increasing demand for metals that were not sought earlier, (2) growth of industrial output, (3) new ore types, and (4) greatly improved geological knowledge and exploration technology. Global demand for industrial commodities has doubled every 20 years. This growth is likely to continue. Global reserves and resources for some commodities are sufficient for several decades. In major producing districts, the reserve and resource grades are declining owing to depletion of high-grade surface deposits. Additional resources will be augmented by ongoing “greenfield exploration” in frontier countries and also by deeper discoveries from known mineral districts. These discoveries will become a major new source of future mineral supply (Woodall and Duncan, 1993). Despite some of the countries have the capacity to support production, it is probable that might be undermined by a few risk factors.

Mineral exploration represents the highest risk of all—risk of failure is great and the cost is high. Even the successes must be followed by capital-intensive long-term, high-risk operating investments. Investments to bring exploration discoveries into production may range in the tens of million dollars. Large mines require from hundreds of million dollars to billion dollar investment. The typical lead time span, from inception of exploration through the investment in mine/mill facilities that will return this investment out of production, is 12–15 or more years. To receive a profitable return on investment commensurate with the risk requires a minimum investment longevity of an additional 10 years, for a total of 20–30 years.

Since most of the surface or near-surface resources have been explored, the search for new mineral resources has to rely on more sophisticated prospecting/exploration techniques. Future ore bodies will probably be more costly to find, mine, and process than those in operation and production now, because most of them will either be of lower grade or found at greater depths. The chances of a mineral occurrence being developed as a mine are low (may be 1 in 1000). Lesser number of identified resources does not imply low mineral potential in an area. It might be due to many reasons like, incorrect geological theories, poor infrastructure and policy of the Government. A typical example is the “Diamond discoveries” in Northwest Territories in Canada. There were no known occurrence of “kimberlite pipe” (host of diamonds) although the geology was known to be favorable. But once the kimberlite pipes were discovered, the area attracted many exploration teams and led to significant resources.

Most exploration projects will not advance to mines. In areas with good potential for discovery, the competition is usually high. Invariably an interdisciplinary team of geologists, geophysicists, and geochemists searches for mineral deposits in prospective terrains. The key to successful exploration programme is to know, when and where to drill, when to “hold the properties” and when to “walkout.”

7.4 EVOLUTION OF EXPLORATION TECHNOLOGY

The exploration has evolved in the past several decades into a highly sophisticated and expensive endeavor in which large corporate entities are involved with trained specialists in myriad fields. The evolution of exploration technology spanning over the past century can be broadly summarized as under:

1900–50	Prospect submittal, mapping, sampling in/near ore bodies; exploration done by trenching, pitting, shafts, drifts, and little drilling
1950–60	Submittals, sampling, geological mapping, drilling; ground and airborne magnetics, electromagnetics, early geochemistry
1960–70	Grassroots become popular, geophysical and geochemical surveys, induced polarization developed, scant drilling, photogeology
1970–80	Mostly grassroots, more regional geophysical and geochemical surveys, ore body modeling, less prospecting
1980–90	Plate tectonics, remote sensing, computer modeling
1990–2000	Increased use of high-tech office techniques, less field work, poor exploration success ratios
2000–	Increasing high-tech office work, extensive use of state-of-the-art 3D and GIS modeling techniques in synthesis and interpretation, increased discovery costs, very less field work

Searching only for outcropping minerals had given most of the present day mines in many areas, but this is approaching a point of diminishing returns in areas that had been thoroughly prospected. Exploration is now increasingly aimed at potential areas within which anticipated mineral deposits are covered by postore cover in the form of alluvium or volcanic sedimentary rocks.

7.5 DEVELOPMENT OF EXPLORATION TECHNOLOGY

In the past six decades, technological acceleration in other sciences, viz., computer science, telecommunication, genetic engineering, rocket science, etc., has more than doubled the sum of human knowledge in shorter time intervals, but the same is not the case in Mineral Exploration Technology. Any new technique in exploration technology needs to be tested for its worth in the field and if successful only, it can be adopted. Hence, it takes a lot of lead time (Fig. 7.2A). The slope of the curve depicting the development of exploration technology represents successive postwar development of magnetometrics, EM systems, that found many massive sulfide ore bodies in the 1950s and 1960s. Magnetic surveys helped to find many iron ore bodies and radiometric surveys found uranium ore bodies. Development in geochemical techniques caused later bumps in the curve. Geochemical techniques found many mines. In the late 60s and early 70s, many porphyry copper–molybdenum deposits were discovered due to better understanding of deposit geology. The improvement in understanding the origin of mineral deposits accounts for the upward slope of the exploration technology curve. Drilling technology and high precision, speedier analytical methods (XRF, mass spectrometer, ICPMS, ICPEs, etc.) augmented geochemical exploration techniques (Lovell, 2000).

The exploration efficiency has slackened down in the recent years hence demanded an increased R&D efforts to develop techniques to locate new resources. In the recent decades, the exploration expenditure, both by the Government bodies and by the private companies, has gone down since the mining industry in general was forced to concentrate on survival during the very lean years.

With the easy to detect and easy to mine deposits nearing the end of their life span, one has to go deeper, hence, over the years, the exploration costs are increasing (drilling can be an expensive event). Similarly, the discovery/success rate tends to decrease, besides the overall decrease of grade of resource, as one does not have direct evidence of mineralization (Fig. 7.2B).

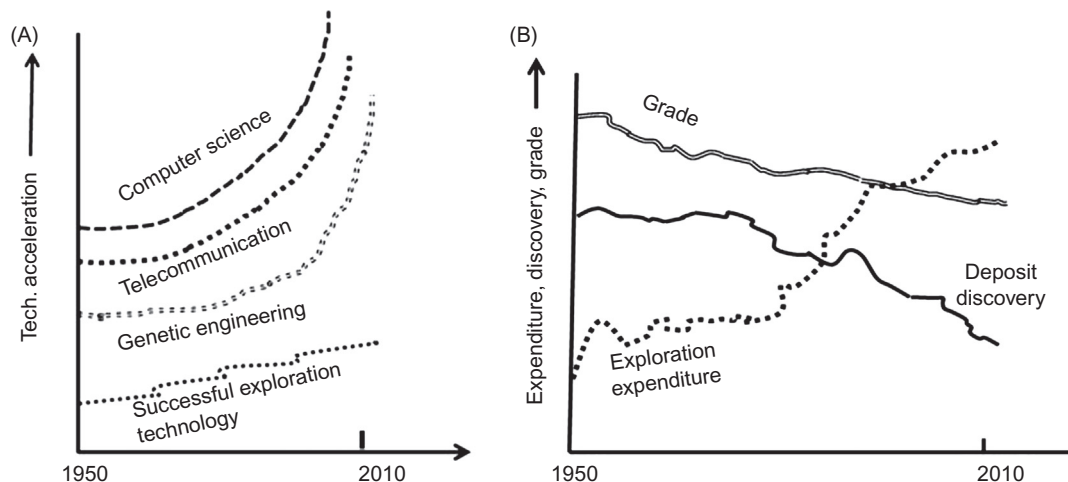


FIGURE 7.2 (A) Sketch map of development of exploration technology. (B) Sketch map of the trends of exploration expenditure versus deposit discovery and deposit grade, over the years. Source: From Gandhi (2013).

7.6 CHALLENGES FOR MINERAL EXPLORATION

Things in the mining business are not the same what they were, a couple of decades ago. Several things have happened, which have acted as disincentives. [Dummette \(2000\)](#) opines that “the mining industry practices its trade in a universe defined by prices, laws, and Governments. Prices, as in what the industry is paid for what it produces and the costs of goods and services. Laws have to be transparent and fair. Government that the industry prefers should be stable and supportive of the industry, catering not corruption.” With the opening up of frontiers of many countries in the world for investment in mineral exploration, it has become a “borderless world.” But at the same time, the companies need to be responsible corporate guests who respect and enhance the social, moral, and societal values of their host countries.

Some of the “emerging challenges” for the exploration industry are discussed here.

- Discoveries are harder to make; exploration costs have risen dramatically over the last three decades; unit discovery costs are rising. Drilling has become an expensive component (But if you do not drill, you would not discover any resource!).
- Rate of world class/large deposit discoveries (both size and grade) is declining with terrain maturity. (Existing mines are getting depleted fast and we need to replace them.)
- Recent undue emphasis on “brownfield” exploration—biggest discoveries tend to be in “greenfield” exploration.
- Growing importance of “native title” (land titles of mineral deposits in SW Pacific, Andean area, North Canada, India, etc.). The mining industry in a globalized business environment will be required to be responsible partners and guests.
- Startling imperatives of “sustainable development.” Since the emergence of environmental awareness, society and mining have been in conflict and are at loggerhead.
- Mining sector is vulnerable to political risk because of the nature of high cost, long-term investments. “Expropriation, confiscation, and nationalization of assets, along with inadequate legal and regulatory systems that heighten contractual work (resource nationalism is the most evident in Latin America, Central Asia, and Africa, and it has become a notable trend in some of the world’s richest territories also). Political risk is region- and asset specific and is not generic within a country/sector.
- Recent worldwide changes and developments in Government policies have become disincentive factors for many exploration companies (some countries have decreased/increased their taxes and royalty rates or introduced “nationalism-type” rules since 2011).
- Many exploration projects are often located in unstable locations that are prone to outbreaks of war and civil commotion or vulnerable to the risk of terrorist attacks. The risk to personnel of kidnap for ransom is high in many mining territories (Mali and Peru in 2012; Central African Republic, Colombia, Kyrgystan, South Africa in 2013). With the result, the importance of political risk insurance (PRI) as a risk transfer mechanism to minimize the impact of the country risk has increased.
- Inability to detect deep-seated mineral deposits and deposits beneath thick cover—a major impediment to success.

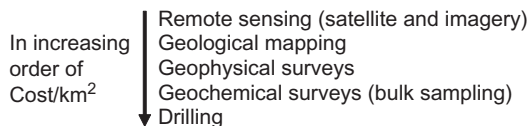
- Declining prices of most of mineral commodities.
- The “boom and bust” financial cycles restrict funding and capacity to advance exploration and technology development.
- Ever-increasing “production cost”; hence “low/diminishing returns” to company and its shareholders. Research by Rothschild has shown that for those major companies that have been around for 25–30 years, the average real return has been around 7–8% per annum.
- Decline of experienced exploration teams and strategies; brief time to assess new targets.
- Cost of collecting geoscientific data is the most expensive aspect of mineral exploration.
- A need to balance risk versus opportunity.
- *Massive restructuring of industry; mergers, joint ventures, partnerships, etc.* It is common nowadays that a mining company has merged with or acquired one, its competitor. The rationale for the merger is the creation of more valuable company because of low production cost and some synergies. The new company will be more profitable and more attractive to shareholders. In reality, study of many merged companies in the world indicates that one-third of the transactions created value, and another one-third were value neutral and the rest were value destroying. Mergers need not make better companies, in many cases, it is just “the opposite.”

7.7 DESIGNING AN EXPLORATION APPROACH

It is necessary to have some knowledge or a hypothesis of how and why a mineral occurs in nature in a particular place in the earth’s crust, in order to design an exploration approach. Gold, silver, and copper are particular type of elements with a metallic luster and have other unique physical properties that distinguish them from nonmetallic element. Metals not only occur in their native form but also occur as a part of a mineral.

The physical properties of minerals and their mode of occurrence facilitate in locating deposits of economic interest. The common mineral characteristics that are used are magnetic susceptibility, specific gravity, electrical conductivity, radioactivity, and velocity of seismic waves. Besides, some minerals of economic interest are found to occur in association with other rocks/minerals that may be easier to locate than the economic minerals themselves. Dispersal of chemical signatures of hidden mineral deposits over wider areas by physical/chemical processes such as weathering or erosion, thereby, making their presence known by sampling stream sediments, soil, glacial till, etc.

Exploration methods in increasing order of cost per square kilometer are:



Number of factors like type of deposit (vein, disseminated, layered, etc.), location of the area, availability of infrastructure, the existence and quality of other available data about

the area dictate the exploration approach to be adopted. An exploration approach designed for locating certain type of deposit (disseminated copper) would be generally not suitable in locating another type of deposit (high-grade gold).

