Mineral Resource Exploration

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Summary
This chapter is concerned with the process of analyzing an area to find mineral deposits, which is termed mineral resource exploration. The information collected during exploration is utilized to evaluate the size and quality of an ore deposit and to establish there is an option for it to be mined. Two main phases can be broadly outlined in mineral resource exploration: reconnaissance exploration and detailed exploration. The geological, geophysical, and geochemical methods applied at different stages of mineral resource exploration are described. The methods are organized in order of scale and stage, from remote sensing to drilling, through photogeology, geophysical, and geochemical surveys. Previously, mineral deposit models are applied to predict how and where mineral deposits might occur. Since large databases are generated in geochemical exploration, the main statistical techniques (univariate, bivariate, and multivariate methods) are commented in this heading. Finally, several exploration case studies are summarized to show the main items of mineral resource exploration.

3.1 Introduction

Mineral exploration can be defined as the process of analyzing an area of land to find mineral deposits (Fig. 3.1). Therefore, mineral exploration covers all the processes that reflect information about the presence of ore deposits. The information collected during exploration is utilized to evaluate the size and quality of an ore deposit and to establish there is an option for it to be mined. Metal prices mainly define exploration expenditures and, in the long run, by demand of metals. Where metal's demand peaks so does exploration expenditure. Most mineral exploration is carried out by companies with a capital base produced either from existing mineral production or from investors. The company size can vary from small venture capital companies (the so-called juniors) with one or two geologists to great multinational mining companies such as Glencore, BHP Billiton, Rio Tinto, Anglo American, or De Beers with operations on several continents (the so-called majors). A junior exploration company can be defined as a company that focuses solely on the exploration and discovery of mineral deposits and does not operate a mine (Stevens 2010). Although the mining industry includes about 6000 companies, the majority are the 4000–5000 junior exploration companies that do not have a mine in operation.

Junior companies, registered principally on stock exchanges in Canada, Australia, and London, carry out most of exploration, especially metals. They have made almost all of the major new discoveries in the past several decades. These junior do not present any cash flow and mainly depend on funding from the stock exchanges. On the opposite, the majors are those companies with annual revenue over USD 500 million and the financial strength to develop a new mine on their own (SNL Metals & Mining). They are often more selective in their choice of exploration properties. Where a junior company can be happy to discover a relatively small deposit, majors are interested in the world-class deposits that could be developed into a large mining operation. Although majors have the largest exploration budgets, they tend to be less successful than juniors at discovering new deposits. Some of the reasons for this include the following: (1) majors spend many of their exploration budgets drilling around deposits that have already been discovered with the aim of expanding the reserves; (2) majors become too focused on the search for large deposits and thus miss opportunities; and (3) majors buy into deposits or junior companies after the discovery has been made; they leave the high-risk discovery stage to the junior (Stevens 2010). The federal state government, Bureau of Mines, and geological surveys also participate in exploration. In general, the role of the geological surveys commonly includes some mineral exploration information to the government, and the private sector presented as a reconnaissance work.

The main features of the mineral exploration process can be summarized as follows:

1. It is a time-consuming process, ranging from 2 years up to 5 years or more.
2. It is also expensive (2 or 3 millions of dollars per year) and high-risk investment, unlike ordinary businesses investments.

Fig. 3.1 Electromagnetic survey in the field for mineral exploration (Image courtesy of Alrosa)

3. It is undertaken in various stages of investigation, each phase conditioned by the results of the previous step.
4. It starts at the broad scale and narrows down the work area to settle on a target or a set of targets.
5. The methods used vary in the different phases of the process, and this variation is defined by the size of the prospect as well as the type density of information needed.
6. Rarely results in a mine are being developed; the rate for finding new profitable mining operations commonly ranges from a high of 4% to less than 1% and even sometimes as low as 1‰.

Exploration field activities take place as part of strategies to locate and define a particular economically mineable mineral commodity in a mineral province. In this sense, the prospect could be an ancient mine, an outcrop including mineralization, an area elected based on geological items, or simply some anomalous feature of the environment such as a geophysical or geochemical result that can be interpreted as showing close spatial relation to a mineralization. Thus, mineral exploration companies usually classify exploration programs into two categories: greenfield or brownfield, a terminology originally used in construction and development. Greenfield exploration means unknown territories where ore deposits are not already known to be present (Fig. 3.2). On the contrary, brownfield exploration refers to prospecting in areas where mineral deposits were previously discovered. Obviously, the risk in brownfield exploration is considerably lower than in greenfield exploration because of the lack of geological information available in the latter.

Historically, discoveries have taken place in waves, after the introduction of new methods or advances in the understanding of ore genesis (Paterson 2003). For instance, discovery rates jumped sharply between 1950 and 1975, following the development of new methods and instruments in exploration geophysics and geochemistry.

Very often, the terms prospection and exploration are used in a misleading way. For some authors, exploration sounds similar to prospecting, but other authors consider prospecting simply as the search for ores or other valuable minerals (first stage) while exploration (second stage) estimates as faithfully as possible the size and value of an ore deposit, by using techniques very similar to but more intensive than those used in the previous phase of prospecting. Thus, the line to differentiate between prospecting and exploration usually is not possible. In this chapter, with the exception of the section devoted to mineral exploration stages, the terms prospection and exploration are used indistinctly to avoid problems of interpretation.

Fig. 3.2 Amulsar region (Armenia): example of a greenfield mineral exploration territory (epithermal-style gold mineralization) (Image courtesy of Lydian International)

The mineral deposits to explore now for the mining companies are mainly hidden by leached and weathered outcrops, with soil or other cover. For this reason, very sophisticated exploration techniques are actually needed to find them since most mineral deposits located at or near the Earth's surface have probably been discovered. As a general rule, the first stage of prospection/exploration involves locating prospective deposits using knowledge of ore genesis and occurrence models. Thus, geological environments associated with the wanted type of mineral deposit are target of investigation. Methods such as geological mapping and sampling, geophysical surveys, and geochemical analysis are commonly used at an early stage of exploration to define potential ore deposits. Thus, the goal of geophysical/geochemical exploration is to find an anomaly something different from the normal or expected; anomalies can indicate the presence of minerals and could be a target for drilling. An anomaly is a geological incongruity that has the possibility of being an ore deposit. Obviously, an anomaly does not necessarily imply a mineral deposit, but every mineral deposit was first an anomaly, that is, something out of the ordinary (Hartman and Mutmansky 2002). Where a mineral deposit has been identified, the next step is to map it more extensively to obtain a first evaluation of the grade and tonnage of the mineral deposit. The target is later drilled to study the mineralization in depth; drilling is undertaken only in advanced mineral exploration. In increasing order of cost per km^2, the main methods used in mineral exploration are remote sensing, geological mapping, geophysical surveys, geochemical surveys, and drilling.

Regarding the exploration trends in the world, mining companies reacted to the poor market conditions of the last years with a strong decrease in their exploration expenditures. The result was a 19% decline in worldwide nonferrous metal exploration budgets in 2015, compared with the previous year, with final investment of about USD 9.2 billion (SNL Metals &Mining). Figure 3.3 shows the main destinations for nonferrous exploration in 2015. Nonferrous exploration means to look for precious and base metals, uranium, diamonds, and several industrial minerals; it particularly precludes exploration for commodities such as iron ore, coal, aluminum, or oil and gas. Regarding allocation of exploration, «Latin America has been considered the leading region for mineral exploration by many companies for the past decade owing to its promising geology, its long history of world-class discoveries, the perception of its mineral policies and its successful historical record of mineral production and development» (Wilburn and Karl 2016).

Fig. 3.3 Top destinations for nonferrous exploration in 2015 (SNL Metals & Mining)

3.2 Mineral Resource Exploration Stages

It is quite difficult to define exactly the number of stages in mineral exploration processes since it depends of several factors such as the commodity to investigate, the region to explore, the overall costs of the different steps, and others. Up to five stages in mineral exploration, the so-called mineral exploration cycle, are usually found in literature: program design, reconnaissance exploration, detailed exploration, prospect evaluation, and preproduction. However, there is consensus that two main phases can be broadly outlined: reconnaissance exploration and detailed exploration (or prospecting and exploration). Commonly, prospecting is the very first stage in the search for mineral deposits, and permits tend to cover large areas in an attempt to see if mineral deposits are present, whereas exploration involves more detailed data gathering over smaller and specific areas. The complete sequence of mineral activity is carried out for only a very low number of mineral projects, being the initial stages abbreviated if the information acquired in those stages is already accessible to the mining company. Thus, a project can be quickly abandoned at any phase if the results obtained are not clearly hopeful. In other words, as commented above, very few discovered mineral deposits become producing mines.

The time required for exploration of a mining project depends on its size and location. The following time requirements can provide a broad approximation: (1) small deposits, from 2 to 4 years; (2) medium-sized deposits, from 4 to 6 years; and (3) large deposits, from 6 to 10 years of exploration. Actually, the process of mineral discovery and its development to production mine can take up to 25 years, because of the large size of the modern mines.

3.2.1 Program Design

At the program design step (generative stage or project generation, or simply planning stage), the management staff of the company, with considerable experience of exploration, defines the economic parameters for mineral targets.

Technicians, usually geologists and/or geophysicists, design the exploration program that promises the best results in the search for such target. According to Sillitoe (2000), the keystone to prospecting organization is to have the best forthcoming staff and appropriate finance in order to generate confidence throughout the organization. The economic parameters vary widely depending on the expected exploration and development of the type of mineral deposit sought and on the economic factors and mine life. The conduct of a good prospecting program is aimed at the discovery of a maximum number of mineral deposits at minimum cost. In this searching process, geologists decide the types of deposits to explore and which geological and exploration models should be applied. Previously, the management staff chooses the commodity or commodities.

The intensive use of mineral deposit models is a defining feature at this stage. This is because the first step in a new program is to acquire information about the study areas to be investigated. Thus, favorable regions are selected, either on the basis of known potential as expressed by existing mines or mineral occurrences or on the basis of general knowledge of their geological characteristics. In summary, the area to be explored is identified based on literature search, looking at history, reports and maps, and thesis works, among many others; these are called desktop studies. At the end of this stage, exploration procedures are recommended to the management by the geological staff, and a time schedule and general budget are established. Regarding the exploration costs, the exploration manager commonly considers them as an expenditure within an organization while it is as a geologist on a specific exploration project that one becomes involved in the exploration costs within the context of the project (Moon and Whateley 2006). Prospection can be commodity- or site-specific. In other words, the search can be limited to a particular mineral or metal or to a particular geographic area.

3.2.2 Reconnaissance Exploration

Since a prospect has been identified, a progressive series of definable exploration stages can be carried out. As a rule, positive results in any stage of exploration will originate an advance to the next stage and an increase of the exploration effort. On the contrary, negative results reveal that the prospect will be commonly abandoned, although further follow-up is possible if the economic conditions have changed. The first stage of mineral exploration is the reconnaissance exploration, although it can be named also in a variety of ways: simply prospection, target identification, early and extended reconnaissance, and many others. In turn, it typically includes two steps: regional appraisal and reconnaissance of region. The main goal of the process is to identify an ore deposit that can be the target for subsequent exploration; the quantities estimated for the deposits are with a low level of confidence, and these estimates are inferred, that is, based on interpretation of geological, geophysical, and geochemical results.

Reconnaissance exploration aims at rapid and low-cost sorting out of prospective parts of an area. Regions ranging from 2000 to 200,000 km^2 are evaluated with an analysis of accessible information, and parts of a region that cover 100–5000 km^2 are studied through field examination, spaced geochemical sampling with wide grids, and geophysical exploration. In this sense, an invaluable information to surface regional geology is that obtained with regional geophysics. Airborne magnetic, radiometric, and regional gravity data are available in a great part of the developed world (Fig. 3.4), and these techniques lead to refining geological interpretation. Regional geochemical surveys also provide much information in areas of poor outcrop.

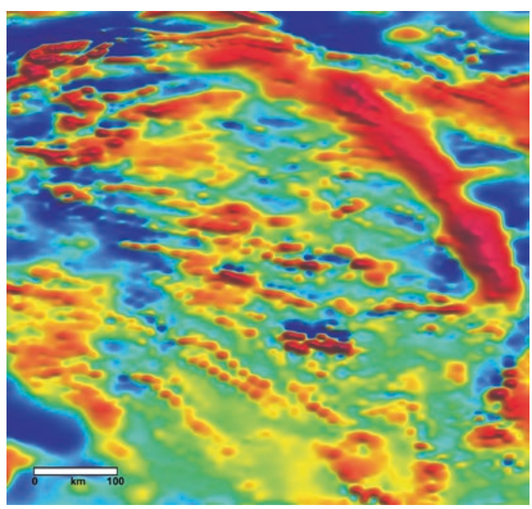


Fig. 3.4 Regional magnetic map in mainland Europe (Image courtesy of Getech)

The results are brought together on maps on 1:50,000 to 1:25,000 or smaller scale. They are geologically analyzed in view of the characteristics of known occurrences of the type of ore deposit being explored. The next step deals with selection of smaller target areas for detailed investigation. In general, the targets are not clearly defined until the first stage has been accomplished: in fact, target identification is the main goal of reconnaissance exploration. It can cost from several thousand to one million or more USD, commonly spending from a several months to 2 or 3 years to complete. Once field studies such as rock and soil sampling have been carried out, the results will be collected and models for the mineralization will be created using specialized computer software.

In the first phase of reconnaissance exploration (regional appraisal), the following procedures are usually performed:

1. Review of all information on the target such as government geological information as well as geophysical and geochemical surveys in the area, the results of previous exploration data and the known occurrence of minerals, and other previous bibliographies
2. Photogeological study of available air photographs
3. Study of accessible remote-sensing information
4. Air and ground field inspection
5. Petrographic and mineralogical studies to determine main rock types, mineral assemblages, and identification of minerals of interest

In the second phase of reconnaissance exploration (reconnaissance of region), techniques are:

1. Geological mapping and sampling
2. Geochemical surveys and indicator mineral studies
3. Geophysical surveys, airborne or ground
4. Shallow pattern drilling for regolith or bedrock geochemistry, including geophysical borehole logging and drilling aimed at increasing geological knowledge
5. Field inspection of outcrops and anomalous areas
6. Petrographic and mineralogical studies, including study of host rock of the deposits and alteration zone, mineralogical studies (ore microscopy, X-ray diffraction, among others), identification of oxidized and primary zones, etc.

3.2.3 Detailed Exploration

If the goal of the previous stage is to locate anomalies due to the presence of a mineral deposit, the objective of detailed exploration is to define and evaluate this deposit in detail. The exploration will focus to determine the geological setting, depth, geometry, grade, tonnage, extent, and worth of the ore deposit identified. Similar techniques than those applied in reconnaissance exploration will be used though in a more comprehensively manner over a much smaller area. Exploration culminates in preparation of a pre-feasibility study that either accepts or rejects the deposit for further consideration. Detailed exploration is restricted to relatively small areas and is intensive and expensive, especially where drilling is carried out. For this reason, it is essential to protect the investment and potential revenue from the prospect by obtaining exclusive exploration or mining rights and to enter in negotiations with owners of surface property in preparation for later mine development (Gocht et al. 1988).

In the final stage of exploration, the target that ranges initially from 2 to 25 or more km^2 is investigated through detailed field inspections, geochemical sampling, and ground and airborne geophysical surveys. It generally begins with establishing a regular grid on interesting areas serving as a base for more detailed geochemical and geophysical studies as well as geological mapping, generally undertaken at 1:10,000 to 1:2500 scales. In this step, it is common to carry out limited trenching, drilling, and systematic sampling as a guideline to developing geological conceptions. In this way, the target is later reduced to a smaller one ranging from 1 to several km^2 for further drilling to establish if the hypothetical valuable mineral deposit really is present. It is clear that investigating if a discovery displays a sufficient size and quality inevitably includes a subsurface investigation. In this case, the geologist usually faces the task of generating a target for drilling. This stage can cost from several tens of thousands to tens of millions of USD, and they will usually take 1 to several years to complete, assuming that there are not disrupts. Once the existence of a valuable ore deposit is determined, perhaps 1 or 2 years after the initial discovery of economic ore, the exploration is considered finished and at that moment the development process of the mine begins.

Classical techniques for this stage are comprehensive geological mapping and sampling; detailed geochemical surveys, with an elaborated grid pattern sampling and analysis; detailed geophysical surveys, usually on the ground; drilling, logging, trenching, and geophysical survey in the holes; and bulk sampling. Drilling involves various types, initially with a relatively wide spacing of holes. In areas of poor outcropping, trenching or pitting is essential (◘ Fig. 3.5) to verify the bedrock source of a geological, geochemical, or geophysical anomaly. Once the samples have been obtained, they must be sent to a laboratory for their analysis (◘ Fig. 3.6). Cost should not be the main factor to select the laboratory. For this decision, accuracy, precision, and an effective proceeding are also requested (Moon and Whateley 2006). Before samples are submitted to the laboratory, it must be ensured that all the elements that can be associated with the explored ore deposit are incorporated in the analysis and very important that this analysis comprises possible pathfinder elements.

The further decision to carry out a feasibility study can be obtained from the information

◘ **Fig. 3.5** Trenching in progress (Image courtesy of Petropavlovsk)

◘ **Fig. 3.6** Preparing samples for analysis in the laboratory (Image courtesy of Anglo American plc.)

provided by detailed exploration, since resource/reserve estimations for the deposits are with a high level of confidence. This is probably the most critical stage of exploration because decisions involving high costs and potential costs have to be made in view of the results. If a decision is taken that a potential ore deposit has been delineated, the costs of subsequent exploration will drastically increase, usually at the expense of other prospects. At this stage, it is essential to consider that if it is decided to make the decision to close prospection of a mineral deposit after this stage, there is always the option that an ore body has been lost (Marjoribanks 2010).

3.2.4 Pre-feasibility/Feasibility Study

The final step in mineral exploration process is the preliminary feasibility study that analyzes all components (geological, mining, environmental, sociopolitical, and economical) relevant to the determination to develop a mine. In very large projects, the costs involved in evaluation are high so that a pre-feasibility study is almost always carried out during the previous step. Thus, the main goal of this type of study is to assess the various possibilities and possible combinations of technical and business issues, to evaluate the project sensitivity to changes in the individual parameters, and to rank various scenarios prior to selecting the most likely for further and more accurate study. Upon completion of a pre-feasibility study, geological confidence is such that it should be possible to publicly declare ore reserves (from measured and indicated resources) (Table 3.1) and any other mineral resources that can become mineable in the future with further study (Scott and Whateley 2006). The results of the pre-feasibility study determine whether the increasingly large expense derived from full geological, technical, and economic evaluation of a prospect is justified. In other words, this study will detect if the costs involved in exploration are suitable for the earnings that logically can be expected.