Having developed an initial exploration concept, if the field work done in that area yields negative results, the same area attracts with renewed interest, a few years later, with the availability of new technology (may be satellite imageries) or a new concept of mineral formation (like diamond discovery in northern Canada). Hence, any unsuccessful exploration does not mean that mineral deposits do not exist. The probable causes could be, incorrect exploration method, insufficient effort or old technology incapable of locating deposits. Thus exploration in an area always follows many cycles by different agencies. In the process, the ownership can also change many hands.

7.8 THE EXPLORATION CYCLE

The exploration cycle includes geological concept formation and reconnaissance exploration, advanced exploration, feasibility studies, and possible development. The information gathered at the end of each stage of this process is evaluated before venturing into the next stage or revise the earlier concept or abandon it entirely. Different types and levels of information are obtained in each stage of the exploration cycle, environmental impacts, expenses and demand different skills.

In the early exploration stage, large areas are identified that may host certain type of ore deposit. The time taken can be long to locate areas that merit further work. Fewer companies are involved at this stage and the cost of exploration rises as drilling and detailed surveys are undertaken. Feasibility studies will be initiated if the results continue to be promising. At this juncture, junior companies may choose to spread the costs and risks of further development by joining hands with senior companies.

7.8.1 Reconnaissance and Preliminary Exploration: Geological Concept Formation

In order to find the type of minerals interested, the type of deposits in which such minerals are to be found and the areas where such resources are likely to be located require sound geological concepts. Geological knowledge gained through education and experience and the geological information of the areas where exploration is likely to be conducted are essential.

7.8.1.1 *Typical Activities*

Exploration starts with regional appraisal of large areas (in one or more countries), primarily for collating known geological information, reviewing of maps, surveys, and reports/records available from the National and Provincial geological surveys, Universities or Academic/Research Institutions, and accessing “company reports” containing prior proprietary knowledge. Selection of particular regions considered favorable for occurrence of the mineral or minerals being sought using air photo or satellite images,

remote sensing technique, regional surveys (geological, geochemical, and geophysical), field reconnaissance, and preliminary engagement with local communities. Large-scale structural trends, potentially controlling mineralization, may also be identified through these studies. The main activities of the geologist are field mapping and sampling. There is nothing better than “boots on the ground” in assessing outcropping geology for its potential. However, many targets are obscured by intense weathering, soil cover, or more recent deposits and have to be detected through their remote geophysical or geochemical responses, as the mineralization cannot be seen at the surface. Grassroot exploration would help to identify promising areas which will be examined in greater detail in the subsequent stages.

The cost of early stage exploration programme depends on the extent of field exploration. Costs are relatively low, up to several tens of millions of dollars.

7.8.2 Advanced Exploration (Detailed Target Evaluation)

Since sufficient encouragement has been obtained from initial exploration, the activities warrant further expenditure at this stage. By now, geophysical and geochemical anomalies have been delineated, identified favorable geology and encouraging assay results of the samples collected. This stage demands greater density of sampling to be carried out than the grassroot level exploration.

7.8.2.1 Typical Activities

In this stage, more subsurface information is gathered, involving trenching, pitting, drilling, and delineation of the mineral resource. The detailed geological mapping, topographical survey, more soil sampling, ground geophysics, and some drilling may be undertaken. Preliminary ore amenability studies, environmental, social baseline studies are to be carried out. Constant interaction with the local communities is to be done. The outcome of these studies in advanced exploration stage leads to “scoping study” which is an “order of magnitude evaluation” of the deposit’s commercial attractiveness. A “preliminary feasibility study” involving more detailed resource estimate, preliminary mine design, and preliminary cost estimates are to be done.

After examining the range of options, the prefeasibility produces a case for a plan that is commercially feasible. It addresses not only the economic outcome but also acceptable risk profile, while there are many areas of uncertainty, such as suitability of ground for foundations, costs have been estimated to within 20–30% of accuracy. If both “scoping and preliminary feasibility studies” suggest that a resource might be commercially feasible, the next stage (deposit development) will be taken up. The cost estimates for advanced exploration programme might be 10 times the cost spent in the initial stage (the expenditure could go up to several hundreds of millions of dollars).

7.8.2.2 Public Consultation

Exploration activities envisaged in advanced exploration stage will become more visible to the community around and probably may have potential impacts. At this stage,

informal meetings, consultations, and public forums are to be carried out with the community, as and when necessary.

7.8.3 Feasibility Stage

This stage is taken up when the exploration results have been highly encouraging to justify detailed economic and engineering studies. These studies will facilitate investigation of possible ways of developing a property as a technically and economically feasible, environmentally sound, mining operation. If the “prefeasibility” leaves a few “fuzzy edges,” the feasibility study will sharpen them. It is a focused process of determining exactly how the option chosen in prefeasibility study will come together and estimating costs to within 10–15% of actual. Between the discovery and delineation of a mineral resource, lying invisible beneath the ground, to the start-up and commissioning of the flow of ore through processing plant, comes the application of technical expertise and planning of the first order.

7.8.3.1 Typical Activities

The activities in this stage involve examination of possible mining and processing methods, estimates of mineable resources, continuation of environmental studies, and marketing and economic studies. In order to have additional confidence on the resource estimates, planning of detailed in-fill drilling is to be taken up. In essence, “feasibility studies” are detailed engineering investigations of the technical, economical, and environmental effects of a proposed mining operation. Besides, many ancillary studies are also to be undertaken which will form part of the feasibility report. Feasibility studies are considered as “major documents” of a project and can comprise of several volumes.

The expenditure in this stage of development will be in the order of US\$5–10 million or more. Depending upon the location of the project and the availability of infrastructure, the companies may provide employment opportunities to the people of local community.

7.8.4 Deposit Development

Acquiring the necessary project capital funding and initiating construction activity are the next two important steps in mineral project development. Some amount of detailed planning and engineering work are often needed at this stage besides what is normally included in a feasibility study. Building a mine is a complex and demanding task fraught with technical obstacles, burdened with uncertainties, and costing sums in 1000s of millions, if not trillion. Mistakes can be very expensive. During all the earlier stages to this point in the sequence, no revenue has come from the campaign except for the expenses to delineate and develop an ore body. There are a few other industries where engineers and scientists, financial experts, and others combine to apply the sophisticated technological, mineralogical, analytical skills necessary.

7.8.4.1 Typical Activities

Typical activities in this stage include detailed, close-spaced in-fill drilling, mine planning, metallurgical testing, the likely environmental degradation of mine development,

and continued community engagement. The land area, obviously, becomes much smaller in this stage (say about 1000 km²). The expenditure may vary from project to project and may exceed US\$1 billion. A company will begin to apply for permits and necessary statutory approvals to proceed to mining. The technical and economic assessment incorporating the latest information will form the basis for developing a mine. Every company prepares a “bankable feasibility study” report. This is a type of feasibility study that a company would take to a bank or other entity in its search for financing.

7.9 ENVIRONMENTAL IMPACTS OF MINERAL EXPLORATION AND DEVELOPMENT

Environmental impacts are bound to happen on natural environment and on local communities at every stage of mineral exploration and development. Fig. 7.3 depicts the important environmental impacts during different stages of exploration and the respective degree of severity. Preliminary exploration rarely spoils too much of Earth’s surface. The disturbance is quite minor or of temporary nature. The impact is very minimal in grassroots exploration because the number of people involved is small and also most of the techniques are noninvasive. Geological mapping involves people taking traverses and collection of samples, etc. In some cases, certain amount of clearing the trees, road construction, etc. might be involved to access and collect samples.

Environmental and social impacts are quite significant during advanced exploration, but less, compared to those of mining. Drilling, trenching, access roads, vehicular traffic, etc. might affect air, water, flora, and fauna. By adopting suitable measures, some of these can be mitigated. Much more significant environmental and social impacts will be there in the deposit development/mining stage. Mine construction, actual mining, waste rock disposal, mineral processing facilities, tailing disposal, etc., although occupy a small acreage, there will be significant effect on the natural environment. The influx of outsiders (may be culturally different from local people) might affect local communities to a certain extent. Eggert (2010) opines that “many of the social impacts of a new mine can be minimized or controlled through deliberate planning but some community change is inevitable and permanent”.

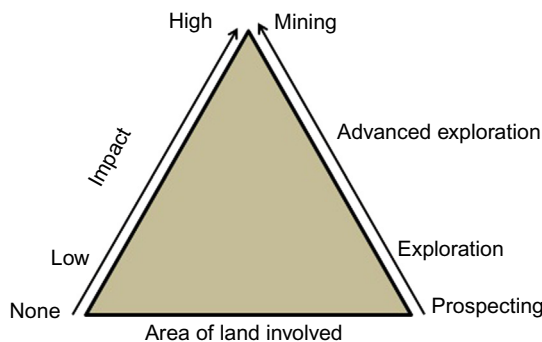


FIGURE 7.3 Sketch map showing environmental impacts during different stages of exploration and the respective degree of severity. Source: From Gandhi (2012).

7.10 MINE CLOSURE PLAN

Every mine faces closure after reaching its estimated life. A range of environmental, social, and economic factors are to be considered in closing a mine. Depending upon the commodity, location, legal framework of the specific region, processing methods involved, the mine closure challenges vary. Since no two mines are alike, the mine closure plan differs from mine to mine. It may involve rehabilitation or remediation of the town near the mine site and associated processing and tailing facilities. In many cases, closure costs constitute a major chunk of funds in developing a mine. But if the mine closure can be planned carefully, a company gets more time to remedy the issues. Postmining land use options need to be identified in advance so as to set out site-specific objectives.

Typically, mine closure involves (1) removal of buildings, plants, other infrastructures in the site, (2) reclamation of the decommissioned areas back to their premining land use, (3) restoration of areas where environmental damages caused by the mining activity, and (4) after care of the mine site till such period to show that the areas are physically, chemically, and biologically stable and safe and do not pose any threat to local community.

7.11 GREENFIELDS VERSUS BROWNFIELDS EXPLORATION

Greenfields exploration is normally conceptual, relying on the predictive power of the ore genesis models, to search for the mineral resource in an unexplored virgin ground. Brownfields exploration is conducted within geological terrains which are closer to known ore deposits. Brownfields is less risky, as the geology is better understood and the exploration methodology is well known, since large deposits have already been found. In such cases, the rewards are less. Greenfields, on the other hand, has a lower strike rate, since the geology is less understood at the conception of exploration programme but rewards are greater because it is easier to find a bigger resource with concerted exploration effort. Exploration done to expand a mineral resource that has already been found and developed into a mine is called “on-mine-site” exploration.

For greenfields exploration, geological analysis is a key component. A territory could have been explored and drilled earlier without the requisite success. But application of new exploration concept or new exploration technology, it is possible to find the area prospective for a mineral resource, not sought there before. Detailed mapping and application of advanced visualization of structural data are essential for brownfields exploration projects for success. Advances in 3D modeling enhance the probability of success in brownfields. Exploration targeting from geophysical data and geochemical data and their interpretation will help to design drilling programme and also search for buried resources. Rock outcrops, detailed drill core logs, evaluation of aerial photos, and geophysical data help an explorationist to decipher the tectonic structure of the area of interest. 3D modeling and visualization will give an idea of the resource and its projection.

7.12 RESOURCING THE FUTURE

Exploration is based on an understanding of the fundamentals of geological processes and the earth's history. In certain areas of the world, a higher density of deposits of particular type of metal or group of metals is a conspicuous feature. Such regions are called "metalogenic provinces" which represent enriched areas of crust where geological processes were suitable for the concentration of metals to form a group of ore deposits of a similar type. These provinces are said to be a manifestation of the regional control of geological processes by tectonic setting. They provide a valuable first step to exploration geologist in the search to further mineral resource (McKinstry, 1962; Lovell, 2000). Studies of how the earth is evolving help to predict which metallogenic provinces or basins have the best potential to host tier-one resources. As the easier and most obvious discoveries have already been made, attention is now turning to the deeper or hidden deposits that are both more difficult and expensive to find and develop. An area of interest is first identified by looking at prospective geology, known mineral occurrences, the maturity of previous exploration, and likely residual potential.

Generally speaking, the best place to start exploring is close to known mineral deposits in what is known as "brownfield" exploration. Brownfield exploration involves looking deeper or laterally for extensions or repetitions of mineralization at, or close to, existing mine operations. Greenfield exploration takes place outside the area of known deposits and requires more creativity, persistence, and some luck to find a significant discovery. In choosing where to explore, nature's distribution of resources needs to be weighed against the available technical ability to make a discovery. In addition, one needs to evaluate the relevant country risk, which involves considering the laws, regulations, and practices governing the minerals industry in that country.

7.13 PROJECT FUNDING

For major exploration companies, project funding is composed of "equity and debt" components. The lenders provide the "debt" portion after having conducted technical due diligence and satisfied that the project is technically and commercially viable. Besides they must be satisfied all necessary permits and environmental issues are properly addressed. Projected cash flow and the level of provision of corporate loan support will decide the amount of debt provided by lenders and the amount varies from project to project.

The sponsors of the project must meet certain cover ratios and other loan covenants prescribed by the lenders. Lenders require metal price hedging to reduce the risk associated with the project. They also ensure that firm marketing contracts covering the sale of mineral products, concentrates, or metals. The amount of equity can be determined once the loan amount and the parameters are established. A provision for cost overruns is also provided in the total project capital. Certain completion tests must be met once the project has been constructed and placed into operation, which ensure that the project has been constructed and is operating within certain design parameters. At this stage, most of the technical risks of the project are eliminated; the lender has recourse only to the project itself for loan security. Equity providers to the project and lenders are sensitive to issues like

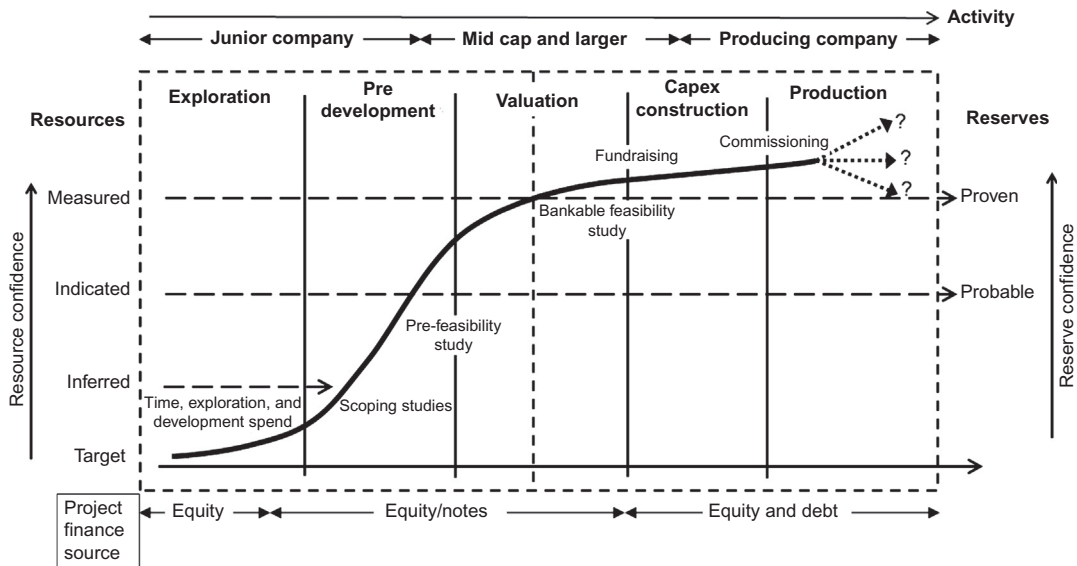


FIGURE 7.4 Funding options available as exploration project matures to production. *Source: From Russell (2012).*

project title, native land claim, environmental, permits, etc. The proposed project financing will suffer if there are impediments to a timely project development. Various funding options are available as an exploration project matures into production stage (Russell, 2012). The project finance sources for junior, mid cap, larger, and producing companies for various stages, from exploration through predevelopment, valuation, and capex construction to production stage are shown in Fig. 7.4.

7.13.1 Exploration Funding by Junior Exploration Companies

Given the inherent riskiness, many major exploration companies generally do not use debt to fund exploration programs. Instead, they mainly use their own equity to fund exploration. This rule applies to many major and junior companies. The major companies fund exploration out of their cash flows (sometimes up to 40%) from operations. However, every dollar spent on exploration is, one less dollar of profits and one less dollar available for dividends or debt repayments. Even though senior management recognizes the long-term necessity of exploration to sustain and grow their business, they often view these expenditures as discretionary in the short term—and so increase/decrease their level of funding inline with the ups and downs of the business cycle. Exploration expenditures by junior companies are more volatile. Junior exploration companies do not have an operating mine to fund their activities; instead, they have to rely on the support of their shareholder for cash—raised through issue shares (equity) in the company. The most high-profile example of this is the initial public offering (IPO) associated with when the company first lists on the stock market. The number of resource-related IPOs is dwindling in number over the years.

As a general rule, IPOs only raise enough money to fund the first 2–3 years of exploration. Consequently, to pay for follow-up work, the company has to go back to its shareholders for more funds, which involves issuing additional equity in the form of shares. To encourage investors to buy these shares, the company needs to demonstrate “good news” on their projects. This is usually in the form of positive exploration results and/or improvements in the business environment (such as strong commodity prices and lowering of business risk). Due to declines in commodity prices and concerns that the mining boom has come to an end, the market has savaged the share price of most junior resource companies. This has made it very difficult for companies to raise funds—as it requires selling the new shares at a heavy discount—thereby diluting the existing shareholder base. Given the difficulties in raising funds, most junior companies have responded by cutting back on expenditures. In extreme cases, in order to survive, they have gone into hibernation mode and are spending the minimal amount in the field. While most majors have resources to fall back on in hard times, their retreat on spending has left juniors in dire straits. Now the institutional investors have almost entirely stopped funding greenfields exploration, hence there is a dire need to tap into retail more than ever. But under the current securities regime, they have failed to do that in recent years and they need to win the retail investor back.

It is estimated that the average life expectancy of a junior exploration company is around 10–20 years and its longevity depends on ongoing funding from its shareholders. To achieve this, the company needs to generate a steady stream of good news on its projects. This, in turn, requires them to actively work their exploration leases. Given the above, it is clear that junior exploration companies do have the ability to fund exploration projects of +5 years duration. Shareholders will continue to invest if they believe that there is a (small but real) chance of a giant discovery. To make new discoveries and deliver new mines, the junior companies need good funding and access to good ideas and good tenements.

7.14 INGREDIENTS OF A SUCCESSFUL EXPLORATION CAMPAIGN

The important ingredients of a successful exploration campaign are:

1. Selection of right geological terrain
2. Optimum level of exploration expenditure,
3. Keeping pace with new technology.

7.14.1 Selection of Right Geological Terrain

The most critical issue in case of all mineral exploration programme is “Are we looking in the right terrain?” It is not only possible to find ore deposits but also to find them easily and cheaply, if the selection of most prospective area in a mineral find or geological terrain is made. By applying the theories of origin, the knowledge of known occurrences of ore and their mode of formation to known geological regions, it is easy to determine potential areas where particular ore type being sought might exist. New styles of deposits may be found that reveal chances to find look-alike deposit styles in rocks previously thought barren. The geophysical and geochemical exploration campaigns, detailed

structural geology, basin modeling, petrology, etc., help to make predictions and draw parallels between known ore deposit and the unknown potential of finding “look-alike” deposits within the area selected.

Ore bodies occur in a typical geological setting with specific structural and tectonic environment. It will be difficult to predict mineral occurrences unless one develops a good understanding of the geological controls and their spatial distribution over wider region. Areas prospective for one mineral need not necessarily be prospective for other minerals. Many major mining companies will look for certain size/class of deposits because smaller deposits may not meet their economic criteria. Previous finds in a terrain (“nearology”) will definitely help the area selection. Financial and taxation incentives and tariff systems of the host countries will also determine the area selection. Besides, the availability of good infrastructure is crucial since the ore/products have to be brought to market eventually.

7.14.1.1 Applying Conceptual Geometrical Models in Evaluating Mineral Prospects

During modeling process, data on geology, structure, alteration, etc. are underused many a times and assay grade takes precedence in interpreting the model. Such models based on grade alone have become unrealistic/unstuck at a later part of exploration, evaluation, and production. Geological structures observed in drill hole logs, conceptual geometrical model to the geology of the deposit can be judiciously incorporated in order to make a more accurate reflection of geology in the 3D models that could be used in realistic “mineral resource estimates.” Large amount of data are usually available but often difficult to integrate and use effectively in brownfields exploration. Similarly the old ideas and exploration models hamper new interpretation and development of new targets. Such challenges are faced by the explorationists. 3D targeting is a new technique available that uses all available geological and other information to build 3D block model of the area of interest. Many canned commercially available 3D modeling software (like Geocad, Leapfrog, Geomodeller) are used to minimize time in making the necessary models in evaluating mineral properties.

7.14.1.2 Targeting and Target Generation

Modern exploration has grown intensely sophisticated with the advent of satellite, supercomputers, and modeling based on the plate tectonic theory. Targeting constitutes the initial stage in any exploration programme. In the initial stage, the activities are focused into specific areas with the highest potential for discovery and develop plans to systematically explore them. Dedicated exploration targeting is often ignored. Integration of all available data helps efficient targeting to make the most well-informed predictions. It is to be ensured that targeting should not create too many “false leads” and should not be also simplistic by missing a “big one.” Combination of available data and expert knowledge will help while assessing the exploration potential of vast areas. Characteristics of known mineral deposits serve as “predictive tools” in order to identify similar features in exploration datasets (such as geology, structure, geophysics, geochemistry). In predictive targeting, two approaches like “expert driven and data driven” are used.

Understanding the mineralizing system for a “mineral system” to occur is the basis for “expert-driven” approach to exploration targeting and is useful in greenfields exploration. An exploration model/rationale for future exploration is developed on sound geological

reasoning, and it is necessary to compare with geological settings with known mineralization. In this approach, the concept of geological processes, in which mineralization and its movement from a source through a pathway, to the trap area where it is localized, is to be noted in detail. Based on explorationist's judgement, each element can be ranked and the features are combined in 2D or 3D GIS packages. The target areas are highlighted by the cumulative effect of all features.

In brownfields exploration, data-driven targeting model provides a robust/repeatable technique with vast amount of data. The empirical evidence of each element is ranked with little knowledge of actual mechanism of mineralization in "data-driven" approach. Such approach is called "weights of measure," where a spatial feature (rock type, structures like fault, fold, etc.) is assigned a statistical weighting, based on its relationship with identified mineralization. Features related to mineralization can be identified allowing exploration to focus on prospective regions independent of past interpretations. A robust geological framework and mineralization models will be provided by targeting processes that can form the base for exploration programme.

7.14.1.3 Target Selection by Airborne Surveying

To ascertain the geophysical aspects of an area having a potential target, many exploration companies use airborne surveying. Areas conducive to mineralization which may have accessibility problems from ground surveys (in remote areas) aerial surveying is done either with helicopters or fixed wing aircraft. The geophysical surveying methods like aeromagnetic, electromagnetic, gravimetric, radiometric, and "light detection and ranging (LIDAR)" have their own advantages. Certain methods may be better applicable than others depending upon the geological conditions and survey objective. Besides company's budget, the selection of survey method is such that the geological and geophysical data can be well understood.

The various advantages of airborne techniques over ground-based surveys are: (1) cost effective to cover large areas rapidly and efficiently, (2) helps development to take place on shorter time scales thereby reducing costs and improving efficiency, (3) can cover many areas inaccessible to ground-based exploration, (4) data coverage over remote terrain is uniform without any ground hindrances, (5) minimizes environmental impact on the ground, (6) helps to narrow down the area to be covered by detailed exploration, (7) can provide regional scale geology and structure for better interpretation and to select the target areas.

For planning an exploration programme, valuable pool of data are obtained by combining all the acquired data integrated into a powerful GIS. By conducting drilling campaign in areas of high potential, an effective exploration programme can be carried out.