The feasibility study is the final evaluation of the profitability of a mining venture in light of the results of exhaustive geological exploration; assessment of mining and processing cost; environmental factors, including mine reclamation; and market

Table 3.1 Example of mineral resource and reserve data presented in a pre-feasibility study of a mining project

Mineral resource table

Category	Tonnage (million tonnes)	Cu Grade (%)	Au Grade (g/t)	Ag Grade (g/t)	Contained Cu (billion pounds)	Contained Au (million ounces)	Contained Ag (million ounces)
Measured	39.5	0.25	0.39	2.58	0.22	0.50	3.27
Indicated	247.2	0.34	0.26	3.81	1.85	2.04	30.26
Total measured and indicated	286.7	0.33	0.27	3.64	2.07	2.53	33.54
Inferred	346.6	0.42	0.24	4.28	3.23	2.70	47.73

Mineral reserve table

	Tonnes (Mt)	Diluted grade			Contained Cu (billion pounds)	Contained Au (million ounces)	Contained Ag (million ounces)
		Cu (%)	Au (g/t)	Ag (g/t)			
Proven probable	69.0	0.606	0.520	4.94	0.9	1.15	11.0
Probable	459.1	0.582	0.291	6.18	5.9	4.30	91.2
Total proven and probable	*528.0*	*0.585*	*0.321*	*6.02*	*6.8*	*5.45*	*102.1*

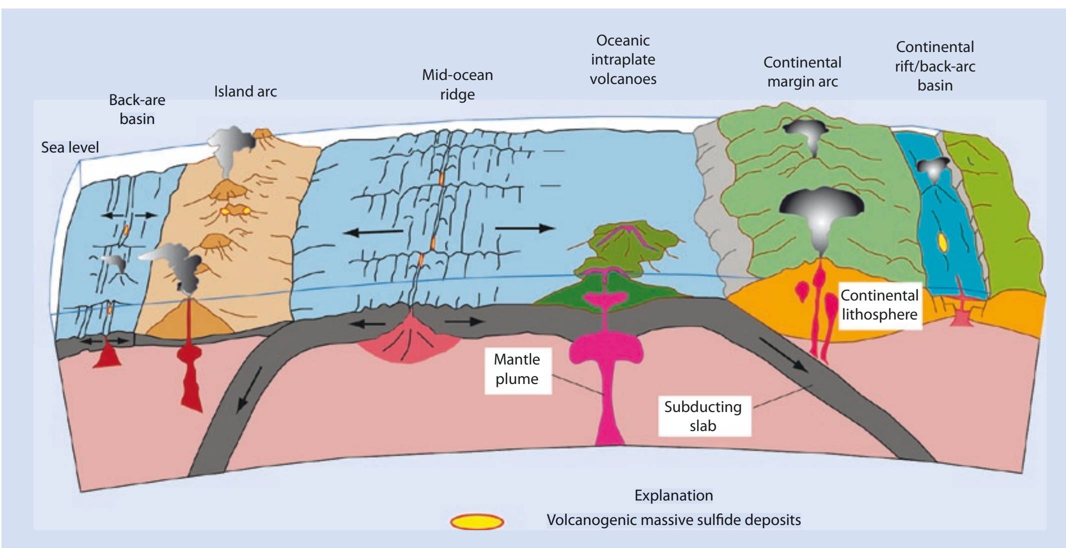
analysis. This study usually forms the basis for the «go/no go» decision on developing a mine (Gocht et al. 1988), that is, it is the basis for an investment decision or decision to proceed to the next stage of development. Obviously, feasibility studies are of higher level of rigor than pre-feasibility studies. Thus, in feasibility studies, social, environmental, and governmental approvals, permits, and agreements, commenced during the pre-feasibility study, will be in place or will be approaching finalization.

A feasibility study incorporates all types of detailed information obtained in previous stages of mineral exploration such as geology, mining, environmental, infrastructure and service, financial data, marketing, economic viability, and many other factors. Moreover, sufficient sample collection and test work have taken place during a feasibility study for more of the resource estimate to be reported in the measured category. Several million dollars are commonly spent in large projects, to bring the project to feasibility study level and sensitivity analyses. They will have been established to analyze the main factors that can have a definitive impact upon the reserve estimation. This will help to calculate the risk associated with the reserve data, which at this stage will enter within the acceptable risk category of the company. It is very common that financial institutes utilize independent consultants to audit the resource and reserve estimations.

3.3 Mineral Deposit Models

To predict and have a better knowledge of how and where an ore deposits can be present, scientists developed mineral deposit models (◘ Fig. 3.7). A working definition of «model» in the context of mineral deposits is «the systematically arranged information describing the essential attributes (properties) of a class of mineral deposits» (Cox and Singer 1986). Models are very useful to organize the information about a mineral deposit because they are simplifications and abstractions based on a large number of individual observations. As such, they need refinement as new data are acquired and have to be set as exploration is carried out. In fact, it is very difficult to find a paper in the contemporary literature on economic geology of a mineral deposit that does not utilize the expression «mineral deposit model.»

Mineral deposit models are developed from the information of a particular important deposit or the combined information of several equivalent deposits. Thus, the grouping of deposits based on common characteristics forms the basis for a classification, but the specification of the features needed for being included in the group is the basis for a model (Barton 1993). Consequently, models contain an element of prediction, particularly where certain physical attributes are characteristic



◘ **Fig. 3.7** Model showing volcanogenic massive sulfide deposits in different tectonic settings (Schulz 2012) of ores of a well-defined deposit type. Models try to be constructed as much as possible «independent of site-specific attributes and therefore contain only those features that are transferable from one deposit to another; this goal is difficult to attain, because it is not always known which features are site-specific» (Cox and Singer 1986).

According the definition of a mineral deposit model, it can aid in identifying areas favorable for finding valuable deposits since they describe all of the essential features of a selected group of mineral deposits (Singer 1995). Obviously, there are a great number of mineral deposit models, new models being created as new types of deposits are identified. The scale of the models can vary from regional size (regional-scale models are constructed through metallogenic studies) to smaller local ore bodies, or even refer to some highlighted part of an ore body.

The application of a particular deposit model will depend on the quality of the database. Some deposit types (e.g., placer gold) are easy to understand and supported by well-developed models while other deposits such as the Olympic Dam mineral deposit model are not still well established and can be represented only by a single deposit. In these cases, the information about the deposit is very difficult to obtain. Thus, the models should be used with caution and with understanding of their limitations. The current trend in exploration and mineral deposit modeling is to incorporate every possible component of individual metal deposits in a database and carry out correlative analyses using computers. This approach is simply a continuation of the mindset that created the descriptive model and the availability of a new tool: the computer. Nonetheless, this model is in reality a simulation, with its inherent case-specific limitations, and as well can give misleading results with limited utility for an emergent phenomenon (Robinson 2007).

The geological surveys of Canada and the USA have originated the vast majority of mineral deposit models as well as a great number of publications describing various mineral deposit types. They are the main source to obtain a complete information about the topic. Interactions between the constructors of published models and the explorationists who use them are critical to the evolution of more accurate and useable models. In this regard, the deposits that cannot be classified or the data that cannot be explained by a previous existing model are commonly those that originate an advance in the knowledge of ore-forming processes.

However, some pitfalls in the utilization of mineral deposit models have been frequently developed. Thus, Hodgson (1990) suggests up to a total of five different pitfalls in the making and using of models all related to corporate or institutional cults and affect industry, academic, and government institutions to an equal extent:

1. The cult of the fad or fashion: an obsession with being up to date and in possession of the newest model.
2. The cult of the panacea: the attitude that one model is the ultimate and will end all controversy.
3. The cult of the classicists: all new ideas are rejected as they have been generated in the hot house research environment.
4. The cult of the corporate iconoclasts: only models generated within an organization are valid; all outside models are wrong.
5. The cult of the specialist: in which only one aspect of the model is tested and usually not in the field.

3.3.1 Types of Models

A subdivision of mineral deposit models into various subtypes can be proposed (Cox and Singer 1986). These are dependent on the attributes used in their definition and on the specific fields of application the modeler has in mind (e.g., applications such as exploration/development, supply potential, land use, education, and research guidance). The following subtypes are proposed (Cox and Singer 1986): (1) descriptive models, (2) occurrence models, (3) grade and tonnage models, (4) occurrence probability models, (5) quantitative process models, and (6) genetic models. The first three are empirical or descriptive models and the last three are conceptual or genetic models. Previously, three basic model types, descriptive, grade and tonnage models, and genetic models, were considered. Basically, the model can be empirical (descriptive), in which several attributes are considered essential, or it can be theoretical (genetic). In the latter, the attributes are interrelated using some fundamental concepts.

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Thus, the empirical or descriptive model is based on deposit descriptions, and the genetic model explains deposits in terms of causative geological processes.

Another model type that is very useful for initial economic analyses is the so-called grade and tonnage model. This type of model displays grade and tonnage data for known deposits, being possible from this information to assess the average size and grade of a mineral deposit and the cash-flow if one was met (Evans and Moon 2006). Ideally, mineral deposit types should reflect how the mineral deposit was actually formed. In many cases, there is considerable debate among geologists as to how a specific deposit was formed, and thus classifications based purely on a given genetic model will encounter problems.

Descriptive Models

The classification of mineral deposits based on empirical features will lead to the unique fingerprint of a particular deposit (Herrington 2011). Thus, descriptive models derive from the documentation of the geological, geochemical, and geophysical characteristics of individual mineral deposits. Of the various kinds of mineral deposit models, well-documented descriptive models are of the most direct use in mineral exploration or resource assessment. A descriptive model can be constructed from a single deposit but more commonly includes the essential common information of a group of related deposits. The attributes or properties of a mineral occurrence are, of course, those features exhibited by the occurrence.

Attributes can be considered on at least two scales: the first deals with local characteristics that can be obtained immediately in the field (mineralogy, local chemical halos, among many others), whereas the second incorporates features related to the regional geological setting and that must be interpreted from the local studies or can be inferred from global tectonic considerations. For instance, «the rock sequence under study represents a deep-water, back-arc rift environment, or the area is underlain by anomalously radioactive high-silica rhyolite and granite» (Cox and Singer 1986).

Grade and Tonnage Models

Grade and tonnage models had a profound influence on the creation of mineral deposit models. The idea of relating grade and tonnage data appears to have originated long time ago (e.g., Lasky 1950). Grade and tonnage models of ore deposits are very helpful for quantitative resource estimations as well as to schedule an exploration program. They are useful to classify the known deposits in a region and provide information about the potential value of undiscovered deposits in the exploration area. Thus, the frequency distributions of average grades and tonnages of deposits of various types are calculated and displayed graphically. In a limited area showing favorable geological features, grade or tonnage frequency distribution curves are used to estimate the amount of metal that possibly exists in the area (Box 3.1: Grade and Tonnage Models for Podiform Chromite Deposits).

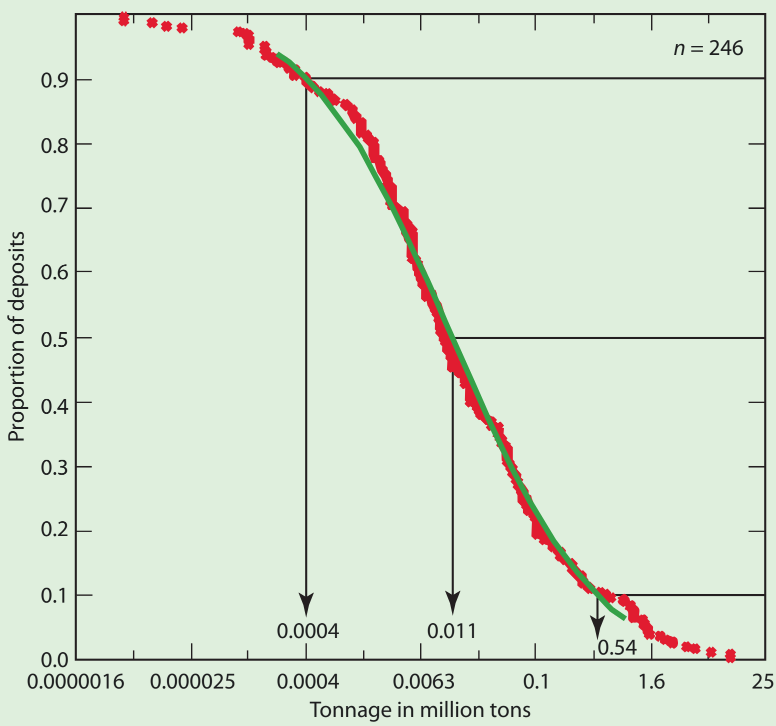
Box 3.1

Grade and Tonnage Models for Podiform Chromite Deposits

Construction of grade and tonnage models for podiform chromite deposits involves multiple steps. The first step is the identification of a group of well-explored deposits that are believed to belong to the mineral deposit type being modeled (Mosier et al. 2012). «Well explored» means completely drilled in three dimensions. After deposits are identified, data from each are compiled. These data consist of average grades of each metal or mineral commodity of possible economic interest and tonnages based on the total production, reserves, and resources at the lowest available cutoff grade. Thus, the grade and tonnage models are the frequency distributions of ore tonnage and grades of Cr_2O_3, ruthenium (Ru), iridium (Ir), rhodium (Rh), palladium (Pd), and platinum (Pt) for the podiform chromite types. The three subtypes of podiform chromite deposits modeled are major podiform chromite, minor podiform chromite, and banded podiform chromite. Percentiles of metal grades from incomplete data sets, such as Ru, Ir, Rh, Pd, and Pt, are based on the observed distributions and are represented by the smoothed curves on the grade plots. Chromic oxide grades for the major and minor podiform subtypes are each significantly different from the normal distribution at the 1% significance level. Only the chromic oxide grades for the banded podiform chromite are not significantly different from the normal distribution at the 1% significance level. In most cases, the departures of the grades from normality appear to be typical for grades greater than 10% in other deposit types.

The reporting of very low grades may be influenced by favorable economics or technology in processing low-grade ores and may indicate regional differences that allow lower cutoff grades. Because these are at the low-grade tail of the distributions and represent a small number of deposits, they may not be important for modeling purposes. For this analysis, grades lower than 30% chromic oxide are excluded. Reports of very high grades may be from deposits where hand sorting of ore was an important processing practice. For metallurgical ores, grades less than 45% chromic oxide are usually rejected at the mills and a Cr to Fe ratio of 3:1 is preferred. For refractory ores, coarser chromite is preferred, and chromic oxide grades can be low as long as the alumina content combines to form at least 60% of the ore. For chemical ores, the chromite must be fine grained, and the chromic oxide grades can be very low as long as there is enough to make chromium salts at a feasible rate. Such a range of chromic oxide grades can contribute to multiple peaks or skewness in the data set.

If there were no differences in grades or tonnages among deposit types, it could be used one model for all types. However, differences in tonnages or grades among the subtypes suggest they should be represented by different models. For example, the deposits associated with major podiform chromite are significantly larger than those associated with minor podiform chromite and banded podiform chromite, and banded podiform chromite deposits are significantly larger than minor podiform chromite deposits.
Frequency distributions of the tonnages and grades of chromic oxide, rhodium, iridium, ruthenium, palladium, and platinum in the three subtypes of podiform chromite deposits can be used as models of the grades and tonnages of undiscovered deposits. Some examples of these frequencies are plotted in ◘ Figs. 3.8 and 3.9. Grade and tonnage models are presented in a graphical format to make it easy to compare deposit types and to display the data. The grade and tonnage plots show the cumulative proportion of deposits versus the tonnage or grade of the deposits. Individual symbols represent the deposits, and intercepts for the 90th, 50th, and 10th percentiles are plotted. Percentiles of grades and tonnages are based on the observed distributions. Relations among grade and tonnage variables are important for simulations of grades, tonnages, and estimated number of undiscovered deposits. These relations also affect the understanding of how deposits form and the assumptions about resource availability. Correlation tests among the variables reveal the relations of grades and tonnage. In general, most of the variables show no relation to each other.



◘ **Fig. 3.8** Cumulative frequency of ore tonnages of major podiform chromite deposits. Each red dot represents an individual deposit (*n* is the total number of deposits). Intercepts for the 90th, 50th, and 10th percentiles of the lognormal distribution are provided. The smoothed green curve represents the percentiles of the data points (Mosier et al. 2012)

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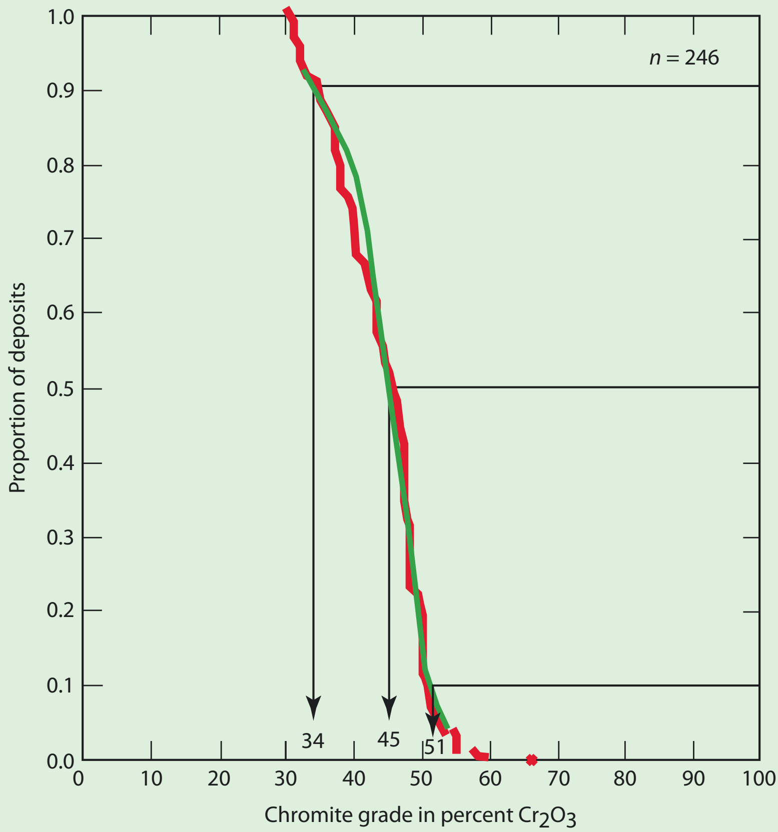


Fig. 3.9 Cumulative frequency of chromic oxide grades of major podiform chromite deposits. Each red dot represents an individual deposit (*n* is the total number of deposits). Intercepts for the 90th, 50th, and 10th percentiles of the normal distribution are provided. The smoothed green curve represents the percentiles of the data points (Mosier et al. 2012)

The mineral deposit density area is a variation of the grade and tonnage model. Deposit density modeling can be used to produce a quantitative mineral resource assessment by estimating the number of undiscovered deposits (Singer et al. 2001). In this type of model, the grade and tonnage model is carried out, and then the number of deposits per unit area is determined for a specific deposit type from a well-explored region. The process originates a frequency distribution that is utilized either directly for an estimate of the resources in a mineral deposit or indirectly as a guideline in some other method.

Genetic Models

Although correct documentation of descriptive models is of the most direct utilization to the exploration geologist, it is almost impossible to develop an adequate descriptive model in the absence of a good genetic one. Similarly, the generation of genetic models depends upon an understanding of the physics and chemistry of ore-forming processes. Therefore, the developing of a mineral deposit model is an iterative process (Duke 1990). Genetic models are more powerful than descriptive models because they provide a basis to distinguish essential from extraneous attributes. In general, the information of a descriptive model is a necessary precondition to create a genetic model.

Genetic models describe the origin of a deposit or deposit type and represent the combination of a descriptive model with one or more process models. Process models simulate physical and chemical ore-forming processes (Fig. 3.10), and they are generic as much as they can apply to a variety of deposit types. In this sense, Duke (1990) affirms that «the geologist engaged in mineral exploration and the government geologist carrying out a mineral-resource assessment combine descriptive deposit models with understanding of the regional geological framework to develop

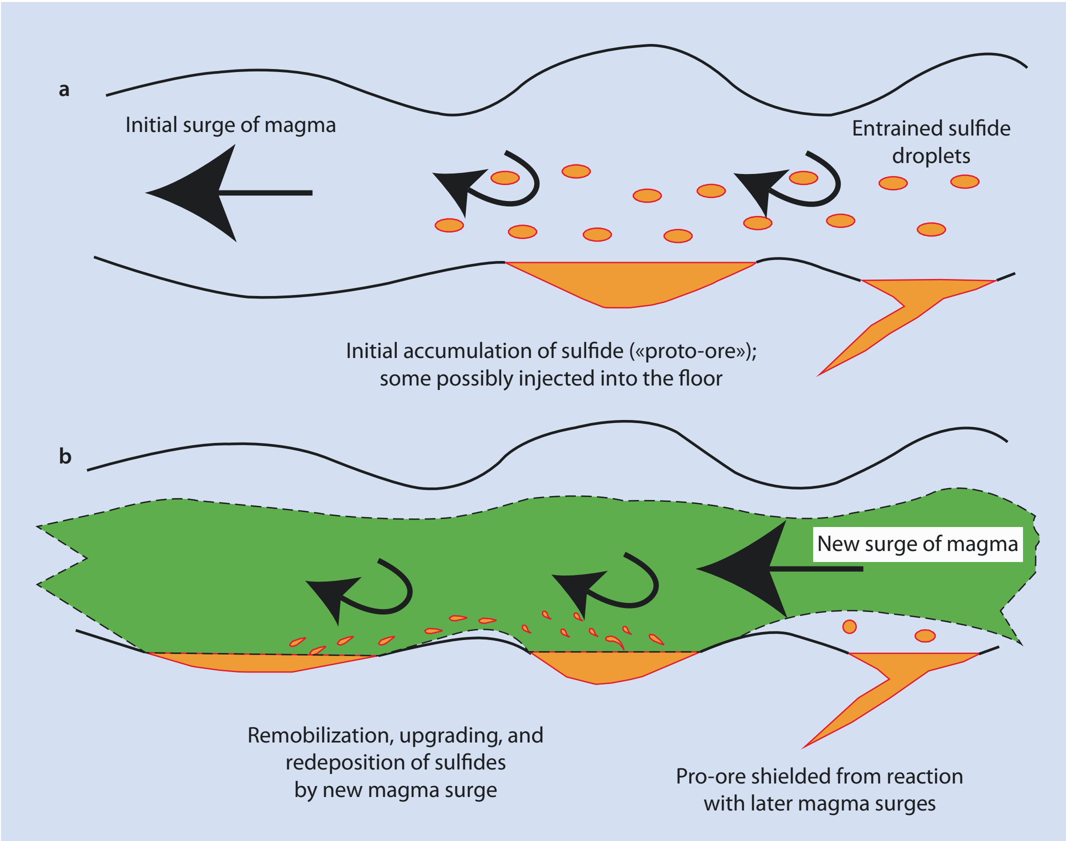


Fig. 3.10 Illustration of the continued flow of magma through an idealized magma conduit (process model) in magmatic sulfide-rich nickel-copper-(platinum-group element) deposits (Schulz et al. 2014)

exploration or resource-potential models.» Even though there are not two mineral deposits identical, empirical descriptions of deposits tend to show natural groupings into a small number of definable categories or types. In turn, these categories tend to coincide with genetically derived models. Therefore, even by using purely physically descriptive classifications, there is often a close coincidence between these and models defined using genetic criteria (Herrington 2011). Descriptive models evolve into genetic models, and as such they become far more flexible and powerful. In fact, there is an iterative relationship among descriptive, genetic, and grade/tonnage models. The consequence of examining these three is that they constituted a linear logical sequence leading toward the «final» model.