7.15 MINERAL EXPLORATION AND DEVELOPMENT— GEOGRAPHIC LOCATION

A good geologic potential and the investment climate are the two factors that determine the geographic location where mineral exploration and development occur. Geologic knowledge gathered from previous exploration/mining and nonmining activities like road

construction, etc. attract the investors. A message of mineralized core in a drill from one exploration agency often leads to a lot of claims staking or purchase of exploration rights in the area by other agencies. Public geological survey organizations play a critical role in attracting exploration in an unexplored area by providing geoscientific research and information. Many companies imitate by taking advantages of research carried out and information gathered by others for their use. Providing basic geoscientific information by Government can act as a catalyst for mineral exploration in unexplored areas. The information types the Government may provide are geological maps, regional geophysical surveys, regional geochemical survey data, etc. In most of the survey organizations, such data are available in digital format which could be downloaded from “internet.”

Different exploration agencies view the same data differently. In fact the exploration programmes/drilling campaign by several companies in the same area led to the discovery of many deposits. Attractiveness of the same piece of land changes over time. A preliminary investigation could have been discarded by one company, but relinquished the area owing to unfavorable economic criteria or due to problems in mineral processing. As time advanced, technological capabilities, economic conditions, and exploration techniques change, chances of detecting subsurface mineralization get improved.

Private investment in mineral exploration and development depends upon the “investment climate” of a country. Political stability, attractive fiscal and tax regimes, attractive royalty policies, legal and permitting systems are the important factors. A nation’s specific policies for mining sector, transparent and nondiscriminatory rules, and investor-friendly environment attract the investors. Besides, investors prefer a simplified single window policy for granting licenses, permits, and approvals.

7.16 EXPECTED REVENUES, COSTS, AND RISKS

The expected revenues and costs adjusted for time and risk are determined by the location and level of investment in mineral exploration and development. An investment opportunity is said to be “more attractive” when the expected revenues are higher or expected costs are lower. The longer an investor has to wait to get the revenues (the riskier the investment), the investment is said to be less attractive. As per [Eggert \(2010\)](#), the main four factors that influence expected revenues, costs, and risks in mineral sector are:

1. Geological Factors: Whether a mineral resource exists in a region? If so, what is the quality and quantity of the anticipated resource?
2. Technical Factors: With the existing or likely future technologies, Can known resources be extracted and processed economically?
3. Environmental, Social, and Political Factors: Whether a resource be extracted in ways which are consistent with a Nation’s preference and policies for environmental protection. Whether it can be extracted in ways consistent with preferences and policies of local communities/people?
4. Economic Factors: Whether a mineral resource can be extracted at a profit? The economic risk is an “overarching” type, since it incorporates and reflects the three earlier categories of risks cited earlier.

How the investing companies manage risks and returns is shown in Fig. 7.5.

The projects which attract mining investments and the risk-return equation are shown in Fig. 7.6.

In their recent survey of business risks facing global mining and metals industry in 2014–2015, Ernst & Young summarized the top 10 “Business Risks Radar” as given below:

1. Productivity and improving
2. Capital dilemmas
3. Social license to operate
4. Resource nationalism capital projects
5. Price and currency volatility
6. Infrastructure access
7. Sharing the benefits
8. Balancing talent requirements

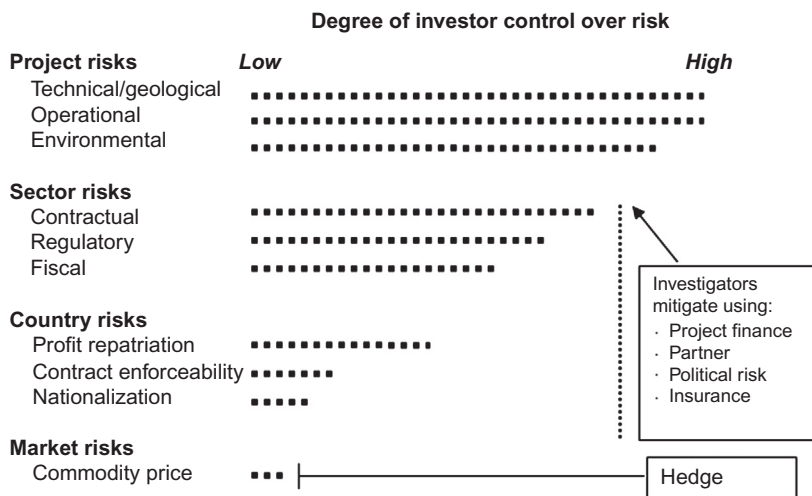


FIGURE 7.5 How the investing companies manage risks and returns.

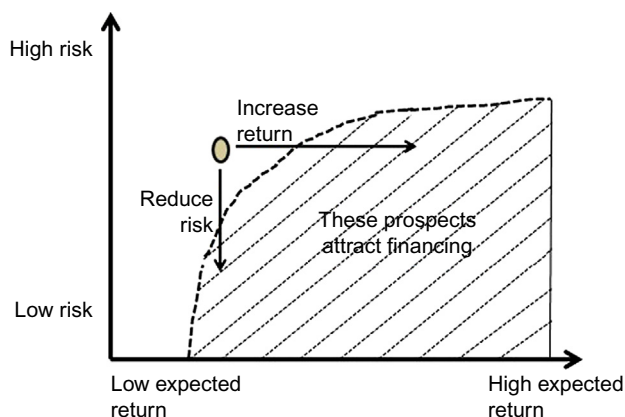


FIGURE 7.6 Projects which attract mining investments and the risk-return equation.

9. Access to water and energy.

They have also listed the following under “the Radar Business Risks”:

10. Cyberattacks and information security

11. Threat of substitutes

12. Pipeline shrinkage

13. Fraud and corruption

14. Competing demands for land use

15. Climatic change concerns

16. New technologies.

The Mega Trends: The top 10 business risks are 1–2 year priorities of mining and metal sector, as influenced by the global “mega trends” that are impacting business, society, culture, and the economy. These include (1) digital transformation, (2) changes in the way we work, (3) the global market place, (4) the urban world and its demands on infrastructure, and (5) health reimaged to meet growing needs. The mega trends by their nature are medium to long term in relevance ([EYGM Ltd., 2014](#)).

7.17 EXPLORATION EXPENDITURE

7.17.1 Sources of Exploration Financing

There are various sources of financing the high-risk exploration activity, viz., (1) the personal funds of the individual prospectors or the funds from friends/families; (2) Governments can fund for exploration surveys either wholly on their own or as partnership programmes; (3) multinational mining companies spend funds from their internally generated cash flow, and (4) private individual investor or institutional fund. In many cases, both major and junior companies are working together jointly sharing their funds and expertise.

The key factors for a gradual increase in exploration expenditures, as per [Ericsson \(2012\)](#), are:

- The location of new found deposits is likely to be in inhospitable and exposed to more extreme weather conditions (deserts and arctic conditions). High altitude and submarine areas are likely to be investigated. Thus new locations of deposits will be far away from metal market centers which will indirectly add transportation cost of the products mined.
- Since surface or near-surface deposits have been located, search has to be gradually concentrated on targets of greater depths with greater expenditure budget.
- General depletion of high-grade ores leaving behind exploration of low-grade ores and the associated metal extraction problems.
- The feeling of local community (wherein the resource is found), being neglected, from not getting the benefits that they are entitled to, besides other political problems.

The exploration expenditure over a period of time will be increasing to cater to the resource depletion and growing due to difficulties of geological, technical, financial, and political/geopolitical character. Mineral exploration activity is a labor-intensive activity

and relies on many consultants, contractors, and other service providers. Exploration has large indirect and induced employment effect. It is said that “three jobs” are indirectly generated for every job directly attributable to expenditure. Although it is difficult to estimate, the employment multipliers are greater due to high labor-intensive activity.

7.17.2 Optimum Level of Exploration Expenditure

Mineral industry companies are spending a lot of money on exploration. The exploration funding is entirely driven by the price cycle of the commodity (gold, base metals, etc.). The size of exploration investment is determined normally by the quality of the opportunity and the project risk, as well as assessment of long-term prospect of the commodity. The total worldwide exploration budgets in 2012, and the forecast, by Region and by Commodity, up to 2020 are given in Figs. 7.7 and 7.8 (Schodde, 2014a,b). The forecast of exploration budget shows a downslide from the peak level of spend in 2012. By commodity, gold is projected to fall the most, whereas spend on uranium is expected to increase a bit.

The percentage of total exploration investment in 2014 in the world, by region, is shown in Fig. 7.9 (SNL-MEG, 2015). The industry is reasonably confident and optimistic that the present trend might show a change in the years to come.

The worldwide mineral exploration investment in 2012 (*in million US\$*) in different places is given in the table (SNL-MEG, 2013).

Latin America (Mexico, Peru, Chile, Argentina, Brazil, Columbia)							5160
Africa (West & Sub-Sahara region)							3455
Canada	3440	Australia	2580	USA	1720	China + Mongolia	1505
Pacific Isles	1290	Europe	860	Russia	645	Rest of the World	645

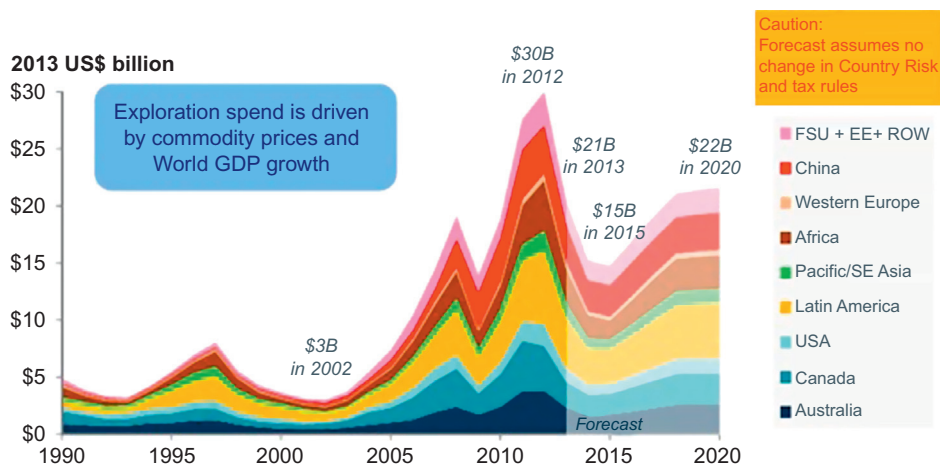


FIGURE 7.7 World exploration expenditure and forecast by region (*forecast based on multiple regression analysis of data $R^2 = 0.95$*). Source: From Schodde (2014b).

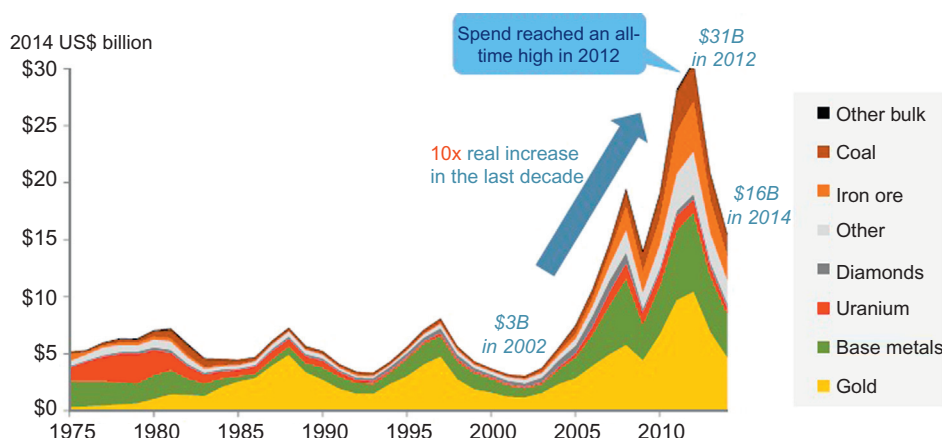


FIGURE 7.8 World exploration expenditure by commodity. Source: From Schodde (2014c).

Compared to these countries, the overall exploration investment in developing countries, in the corresponding fiscal year, was very less/abysmal. With the ever-increasing price and the lure of gold, Latin America continues to be the most favorite place for investment by exploration companies. “After all, the honey bees go where the honey is!” As in the previous years, globally, gold remained the top exploration target, followed by base metals, PGM, uranium, diamonds, etc. Gold and base metals constitute almost 85% of the global exploration target.

The commodity price, availability of funds, and long-term growth in metal demand are the key drivers for exploration spend. There are a few secondary drivers like new geological concepts and search techniques (like Cu-porphyry model), new processing technologies that make low-grade ores economic (CIP Au recovery, SXEW of Cu), and bioleaching for base metals. Historical review of exploration investment in major countries like the United States, Canada, and Australia indicated that to discover a world class mineral deposit with an anticipated gross metal value in excess of US\$600 million, the cost for discovery may be in the range of US\$100–150 million (1990 prices). One has to spend more (~1.25–2 times) to improve higher probability of success. Traditionally, mining companies allocate between 10% and 40% of their posttax cash flow to exploration investment, in order to stay in business (Woodall, 1993).

When there is a cyclical behavior in exploration expenditure in the world over, China’s exploration expenditure is increasing strongly. With the present pace, China may probably end up as the largest exploration country of all. Chinese exploration expenditure figures do not show up in the common figures published over global exploration. The total exploration expenditure for all minerals in China is said to be 25–26 billion RMB (~4 billion US\$) in 2010. Excluding the figures for coal and iron, the total Chinese expenditure is reduced to 14 billion RMB (a little more than 2 billion US\$).

7.17.3 New Technology Adoption

Adoption of right technique or a combination of techniques is warranted to conduct exploration in a cost-effective manner. The impact of technology on mineral exploration is

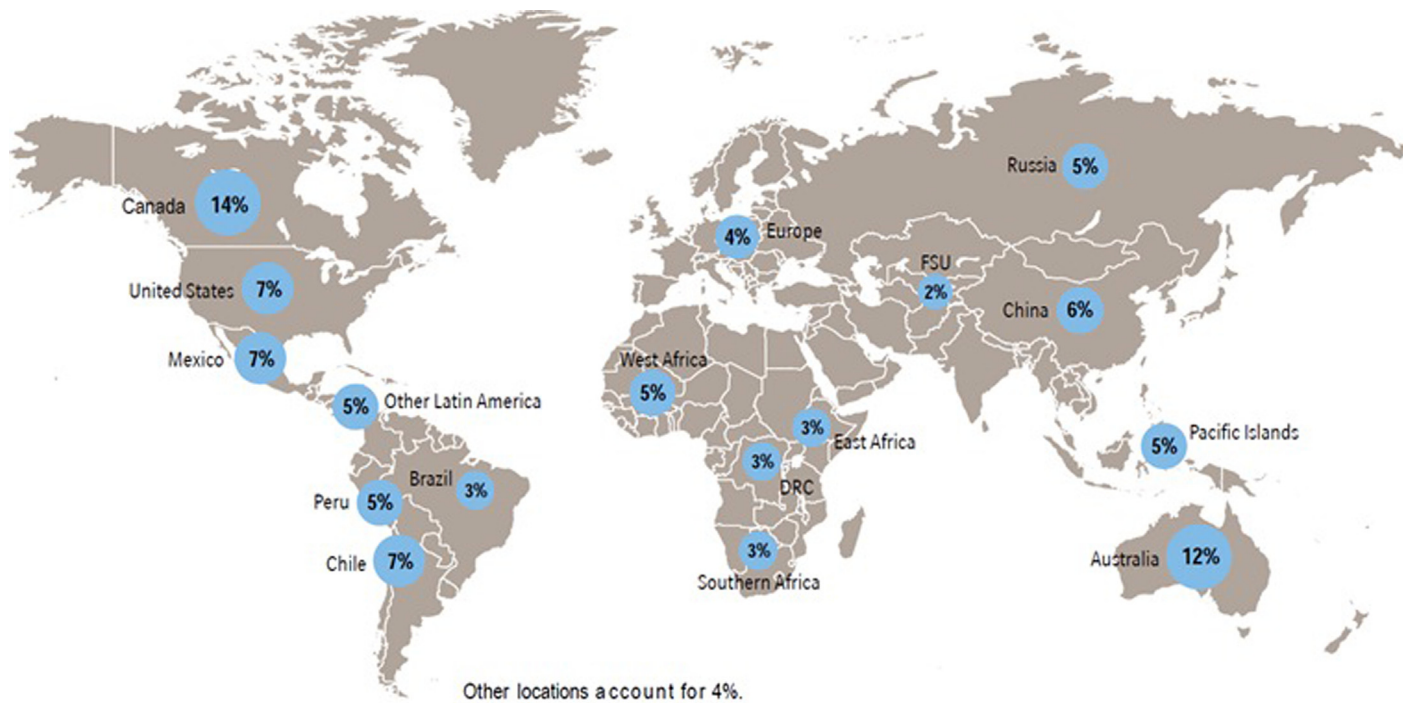


FIGURE 7.9 The percentage of total exploration investment in 2014 by region. *Source: Courtesy from SNL-MEG (2015).*

dramatic in the 21st century, compared to the decades of discoveries in the mid-20th century. We now process “terabytes of data” in minutes and days. A variety of GIS software systems integrate layers of a wide range of data types and formats. High-resolution (100–400 m line spacing) airborne surveys for electromagnetics, magnetics, and gravity mapping guide exploration targeting. GPS navigation and digital revolution have brought huge improvements in airborne geophysical technology. Multiarray and multichannel geophysical setups detect electrical conductors at 1000 m depth and map fault structures and rock alteration to 2 km depth. Challenges, however, impede the rate of discovery in the 21st century. Detailed geological integration does not keep pace with geophysical surveys. Drill targeting and discovery at depth and in remote areas is largely unsuccessful or difficult. New remote discoveries are the result of a combination of persistent teamwork of experienced specialists and timing. Many companies are in the race to develop better methods to integrate multiple datasets to obtain more comprehensive and confident interpretation of geological structure and targets.

Unmanned aerial vehicles (UAVs) are being used now, for a number of applications, viz., aerial photography, geophysical surveying, mapping mission, etc. The low altitudes of UAV can result in higher accuracy than conventional aerial photogrammetry techniques, ease of operation, and overall visibility.

7.18 DISCOVERY DEPENDS UPON VARIOUS FACTORS

Discovery is the crucial moment of exploration when the first unequivocal high-grade, and potentially economic, mineralization is encountered. Some discoveries are obvious from the first outcrop or drill hole, while others are only made after dozens or even hundreds of drill holes and often after the project has passed through many owners, each finding subtle and elusive signals without discovering the prize. Often, the significance of a discovery is not immediately understood, and it may be some time, after follow-up drilling, before the true potential of a resource is recognized and appreciated. Only a small number of discoveries ever lead to large-scale mines that make a material difference to the producer, customers, host government, and community. The long sweep of history suggests that we have not run out of mineral deposits. The number of discoveries and the exploration spend (red line) in the world are shown in [Fig. 7.10](#) and the number of discoveries by commodity is shown in [Fig. 7.11](#).

Out of worldwide deposits, about 30% were “*accidental or chance discoveries*.” Some of the accidentally discovered mineral deposits in the world were: Rio Tinto (Cu, Au), Sar Chesmeh (Cu), Cornwall (Sn, Cu), Chiquicamata (Cu), El Teniente (Cu, Au), Yanacocha (Hg, Cu, Au), Kiruna (Fe), Rammelsberg (Ag, Pb, Zn), Mexican (Ag), Sudbury (Ni), Cobalt (Ag), Kalgoorli (Au), Broken hill (Pb, Zn, Ag), Erstberg (Cu), Rand belt (Au), Lake Superior (Fe), Bisbee (Cu, Ag), Bingham (Cu, Au, Pb), Porgera (Au), Red Dog (Pb, Zn, Ag), Rampura-Agucha (Pb, Zn), Sukinda (Cr), etc. About 32% were due to complex, purposeful exploration by Private Exploration Companies/Corporations; about 20% were discovered due to unsophisticated prospecting and about 18% were discovered due to Government enterprises or agencies. Literally, thousands of properties must be examined in regional surveys carried out, before a success is registered. Generally accepted yardstick

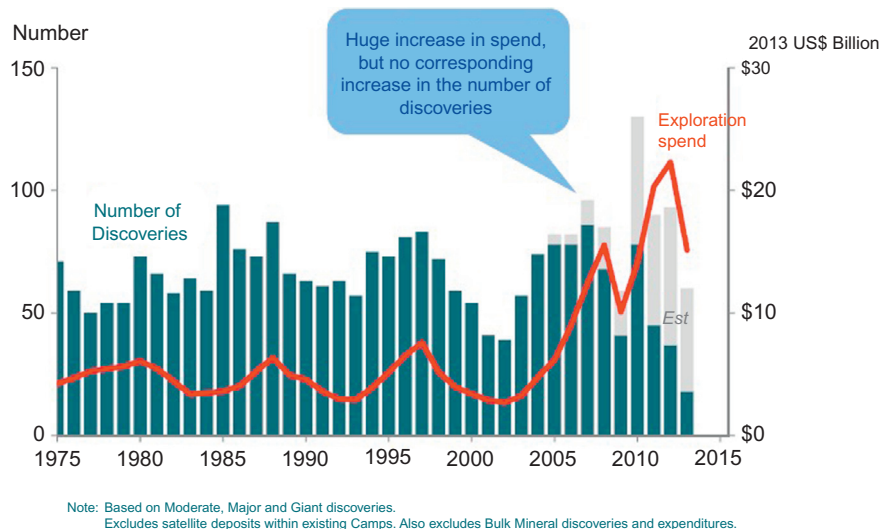


FIGURE 7.10 Exploration spend (red line) and number of discoveries in the world.
Source: From Schodde (2014b).

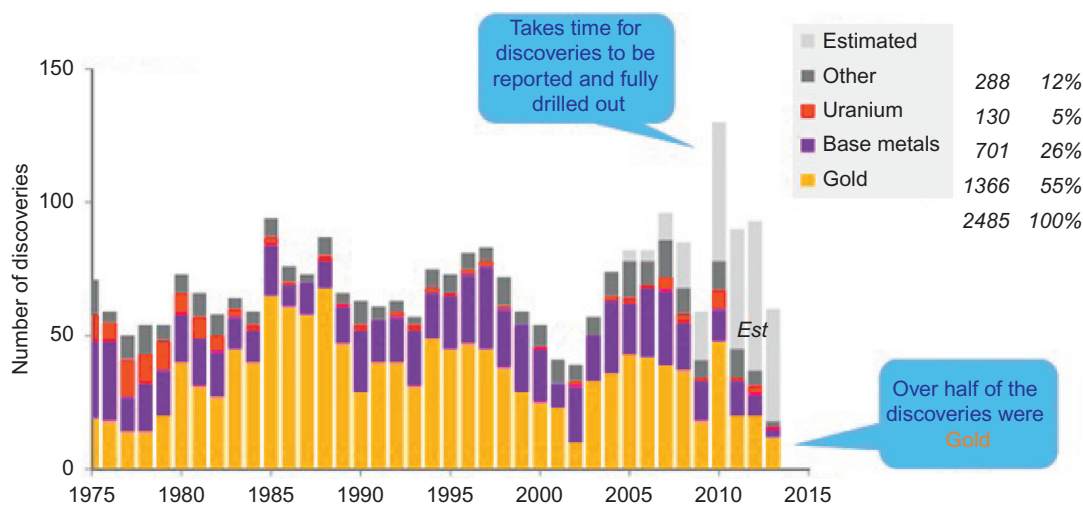


FIGURE 7.11 Number of discoveries, by commodity, in the world. Source: From Schodde (2014b).

is that 1 in 1000 discoveries turns into an ore body. The typical time frame from the inception of exploration through the investment in mine/mill facilities that will return this investment out of production is 12–15 years. To receive a profitable return on investment commensurate with risk requires minimum investment longevity of additional 10 years, hence a total of 20–30 years.