One factor favoring the genetic model over the simply descriptive is the great amount of descriptive information needed to represent the many features of complex deposits. If all such information were to be included, the number of models would reach the total number of individual deposits considered. As a consequence, the compilers must use the genetic concepts at their disposal to distinguish the critical from the incidental attributes (Cox and Singer 1986). From both the empirical and the genetic models, the exploration geologist assembles an exploration model, which is a set of recognition criteria for exploration. Some of these criteria are diagnostic for the presence or absence of an ore deposit while others are permissive. The criteria chosen should be as diagnostic as possible and should be both cost- and time-effective (Gocht et al. 1988).

Other Types of Models

In general, because of the previous models, two more model types can be originated: occurrence probability models and quantitative process models. The former are models that predict the probability of a deposit, size, and grade indicated by the appropriate grade and tonnage models, occurring within a given area. The latter are models that describe quantitatively some process related to ore deposit formation, being in fact only branches of the genetic model. All these models can be parts of the «final» model, and recycling of the model back to the early grouping phase assists in refining the selection procedure (Cox and Singer 1986).

Other types of models have also been described by different authors and applied to mineral deposits: cause-effect models (Knox-Robinson 2000; Sirotinskaya 2004), fractal and multifractal models (Mandelbrot 1983), fluid flow-stress mapping models (Heinrich et al. 1996), statistical/probabilistic models (Agterberg 1974), structural models (Kutina 1969), and spatial-temporal models (Ludington et al. 1993). As an example, probabilistic regression models have been especially attractive and useful to mineral resource exploration. In this model, an area of concern is splitted into a grid of square cells, and the presence or absence of the various predictive attributes (e.g., different lithologies, hydrothermal alteration, geophysical or geochemical anomalism) is expressed for each cell, in the form of magnitude, counts or occurrences, or percentage area occupied.

Geoenvironmental Models

Geoenvironmental models are specific because they are designed as natural extensions of mineral deposit models. A geoenvironmental model of a mineral deposit can be defined as «a compilation of geological, geochemical, geophysical, hydrologic, and engineering information pertaining to the environmental behavior of geologically similar mineral deposits prior to mining» (Plumlee and Nash 1995). Thus, the model offers information about natural geochemical variations associated with a particular deposit type and geochemical variations associated with its mining effluents, wastes, and mineral processing facilities, including smelters. Such information should prove beneficial to (1) environmental scientists interested in mitigating potential environmental problems associated with proposed mines; (2) environmental scientists interested in remediating existing problems at abandoned mine sites; (3) land-use planners that are involved in permitting proposed mines or reclaiming abandoned mine lands; and (4) industry interested in mine planning and mineral exploration (Seal et al. 2002).

3.3.2 Maturity of Descriptive-Genetic Models

The current level of genetic knowledge varies considerably from one deposit type to another. For example, placers and evaporites are genetically well-known types of deposits, and the problems in their exploration concern mainly local site-specific geological problems rather than mineral genesis. In contrast, deposits such as the Coeur d'Alene Ag-Pb-Zn veins remain genetic enigmas despite extensive research for a long time. Other deposits are geologically well understood regarding their origin but still very poorly understood in terms of the reasons for their existing at any particular site. Thus, the rate of acquisition of information is very irregular. The several scarps between plateaus in the knowledge curve for some mineral deposit models might mark, successively, the recognition of very important aspects related to the genesis of the deposit, while plateaus denote periods of absence of new knowledge. For instance, «a scarp in the Mississippi Valley-type ores might involve recognition, from fluid-inclusion evidence, that the ores were deposited from warm, about 100 °C, highly saline solutions that could represent neither simple surface nor marine waters» (Cox and Singer 1986).

Moreover, some aspects of any model always remain to be determined and the model never reaches a definitive format. Indeed, «the approach to complete understanding is asymptotic, and a lot of additional effort to clear up the last uncertainty in a nearly perfect model is probably unwarranted» (Cox and Singer 1986). However, new ideas and new technologies can provide the impetus for new improvements in knowledge for until now incomplete models. Obviously, different deposit types can require different amounts of effort to achieve a similar level of genetic understanding.

3.4 Exploration Methods

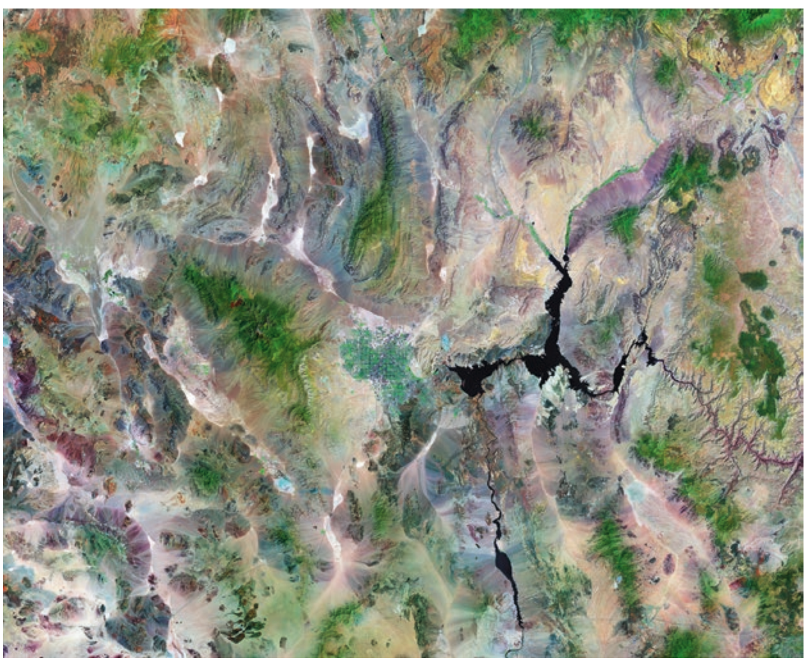
The geological, geophysical, and geochemical methods applied at different stages of mineral resource exploration are described in the next sections. The methods are organized in order of scale and stage, from remote sensing to drilling, through photogeology, geophysical, and geochemical surveys.

3.4.1 Remote Sensing

Remote sensing is the characterization of the surface of the Earth based on measurements of its reflected or emitted electromagnetic radiation in wavelengths from 0.3 to 3 m, being satellites the main observation platforms. These wavelengths cover the range from the ultraviolet to the microwave radar spectrum although a great number of measurements are made in the visible range by passive methods, in which the reflected natural radiation is estimated. Remote sensing lead to the recognition of major regional topographic features and geologic relationships and helping in the discovering of regions with mineral potential. Since remote sensing was forthcoming since the late 1970s, the data from land observation satellites have supplied a powerful tool for the exploration of mineral resources. Moreover, satellite imagery (◘ Fig. 3.11) investigates the geological characteristics of remote areas of the surface of the Earth without the requirement to access the region on the ground. Thus, remote sensing is providing information on mineral deposit exploration targets without being in contact with the objects.

Remote sensing can highlight ore bodies and their respective mineralization or alteration signatures as well as associated other features such as lineaments and faults. For instance, this method originates strong signals where gossans associated with hydrothermal alteration and oxidation of porphyry deposits are present. Another example would be the discovery of fractures and faults in volcanic regions with veins of precious metals. On the other hand, the interpretation of satellite imagery can originate very useful models before the start of geophysical investigations. In turn, geological and geophysical data can gage models obtained from this technique.

The resolution of remote sensing is restricted by the resolution of the imagery. According to this



◘ **Fig. 3.11** Satellite image (Landsat) used in mineral exploration (pixel = 14.5 m × 14.5 m) factor, satellites can be classified into three main categories: (1) VHR (very high resolution), sub-meter pixels; (2) HR (high resolution), 2.5–10 m pixels; and (3) MR (mid resolution), greater than 10 m pixels. An image with 50 m resolution would start to pixelate at scales larger (more detailed) than 1:100,000. By contrast, a very high-resolution (VHR) satellite scene with a 50 cm resolution could be viewed at scales to 1:2500 before pixelation became apparent. Mid resolution data can be used for the initial, broad-scale study, to derive, locate, and designate smaller areas of interest, while higher-resolution data are utilized for subsequent analyses.

In contrast to electrical, magnetic, and gravity methods that compute force fields, remote-sensing technique is usually referred to methods that use the electromagnetic energy as radio waves, light, and heat as the means of finding and measuring target features. In the context of geological mapping, electromagnetic methods can be classified as (1) passive optical methods (utilize the sunlight as the source and estimate the reflectance of the surface of the Earth in the visible and infrared spectral bands) (e.g., Landsat 7 ETM+ and the ASTER instrument from the Terra satellite) and (2) active microwave radar methods (use a microwave source onboard of the satellite and calculate the backscatter from the Earth) (e.g., Radarsat-1 and the radar sensor from the Shuttle Radar Tomographic Mission [SRTM]). For its part, infrared imagery is divided into three classes: (1) very near infrared, which detects particularly vegetation; (2) short wave infrared, the best possibility to discriminate sedimentary rocks; and (3) thermal infrared, utilized to discriminate dark materials such as non-sedimentary rocks (Laake 2011). The most famous satellite used in geological studies is Landsat (Box 3.2: Landsat Program).

Box 3.2

Landsat Program

The Landsat program is a series of Earth-observing satellite missions jointly managed by NASA and the US Geological Survey. In the mid-1960s, stimulated by the USA's successes in planetary exploration using unmanned remote-sensing satellites, the Department of the Interior, NASA, and the Department of Agriculture embarked on an ambitious effort to develop and launch the first civilian Earth observation satellite. Their goal was achieved on July 23, 1972, with the launch of Landsat 1, originally named «ERTS» for Earth Resources Technology Satellite. Thus, the Landsat program, a joint effort of the US Geological Survey (USGS) and the National Aeronautics and Space Administration (NASA), was established to routinely gather land imagery from space. NASA develops the remote-sensing instruments and spacecraft, then launches and validates the performance of the instruments and satellites. The USGS then assumes ownership and operation of the satellites, in addition to managing all ground reception, data archiving, product generation, and distribution. Since 1972, Landsat satellites have continuously acquired space-based images of the Earth's land surface, coastal shallows, and coral reefs. Landsat satellites image the Earth's surface along the satellite's ground track in a 185 km-wide swath as the satellite moves in a descending orbit (moving from north to south) over the sunlit side of the Earth. Landsat 7 and Landsat 8 orbit the Earth at 705 km altitude. They each make a complete orbit every 99 min, complete about 14 full orbits each day, and cross every point on Earth once every 16 days.

For most geologists and other Earth scientists, multispectral imagery is synonymous with NASA's Landsat series. The primary sensor onboard Landsats 1, 2, and 3 was the Multispectral Scanner (MSS), with an image resolution of approximately 80 m in four spectral bands ranging from the visible green to the near-infrared (IR) wavelengths. In July 1982, the launch of Landsat 4 saw the inclusion of the Thematic Mapper (TM) sensor with a 30 m resolution and 7 spectral bands. Although the Landsat series was designed initially to provide multispectral imagery for the study of renewable and nonrenewable resources, geologists immediately recognized the geological potential of the Landsat images, and the bands 5 and 7 in the TM were chosen specifically for their geological applicability. The approximate scene size of TM images is 170 km north-south by 183 km east-west, and the radiance measured by the Landsat sensor is a measure of the integration of soil, rock, and vegetation characteristics. Landsat 7 carries the Enhanced Thematic Mapper Plus (ETM+), with 30 m visible, near-IR, and SWIR bands, a 60 m thermal band, and a 15 m panchromatic band. Landsat 8 is the latest satellite (2013) in this series (Fig. 3.12) and operates in a near-circular, near-polar, sun-synchronous orbit with a 705 km altitude at the equator. It carries two push-broom sensors: the Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS), both of which provide improved signal to noise ratio and 12-bit radiometric quantization of the data.

The use of satellite imagery is now a standard technique in mineral exploration, and Landsat imagery has been used to provide basic geological maps, to detect hydrothermal alteration associated with mineral deposits, and to produce maps of regional and local fracture patterns, which can have controlled mineralization or hydrocarbon accumulations. For instance, TM band 7 (reflected IR) of Landsat satellite, with wavelengths between 2.08 and 2.35 micrometers and resolution of 30 m, is very useful for mapping hydrothermally altered rocks associated with mineral deposits.

Fig. 3.12 Artist concept of Landsat 8 (Image courtesy of NASA's Goddard Space Flight Center)

Because different rock types reflect radiation to different degrees and in different spectral ranges, remote sensing allows preliminary geological interpretations of an area. Thus, some of the geological features intimately associated with ore deposits provide strong signals that can be detected by this technique. These features are often clearly recognizable, even through soil cover or vegetation. Different surface materials such as water, vegetation, or clay alteration generate different signals of radiation in varying wavelength bands. This pattern of reflectance is characteristic for each type of land surface and is known as its reflectance signature. In mineral exploration, this can be especially meaningful in looking for surface alteration systems where argillic alteration can be present (Sabbins and Oliver 2004). Finally, the full potential of remote-sensing data can only be obtained by combining all forthcoming spectral bands in digital processing. This is because the combination enables improving the interpretation of linear structures, gossans, hydrothermal alterations, and so on.

3.4.2 Photogeology

World War I was the onset of the development of aerial photography and photointerpretation. Photointerpretation is the study of the character of the ground surface using the aerial photographs. Aerial photographs are pictures of the ground surface taken from the air with a camera pointing downward, and they are mainly used for the production of topographic maps. Some important additional uses are regional geological mapping (1:36,000 to 1:70,000), detailed geological mapping (1:5000 to 1:20,000), open-pit management, land use, agricultural and forestry applications, water resource applications, urban and regional planning, and environmental impact assessment, among many others. While satellite imaging covers very large areas of the Earth's surface, aerial photography and photogeological interpretation provide the topographic and geological basis for exploration work of smaller areas of 10 km^2 or less. For this reason, most exploration studies involve multi-image interpretation.

Interpretation of standard aerial photographic images remains as an important tool, being highly effective especially when used for logistic and planning. The study of the aerial photographs cannot substitute the field investigations, but rather it helps and contributes to them. The advantages of the study of the aerial photographs are as follows: (a) they save time and provide to observe a larger area; (b) they have more detailed ground surface than maps; (c) they can be studied anytime and anywhere; and (d) the studies carried out on the photographs are cheaper and easier than studies in the field.

In turn, photogeology is the interpretation of the geological and geomorphological features as well as various lithofacies on the aerial photographs, a source of geological information that can be unobtainable elsewhere. The use of aerial photographs in geology includes (a) outlining the structure and structural relationship in an area; (b) outlining the stratigraphic succession; (c) preparation of a geological map; (d) measurements of stratigraphic sections; (e) measurements of dip and strike and thickness of formations; and (f) inferences about rock types present in the area (Dirik 2005).

Based on scale, there are different types of aerial photographs: large-scale (1:5000 to 1:10,000), medium-scale (1:10,000 to 1:20,000), small-scale (1:20,000 to 1:60,000), and very small-scale (>1:60,000) aerial photographs. The photographs used mostly are at the scale of 1/35000, with a size of 18 × 18 cm. The size of the photograph cannot be greater than 25 × 25 cm because stereographic viewing is only possible for this size. In turn, based on film used, aerial photographs can be panchromatic black and white photographs, infrared black and white photographs, and infrared colored photographs. Aerial photographs can also be classified as oblique or vertical. Oblique photographs can be either high angle oblique photographs or low angle oblique photographs. Vertical photographs are those taken by a camera pointing vertically downward.

The factor that produces the strongest three-dimensional effect in photointerpretation is stereoscopic vision. Two photographs of the same terrain, but taken from different camera stations, generally permit three-dimensional viewing and are said to comprise a stereoscopic pair, also commonly referred to as a stereo pair. Overlapping adjacent photographs (overlap of 60–90%) along the flight path enable subsequent stereoscopic (three-dimensional) viewing. The two main pieces of photointerpretation equipment are field stereoscopes and mirror stereoscopes. The latter are mainly utilized in the office and can view full 23 cm × 23 cm photographs without overlapping.

Where available at a suitable scale and resolution, aerial photographs are the best medium upon which to construct a geological map. Thus, the initial interpretation made from the images will provide: «(a) definition of areas of outcrop and areas of superficial cover; (b) preliminary geological interpretation based on topographic features, drainage patterns, colors and textures of rocks, soils and vegetation, trend lines of linear features, etc.; (c) geological hypotheses for field checking; (d) selection of the best areas to test these hypotheses; and (e) familiarity with the topography and access routes to assist in logistic planning of the field programme: access roads and tracks, fording points for streams, potential helicopter landing sites, etc.» (Marjoribanks 2010) In this sense, topographic studies using drones are common in mineral exploration (◘ Fig. 3.13).

Tone in aerial photographs refers to the brightness at any point on a panchromatic photograph and is affected by many factors (e.g., nature of the rock – sandstone is light, but shale is dark). Basic extrusive and intrusive igneous rocks display usually darker tone while bedded sandstone, limestone, quartzite, and acid igneous rocks are commonly lighter; mudstone, shale, and slate show intermediate tones (Whateley 2006). With regard to the texture, there is a large variation in apparent texture of the ground surface as seen on aerial photographs. Moreover, texture is often relative and subjective. However, drainage pattern indicates the bedrock type that affects soil characteristics and site drainage conditions. For instance, dendritic drainage occurs on relatively homogenous material such as flat-lying sedimentary rocks and granite, and radial drainage radiates outward from a central area, typical of domes and volcanoes. Moreover, the distribution of vegetation commonly offers information about the rock types. For example, sandstone and shale can be cultivated, while dolerite is left as rough pasture. On the other hand, lines of vegetation (e.g., trees) are the best indicator of fractures, faults, veins, and joints.