Many fine, productive mines were discovered in the 1950s and the peak of discoveries was between 1960 and 1975 with the advent of new geophysical survey tools and geochemical techniques (Blain, 2000). Since then, the rate and number of discoveries have fallen off drastically later. When the genetic models of mineral deposits became accepted and widely known, great discoveries were made through the years: during the 1950s, roll-front uranium deposit discoveries; in the 1960s, porphyry copper–molybdenum deposits; in the 1970s, “sedex” zinc–lead deposits, unconformity uranium deposits; in the 1980s, “carlin type of gold deposits”; and in the 1990s, IOC gold deposits. The application of such models by the exploration teams facilitated to locate many potential deposits yielding a burst of discoveries. Many of these discoveries were brought to production much later owing to various reasons. Besides, the development of new technology enabled mining of many low-grade ore deposits.

The exploration costs have risen dramatically over the past few decades. The most expensive component is exploratory drilling. With the terrain maturity, the rate of discovery of world class deposits has declined. Concomitantly, the overall grade of the ore deposit has shown a declining trend over the years (Fig. 7.2B). Most discoveries have been made not only in the right geological terrains but in countries that traditionally have a sound set of mining tenancy and investment laws, these include the United States, Canada, Australia, South Africa, some countries of the SW Pacific, and some countries in South America, particularly Chile, Argentina. Mining industry has traditionally chosen to put its money, where it is safe. The worldwide significant mineral discoveries in the period 2000–2013 and the current hot spots of exploration activity are shown in Fig. 7.12.

Discovery of economic resource depends upon various factors. In exploration stage, mineral activity is a very risky business since there are many unsuccessful projects before finding one successful project which may end up in an economic deposit. So, the cost of discovery includes the total costs involved in both “successful and unsuccessful” ones. Generally, a few good successes must be profitable enough to compensate the other failures (USBM, 1977). In mineral exploration, the “key performance indices” are drilling density, the amount spent per discovery, and the \$/kg of metal found. These factors will show the “measure of efficiency.”

In the past decade, owing to higher input costs for drilling, salaries, and administration, etc., the unit cost of discovery has doubled or tripled. The impact of increasing depth of cover reflects on the discovery performance. Especially for brownfield areas, there has been a gradual move to deeper discoveries (Fig. 7.13).

The overall conversion rate of all the discoveries made since 1950 into mines is only 45% and in terms of contained metal, it is 57%. It has been found that gold prospects have higher rate of conversion. The size and depth of cover have no bearing on the delay of the project except that “brownfield” discoveries were quicker to develop. Besides, the country risk was also a critical factor; in low-risk countries, the projects were developed 40% quicker.

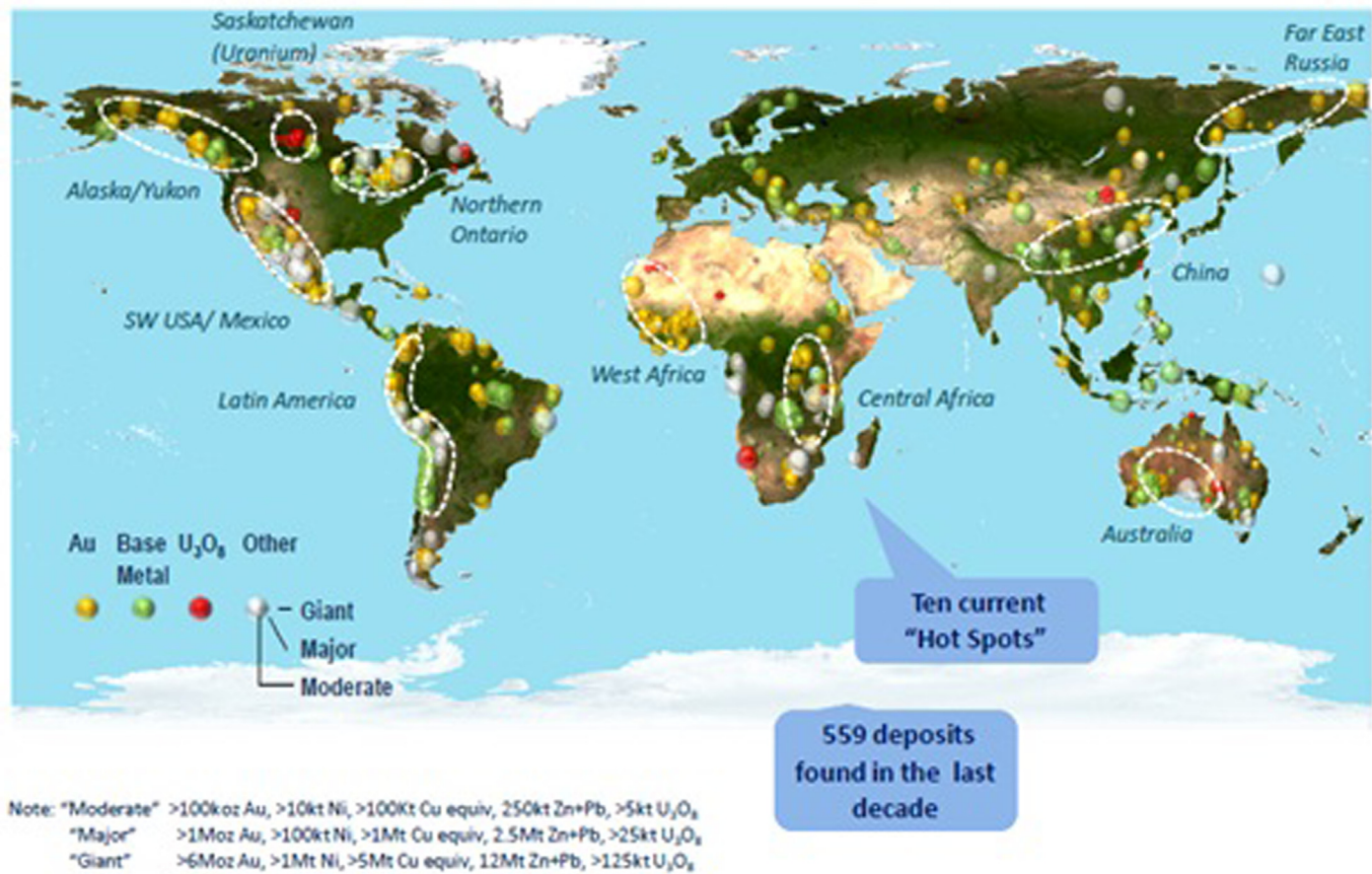


FIGURE 7.12 Significant mineral discoveries, worldwide and current hot spots. Source: From Schodde (2014a).

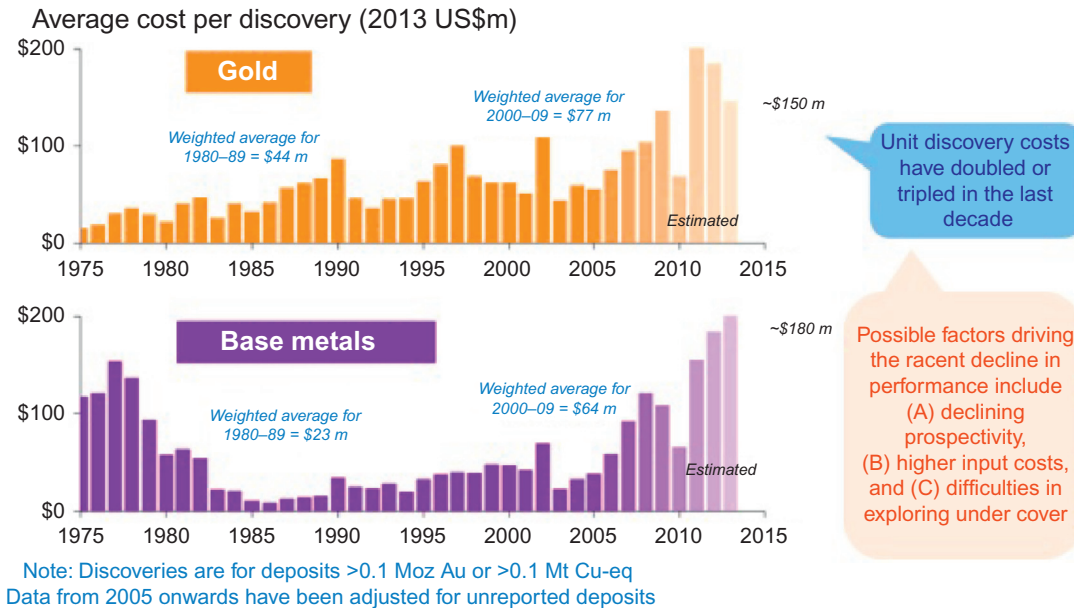


FIGURE 7.13 Rising discovery costs (unit cost/moderate-sized gold and base metal discovery in the world).
Source: From Schodde (2014c).

The rates of success calculation and interpretation, and the cost per success (including cost of failures) for mineral exploration projects are complicated by many factors. The very basis of division of projects as “success or failure” is artificial and misleading. Exploration success is defined as a discovery of significant concentration of mineralization, currently developable. But many a times, an economic resource is discovered which may not be currently economical but commercially developable in the course of time, as a result of advance in technology, infrastructure or higher prices for the minerals/metals (Woodall, 1984a–c). Such discoveries are termed as “technical successes” or “on-the-shelf” deposits. Even if there is no concentration of mineralization, the detailed information gathered by exploration will be important additional information, which in the days to come might be very valuable when new technology/new theories of ore formation are considered. It is normally difficult to assess trends of exploration productivity. Exploration productivity can be determined by dividing the expected financial return by exploration costs, after these have been adjusted to take account of inflation.

Blain (2000) analyzed the mineral exploration success rate with the available data. With the advent of modern geophysical exploration surveys and geochemical exploration techniques in the 1950s, large number of significant mineral discoveries was made, but many of them remain undeveloped. The discovered deposits developed since 1980 (giant Andean copper-porphyry deposits of Chile/Peru) are low-cost producers. Since then, the rate and number of discoveries have fallen off drastically later. The decline of discoveries in nongold sector (from mid-1970s onwards) is largely due to the difficulty explorationists have in finding a viable deposit in an unfavorable economic climate.

The discoveries were a series of waves; offset over time, in different commodities, viz., copper, gold, base metals, and nickel. Most of the discoveries in the 1980s and 1990s have been of gold deposits, but the rate of discovery drastically fell later. After World War II, the price of gold remained low with little fluctuations for about three decades. When the fixed link between US\$ and gold was removed by Nixon administration, the price levels soared to record high (about US\$800/oz), an inconceivable figure at the beginning of the 1970s, it then fell back during the late 1990s. The rise in gold price after 1972 led to an increase in prospecting and the discovery of many large deposits. The trend continued until 1993 and gold production increased and reached the peak in 2001. Unfortunately, the demand for gold is not determined by industries but by unpredictable and variable factors like fashion (jewelry), sentiment, and investors. Many companies had to adopt a cautious approach in their exploration strategy, not concentrating on a commodity of volatile and uncertain price levels but putting more emphasis on exploration of other commodities (like base metals), besides gold.

The success of the discoveries should be measured in terms of outputs (ie, number of economic discoveries) rather than inputs (such as expenditure). Not all discoveries turn into mines, the conversion rates vary between 60% and 75%, in different commodities, depending upon various factors. Taking into consideration of losses on mining and the demand of the metal in question, the discovery of more resources is a must. Given the long delays to convert a discovery into a mine and considering the future size of the market, we need to find resource, at least twice ($2 \times$) as much as we mine, in order to sustain.

Mackenzie and Woodall (1988) studied “*base metal exploration*” only and compared the period 1955–78 for Australia with 1946–77 for Canada. Australian exploration was found to have been uneconomic but Canadian exploration, financially very favorable. Although exploration expenditures in Canada were double those in Australia the resulting number of economic discoveries were eight times greater. Finding an economic deposit in Australia costed four times as much and took four times longer to discover and assess as one in Canada. By contrast, the deposits found in Australia were generally three times larger than those found in Canada. Comparable exploration expertise was used in two countries. Australia is either endowed with fewer and larger deposits, or the different surface blankets (glacial vs weathered lateritic) render exploration, particularly geophysical, more difficult in Australia, especially when it comes to searching for small- and medium-sized deposits. The latter is the more probable reason for the difference in productivity, which suggests that improved exploration methods in the future may lead to the discovery of many more small- and medium-sized deposits in Australia. Mackenzie and Dogget (in Woodall 1992) have shown that the *average* cost of finding and proving up *economic* metallic deposits in Australia over the period 1955–86 was about \$A51M or \$A34M when discounted at the start of exploration. The average reward discounted in the same manner is \$A35M. This is little better than a breakeven situation.

Schodde (2014a, 2014b, 2014c) after having examined all worldwide discovery of deposits, their sizes and the costs involved between the periods 1980 and 2011, came up with the costs per discovery, by the sizes, are given in Table 7.1.

Exploration is increasingly getting tougher. Despite a 10-fold increase in the amount of money spent on exploration over the last decade, the pace of new discoveries remained relatively tame. This means that more amounts was spent per discovery owing to doubling

TABLE 7.1 Discovery Rates and Costs, by Size

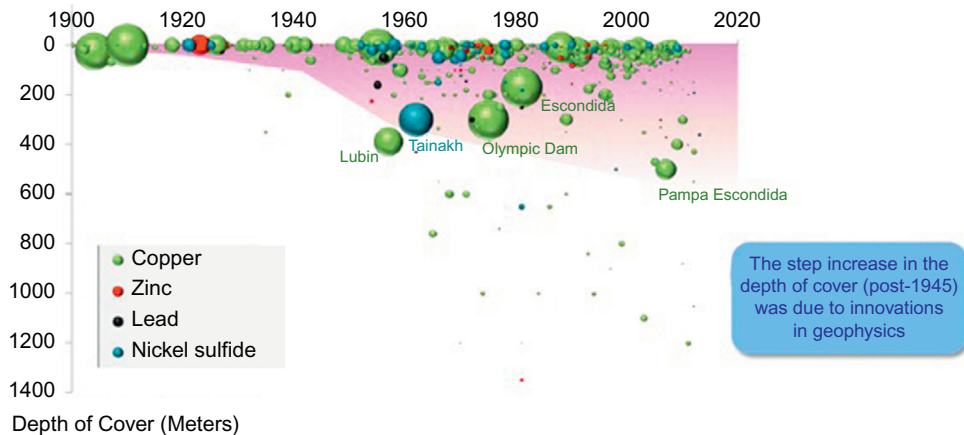
Period	No. of Discoveries Worldwide	Cost per Discovery, US\$
MODERATE DISCOVERIES		
1980–89	520	\$85 m
1990–99	559	\$79 m
2000–11	412	\$189 m
MAJOR DISCOVERIES (INCLUDING LARGER SIZE RANGE)		
1980–89	260	\$171 m
1990–99	313	\$133 m
2000–11	221	\$329 m
GIANT DISCOVERIES		
1980–89	55	\$742 m
1990–99	87	\$475 m
2000–11	44	\$1564 m

of input costs such as drilling, salaries for geologists, engineers and for general administration. Besides, with the ebullient market, much amount was wasted on projects with negligible odds of success. Given the volatile outlook for price and exploration, exploration agencies need to develop new strategies to survive and position themselves for growth in the longer term.

7.19 MINERAL EXPLORATION UNDER DEEP COVER

New mineral deposits must be found to replace deposits currently being mined and to meet the anticipated increases in global consumption rates of many minerals/metals. Since many of the identifiable surface or near-surface mineral deposits have been found thus far, it is necessary to focus the efforts in locating mineral resources from depth or under deep soil cover. The depth of cover of various base metal deposits discovered between 1900 and 2014 is shown in Fig. 7.14. The increase in the depth of cover, past 1945, was basically due to the innovations in geophysical exploration methods.

There has been a growing trend in the discovery of buried deposits (a few 100 m below surface). The challenge of exploration under cover will be in the order of about 1–1.5 km deep. The traditional exploration methods adopted to find new deposits will be of little help for locating mineral resources under deep cover which normally masks the clues/guides to mineralization. Deeper ore targets although have the ability to show up the detectable primary footprint, it dilute the signals. So, in order to detect the secondary or tertiary footprints of mineral systems against a regional level, it is necessary to understand the processes controlling the formation of cover and its mineralogical, geophysical, and geochemical character.



Based on an analysis of 818 Primary Cu, Zn, Pb and Ni deposits >0.1 Mt Cu-equivalent
 Bubble size refers to Mt Cu-eq of pre-mined Resource, as calculated using the average metal price for 2011-2013
 Excludes satellite deposits within existing Camps. Excludes nickel laterite deposits

FIGURE 7.14 The depth of cover of various base metal deposits discovered between 1900 and 2014. *Source: From Schodde (2014c).*

With many incentives world over, more areas of the world have been opened up for exploration and development including unexplored areas which are in remote areas which were unavailable for exploration due to various reasons (political, economical). Besides these, the areas which were previously felt too deep to explore also demand a “reinvestment.” Thus the “search space” for greenfield exploration has widened and may be good for locating new targets. In areas where the bedrock exposure is minimal, mineral exploration efforts have to rely heavily on predictive quality of geological, geophysical, and geochemical data. The exploration efforts in areas under cover can demand new approaches of locating prospecting areas, viz., well-defined target models, and emphasis on geological and geophysical modeling in a 3D environment.

The exploration style has to have much reliance on subsurface imaging using innovative techniques to subsurface geology in order to detect deep-seated ore bodies rather than the customary outcrop-based exploration style. Better tools and techniques are required to accurately describe the geology of the Earth’s crust in four dimensions, viz.

- New and improved targeting models to guide good selection of potential targets
- New insights that are not geological, geophysical characteristics of mineral systems and mineral deposit
- More powerful geophysical exploration tools to directly detect possible mineralization of a wide variety of depths
- Cost-effective drilling technologies to test-drill the zones of interest/deep mineralization.

The targets for exploration under cover have to be of a size much larger so that they can be detected from distance and also have a value that permits their exploitation a profit.

7.20 INTERPRETATION AND 3D MODELING

With the advent of technology comes an avalanche of data. We can do things faster and more efficiently than we ever thought possible. It facilitates to make decisions instantaneously. The volume of data generated in many exploration campaigns is tremendous and most of it remains unused, sitting in server or on the cloud gathering dust. The technological challenge in mining industry is not how to create more data but how to manage and leverage whatever data available. The companies that fail to adjust to the rapidly changing environment could see their operation, efficiency, productivity, and profitability affected. Those companies which embrace change to look for innovative ways to address these challenges may uncover distinct competitive advantages.

Big data utilization and extraction is the “next boom” in the mining industry. The key is identifying problems, then using the data help solve them. One has to sort through massive amounts of data to find the correlation of different datasets and disregard the incorrect data and deviations in order to find patterns that could lead to improved decision making. It is up to the exploration teams to prioritize what they want to see and do what the data available. Sometimes it is difficult to make decision when you do not know where to start.

Generation of 3D subsurface models which are capable of visualizing, analyzing, and interpreting of many complex tectonic setting is possible now by the synthesis of QA/QC-validated geological data. Data from different exploration methods such as geophysical surveys (seismic, gravimetric, geoelectric, well-logs, etc.), drilling or remote sensing can be integrated into a single data model (McGaughey, 2007). It supports the geologist’s task to achieve a comprehensive evaluation of the underground by reducing uncertainties.

Of late, many innovations have been made in graphic design and 3D modeling in exploration and mining owing to the modern day advances in computational power. Based on a thorough understanding of the deposit geology, structural analysis, etc., a 3D model is built for validation. Plenty of canned softwares (like Leapfrog, FracSIS, Gemcom, etc.) are now available for construction and validation of 3D models. Innovation rarely comes without pitfalls; hence, care must be exercised to construct interpretation models. Prolific use of advanced 3D capabilities and more time spent generating interpretations facilitate an explorationist to focus on their projects, by reducing risks before taking a final decision to initiate drilling campaign. By application of modern technology to the data of the old projects, many recent discoveries (HudBay’s Lalor Lake Rio Tinto’s Bingham Canyon mine) have been made. These were possible because of fresh perspectives that came from deeper exploration techniques and 3D visualization capabilities.

First-order distribution of numerical datasets (grade, magnetic susceptibility, geotechnical parameters, etc.) can be modeled rapidly using “Leapfrog,” which often highlights unforeseen geological trends which were poorly represented in traditional geological models. Multiple 2D–3D datasets can be integrated using “FracSIS,” thereby interrogation can be possible of drill hole versus geological mapping data, geophysical data, satellite imagery, and existing 3D geological models. 3D graphics and geological modeling capabilities have been expanded in “Gemcom.” Although no single software program package provides a complete solution for geological modeling, the integrated use of all the three softwares cited earlier can offer significantly advanced geological models in lesser time

frame and many a times highlight unforeseen exploration potential especially in “brown-field targets.”

Geosoft has developed its robust exploration information management solution (EIMS), a web-based technology around its core DAP server and search technology, to integrate plethora of exploration data (Fig. 7.15). It helps to work faster and smarter by organizing and sharing data and information across teams as they can manage and make sense of large amount of digital data for exploration decision making.

Effective data use and management: In the past decade, the greenfield discoveries have fallen every year despite steep rise in exploration expenditure. It is necessary to harness the power of “big data use” and “cloud computing,” probably to narrow down the gap. In several cases, plenty of data are available with the exploration agencies but got nothing remarkable out of it, mainly because of time constraints and inability to find a noteworthy thing (discover) from that data. The key factors in the current challenging mineral exploration market are to make best use of available data through better modeling and interpretation, linked with new technology ([Fresh Perspective](#)).

7.21 ECONOMIC CONCEPTS FOR EXPLORATION STRATEGY

The process of discovery of an economic resource is characterized by a high element of risk, large time span, and sustained cash outflow, which is a total loss, in case of failure to make an economic discovery. A typical exploration process evolves from a generative stage that results in:

- Identification of targets
- Testing and evaluation of the targets culminating into discovery of mineral occurrences
- Definition and delineation of the deposit
- Development stage.

The full process involves inherent risk at each stage that requires testing of a large number of ventures of mineral occurrences to discover and delineate an economic deposit. The risk is related to the factors of uncertainty associated with mineral endowment with respect to their location, size, shape, quality, depth, and the techniques of exploration used. The risk, therefore, could be minimized within given limitations by evolving an exploration strategy which judiciously combines sound geological concepts with economic and commercial judgement at each stage of exploration.

Brant (1968), Mackenzie (1973, 1981), Snow and Mackenzie (1981), Mackenzie and Belodeau (1984), Eggert (1987), Mackenzie and Woodall (1987), Tilton et al. (1988), and Silver (2000) have developed several criteria for assessing risk on investment in mining through mineral exploration using probability considerations to examine actual or likely returns. The “Expected Net Present Value (EV)” and “Expected Rate of Return (ROR)” concepts of Bilodeau and Mackenzie (1979) provide an effective means to estimate the possible risk in investment in mineral exploration.