Fig. 3.13 Drone for topographic study at Nigeria (Image courtesy of Eduardo Revuelta)

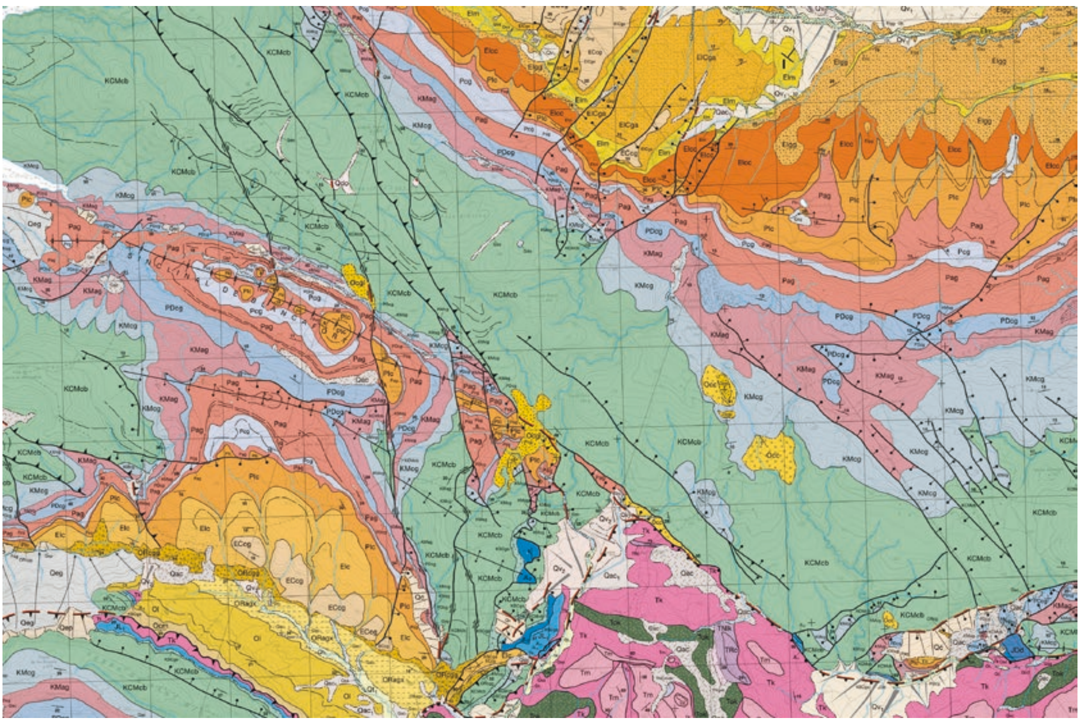


Fig. 3.14 Part of a 1:25,000 geological map (IGME, Spain)

3.4.3 Geological Mapping

Publication in 1815 of the first colored, hand-painted geological map of England and Wales by William Smith heralded the birth of modern geology (Winchester 2001). Today, two centuries after this early mapping was done to locate bedrocks suitable for construction of canal systems, geological maps (Fig. 3.14) are used as a means of presenting the observations as well as constructing geological hypotheses. Geological mapping plays an important role throughout the mine life cycle, from regional- to district-scale exploration targeting, through drilling and ore discovery, to deposit assessment, ore-reserve estimation, pre-production mine planning to production, and, ultimately, mine closure.

Geological mapping has been used extensively for mineral exploration for more than 100 years. Beyond the use of traditional paper-based mapping tools, recent technological advances incorporate global positioning systems, pen tablet computers, and laser ranging devices that all support direct (paperless) field-based digital geological mapping. In this sense, geographic information systems (GIS) revolutionized exploration practices (Box 3.3: Geographic Information Systems).

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Box 3.3

Geographic Information Systems

A geographic information system (GIS) is a computer system (hardware, software, and netware) and associated database designed to efficiently capture, store, update, manipulate, analyze, retrieve, and display all forms of geographically referenced information. The first known use of the term geographic information system was in 1968. In 1986, Mapping Display and Analysis System (MIDAS), the first desktop GIS product emerged for the DOS operating system. Then, this was renamed in 1990 to MapInfo for Windows when it was ported to the Windows platform. Recently, a growing number of free, open-source GIS packages run on a range of operating systems and can be customized to perform specific tasks.

Modern GIS technologies use digital information, for which various digitized data creation methods are used. The most common method of data creation is digitization, where a hard copy map or survey plan is transferred into a digital medium through the use of a CAD program and geo-referencing capabilities. Geographic data can be stored in a vector or a raster format. Using a vector format, two-dimensional data is stored in terms of X and Y coordinates. For instance, a road or a river can be described as a series of X and Y coordinate points. Thus, the vector system is good for describing well-delineated features. A raster data format expresses data as a continuously changing set of grid cells. The raster model is better for portraying subtle changes such as soil-type patterns over an area. Most geographic information systems make use of both kinds of data. Once all of the desired data have been entered into a GIS system, they can be combined to produce a wide variety of individual maps, depending on which data layers are included.

In mineral exploration, the data are usually organized in layers of different types such as topography, remote sensing, geophysical and geochemical results, etc. Some GIS applications, for instance using ArcGIS, are specifically developed to represent and process particular types of geological, geochemical, and geophysical information. Raster images, such as satellite or geophysical imagery, can be integrated and overlain with vector data such as geology, faults, and sample information. Thus, GIS is essential in customizing and integrating a broad range of mineral exploration data consisting of information on drillholes with summary stratigraphic logs, rock sample and drillhole sample geochemistry, mineral occurrences, magnetic and gravity images, digital geology, current and historic exploration details, and much more (Fig. 3.15).

The ultimate objective of using a GIS during Mineral exploration is to predict the approximate positions of new mineral deposits. For doing this, the data to be integrated should be indicative of the mineral deposits searched according to an exploration model customized for the area under analysis. In this sense, remote-sensing data often constitutes an important part of the database introduced in a GIS because of its intrinsic digital nature and because it can be used as the base over which to overlap other data. By combining GIS technology with the enormous progress in recent years in remote sensing, it has been possible to extend the mineral exploration all over the world. Moreover, recent integration of exploration data with GIS, supported by intelligent systems, has greatly enhanced the acquisition, analysis, and interpretation of complex problems of probabilities and decisions involved in mineral projects. Mapping of mineral potential using GIS is conducted to delineate areas with different probabilities of hosting certain types of mineralization. The main steps in generating mineral potential maps are (a) establishing the exploration conceptual model; (b) building a spatial database; (c) spatial data analysis (extraction of evidence maps and assigning of weights); and (d) combination of evidence maps to predict mineral potential.

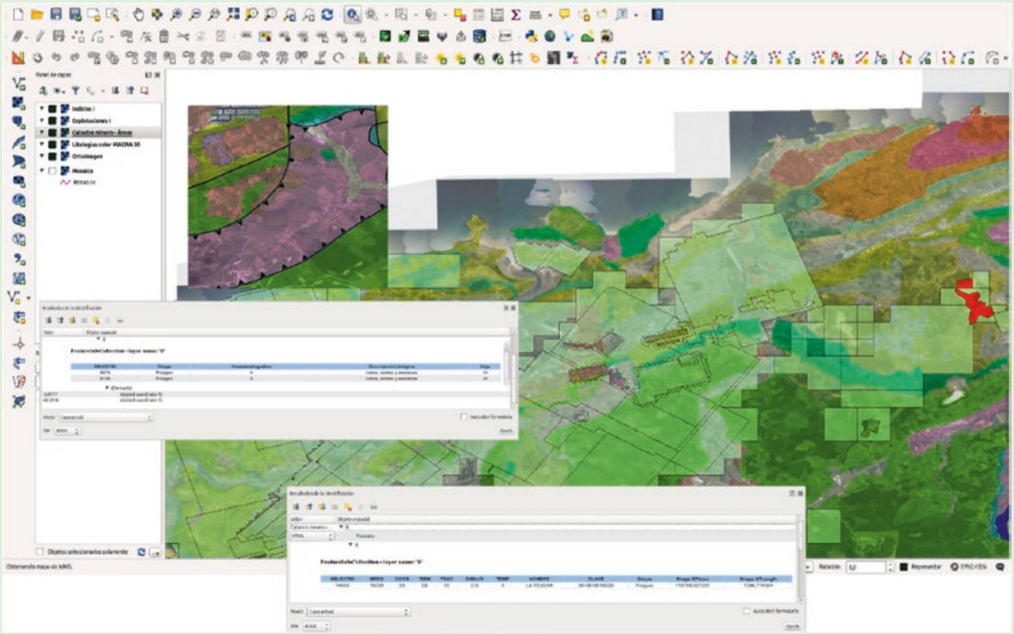


Fig. 3.15 GIS image released with QGIS (a free and open-source geographic information system) including different types of information such as geology or mining data (Image courtesy of Miguel Ángel Sanz)

There are two main reasons that mapping remains an essential part of mineral exploration. First, mapping creates the geometric patterns that represent the geological attributes of an exploration target. Second, there are scientific, engineering, and financial implications of mapping because subsequent geophysical modeling, ore-reserve estimation, financial forecasting, and economic evaluation are based on the interpretation of such work (Brimhall et al. 2006). The quality and scale of the geological map will vary with the importance of the program and the finance available. Scales of geological maps range from reconnaissance (1:24,000 or smaller) to detailed project scale (1:100 to 1:12,000).

Geological mapping is widely used in planning exploration strategies such as the selection of regions to explore for certain types of ore deposits. Prior to mapping campaigns, existing geological maps are examined and can be compiled to emphasize key geological features to assess exploration potential. Exploration geologists commonly use existing maps as the basis for preliminary examinations to assess mineral potential, frequently in conjunction with geochemical, geophysical, or remote-sensing surveys or compilation of mine and prospect data.

However, geological maps available today, either published by government surveys or in many scientific journals, are generally not well suited for special needs of mineral exploration and development and require exploration geologists to undertake specialized mapping. Whereas published maps of general geology do outline information essential to exploration, including rock units, stratigraphy, ages of rocks, and general structure, they are in most cases not sufficiently detailed to help delineate mineral deposits that are typically 1–2 km^2 in outcrop area even for world-class deposits. Consequently, the geological mapping at this stage generally is done at a more detailed and larger scale than published mapping, and key lithologic units and features of mineralization or hydrothermal alteration are mapped using the reconnaissance techniques.

Since geological information is commonly recorded on maps and cross sections at a scale appropriate to the aims, property geology must be defined at a scale of 1:5000, while mineral deposit geology must be mapped to a scale of 1:1000 or even more detailed. Information displayed in this type of map includes faulting, folding, rock types, fracture/vein density and orientation, evidence of primary porosity/permeability, and phases of mineralization, among many others.

Regarding geological mapping in underground mines, it can play an essential role in mineral exploration. Abandoned mine workings are the most direct guides of the mineralization in a region and provide the immediate information on ore occurrences. If the workings are active, they provide a series of fresh geological exposures with each meter of advance, and they supply well-located sites for underground drilling and sampling.

3.4.4 Geophysical Exploration

Introduction

Mineral exploration is increasingly being addressed to searching for buried and deep targets since there are few large ore bodies to be found at the surface. Unlike geochemistry and other remote-sensing techniques, geophysics helps to look at into the subsurface and to provide information about the concealed geology. Thus, geophysics is an integral part of most mineral exploration programs. Geophysical techniques have been used in mineral prospecting for the past 300 years, beginning in Sweden around 1640 with the use of magnetic compasses in exploring for iron ore. These techniques are essential in areas where outcrop is poor or has been subject to intense mineral search over a long period. In some cases, geophysical techniques also enable for quick regional appraisal of areas where ground access is almost impossible, for instance, rain forest terrain or developing countries with insufficient infrastructure (Marjoribanks 2010).

For a geophysical technique to be useful in mineral exploration, there must be a clear contrast in the physical characteristics of the minerals, rocks, and ores related to the existence of valuable minerals. Geophysical anomalies, defined as differences from a constant or slowly varying background, can be recorded. Ideally, the actual economic minerals will produce them, but even the presence of a clear physical contrast between mineralization and surrounding rocks does not imply a significant anomaly (Milson 2006).

Geophysical measurements in the natural environment will be contaminated with unwanted information. This is called noise, which is a source of error, while the information being sought in the measurement is known as signal. Signal amplitude should be as high as possible whereas noise signal should be as low as possible, in order to obtain an accurate measurement of the parameter of interest. In any case, suppression of noise is of outmost importance and must be considered at every stage of the geophysical program, from data acquisition to presentation of the data for interpretation (Dentith and Mudge 2014).

Geophysical methods can be classified as passive (magnetism, specific gravity, and radioactivity) and active methods (electric conductivity, electromagnetic properties, and seismicity). Passive methods use natural sources of energy, of which the Earth's gravity and magnetic fields are two examples, to investigate the ground. The geophysical measurement is made with a detector, sensor, or receiver, which measures the response of the local geology to the natural energy. In turn, active geophysical methods involve the deliberate introduction of some form of energy into the ground, for example, seismic waves or electric currents. Again, the response of the ground to the introduced energy is measured with some form of detector (Fig. 3.16). These methods are more complicated and expensive to work with.

Fig. 3.16 Geophones for receiving seismic signal (Image courtesy of International Geophysical Technology)

The geophysical signal can be directly related to mineral deposits, for example, a magnetic anomaly caused by magnetite ore in an iron deposit. More commonly, geophysical methods provide indirect evidence that leads to interpretations of the subsurface geological distribution of rocks, but it does not directly or necessarily reflect the presence of a mineral deposit. These types of methods are applied to both mineral discovery and geological mapping. They are useful because geophysical responses of materials can be measured through vegetation, soil cover, and extraneous overburden. In many cases, geophysical measurements provide the only means of interpreting the geological characteristics of the subsurface short of drilling, which is much more expensive (Gocht et al. 1988).

Over the area of interest, geophysical instruments are deployed in the field to measure variations in a physical parameter associated with variations in a physical property of the subsurface, and the measurements are used to infer the geology of the survey area. Of particular significance is the ability of geophysical methods to make these inferences from a distance and, for some methods, without contact with the ground. A considerable number of geophysical exploration methods are available for mineral exploration, and each method exists in several variants. The specific choice is a function of the geological and exploration model of the targeted deposits; of general conditions such as remoteness, climate, and human land use; and of the costs (Shen et al. 2008). Through either ground, airborne, or in-ground (downhole) methods, geophysical studies employ the types of surveys cited above to detect anomalous signals related to the presence of minerals.

The chief advantages of airborne surveying relative to ground surveying are the greater speed of data acquisition and the completeness of the survey coverage. After their introduction in the 1950s, airborne geophysical surveys became commonly used as a first step in geophysical exploration. They provide the quickest, and often the most cost-effective, ways of obtaining geological information about large areas. Two or more methods are commonly combined in one survey to obtain data that are more accurate. In surface geophysics, geophysical work on the ground is normally rather slow. Results from airborne and surface surveys are matched with surface geological data to decide if it is worth proceeding with further exploration.

Geophysical techniques are routinely used in exploration programs to help the project geologist delineate areas favorable for the type of target being pursued. They can be used to directly detect some minerals, indirectly detect others, and map geological and structural features in exploration programs. Direct detection includes using induced polarization (IP) to find disseminated sulfides, magnetics to delineate magnetite-hosting rocks, and gravity and electrical techniques for massive sulfides. For instance, indirect detection of targets includes «using IP to detect pyrite in association with sphalerite and gold (both non-responders to IP geophysical techniques), and copper and molybdenum in porphyry systems; magnetics are routinely used to search for hydrothermal alteration in association with porphyry systems, and can be used to map buried stream channels (e.g. magnetite sands) that might host placer gold» (Mukherjee 2011). Seismic surveys are highly effective for investigating layered stratigraphy, so they are the mainstay of the petroleum industry but are comparatively rarely used in the minerals industry. Regarding costs of geophysical surveys, the seismic method is the most expensive, while airborne magnetic and radiometrics are the less expensive.

It is very important to note that most important advances in geophysical exploration for ore deposits in the last 25 years dealt with advances in theory or practice of the different methods but also with the development of more sophisticated instrumentation and especially more powerful data processing. These advances together with the use of GPS for survey positioning control have greatly reduced the cost and time involved in all geophysical surveys and have increased their resolution in the detection of anomalous signals in the data.

Traditionally, most geophysical data has been presented for interpretation in the form of contoured or raster plans and sections that can be interpreted in terms of the geology and ore mineralization that they represent. However, new methods of analyzing and presenting geophysical data have been introduced in the last two decades to revolutionize the interpretation process. These methods are generally referred to as «data inversion» (McGauchy 2007; Oldenburg and Pratt 2007) (◘ Box 3.4: Data Inversion in Geophysical Exploration).

Box 3.4

Data Inversion in Geophysical Exploration

Geophysics is traditionally used to predict the position of a mineralized body by seeking out geophysical anomalies. The new inversion techniques establish the geophysical properties of rocks and then measure their geophysical signatures in the field. Thus, it is possible to generate three-dimensional models of their potential mineralization and the surrounding geological environment. Inversion models are generally much easier to interpret than the original data and provide a superior understanding of the subsurface.

The target deposit in mineral exploration is commonly buried within a complex geological structure, and the contribution of the other units masks the sought response. In such cases, direct visual interpretation of the target location is difficult or impossible. Thus, the geophysical data need to be «inverted» to recover a distribution of the relevant physical property that can explain the observations. Geophysical data inversion enables resource explorers to extract more insight from geophysical data by converting geophysical measurements into 3-D images of the subsurface that can be integrated with other surface and subsurface geologic observations. Insights generated from geophysical inversion have helped to improve prospecting and focus drill targeting, particularly in deeper and more complex subsurface environments. The 3-D geophysical inversion is now possible for almost all geophysical methods that are commonly used in mineral exploration. Over the past decade, geophysical inversion has proved its effectiveness in exploring for ore deposits and major oil reserves around the world.

Inversion techniques make use of complex computer algorithms and information of the geophysical properties of the rocks and potential mineral deposits of the prospect, to construct mathematically a geological model that agrees, or is at least compatible, with the geophysical observations. The results are presented as a 2-D or 3-D geological model of the body of rocks that were surveyed (Fig. 3.17). Instead of finding the single possible response to a given earth model (forward modeling), inverse modeling will help determine what 3-D distribution of physical properties yields a measured field response. The known information (e.g., overburden thickness, lithology from drill data, and borehole assay results) can help constrain the inverse problem to a limited number of plausible models. The most useful models are the result of exploring the inversion model space by running many scenarios with different constraints and sensitivity to other geological information. Therefore, new algorithms and faster computers have a huge impact on the success of geophysical inversion for exploration. Similarly, the ability to easily integrate and use supplementary information to better constrain the inversion is critical to producing reliable models. In summary, geophysical inversion produces physical property models from geophysical data whereas forward modeling produces data from a physical property model of the Earth.

However, it is important to realize that, as with all computer

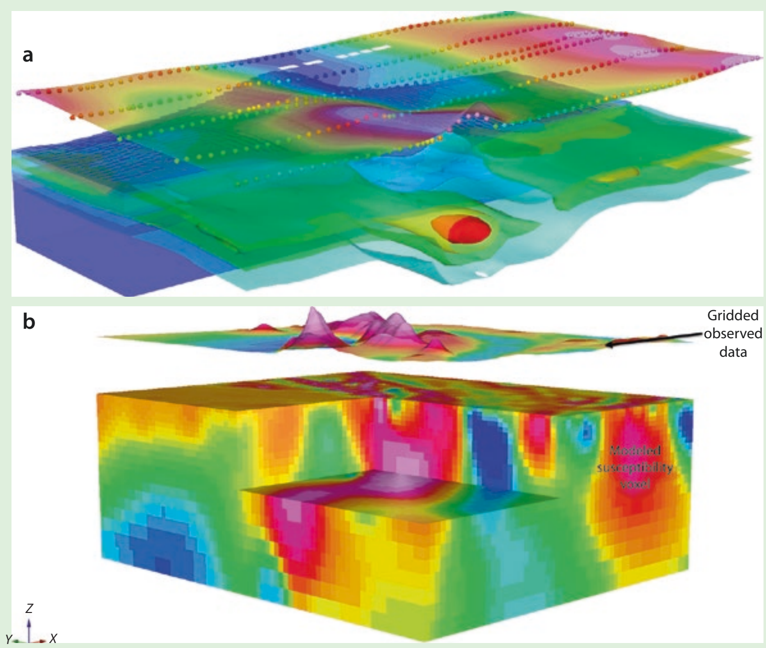


Fig. 3.17 3-D geophysical inversion images. **a** 3-D conductivity model from frequency-domain electromagnetic field inversion (Geosoft VOXI Earth Modelling); **b** 3-D susceptibility model from magnetic field inversion (Geosoft VOXI Earth Modelling) (Images courtesy of Geosoft)

models, the product of inversion modeling is only as good as the geological choices made in setting up the model parameters and the accuracy of the geophysical properties that are used in its construction. It is a feature of geophysical inversion models that shows they are not unique: many different models can be constructed that will reproduce the geophysical pattern that was measured in the field. Choosing between different possible models requires geological knowledge about the area, and the better that knowledge, the more useful and realistic the inversion model.

Gravity Methods

In this geophysical method, subsurface geology is investigated based on variations in the Earth's gravitational field developing from differences of density between subsurface rocks. Gravity surveys have been widely used to understand general subsurface structure as measurement of gravity by gravimeters is relatively easy. The mean value of gravity at the surface of the Earth is about 9.8 m/s^2, and variations in gravity caused by density variations are of the order 100 µm/s^2. This unit of the micrometer per second squared is referred to as the gravity unit (gu). An accuracy of ±0.1 gu is quickly attainable in gravity surveys on land and corresponds to approximately one hundred millionth of the normal gravitational field (Kearey et al. 2002). The instrument used in gravity surveying is called a gravimeter (◘ Fig. 3.18), an extremely sensitive weighing machine. At each survey station, location, time, elevation, and gravimeter reading are recorded. The measurement of relative values of gravity, which is the differences of gravity between locations, is the standard procedure in gravity surveying. Before the results of a gravity survey can be interpreted, it is necessary to correct for all variations in the Earth's gravitational field that do not result from differences of density in the underlying rocks. This process is known as «gravity reduction» (LaFehr 1991) and basically includes instrument drift, latitude, elevation, and tidal corrections.

◘ **Fig. 3.18** Gravimeter (Image courtesy of International Geophysical Technology)

Gravity differences over the surface of the Earth are due to density differences between adjacent rocks. Density contrasts of different materials are controlled by a number of factors such as type of rock, grain density of the particles forming the rock, and the porosity and interstitial fluids within the material. Rock densities are among the least variable of all geophysical parameters and range from less than 2.0 g/cm^3 for soft sediments to more than 3.0 g/cm^3 for mafic and ultramafic rocks. Obviously, many ore minerals (e.g., metal sulfides) are clearly denser than their host rock. For this reason, the ore bodies are commonly denser than their surroundings. However, it is important to note that actual effects are tiny, usually amounting to less than 1 ppm of the total field of the Earth, even considering large massive sulfide deposits. Gravimeters must then be very sensitive, a specification which is commonly in conflict with the request to be also rugged and field worthy.

The variations in the density of the crust and cover are presented on a gravity anomaly map (◘ Fig. 3.19). A gravity anomaly map looks at the difference between the value of gravity measured at a particular place and the predicted value for that place. Gravity anomalies form a pattern, which can be mapped as an image or by contours. The wavelength and amplitude of the gravity anomalies give geoscientists an idea of the size and depth of the geological structures causing these anomalies. Deposits of very dense and

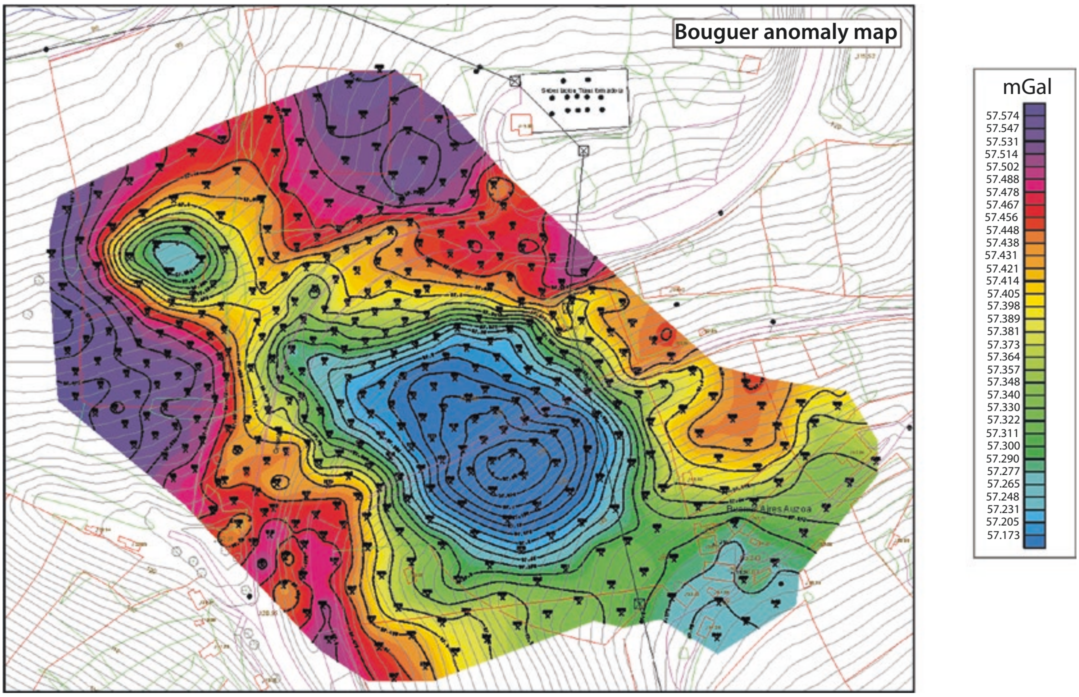


Fig. 3.19 Bouguer anomaly map (Illustration courtesy of International Geophysical Technology)

heavy minerals will also affect gravity at a given point and will produce an anomaly above normal background levels. Anomalies of exploration interest are often about 0.2 mgal, and data have to be corrected for variations due to elevation, latitude, and other factors.

Much less can be deduced about the shape or the depth of the investigated mineral deposit. A deeper body will, other things being equal, give rise to a broader and flatter anomaly. Likewise, the peaks of gravity anomalies are generally situated just above the causative bodies (a causative body is a rock unit of different density from its surroundings), which is not the case for many other geophysical methods. Regarding the interpretation of the measurements, «the reliability of any interpretation, no matter how sophisticated the technique, depends, of course, on the validity of the input assumptions» (Milson 2006).

Gravity surveys can be carried out either from airborne or ground surveys, but the most sensitive measurements are currently achieved from the ground. They are used to evaluate the amount of high-density mineral present in an ore body, and as a general rule, gravity prospecting is only used for mineral exploration if substantial density contrasts are expected. Thus, chromite and sulfide bodies possess very high densities, and buried channels, which can contain gold or uranium, can be detected because they have relatively low density. In fact, gravity surveying is rarely used in reconnaissance exploration because it is relatively slow to execute and therefore expensive. However, gravity methods are very useful as a follow-up method utilized on a target defined by another, more cost-effective method. In this sense, gravity surveys, along with regional aeromagnetic data, played a significant role in the discovery of the giant deeply buried Olympic Dam mineral deposit in Australia (Rutter and Esdale 1985), and the discovery of the Neves Corvo sulfide deposits in Portugal was carried out utilizing regional gravity surveys of the Portuguese pyrite belt on 100 and 200 m grids (Leca 1990).

Magnetic Methods

Magnetic methods, which are probably the oldest of geophysical exploration methods, thrived after the World War II. Magnetic surveys (Fig. 3.20) measure variations of the Earth's magnetic field

Fig. 3.20 Magnetic survey (Image courtesy of International Geophysical Technology)

caused by the presence of magnetic minerals. Magnetic outcomes result primarily from the magnetization induced in susceptible rocks by the magnetic field of the Earth: everywhere in the Earth there is a natural magnetic field. These methods are widely used, both as an essential assistance in regional mapping and for direct location of those mineral deposits that show distinct magnetic signature. Magnetic and gravity methods have much in common. The magnetic map, however, is generally more complex, and the variations in field are more erratic and localized than the gravity map. Thus, the precise interpretation of magnetic field data is usually much more difficult than for gravity.

Magnetic surveys are often utilized in metallic mineral exploration, particularly locating iron ores. However, ordinary hematite, the most abundant ore of iron, rarely produces anomalies large enough to be detectable in conventional aeromagnetic surveys. The combination effect of several geophysical techniques such as aeromagnetic interpretation with study of regional gravity and radiometric data can produce further gains in the interpretation of the underlying rocks.

Minerals can be diamagnetic, paramagnetic, or ferromagnetic. In diamagnetic minerals, all the electron shells are full; there are no unpaired electrons. Diamagnetic minerals show negative susceptibilities and examples of these materials are quartzite and salt although many of the elements and compounds exhibit diamagnetism. Salt domes thus give diamagnetic anomalies (weak negative anomalies). Paramagnetic minerals are ones where the electron shells are incomplete; as a result, they generate weak magnetic fields. By definition, all materials that are not diamagnetic are paramagnetic. Examples of materials that are paramagnetic are the 20Ca to 28Ni element series. Finally, ferromagnetic minerals are minerals that are paramagnetic, but where groups of atoms align to make domains. There are only three ferromagnetic elements: iron, cobalt, and nickel. Almost all natural magnetic minerals are of this kind. Magnetite, which is the most abundant, ilmenite, hematites, titanomagnetite, and the oxides of iron or iron and titanium are common ferromagnetic minerals. Magnetite (Fe_3O_4) is found disseminated through most rocks in differing concentrations. The magnetization can be either temporary (induced) in the same direction as the field of the Earth or permanent (remanent) and fixed in direction with respect to the rock, regardless of folding or rotation. All geologically significant magnetic minerals lose their magnetic properties at about 600 °C, a temperature reached near the base of the continental crust. Consequently, local features on magnetic maps are virtually all of crustal origin (Milson 2006).

As a rule, the magnetite content and, therefore, the susceptibility of rocks are very variable, being present a considerable overlap between different mineralogies and lithologies (Table 3.2). Basic igneous rocks are commonly highly magnetic because this type of rock has a relatively high magnetite content. In this sense, the proportion of magnetite in igneous rocks usually decreases with increasing acidity; for this reason, acid igneous rocks are generally less magnetic than basic rocks. Metamorphic rocks are also very different in their magnetic character, depending of the metamorphism grade. Regarding sedimentary rocks, they are effectively nonmagnetic unless they contain a significant amount of magnetite in the heavy mineral fraction. Thus, if magnetic anomalies are detected in areas covered with sediments, these anomalies are mainly originated by an underlying igneous or metamorphic basement or by intrusions into the sediments.

3

Table 3.2 Magnetic susceptibility of some common rocks

Rock types	Maximum volume susceptibility (SI units)
Igneous rocks	
Andesite	0.17
Basalt	0.18
Dolerite	0.062
Diabase	0.16
Diorite	0.13
Gabbro	0.09
Norite	0.09
Dacite	0.05
Granite	0.05
Granodiorite/tonalite	0.062
Peridotite	0.2
Quartz porphyries/quartz-feldspar porphyries	0.00063
Pyroxenite/hornblendite (Alaskan type)	0.25
Rhyolite	0.038
Dunite	0.125
Trathyte/syenite	0.051
Monzonite	0.1
Phonolite	0.0005
Spilites	0.0013
Avg. igneous rock	0.27
Avg. acidic igneous rock (pegmatites	0.082
Avg. basic igneous rock (komatiites, tholeiite)	0.12
Sedimentary rocks	
Clay	0.00025
Coal	0.000025
Silt/carbonates	0.0012
Dolomite	0.00094
Limestone	0.025
Red sediments	0.0001
Sandstone	0.0209
Shale	0.0186
Tuffs	0.0012
Conglomerate/akose/pelites	0.0012
Arenites/breccia	0.0012
Avg. sedimentary rock	0.05
Metamorphic rocks	
Amphibolite	0.00075
Gneiss	0.025
Granulite	0.03
Acid granulite	0.03
Basic granulite	0.1
Phyllite	0.0016
Quartzite	0.0044
Schist	0.003
Serpentine	0.018
Slate	0.038
Marble	0.025
Metasediments	0.024
Migmatites	0.025
Magnetite skarn	1.2
Avg. metamorphic rock	0.073
Magnetite ~0.1%	0.0034
~ 0.5%	0.018
~ 1%	0.034
~ 5%	0.175
~ 10%	0.34
~ 20%	0.72

The practical unit of magnetic field for survey work is the nanotesla (nT), sometimes also known as the gamma. At the magnetic poles, the field is about 60,000 nT and vertical, while at the equator it is about 30,000 nT and horizontal. The magnitude of the Earth's magnetic field averages to about 5×10^{-5} T (50,000 nT). Magnetic anomalies as small as 0.1 nT can be measured in continental magnetic surveys and can be of geological significance. Today, «with improvements in instrumentation, navigation and platform compensation, it is possible to map the entire crustal section at a variety of scales, from strongly magnetic basement at a very large scale to weakly magnetic sedimentary contacts at small scale» (Likkason 2014). Methods of magnetic data treatment, filtering, display, and interpretation have also improved significantly, especially with the advent of high performance computers and color raster graphics as well as GPS technology.

The instrument used for magnetic surveys is called a magnetometer. Magnetometers record disturbances in the Earth's magnetic field caused by magnetically susceptible rocks. Since the early 1900s, a variety of surveying instruments have been designed. The first device to be developed was the fluxgate magnetometer, which found early application during the Second World War in the detection of submarines from the air. Actually, three types of magnetic sensor are commonly used in geophysical surveying, namely, the proton-precession, the Overhauser, and the alkali-vapor sensors. The operation of all three is based on quantum-mechanical properties of atoms. Importantly, they are sensitive to the strength of the Earth's magnetic field, but they do not however measure its direction but the total magnetic intensity (TMI) (Dentith and Mudge 2014). With the magnetometer data, a map of magnetic variation at the surface, called a TMI map, can provide an image of lithology distribution.

Magnetic methods are used to detect different types of ore bodies in mine prospecting. Magnetic surveys are fast, provide a great amount of information for the cost, and can offer information about the distribution of rocks under thin layers of sedimentary rocks, useful when trying to locate ore bodies. Therefore, magnetic observations are obtained relatively easily and cheaply, and a few corrections are applied to them, explaining why the magnetic methods are one of the most frequently utilized geophysical tools. Three types of correction are carried out in magnetic methods to remove all causes of magnetic variation: diurnal variation, geomagnetic, and elevation and terrain corrections.

Despite these obvious advantages, interpretations of magnetic observations suffer from a lack of uniqueness due to dipolar nature of the field and other various polarization effects. The greatest limitation of the magnetic method is that it only responds to variations in the magnetic properties of the materials of the Earth, which means that many other characteristics of the subsurface are not solvable. «The inherent ambiguity in magnetic interpretation for quantitative techniques is problematic where several geologically plausible models can be attained from the data».

Most magnetic work for mineral exploration is carried out from the air since aeromagnetic surveying is quick and cost-effective, with a cost some 40% less per line kilometer than a ground survey. In this type of survey, the flight lines are spaced 0.5–1.0 km apart at an elevation of roughly 200 m above the ground. Line separations have decreased over the last years and can now be as little as 100 m. Data are recorded digitally and presented commonly as a contour map. Obviously, flying at lower altitudes and decreasing the spacing of the flight line increase the final sensitivity of the survey. In this sense, it is noticeable that extremely detailed surveys, comparable in their resolution to ground magnetic surveys, can be developed using low-flying helicopter.

Ground surveys are conducted to follow up magnetic anomalies identified through aerial surveys. Such surveys can involve stations spaced only 50 m apart. The magnetic survey is generally suspended if periods of large magnetic fluctuation (e.g., magnetic storms) are present. Solar activity, such as spots and flares, cause short-term irregular disturbances with amplitudes that can surpass 1000 nT. Although data are usually displayed in the form of a contour map of the magnetic field, interpretation is often made on profiles. According to Kearey et al. (2002), magnetic anomalies range in amplitude from a few tens of nT over deep metamorphic basement to several 100 nT over basic intrusions and can reach an amplitude of several 1000 nT over magnetite ores.

Direct search for magnetic targets related to mineralization is an important exploration method, especially in those provinces with banded iron formations, IOCG mineralization types, strongly oxidized porphyry copper intrusives, magnetite skarns, or pyrrhotite-bearing massive sulfides. In such cases, favorable anomalies are commonly obtained from high-quality low-level aeromagnetics, followed up then by ground magnetometer traverses and magnetic modeling to define a drill target. «Magnetics have been also used to define subtle exploration targets such as heavy mineral concentrations in palaeo-strand lines and potential iron ore and gold orebodies in palaeochannels» (Marjoribanks 2010). Examples of ore deposits found largely as a result of their magnetic response are the Olympic Dam mineral deposit (Reeve et al. 1990) and the Broken Hill-type deposit of Cannington in Australia. This deposit was discovered as a consequence of drill testing and an air magnetic anomaly, generated by associated pyrrhotite, in a zone of thick younger cover (Walters et al. 2002).

Radiometric Methods

Radiometric surveys carried out the estimation of the gamma rays emitted from the Earth by natural decomposition of frequent radiogenic minerals, being a useful technique to map fault zones or boundaries between geological units. Natural radioactive decay produces alpha particles, beta particles, and gamma rays. These are very high-frequency electromagnetic waves. Thus, radiometric survey is a passive geophysical method because it measures a natural source of energy, similar to gravity and magnetic methods. Most gamma rays are produced in the top 30 cm of soil and rocks that can be sensed by airborne investigations and on surface rocks utilizing a portable spectrometer. Radiometric surveys for mineral exploration are made from the air, on the ground, and within drillholes. Airborne radiometrics is particularly common in mineral exploration where the radiometric data are acquired simultaneously with magnetics during airborne surveying, measurements usually calculated from a low-flying aircraft simultaneously as air magnetic studies. As aforementioned, aerial and ground use are restricted to areas with little soil cover, because most radiation on the surface comes from the uppermost 10–50 cm.

Although the Geiger-Muller radiation detector was used in the early era of radiometric surveying, the instruments used nowadays are scintillometers, the simplest form of instrument, and spectrometers, a more complex type, that detect gamma rays by their interaction with matter. Small handheld and larger portable spectrometers for ground surveying have internal memories to store the large quantity of data acquired, which is generally restricted to measurements in the K, U, and Th energy windows and the total count (Dentith and Mudge 2014). The presentation of the obtained data in radiometric methods is similar to that of magnetic data. In this sense, the high geochemical mobility of elements such as K and U in surficial environments is the motive for the common use of ratios (U/Th, K/Th) in these maps due to the almost immobile Th. With respect to the presentation of the obtained data in radiometric methods, it is similar to that of magnetic data. As in gravity and magnetic methods, corrections must be also made in radiometric surveys for the effects of scattered thorium radiation in the uranium window and for the effect of both thorium and uranium in the potassium window.

There are over 50 occurring naturally radioactive elements, but the elements of main concern in radiometric studies are uranium (^{238}U), thorium (^{232}Th), and potassium (^{40}K). The latter is common in potassium-rich rocks that cannot be related to concentrations of U and Th. The most abundant radioactive element in the crust is the potassium isotope ^{40}K, which is widely included into the crystal structure of the rock-forming

Fig. 3.21 Instrumentation for ground radiometric (Image courtesy of International Geophysical Technology)

mineral orthoclase. Therefore, potassium can interfere with the existence of valuable mineral deposits, constituting thus a form of noise in this type of surveying. Nevertheless, it facilitates the recognition of potassium salts in evaporites, beach placer horizons in sand, and other economically important deposits.

Ground radiometry (Fig. 3.21) was proving very useful in the discovery of major uranium districts in the last decades because this element is essential for nuclear fuels. Nevertheless, the present unpopularity of nuclear power and the availability of uranium from dismantled nuclear bombs made exploration for uranium much less attractive, and the importance of radiometric methods has declined accordingly (Milson 2006). Anyway, this geophysical method is attractive in geology since many rocks can be differentiated from their distinct radioactive signal. The advent of new multichannel detectors, which are capable of separating radiation from different radioactive elements, the better sensitivity and resolution of airborne surveying methods, and the development of new data reduction algorithms have approached airborne radiometric surveys toward new applications. These include detecting and mapping areas of hydrothermal alteration as well as weakly radioactive mineral deposits such as heavy mineral sands (Dentith and Mudge 2014).

Electrical Methods

Electrical methods use direct currents or alternating currents of low frequency to study the electrical properties of the subsurface, being all of these methods ground based. This is in contrast to the electromagnetic methods, described in the following section, which use alternating electromagnetic fields of higher frequency for this purpose. The most commonly measured property is electrical conductivity (Siemens per meter, S/m) or its reciprocal, resistivity (Ohm). In general, these surveys are applied: (a) to locate mineral deposits at shallow depth, (b) to map geological structures, and (c) to trace groundwater table in hydrogeological investigations. There are different methods of electrical surveying: resistivity, induced polarization (IP), and self-potential (SP). Some utilize fields within the Earth (SP), while others need the incorporation of artificially produced currents into the ground (resistivity and IP). In general, resistivity surveys are often accompanied by induced polarization measurements.

Rocks and minerals show widely varying resistivity, with lowest values displayed by clay, saline pore water, acid rock drainage, sulfide ore, native metals, and graphite, whereas common rocks and minerals have low conductivity, being this contrast used in exploration. Thus, the induced polarization method utilizes the capacitive action of the subsurface to identify areas where conductive

Fig. 3.22 Electrodes arrangement (Image courtesy of International Geophysical Technology)

minerals are scattered in their host rocks. The self-potential method uses natural currents present in the ground and originated by electrochemical processes with the aim of finding shallow bodies that display anomalous conductivity. Although the origin of the potentials is not well understood, conductive mineralization can be associated with a negative self-potential anomaly.