The Expected Net Present Value can be expressed as

$$EV = R - E$$

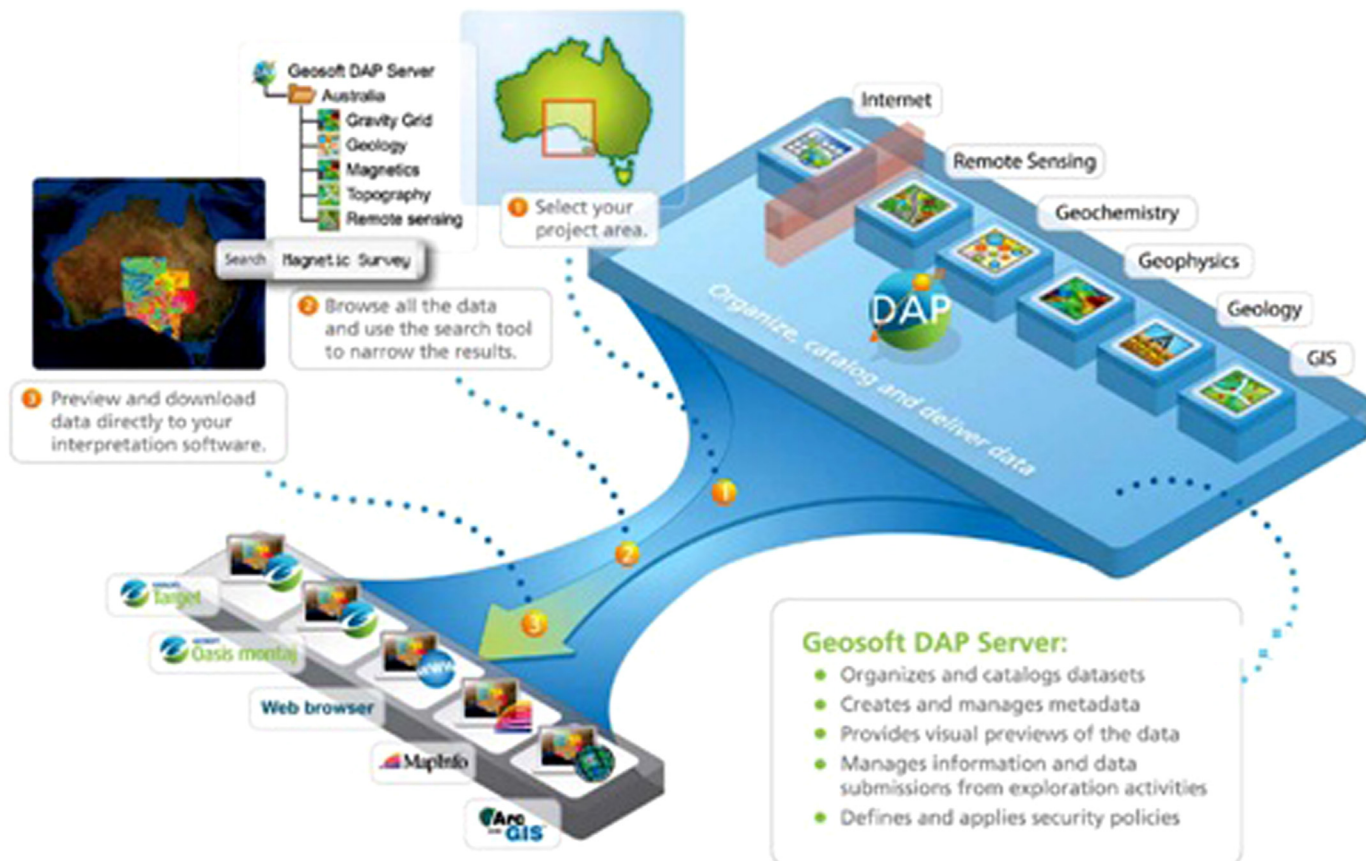


FIGURE 7.15 Exploration information management solution. Source: Courtesy from Geosoft.

where

EV is average expected net present value per economic discovery

R is average return associated with an economic deposit after discounting cost of development and production

E is average exploration cost required to find and delineate an economic deposit.

The relationship between the time distributions of an average cash flow to the expected value of an economic deposit is illustrated in [Fig. 7.16](#).

Any investment in exploration which would yield satisfactory return on capital should satisfy the following conditions: (1) $EV > 0$ or $R > E$ and (2i) risk criterion is minimum.

The relationship of positive EV in the long run when successes and failures of large number of discoveries are considered would depend on minimizing cost of exploration (E) which in turn is related to discovery risk or the number of exploration ventures required to discover and to delineate an economic deposit. The exploration cost is mathematically defined as

$$E = C/P_s$$

where C is the cost of discovering a mineral occurrence and P_s is the probability of discovery of an economic deposit.

Thus, the lower the probability of a discovery, the higher is the risk involved in the process. The link between cost and return is, therefore, the probability of failure ($1 - P_s$), where

$P_s = P_1 \times P_2 \times P_3$, in which

P_1 is the probability of occurrence of an economic deposit in a prospect

P_2 is the probability of actual discovery of that deposit

P_3 is the probability that the deposit has sufficient economic value to compensate the cost of exploration.

These probabilities are interdependent on each other. If any one of these values is zero, the net result is a failure ($P_s = 0$). These probabilities are substantially affected by man-made constraints such as selection of proper geological environment, exploration techniques used, identification of minimum acceptable economic targets, monetary and time cost of exploration together with the quality, skill, and motivation of scientists and technologists involved in the search.

7.22 RESEARCH AND TRAINING

Successful exploration relies on efficiently managing exploration campaign based on effective application and interpretation of geology, geophysics, and geochemistry, to generate and test exploration targets. In order to discriminate and select best terrains at the regional scale, it is imminent to have a good baseline exploration data (geological, geophysical, geochemical) and drilling data. In addition, access to such data (updated high quality) should be possible, either online or web-based data portals in order to have real-time collaboration. Access to new collaborative tools, viz., net meeting, web conferencing,

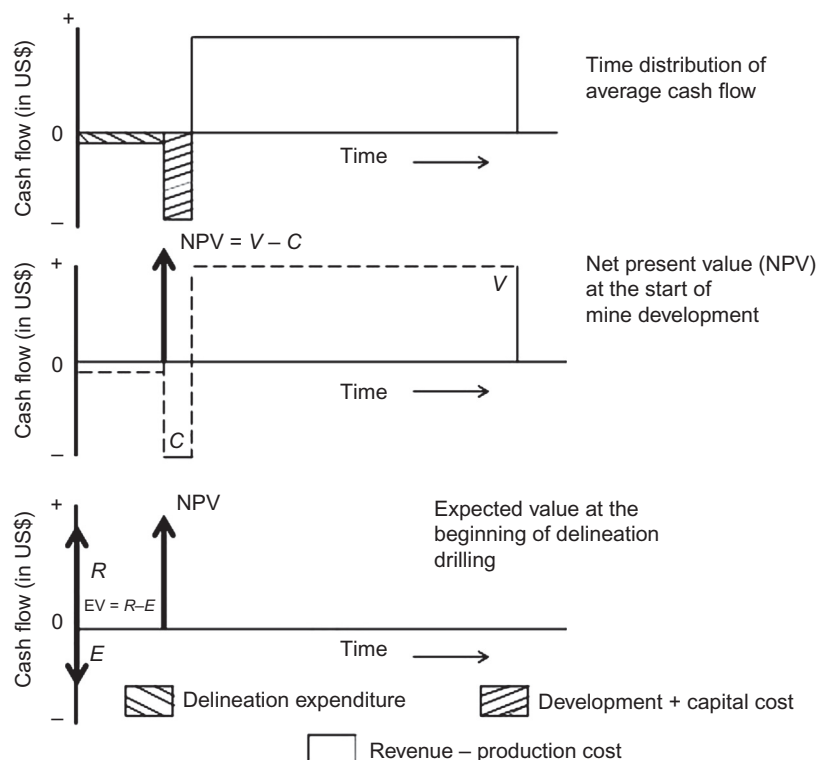


FIGURE 7.16 Relationship of time distribution of average cash flow to net present value and expected value of an economic mineral deposit. *Source: From Kala et al. (1994).*

data streaming, data and metadata harvesting and to innovative thinking, new ideas and interpretation through effective collaboration and knowledge sharing initiatives are imminent. It is needed to access–integrate–manipulate data more effectively by live 3D modeling, advanced processing, and visualization. One has to have free access to supercomputers, more web-enabled access to public processing and research software or the ability to use proprietary software and also seamless access to large amounts of data with fast display speeds. Exploration teams should have an access to researchers and specialists. Normally, the researcher’s timelines are not always aligned with exploration requirements. Establishment of portals such as “innocentive” will bring industry and key researchers, consultants together more effectively. The research teams need to focus on “mineral discovery” not “mineral genesis.”

A combined R&D effort of Universities, Industry and Government agencies in geoscientific field and exploration techniques will help to achieve the desired result of better success rate in future exploration efforts. Of late, one to one research collaboration is becoming more popular between Researchers and Exploration companies with good funding. It is desirable to have teams from Industry, Government, and Academic, to develop team-oriented 3D interpretative approach focusing on the 3D maps of the mineral endowed belts.

Exploration is based on an understanding of the fundamentals of geological processes and the earth's history. There is a need for exploration geologists to go back to basics too. It is seen that there is a decline of experienced exploration teams, because there is a declining trend in students opting hard rock geology in the universities and the focus has increasingly shifted to environmental studies, sustainable energy, etc. (which need to be explored too). This trend has significantly affected the exploration industry.

There is more to the process than rushing to initiate a drilling campaign by many mining companies, after selecting anomalies outlined from remote sensing data. Knowing when and where to concentrate drilling campaign, where to retain the properties, and when to relinquish them are the key elements to a successful exploration programme. Good geologists carry out diligent field work, geological, structural mapping, measurement of rock properties, and other evidences before advancing a theory or model. Basic structural mapping by experienced people using the newest technologies has proved to be a cost-effective exploration method. Field exploration geologists, geophysicists, and geochemists should work in tandem in an exploration campaign and the combined effort is critical to identify potential mineral targets. It is necessary to motivate more cross-training of disciplines in geology, so that everyone is clear on what to get from the data and what kind of data to use on each situation.

Nowadays, the proliferation of software packages makes life way easier. It is not just software training that is needed but one should know what to do with the data and how to use the software. University cooperative programme can work with students concentrate regular university terms with working in the industry, it helps to expose them with real problems using real tools. It may take a while to evolve, but a beginning has to be initiated, so that ultimately will facilitate to produce exploration teams for the industry. With the arrival of computers, satellites and plate tectonic theory, modern geophysical and proven geochemical techniques, etc., mineral exploration has grown intensely sophisticated. In spite of space age technology, mineral exploration still remains some vestiges of the time-honored, empirical "pick and hammer" artistry, that flourished in the past, that helped to discover giant deposits like Butte, Bisbee, etc., about two centuries ago. The combination of time-proven technology of exploration with unproven but promising discovery techniques illustrates that the foundation of minerals exploration is cumulative as well as deeply rooted in tradition.

It is concluded with a famous conundrum "Whilst success in mineral exploration is clearly achieved through new high quality mineral discoveries and also comprehend what, represents best practices in industry research collaboration in exploring geosciences, we still remain poor at closely linking the two together and in tracking the impact and influence of research collaboration upon discovery" (anon.).

7.23 SCARCITY OF EXPLORATION GEOSCIENTISTS

Exploration geoscientists are becoming a scarce resource, since in the recent past, not many come forward to opt the curricula in geosciences in the collegiate level, as the avenues of employment opportunities in other fields like computers/biotechnology/telecommunication, etc. have increased manifold. In order to meet the current and planned

exploration projects in pipelines, there is shortage of geoscientists/exploration team. Many exploration companies face difficulties in retaining experienced geological staff as there is an acute shortage and the demand is high. The retirement of many experienced people adds further scarcity. As the exploration budgets increase, more projects come up and need more geoscientists to man the projects (Taranik, 2009).

Employment in Geosciences has been cyclic, in a period of 3–5 years. The uphill periods and the peaks are always exciting. The employment opportunities of geoscientists vary in different parts of the world. Depending upon the skills acquired both in the academics and field, the geoscientists are hired by exploration companies and put them with their teams to enrich experience and other skills. Generally, multinational exploration companies expect the following traits for employing field geologists in the entry level:

- Good, balanced all-round geological education (undergraduate degree, OK; Graduate level, useful)
- Good computer and numeracy skills
- Good mapping and field skills, capability to identify minerals/rocks in the field
- Willingness to travel and work in remote areas
- Language skills, ability or willing to try, ability to get on with people
- Enthusiasm, cultural sensitivity, and a Driving Licence.

As the years pass by, the companies also expect them to keep themselves up-to-date and stay current in their field by associating themselves in “national/professional geological bodies” (like Geological Societies/Economic Geological Society, etc.). The field geologists are expected to develop interest in Economics, Finance Law, etc. Besides enhancing the core skills and try to get experience, they should develop courage, communication/negotiation skills, and interest in social, environmental and current world affairs.

Whenever the unpleasant event of retrenchment happens, that time should be constructively used for company move and acquiring higher/extra qualification. Finally, a geoscientist should be an “optimistic realist” and look for the uphill periods/peaks to come.

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