Electrical methods are used at regional and prospect scale for direct detection of electrically anomalous targets and, in particular, to detect metal sulfide and metal oxide mineralization. Establishing the depth of the source of the response is problematic in electrical methods. Varying the position of the electrode array and the separation of the electrodes (Fig. 3.22), lateral and vertical variations in electrical properties can be mapped and used to produce data pseudosections, volumes, and maps. However, moving cables, electrodes, and equipment from one point to the next makes these methods laborious and slow. Electrical methods, as with electromagnetic methods, operate much better in the upper few 100 m of the surface with unweathered rocks relatively close to the surface.

As a rule, the resistivity method is scarcely used in mineral resource exploration. Conversely, IP is important in base metal exploration because it depends on the surface area of the conductive mineral grains rather than their connectivity, being successfully employed to a maximum depth of around 600 m. Induced polarization (IP) surveys cause an electric field in the ground and calculate the chargeability and resistivity of the subsurface. Thus, this method is capable of identify changes in the electric currents produced by the existence of different rocks and minerals. IP surveys are conducted along grid lines with readings taken at receiving electrodes planted in the ground and moved from station to station.

IP is especially sensitive to disseminated mineralization that can produce no resistivity anomaly. After magnetic methods, IP technique is probably one of the oldest geophysical methods utilized in

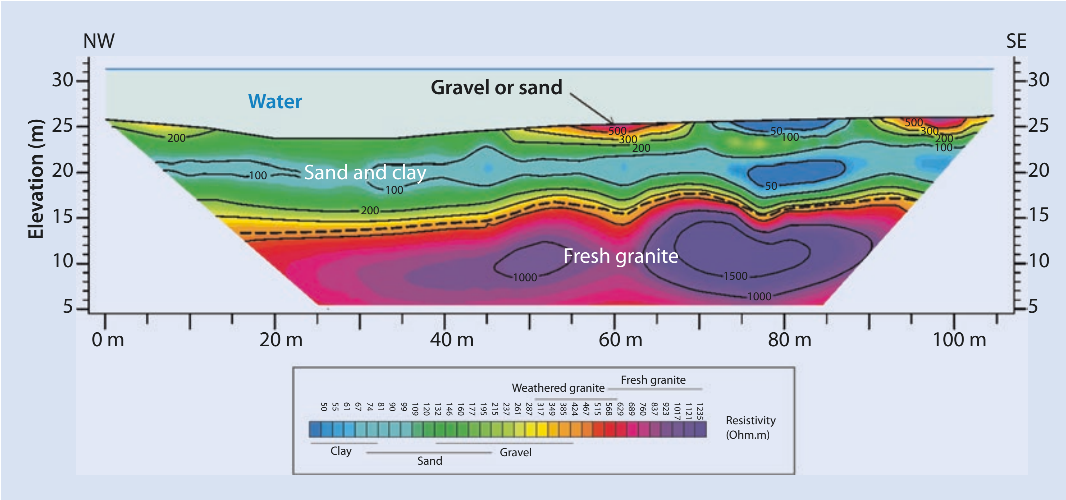


Fig. 3.23 Graphic display of an IP survey (Illustration courtesy of International Geophysical Technology)

mineral deposit exploration. Figure 3.23 shows a graphic display of the interpretation of an IP survey. This method commonly detects sulfide ore minerals (e.g., of Cu and Mo in porphyries) or other minerals that are disseminated in a matrix with high resistivity. Since both massive and disseminated deposits can be identified, IP is very widely used although the method is slow and commonly relatively expensive. In fact, IP is virtually the only geophysical method to detect direct disseminated sulfides in the ground. Examples of the successful use of an IP survey in mineral resource exploration are the detection of the blind, sediment-hosted, lead/zinc sulfide Gortdrum deposit of Ireland (Hitzman and Large 1986) and the discovery of San Nicolas VMS deposit in Mexico (Johnson et al. 2000).

Electromagnetic Methods

Electromagnetic induction (EM) utilizes the induction principle to estimate the electrical conductivity of the subsurface. Thus, EM surveys are based on variations of electric conductivity in the rock mass commonly using an external electromagnetic field, the primary field, and inducing a current to flow in conductive rocks below. These are classified as natural field methods and controlled source methods, respectively. In the latter, a transmitter is used to create a primary alternating electromagnetic field. The passage of current in the general frequency range of 500–5000 hertz (Hz) induces in the Earth electromagnetic waves of long wavelength, which have considerable penetration into the Earth's interior. Induced currents (eddy currents) produce a secondary field in the rock mass. The resultant field can be traced and measured, thus revealing the conductivity of the underground masses.

Electromagnetic methods are often employed as the reconnaissance tools used to identify anomalies for greater detailing because EM instruments provide rapid and easy data collection. As a rule, higher resolution is achieved by using higher frequencies and greater depth penetration by lower frequencies. The problems to analyze the results of EM investigations commonly increase with depth of penetration, and electromagnetic methods thus operate best for ore bodies located as much as 200 m below the surface. Most of the sensor devices of the electromagnetic methods are useful without contact from the ground, having a high operational efficiency in the field.

There are two fundamental categories of electromagnetic measurements: frequency-domain and time-domain measurements. In the frequency domain, a continuous sinusoidal current is used. It is a very sensitive tool' detecting variations as little as 3%. In the time domain, the change in the primary magnetic field is produced by either abruptly turning off or turning on a steady current. It is a powerful transmitter and receiver, and the method can approach the depth, thickness, and

Fig. 3.24 DHEM survey (Illustration courtesy of International Geophysical Technology)

conductivity of layers down to 300 m below surface. Unlike conventional resistivity techniques, EM works without a physical contact to the ground, without electrodes, which is in advantage for use above ice, water, swamps, frozen, or arid ground.

EM surveys are conducted from the air (AEM), on the ground surface, and in drillholes (downhole electromagnetics – DHEM) (Fig. 3.24). Ground-based EM methods are relatively expensive, being used mainly to define targets for drilling in specific mineralization styles. For its part, airborne investigations incorporating this geophysical method have been commonly utilized for direct ore location and sometimes in regional geological mapping. They were originally developed in the frequency domain to detect conductive massive sulfide bodies within the resistive rocks of the Precambrian shield of Canada. The subsequent need to explore other kinds of geological environments, combined with developments in EM systems, has led to higher-sensitivity time-domain systems now being used almost exclusively for mineral exploration. Airborne electromagnetic surveys are used in mineral exploration to discover mineral deposits such as sulfides containing copper or lead, magnetite, pyrite, unconformity-style uranium mineralizations, kimberlite pipes, certain manganese minerals, and paleochannels as potential hosts for placer deposits and sandstone- and calcrete-hosted uranium deposits (Dentith and Mudge 2014). On the other hand, the discovery of massive sulfide deposits that form major base metal producers in eastern Canada is immediately related to the development of airborne electromagnetic surveys (Lulin 1990).

EM surveys can be also applied in drillholes (DHEM) measuring the effects of currents flowing between the drillhole and the surface or between contiguous holes. This method can reduce the amount of delineation drilling required. In general, DHEM is one of the most important geophysical tools in the exploration for conductive massive sulfide mineralization, especially deep nickel sulfide bodies. For many reasons (e.g., many host rocks and mineralization can give a similar geophysical signal), electromagnetic methods are useful in locating ores in some regions of the world where fresh and not oxidized rocks are present near the surface. An example of this type of regions is the recently glaciated areas of North America, northern Europe, and Russia.

Besides the described techniques, the magnetotelluric method (MT) is a passive electromagnetic technique used for exploring the conductivity structure of the Earth from tens of meters to a depth of more than 10,000 m. It is a survey method that utilizes the Earth's telluric current produced in the ground by variations of the Earth's magnetic field. The main applications of this technique are in hydrocarbon exploration. Finally, ground-penetrating radar (GPR) is a geophysical method that uses radar pulses to image the subsurface, being utilized in rock, soil, ice, fresh water, structures, etc. It can detect changes in material as well as voids and cracks.

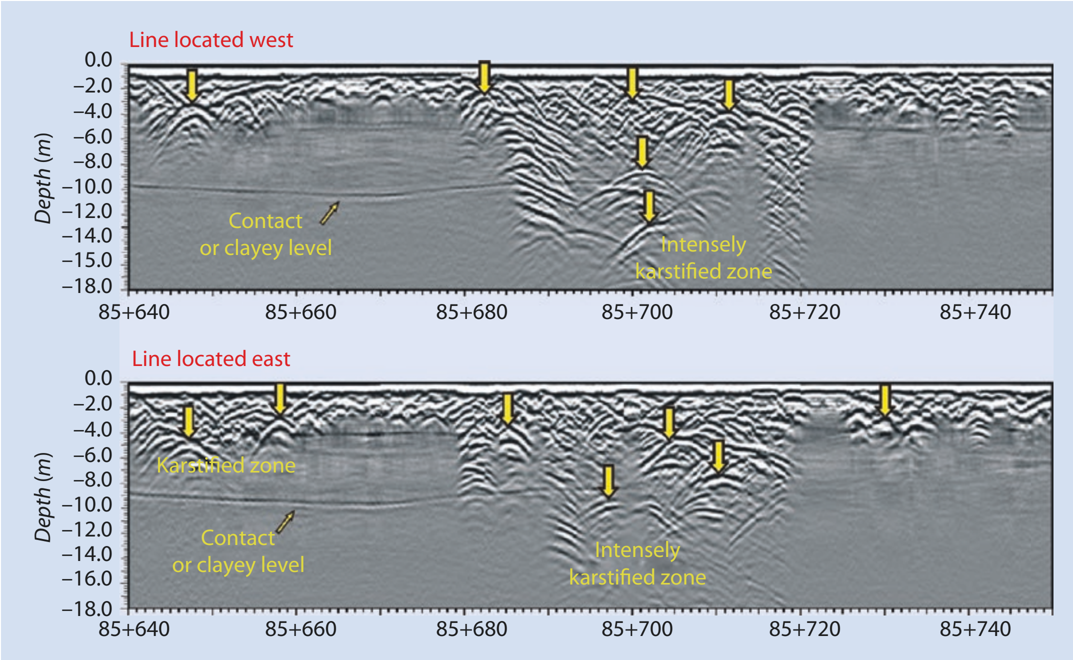


Fig. 3.25 Results of a GPR survey (Illustration courtesy of International Geophysical Technology)

This method has a great similarity with seismic method and may be considered as a mini reflection seismic survey. Figure 3.25 is an example of a GPR survey.

Seismic Methods

Seismic methods are based on measurements of the time interval between initiation of a seismic (elastic) wave and its arrival at detectors in order to obtain an image of the subsurface. The seismic wave can be generated by an explosion, a dropped weight, a mechanical vibrator, a bubble of high-pressure air injected into water, and other sources. The seismic wave is detected by a geophone on land or by a hydrophone in water. Since seismic waves (e.g., P-waves and S-waves), which propagate with different velocities in different rock types, are reflected and refracted at bedding or fault contacts, reflection and refraction are the most commonly used seismic techniques. Refraction methods use simpler equipment (Fig. 3.26) and need less processing than reflection methods. Compared with other geophysical methods, the seismic method, in any of its forms, is rarely used in mineral exploration.

Most seismic work uses reflection methods because they produce better resolution than other techniques, with the exception of measurements made in close proximity (e.g., as with borehole logs). Seismic methods dominate oil industry since reflection seismic is the most important geophysical method to prospect for oil and gas at greater depths. As aforementioned, these techniques are comparatively little used in mineral exploration, mainly due to their high cost and because most mineralizations in igneous and metamorphic rocks display incoherent layering. Applications of these techniques include searching offshore placers or subsea resources of bulk minerals such as sands and gravels. Where ores occur in sedimentary rocks that are just gently folded or faulted, seismic surveys can be useful. However, reflection work onshore is slow and expensive because geophones have to be positioned individually by hand and sources can need to be buried. The use of reflection in onshore exploration for solid minerals other than coal is consequently rare, although Witwatersrand gold reefs, flat-lying kimberlite sills, and some deep nickel sulfide bodies have all been investigated in this way (Eaton et al. 2003).

Fig. 3.26 Seismic refraction survey (Image courtesy of International Geophysical Technology)

Fig. 3.27 Electromagnetic airborne survey (Image courtesy of Geotech)

Likewise, the mining industry uses detector and/or seismic sources located in the subsurface, with access provided by drillholes or underground workings. Thus, seismic surveys can map mineralization between drillhole intersections and are used for exploration at a prospect scale and during mining. Seismic survey also utilized seismic waves that are deliberately guided through coal seams to gather information of its characteristics prior to mining (Dentith and Mudge 2014).

Airborne Geophysics

Magnetic, electromagnetic (Fig. 3.27), gamma-ray, and more recently gravity measurements do not need physical contact with the ground; therefore, they can be carried out from aircraft. Obviously, there is a loss of sensitivity because detectors are far away from sources. The main merit of airborne work is that it enables coverage of large areas quickly and inexpensively per unit area. Moreover, airborne surveys measure physical properties of rocks and ores through dense vegetation, swamps, lakes, and soils, among many others. They are usually part of the reconnaissance phase of mineral resource exploration, although some modern airborne systems offer higher resolution by surveying very close to the ground and can find application in the later stages of exploration. Airborne geophysical surveys are typically undertaken using low-flying helicopters or light aircraft that fly in a grid pattern, being the instruments mounted on the aircraft or positioned underneath. According to the survey type, the aircraft can fly ranging from 20 to 70 m above the ground and the flight lines can be delimited from 20 to 200 m apart. Airborne investigations can be flown either at a constant altitude or at a nominally constant height above the ground, which is more common in mineral exploration.

Since airborne methods need a very good navigational control, airborne surveys have been completely transformed by the use of global positioning satellites (GPS). With this instrument, velocities can be estimated with great accuracy, making airborne gravimetry, which requires velocity corrections, usable for the first time in mineral exploration. In the near future, pilotless drones can fly some airborne surveys, especially aeromagnetic surveys. In fact, drones are already used in topographic applications (◘ Fig. 3.13).

The most frequently used first stage in geophysical exploration includes the aeromagnetic survey. Thus, a magnetometer or a series of magnetometers attached to an aircraft estimate the intensity of the Earth's magnetic field, producing the detection of magnetic anomalies originated by the minerals present in the ground. Among other factors, the resolution of the data is dependent upon (a) the distance between the traverse line spacing, (b) the distance between the aircraft and the ground, (c) the magnetic signature of the aircraft itself, and (d) variations in the diurnal activity.

Airborne electromagnetic surveys generate the strongest EM responses from massive sulfides and can use man-made primary electromagnetic fields to measure the electromagnetic properties of rocks. Very low-frequency EM system can be useful as a mapping tool, particularly when combined with magnetics. Finally, airborne gravimetry measures the changes in the gravity field with an airborne gravimeter on a helicopter or an aircraft. It involves using ultra-sensitive equipment, called a gravimeter, to look at the structure density of rock in the subsurface of the Earth. New generation gravimeters back out the movement of the aircraft from the data, providing a more accurate measurement. Once corrections are made to the data, critical information can be derived for mapping purposes.

◘ **Fig. 3.28** Caliper geophysical borehole logging (Image courtesy of Robertson Geologging)

Borehole Geophysical Logging

Because exploration drillholes are usually cored completely, the industry has been slow to identify the importance of geophysical borehole logging (◘ Fig. 3.28). However, since drilling is expensive, geophysical borehole logging is essential to obtain the maximum possible information from each drillhole; in this sense, the geophysical characteristics of the rocks surrounding a borehole are often the best guides to discover the existence of ore (◘ Box 3.5: Borehole Geophysical Logging). Borehole geophysical surveys result in the higher resolution of data, especially in conjunction with geological, physical, and chemical core logging results (Ellis and Singer 2007). Downhole geophysical surveys increase the radius and depth of investigation and provide greater resolution of buried targets. For instance, in the uranium industry, borehole logging is actually a basic tool in the exploration and delineation of uranium deposits (Mwenifumbo and Mwenifumbo 2013).

3

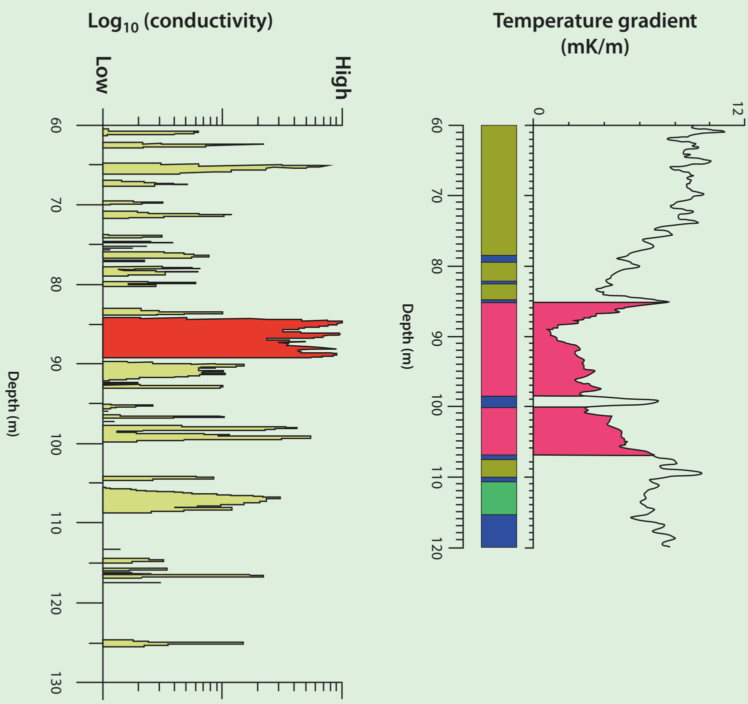
Box 3.5

Borehole Geophysical Logging

Most geophysical techniques can be modified for use in boreholes. Thus, borehole geophysics is the science of recording and analyzing measurements of physical properties made in boreholes. Compared to geophysical measurements made on the ground surface, they have better resolution in the depth dimension. Probes that measure different properties are lowered into the borehole to collect continuous or point data that is graphically displayed as a geophysical log (Fig. 3.29). Multiple logs typically are collected to take advantage of their synergistic nature because much more can be learned by the analysis of a suite of logs as a group than by the analysis of the same logs individually. The primary components of a geophysical logging system include the probe, cable, winch, wellhead pulley assembly at the top of the hole, a depth counter, and the surface recording instrumentation that displays the data and usually supplies the power to the probe. In most cases, the probe sends information up to the surface in real time, either wirelessly or via the cable. A string of different probes can be connected to collect more than one type of geophysical information. Borehole geophysical measurements are made by sensors (receivers/detectors) that are housed inside a probe. The probe is lowered downholes in which the measurements are to be made. A series of continuous measurements are made with the data transmitted to the surface. The logging speed is commonly about 6 m/min. Data sampling rates range from one sample to five samples and provide measurements every 2–10 cm along the hole.

There are two quite distinct modes of making downhole measurements: downhole logging and downhole surveying. The first is used where the in situ physical properties of the rocks penetrated by a drillhole are measured to produce a continuous record of the measured parameter. Measurements of several physical parameters, producing a suit of logs, allow the physical characterization of the local geology. Despite the valuable information obtainable, multiparameter logging is not ubiquitous in mineral exploration, but its use is increasing along with integrated interpretation of multiple geophysical data sets. On the other hand, downhole surveying is designed to investigate the larger region surrounding the drillhole, with physical property variations obtained indirectly, and to

Fig. 3.29 Borehole geophysical logs



indicate the direction and even the shape of targets. For instance, downhole electromagnetic survey detects conductivity variations, probably owing to mineralization, in the volume surrounding the drillhole. Downhole geophysical surveys increase the radius and depth of investigation and provide greater resolution of buried targets. For instance, exploration of an iron ore body could be improved by a density log. The located mineralization can be split into layers of magnetite and hematite using a magnetic susceptibility log. Common geophysical logs and/or probes include caliper, gamma, single-point resistance, spontaneous potential, normal resistivity, induced polarization, fluid resistivity, temperature, flowmeter, television, and acoustic and optical televiewer (Fig. 3.30). For instance, the caliper probe (Fig. 3.28) measures the diameter of the borehole as a continuous record against depth and is used as a check of borehole condition before casing operations or before running more expensive logging probes. Gamma logs record the amount of natural gamma radiation emitted by the rocks surrounding the borehole; clay- and shale-bearing rocks commonly emit relatively high gamma radiation because they include weathering products of potassium feldspar and mica and tend to concentrate uranium and thorium by ion absorption and exchange. The optical televiewer probe gets optical views of the wall and is useful in locating structures such as faults and also bed boundaries where there is a significant change in rock formation colors. Acoustic televiewer tools have a transmitter that scans the borehole wall with an acoustic beam, and the acoustic energy reflected at the borehole fluid and rock interface is recorded by a receiver.

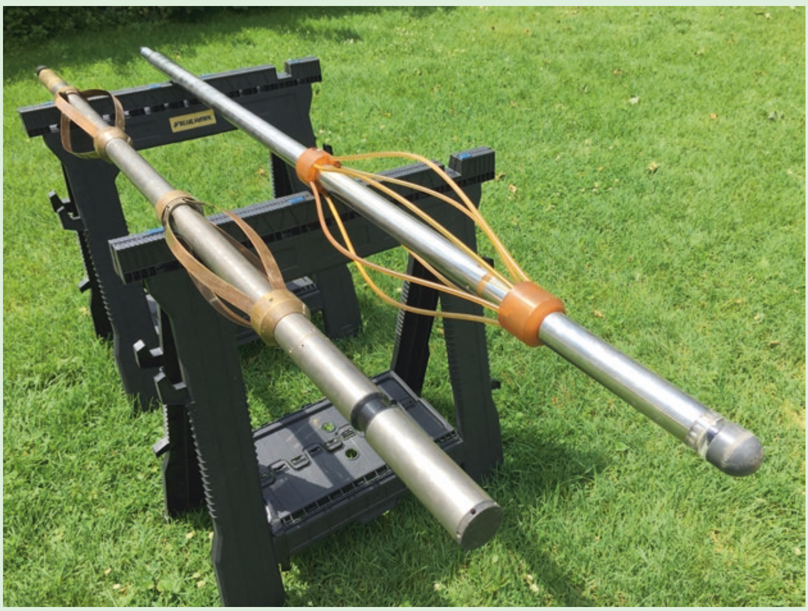


Fig. 3.30 Acoustic and optical televiewer probes (Image courtesy of Enviroscan)

3.4.5 Geochemical Exploration

Introduction

In geochemical exploration, anomalous surface enrichments of elements that point to potential mineral deposits in the subsurface are sought. For this reason, geochemical surveys play an essential role in mineral exploration because it is an essential component in most modern integrated mineral exploration programs. Geological mapping and geophysical surveys are usually carried out simultaneously with geochemical exploration. Several elements caused the quick development of geochemical exploration during the twentieth century. First, most metallic mineral deposits are surrounded by zones of uncommon trace element concentrations in the nearby and enclosing rocks. Thus, chemical deviations can be expressed by enrichment or depletion of certain minerals, elements, isotopes, etc. On the other hand, geochemical exploration has gained widespread acceptance with the development in the last decades of rapid, sensitive, and accurate analytical methods. This type of mineral resource exploration is conducted at several scales, from regional reconnaissance to very detailed local sampling at high sampling

Fig. 3.31 Soil for geochemical sampling (Image courtesy of Mari Luz García)

densities. Most exploration programs begin with regional stream sediment sampling followed by soil and then rock sampling. Geochemical surveys in mineral exploration are based on two features of an ore deposit: (1) association with abnormal concentrations of elements in the nearby rocks, and/or (2) association with secondary scattered patterns of elements in the surficial materials of their weathering and erosion; it substantially increases the area in which evidence for the presence of a mineral target can be detected.

The most commonly measured chemical property in a mineral or rock is the trace content of an element or cluster of elements. The analyzed material can be rock, soil (Fig. 3.31), gossan, glacial debris, vegetation, stream sediment, or water. Thus, «the purpose of the measurements is the discovery of a geochemical anomaly or area where the chemical pattern indicates the presence of ore in the vicinity» (Hawkes 1957). Obviously, the absence of such anomalies helps to eliminate areas for further consideration. However, it is essential to bear in mind that the basic geochemical question required 60 years of discussion: what constitutes a geochemical anomaly and how can this be enhanced (sample processing and analytical methods) and detected (a number of univariate and multivariate mathematical techniques)? (Cohen et al. 2007).

The modern techniques of geochemical prospecting originated in the Soviet Union and Scandinavia where extensive research was conducted during the 1930s (Garret et al. 2008). Modern surveys are conceptually similar to earlier surveys but are considerably more complex in their details. This complexity in modern geochemical surveys arises from several sources (Adcock et al. 2013): (1) the number of samples collected in a single survey can sometimes reach several thousand, and national- or continental-scale projects can involve numerous surveys carried out over several years. (2) different sample types (e.g., glacial sediment, multiple soil horizons, water, vegetation) can be collected at each sampling site. (3) a sample can be processed in various ways (crushing, sieving, heavy and/or magnetic mineral separation, washing, etc.) before being subjected to chemical analysis. (4) the sample can be analyzed by a variety of different methods, by different laboratories, over a time period of years or even decades. A clear example of this complexity is the China Geochemical Baselines project, which was carried out in 2008, being sampling completed in 2012. The main goal was to establish the abundance and spatial distribution of chemical elements throughout the whole China. Running the project, 6617 samples from 3382 sites were collected across the country (Wang 2015).

In general, a geochemical survey is divided into the following phases: (1) planning, (2) sampling, (3) chemical analysis, and (4) interpretation of data. As a general rule, samples are collected in

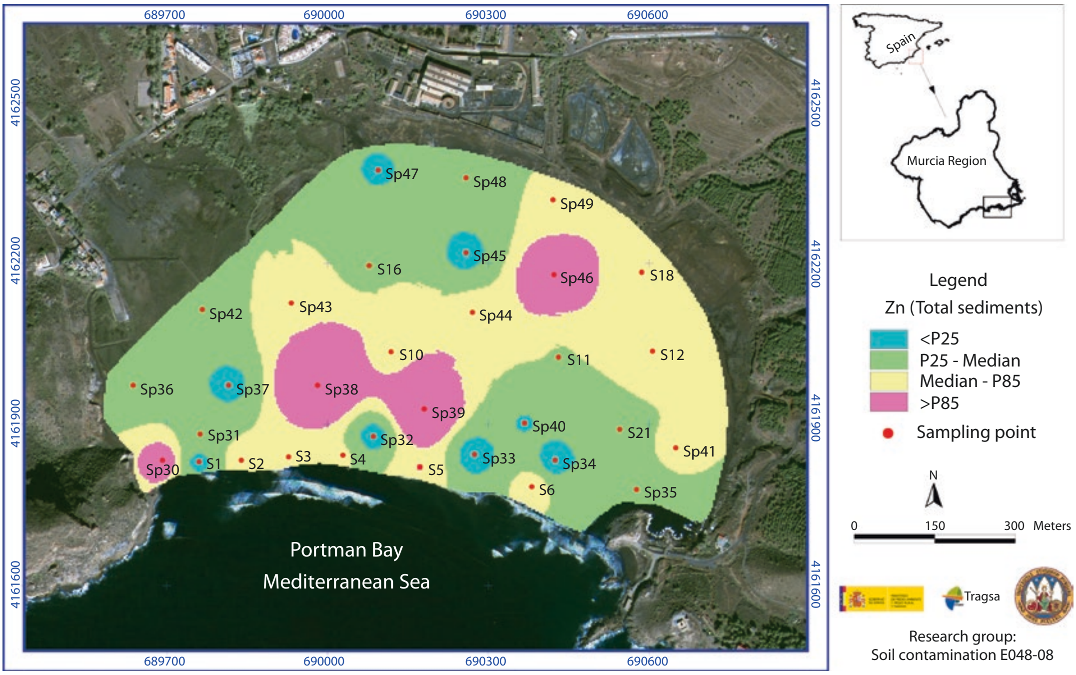


Fig. 3.32 Color contour map of a geochemical survey (Spain) (Illustration courtesy of Mari Luz García)

the field. They are brought to a laboratory facility where they are subjected to preparation prior to analysis, including crushing, sieving, drying, and filtering. The prepared samples are then sent to different laboratories for chemical analysis. Where the data are returned, they are verified and reported typically in a spreadsheet format, with a set of rows and columns. Finally, these data are processed using different statistical methods (e.g., multivariate analysis) and displayed commonly as color contour map (Fig. 3.32). The objective is to establish a geochemical anomaly that separates the mineral deposit from enhancements in background and nonsignificant deposits.

Primary and Secondary Geochemical Anomalies

Geochemical anomalies are commonly divided into primary or secondary. The primary geochemical anomalies are formed as by-product of the processes that concentrate ore; they are larger than the ore target itself. As defined originally by Safronov (1936), «the primary halo of a mineral deposit is an area including rock, surrounding mineral deposit (ore bodies) and enriched elements that make up that deposit.» In general, primary dispersion halos are produced in the host rocks at the time of ore formation. For instance, some of the fluid permeates into wall rocks in hydrothermal deposits causing different alterations which include chemical changes. Halos of this type are very useful in exploration since they can commonly be hundreds of times larger than the mineralization they surround. Moreover, they extended both laterally and vertically, hence being easier to locate. Primary dispersion halos have a great variety of sizes and shapes due to the numerous variables that influence fluid movement in rock. Thus, some halos can even be identified at distances of hundreds of meters from their related mineralization. The factors that control the development of primary halos are manifold: fractures in the host rock, porosity and permeability of the host rock, inclination of mineralizing fluids to react chemically with the host rock, and so on. Obviously, the composition and distribution of these primary halos depend on the type of deposit. For instance, porphyry copper deposits usually display chemical halos that measure hundreds of meters horizontally and vertically.

Since trace elements of mineralization and their linked primary halos are commonly discharged by weathering processes to soils, overburden, and vegetation, they generate a subsequent generation of enrichment called secondary halos. Thus, secondary geochemical anomalies or halos are formed by processes that acted on the deposit after its formation. These types of halos are generated by mechanical breakdown and chemical dissolution of rocks and ores. Chemical weathering involves breakdown of rocks and minerals by chemical means with further discharge of their contained trace elements to the environment. It requires abundant water, oxygen, and carbon dioxide. In general, chemical weathering is more abundant in tropical regions although it can also be substantial in temperate areas. In turn, physical weathering includes all processes of rock disintegration not involving chemical changes, being more frequent in very cold or hot arid regions.

Mechanical breakdown and further transport in surface water runoff concentrate resistant minerals such as cassiterite, rutile, monazite, diamonds, gold, etc. Therefore, anomalies are detected by heavy mineral panning of stream sediments or soils. Other minerals can be dissolved and the metals can be either redeposited locally or carried away into solution by ground- and surface water. Groundwater frequently dissolves some of the constituents of mineralized bodies that can be transported along considerable distances before eventually emerging in springs or streams. During dispersal, the elements can be reconcentrated in vegetation, on clay minerals, or in organic matter, all of which are attractive sampling media in geochemical exploration. Regarding the vegetation, some metals in solution can be collected by plants and trees and then concentrated in the living tissue. In some cases, the element that originates the most important primary halo is not necessarily the one of greatest economic significance in the mineralization.

Mobility is an indicator of how far an element can go dissolved in water, broadening the signal originated from the mineral deposit. For this reason, the usefulness of the mobility of an element is essential in geochemical prospection. This type of element is commonly referred to as a pathfinder. The pathfinders are very useful in geochemical exploration since their halo is generally greater than that of the element with the most economic interest or because it can be identified more easily by classical analytical procedures (Table 3.3). For instance, arsenic is commonly utilized as a pathfinder in exploration for gold. The choice of pathfinder elements/metals depends on many factors such as consistency of association with the ore deposits sought, characteristics of primary dispersion, and ease with which geochemical analysis can be performed (Levinson 1974).

The variable mobility of elements is of great significance in the process that causes secondary dispersion. Elements with high mobility under surficial conditions enlarge the anomalous zone. For instance, a project targeting polymetallic deposits of Pb, Zn, and Cu would use mobile Zn for regional sampling with a low density, whereas dense sampling of Zn anomalies for Cu and Pb should reveal the drilling targets (Pohl 2011). In this context, there are many important properties in the elements such as electronic configuration, ionic potential, pH and Eh, trend to originate complexes with organic matter, and trend to coprecipitate or to be absorbed with iron or manganese hydroxides.

The mobility of elements in secondary dispersion is strongly influenced by factors including the nature of rocks, climate, vegetation, relief, and groundwater flow. Thus, in cold climate, large and well-defined anomalies do not develop because chemical dissolution is inefficient and drainages are poorly developed; in dry, arid climate, chemical dissolution is ineffective and dispersal by occasional flash floods does not lead to the formation of well-defined anomalies. By contrast, in tropical climate decomposition and leaching of the ore-forming elements can be so complete that no traces of the metals remain in weathered rocks or soils. Therefore, the best environment for geochemical exploration is located in a temperate climate in regions of gentle topography, in which abundance of water and warm temperatures leads to effective dissolution of ore minerals and the gentle topography fosters both chemical dissolution and the development of good secondary dispersion halos (Gocht et al. 1988).

Stream Sediment Sampling

Stream sediment geochemical surveys are the cornerstone of all types of reconnaissance exploration, mainly in regions undergoing active weathering.

Table 3.3 Major components and pathfinders for different types of mineral deposits (Moon 2006)

Type of deposit	Major components	Pathfinders
Magmatic deposits		
Chromite ores (Bushveld)	Cr	Ni, Fe, Mg
Layered magnetite (Bushveld)	Fe	V, Ti, P
Immiscible Cu–Ni–sulfide (Sudbury)	Cu, Ni, S	Pt, Co, As, Au
Pt–Ni–Cu in layered intrusion (Bushveld)	Pt, Ni, Cu	Sr, Co, S
Immiscible Fe–Ti–oxide (Allard Lake)	Fe, Ti	P
Nb–Ta carbonatite (Oka)	Nb, Ta	Na, Zr, P
Rare-metal pegmatite	Be, Li, Cs, Rb	B, U, Th, rare earths
Hydrothermal deposits		
Porphyry copper (Bingham)	Cu, S	Mo, Au, Ag, Re, As, Pb, Zn, K
Porphyry molybdenum (Climax)	Mo, S	W, Sn, F, Cu
Skarn-magnetite (Iron Springs)	Fe	Cu, Co, S
Skarn–Cu (Yerington)	Cu, Fe, S	Au, Ag
Skarn–Pb–Zn (Hanover)	Pb, Zn, S	Cu, Co
Skarn–W–Mo–Sn (Bishop)	W, Mo, Sn	F, S, Cu, Be, Bi
Base metal veins	Pb, Zn, Cu, S	Ag, Au, As, Sb, Mn
Sn–W greisens	Sn, W	Cu, Mo, Bi, Li, Rb, Si, Cs, Re, F, B
Sn–sulfide veins	Sn, S	Cu, Pb, Zn, Ag, Sb
Co–Ni–Ag veins (Cobalt)	Co, Ni, Ag, S	As, Sb, Bi, U
Epithermal precious metal	Au, Ag	Sb, As, Hg, Te, Se, S, Cu
Sediment hosted precious metal (Carlin)	Au, Ag	As, Sb, Hg, W
Vein gold (Archaean)	Au	As, Sb, W
Mercury	Hg, S	Sb, As
Uranium vein in granite	U	Mo, Pb, F
Unconformity associated uranium	u	Ni, Se, Au, Pd, As
Copper in basalt (L. Superior type)	Cu	Ag, As, S
Volcanic-associated massive sulfide Cu	Cu, S	Zn, Au
Volcanic-associated massive sulfide Zn–Cu–Pb	Zn, Pb, Cu, S	Ag, Ba, Au, As
Au–As rich Fe formation	Au, As, S	Sb
Mississippi Valley Pb–Zn	Zn, Pb, S	Ba, F, Cd, Cu, Ni, Co, Hg
Mississippi Valley fluorite	F	Ba, Pb, Zn
Sandstone-type U	U	Se, Mo, V, Cu, Pb
Red bed Cu	Cu, S	Ag, Pb
Sedimentary types		
Copper shale (Kupferschiefer)	Cu, S	Ag, Zn, Pb, Co, Ni, Cd, Hg
Copper sandstone	Cu, S	Ag, Co, Ni
Calcrete U	U	V

Stream sediment sampling can be applied only if a well-developed drainage system is present. In this technique, stream sediments are taken from active stream channels and studied to find anomalous element concentrations since the sediment sample from an active riverbed is considered to represent an average of its upstream watershed. Thus, the objective is to obtain sample(s) representative of the catchment area. The relatively easy use of the method leads to a quick evaluation of regions at fairly low cost.

Small streams give maximum resolution and sharpest contract, as opposed to large streams in which any anomaly from a mineralized zone will be diluted by large amounts of stream sediment from barren areas. Sampling densities are about one sample per two square kilometers in regional reconnaissance programs. In more detailed investigations, higher density of sampling density is usually carried out depending on the local conditions and the characteristics of the target. For instance, sampling densities can range from one sample over 100 km^2 in reconnaissance studies to a few samples per km^2 in more specific follow-up. In general, the values of the background and anomalous element concentrations are computed statistically, and metal distributions are illustrated in geological maps. Previously, samples are sieved to 80 mesh (0.157 mm) and the fine fraction is analyzed since it reflects better metal anomalies. It is important to remember that the coarser fractions commonly include pebbles, which are usually depleted in trace elements.

Panning heavy minerals to obtain concentrates is also a classical method of stream sediment studies, being a very useful geochemical prospecting technique (e.g., panning for gold). Panning refers to the process in which a sample is agitated in water to separate minerals by their specific gravity. Thus, heavy mineral panning is widely employed for searching native elements such as gold grains, platinum, diamonds, and heavy resistant mineral grains such as magnetite, zirconium, ilmenite, rutile, monazite, and cassiterite. If positive results are obtained, immediately follow-up campaign is carried out to look for the source of the anomaly.

Soil Sampling

Soil sample geochemistry is a powerful tool in the exploration of anomalies found by stream sediment investigations. The method works very well since weathering and leaching of buried deposits can discharge anomalous concentrations of elements to soil and groundwater. The released heavy metals spread outward and originate a dispersion halo in the soil that is much larger than the mineral deposit itself. As a rule, the dispersion halos in soils are smaller than those in stream sediments but larger than those in primary halos in rocks. Similar to stream sediment sampling, samples collected (■ Fig. 3.33) are commonly the fine silty or

■ **Fig. 3.33** Soil sampling (Image courtesy of Mari Luz García)

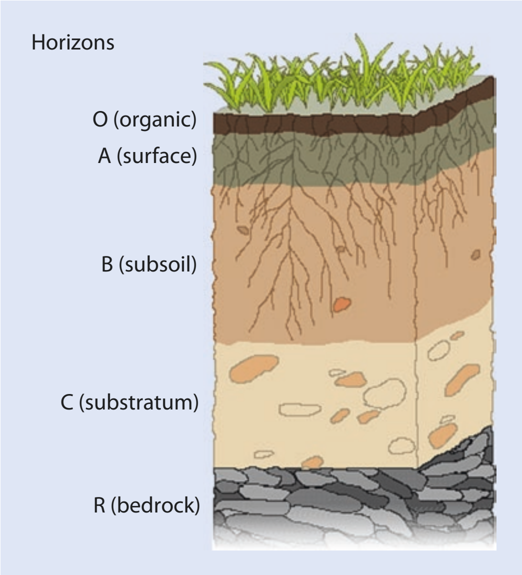


Fig. 3.34 Soil profiles

clayey material that results from weathering of the underlying bedrock, being usually obtained just below the organic-rich surface grassroots layer.

It is a comparatively expensive technique and is typically carried out in detailed exploration where it is used to identify specific targets for drilling. Soil geochemistry surveys can be performed on a regional basis in areas without well-developed drainages to allow stream sediment surveys. The dispersion halos of elements in soils are much smaller than those in stream sediments but still considerably larger than those in primary halos in rocks. Soil sampling is especially recommended in areas of residual soil over any bedrock and in areas with soil developed on in situ regolith.

Elements can accumulate in different forms within a soil profile (Fig. 3.34). Traditionally, B-horizon has represented a position where elements have concentrated as minerals such as silicates, iron oxyhydroxides, and carbonate crusts. This preconcentration can represent an ideal sample material for collection. It is also the most homogeneous horizon and provides the best sampling medium. The C-horizon, which is closest to the rock, generally shows little dispersion of the target elements. The A-horizon, the uppermost soil horizon, can show the largest dispersion, but a variable content of organic matter leads to irregular element distribution. AS analytical technology has advanced, becoming increasingly sensitive, new possibilities have been developed related to the positions where the target and pathfinder elements can be analyzed.

Regarding the sample spacing in soil sampling, sampling density and patterns are determined by the style of target, stage of exploration, topography of the exploration area, prospective geology, and orientation of the anomaly. Soil samples are typically collected on a rectangular pattern, generally with closer spacing of sample sites along more widely space sample lines. The optimum spacing between sampling lines and sample sites will depend on the purpose of the survey and the expected size of the dispersion halo to be detected. For instance, usual sample spacing for reconnaissance studies ranges from 200/400 to 400 m. For more detailed anomaly investigation, samples are taken at 100 m intervals on 200 m spaced lines. In this case, an infill sampling down to 50 m on 100 m spaced lines is commonly carried out. The main goal is to acquire at least two samples from the detected anomaly on a sampling line.

Water Sampling

In general, water samples collected from springs, wells, boreholes, and streams are rarely useful for mineral deposit exploration. According to Pohl (2011), dissolved metal content in water is usually very low, in the ppb range, and varies strongly with pH and Eh, which makes interpretation difficult. Thus, the concentration of elements of geochemical interest is very low compared to that in stream sediments. For these uncertainties, hydrogeochemistry is not a widely method used in exploration. However, high concentrations of chemical elements can be found in groundwater. For this reason, groundwater surveys are preferred to surface water studies. Groundwater surveys are commonly conducted in conjunction with soil studies for detailed surveys. Thus, groundwater has the potential to be a powerful mineral exploration tool for different considerations: «(1) recent advances in analytical methods have resulted in lower detection limits; (2) groundwater is chemically reactive with mineralization and host rocks, in particular where water is O_2-bearing; (3) groundwater flows away from the site of reaction with mineralization, providing a potentially broader exploration target than lithogeochemistry; and (4) for many species of interest, background concentrations are low, enhancing anomaly contrast» (Leybourne and Cameron 2007). Interpretation of groundwater geochemistry in mineral exploration is easier if data related to the local and regional hydrology is available.

Rock Sampling

Rock geochemical surveys seek the primary dispersion halo around mineral deposits. Because this type of halos is restricted to a small area immediately surrounding any prospective mineral deposit, rock surveys are mainly applied to evaluate specific targets outlined by regional surveys. Although this technique has been also applied with relatively good results in regional reconnaissance, it becomes most effective in detailed campaigns (Moon 2006), being rock sampling included in the techniques devoted to for follow-up mineral exploration. It provides direct evidence about the geochemical characteristics of the rocks that cause the anomaly, helping in the geological interpretation of stream sediment and soil surveys (Govett 1983).

Geochemical exploration with rock samples or selected minerals is based on specific geological-petrological models. Examples include regional sampling of granites in order to locate fertile intrusions, discrimination of prospective and barren porphyries by analyzing copper in biotite, and identification of rare metal pegmatites by muscovite analysis (Pohl 2011). On a regional basis, the most successful applications deal with delineation of mineralized felsic plutons and exhalative horizons because these plutons with mineralization of copper and tungsten are commonly enhanced in these elements, although invariably display a high variability inside the pluton. For instance, tin mineralization associated with highly evolved and altered intrusive bodies is delineated examining the geochemistry of minerals such as micas.

Biogeochemical Sampling

Biogeochemistry is a viable first-pass exploration method, and it can show multi-element halos at small scale, being more refined if more detailed exploration methods are carried out in the target. Biogeochemical sampling is a relatively cheap, efficient, and environmentally passive method in the initial stages of mineral exploration programs (Reid and Hill 2010). Biogeochemical techniques utilized in mineral deposit prospecting are based on soil and plant relationships. In this sense, plants incorporate elements from soil and groundwater into their branches and leaves, and this absorption of trace elements depends on the plant species, plant organs, grow stage, and soil type. Biogeochemical exploration with sampling and chemical analysis of plant tissues has been utilized extensively in Canada and Russia and more recently in Australia (Närhi et al. 2014).

Plant samples (Fig. 3.35) have benefits compared to other sample media in terms of providing data that represent a broad area, due to their deep spreading root systems. Biogeochemical

Fig. 3.35 Biogeochemical sampling of plants (Image courtesy of Andrea Castaño)

exploration «relies on the fact that plant roots penetrate soil horizons, have access to weathered/fractured bedrock and associated groundwater, and accumulate elements in their organs» (Dunn 2007). Accordingly, if some plant organs include excessive amounts of particular metals, they can be used as indicators of ore zones in bedrock for geochemical exploration (Brooks et al. 1995). Plant growing on soil is dramatically affected by the host soil composition, which leads to the selection of specific flora. Thus, plants answer to elemental composition of soil in three ways: exclusion, indication, and accumulation (Rajabzadeh et al. 2015). Biogeochemists use soil indicator plants for prospecting ore deposits. For instance, because serpentine plants have been studied and ultramafic rocks are profuse on the crust of the Earth, plants growing on serpentinized materials are satisfactorily utilized in biogeochemical exploration (Freitas et al. 2004).

Gas Sampling

At present, mineral deposits susceptible to be prospected are commonly buried deep below the surface of the Earth. However, the alteration and oxidation of a deposit release gaseous components that can be detected at the surface using gas samples from soil or down drillholes. This method can identify a few different gases if they are present in sufficient amount (e.g., mercury, oxygen, CO_2, and radon) (◘ Fig. 3.36). The characteristics of these gases and their concentration can provide hints on minerals occurring at depth and, consequently, where a mineral deposit can be present.

Gases are potentially an attractive medium to sample because they can diffuse through thick overburden. Thus, a number of gases have been used in mineral exploration: sulfur vapors indicate the presence of sulfide deposits, radon gas guides to uranium deposits, and gaseous hydrocarbons reflect the presence of petroleum and natural gas. However, mercury has been the most successful gas studied in mineral prospecting due to mercury is the only metallic element that constitutes a vapor at room temperature. Thus, it is widely present in sulfide deposits, particularly volcanic-associated base metal deposits. Enrichment of carbon dioxide and depletion of oxygen produced by weathering of sulfide mineral deposits have been tested recently. The results are commonly inconsistent due to the large changes in gas concentration (partial pressure) caused by variations in environmental conditions, specifically changes in pressure and rainfall.

Indicator Minerals

Indicator minerals are mineral species transported as grains in clastic sediments and indicating the presence in bedrock of a specific type of mineralization, hydrothermal alteration, or lithology (◘ Fig. 3.37). The preservation and identification of these minerals is provided by their physical and chemical characteristics, including relatively high density. They are quickly recuperated at the parts per billion level from stream, alluvial, glacial, or aeolian sediments or soils producing large exploration targets. Indicator mineral methods differ from

◘ **Fig. 3.36** Measurement of soil radon using a soil gas probe (Image courtesy of DURRIDGE Company Inc.)

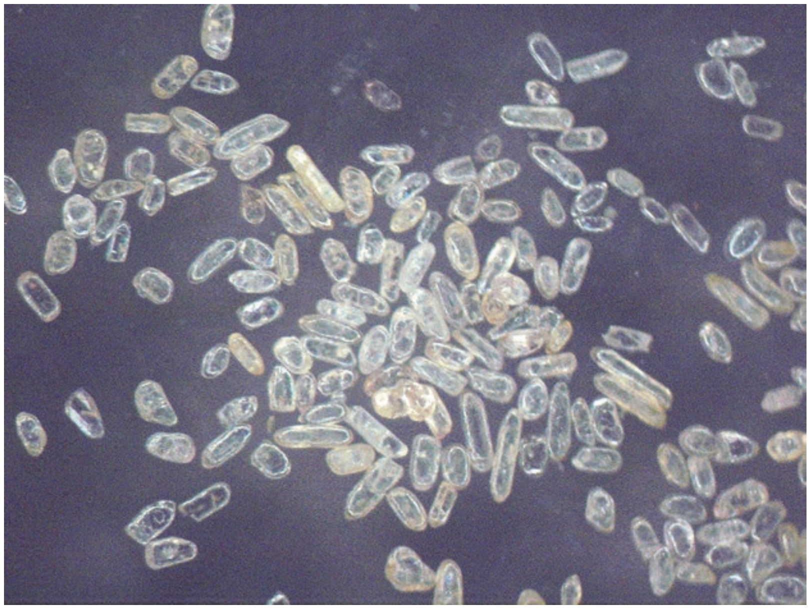


Fig. 3.37 Zircons used as indicator minerals (Image courtesy of Javier Fernández)

traditional geochemical methods for soil, stream sediment, or till sampling in that the indicator grains reflect mechanical dispersion and the individual grains are visually examined and counted. The greatest advantage of indicator mineral methods over traditional geochemical analysis of the heavy mineral or some other fraction is that the mineral grains are visible and can be studied (McClenaghan 2005). The choice of sample media will depend on the climate, topography, and size of area to be sampled. For example, in glaciated terrain, till is most often used for indicator mineral surveys due to its simple transport history. Stream and alluvial sediments are sampled in glaciated, temperate, tropical, and arid terrains. In turn, aeolian sediments can be sampled in arid terrain where other media are not available.

Nowadays indicator minerals are used to detect a great number of mineral deposits such as diamond, gold, Ni–Cu, PGE, porphyry Cu, massive sulfide, and tungsten deposits. The resulting benefits of using indicator minerals are numerous: (1) the ability to detect halos or plumes much larger than the mineralized target including associated alteration; (2) physical evidence of the presence of mineralization or alteration; (3) the ability to provide information about the source that traditional geochemical methods cannot, including nature of the ore, alteration, and proximity to source; (4) sensitivity to detect only a few grains, equivalent of ppb-level indicator mineral abundances (Averill 2001). One of the most important and typical occurrences in the application of indicator mineral techniques was the bloom in diamond exploration activity in the glaciated terrain of Canada, which originates drastic changes in the concepts of sampling and processing methods because indicator minerals improved the knowledge of kimberlite host rock. Since most of Canada has been glaciated, the glaciers advanced, eroded, homogenized, and redistributed the components of the bedrock that they pass over. For this reason, diamonds in glacial drift are the best indicators of a bedrock source of diamond. However, they are very scarce even in the highest-grade diamond-bearing rocks. For example, one carat – 0.2 g – of diamond per ton of mineralization is regarded a very high-grade diamond deposit. As a result, indicator minerals are an indirect but very useful tool to locate bedrock sources of diamond.

Analytical Methods

The analytical methods applied in geochemical exploration depend on the requirements of exploration stages. Techniques can be grouped according to the attribute being measured. Some techniques utilize X-rays in different forms for analytical objectives, while other techniques use the optical effects of samples. Obviously, each method has a minimum detection limit and below the concentration cannot be calculated. Therefore, geochemical analysis has a degree of uncertainty, being uncertainty expressed in terms of precision. The theoretical lower detection limit is an intrinsic function of the technique, although the quality of the calibration and the cleanliness of the equipment used in sample and standard preparation also limit detection. The goal of most analysis is the determination of the trace metal concentrations in a sample, but currently it is still impossible to analyze all elements simultaneously at the needed levels.

The differences between methods are the costs involved, analysis detection limits, velocity of analysis, and the requirement to take material into solution. The method selected will depend upon the element being analyzed and the amount expected. In developed countries, most common analysis is actually performed by inductively coupled plasma optical emission spectrometry (ICP-OES), often in combination with inductively coupled plasma mass spectrometry (ICP-MS) and X-ray fluorescence (XRF) (◘ Box 3.6: X-Ray Fluorescence Analysis). The three methods require numerous constraints such as highly sophisticated laboratories, very pure chemicals, continuous and nonfluctuating power supplies, and readily available service personnel, among others. In less sophisticated situations, relatively high quality analysis can be carried out using atomic absorption spectrophotometry (AAS), which was the most commonly utilized technique in developed countries until 1980. Regarding individual minerals, detailed identification is commonly provided

Box 3.6

X-Ray Fluorescence Analysis

X-ray fluorescence (XRF) analysis (◘ Fig. 3.38) is one of the most common relatively nondestructive methods for qualitative as well as quantitative (more interesting in mineral exploration) determination of elemental composition of materials. This technique is extremely versatile and is suitable for solids, liquids, as well as powders and can be used to measure many elements simultaneously. The relative ease and low cost of sample preparation and the stability and ease of the use of X-ray spectrometers make this one of the most widely used methods for analysis of major and trace elements in rocks and minerals. In the field, portable X-ray fluorescence analyzers are increasingly used for on-site data acquisition. The lightweight portable nature of the this instrument allows it to be used in the field to survey locations of potential mines directly as well as measuring drill cores to determine the depth profiles of the mineral deposit.

X-rays cover the part of the electromagnetic spectrum between ultraviolet and gamma radiations and are produced by a radioactive source, an X-ray tube, and a synchrotron radiation. XRF technique consists in the study of the produced characteristic spectrum because each element has its unique characteristic energy spectrum (fluorescence spectrum) composed by the allowed transitions of the specific atom in the result of X-ray excitation. In general, a quantitative XRF analysis can be conducted using two basic methods: (a) creating a standard curve: this method involves measuring several samples with a known element concentration (standard reference materials) and finding the relationship between the intensity of the measured element's fluorescent X-ray and the concentration; by referring this relationship, element concentration of unknown sample is obtained only with information on its fluorescent X-ray intensity; or (b) considering the type and properties of all elements that compose a sample, the intensity of each fluorescent X-ray can be derived theoretically: with this method, the composition of unknown sample can be extrapolated by the fluorescent X-ray intensity of each element.

XRF is useful for the geochemical analysis of a wide range of metals and refractory compounds, such as SiO_2 and Al_2O_3, and even some nonmetals (chloride and bromide). The quality of XRF data is a function of the selection of appropriate standards. It is considered best practice to use standards that are similar to the samples in question to minimize matrix effects. XRF can measure down to parts per million concentrations and lower, depending on the element and the material. Regarding the detection limit of each element, it depends upon the specific element and the sample matrix, but in general heavier elements have higher detection limit.

Because X-ray spectrometry is essentially a comparative method of analysis, it is vital that all standards and unknowns be presented to the spectrometer in a reproducible and identical manner. Any method of specimen preparation must give specimens which are reproducible and which, for a certain calibration range, have similar physical properties such as surface roughness, particle shape, particle size, homogeneity, and particle distribution. In addition, the specimen preparation method must be rapid and cheap and must not introduce extra significant systematic errors, for example, the introduction of trace elements from contaminants in a diluent. Thus, specimen preparation is essential in the ultimate accuracy of any X-ray determination.

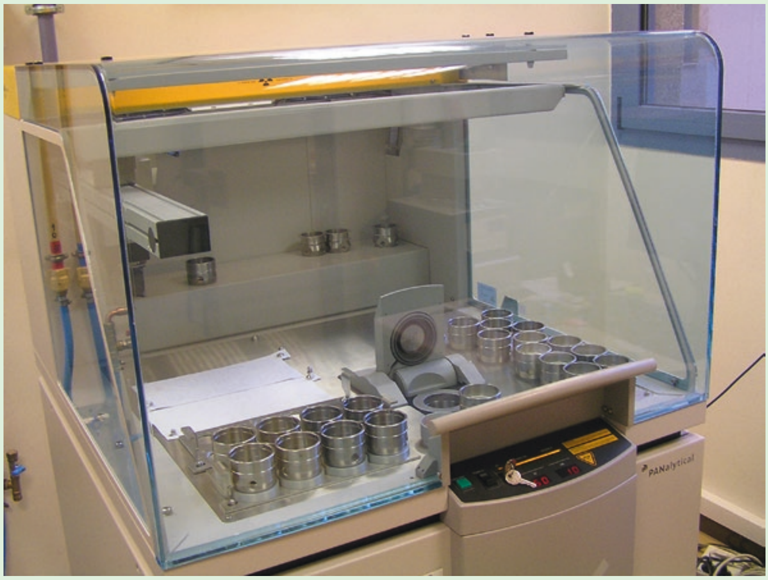


Fig. 3.38 XRF analyzer (Image courtesy of AGQ Labs)

utilizing a scanning electron microscope (SEM) or an electron microprobe.

The advent of sensitive, rapid throughput instrumentation such as ICP-OES and ICP-MS used to complement one another has revolutionized exploration geochemistry in the last decades. ICP-OES and ICP-MS are widely used because of their convenient, virtually simultaneous multi-element capabilities. Plasma used in these techniques permits the simultaneous analysis of up to 40 elements, which means that ICP-MS and ICP-OES (Fig. 3.39) are multi-element techniques. In some cases, detection limits for certain elements can be as low as parts per trillion level in aqueous solutions. AAS uses the absorption of light to estimate the concentration of gas-phase atoms. Concentrations are commonly established using a working curve after calibrating the instrument with standards of known concentration.

In exploration geochemistry, it is very important to note that absolute element content in a sample is not always necessary or, in other words, accuracy cannot be essential. Deviations of ±30% from the absolute value, for example, using international standards, are

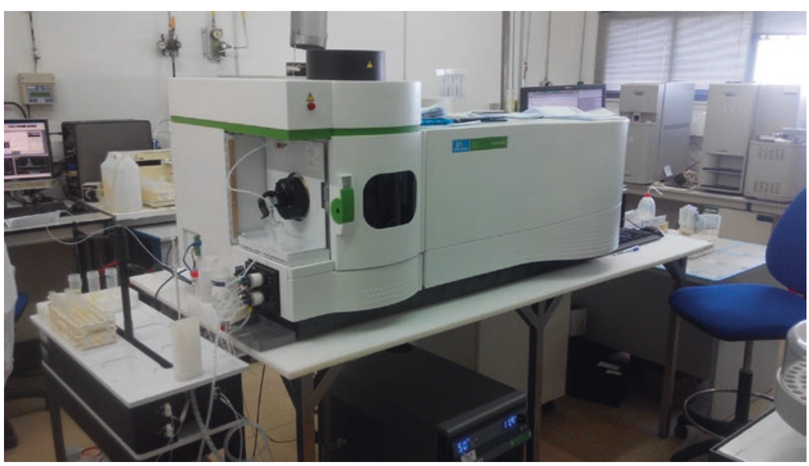


Fig. 3.39 ICP-OES instrument (Image courtesy of AGQ Labs)

endured, if the relative error remains within narrow limits. In contrast, excellent reproducibility of results (high precision) is needed. In fact, this is the most important characteristic of any data evaluation, particularly if the contrast between background and anomalies is small. In all geochemical programs, error control is a fundamental aspect, and for this reason, it is good practice to repeat at least 10% of sampling and/or control the data by another laboratory (Pohl 2011). The process of analysis is generally done at some distance from the exploration project, which means that analytical data is usually accepted and utilized without making criticisms. However, while most laboratories generate good quality results, they are usually looking for a business to make a profit. For this reason, a good quality control minimizes biases, confirms that laboratory assays are correct within a defined degree of accuracy and precision, and detects the presence of contamination between samples.

Interpretation of Data

Introduction

Once the analytical data have been obtained from the laboratory and the results are checked for precision and accuracy, the next question is how to treat and interpret the data. A geochemical exploration data set consists mainly of sample location and values of element concentration in many samples. Since the data are usually multi-element and the number of samples is large, the use of statistical analysis using computer software is essential. This is because the development of low-cost, rapid multi-element analytical techniques has originated large geochemical databases in many exploration programs, including usually thousands of observations with as many as fifty or more elements. Thus, the resulting data matrix is enormous, and effective interpretation utilizing all of the elements becomes cumbersome.

To study these large matrices, the use of multivariate statistical techniques can extract geochemical patterns related to the underlying geology, weathering, alteration, and mineralization. Modern methods of evaluating data, structures, and patterns are clustered under the term «data mining.» This term involves the use of multivariate data analysis and statistical methods in combination with geographic information systems and significantly assists the objective of data interpretation and further model building (Grunsky 2010). It involves the use of automatic and knowledge-based procedures for the recognition of patterns that can be attributed to known processes (e.g., crystal fractionation, hydrothermal alteration, or weathering).

According to Grunsky (2010), issues dealing with geochemical data are numerous: «(a) many elements have a censored distribution, meaning that values at less than the detection limit can only be reported as being less than that limit; (b) the distribution of the data is not normal; (c) the data have missing values: not every specimen has been analyzed for the same number of elements; often, missing values are reported as zero, which is not the same as a specimen having a zero amount of an element and this can create complications in statistical applications; (d) combining groups of data that show distinctive differences between elements where none is expected; this can be the result of different limits of detection, instrumentation or poor quality control procedures; and (e) the constant sum problem for compositional data.» These problems generate difficulties to apply typical statistical procedures to the data. For instance, in the case of varying detection limits, the data need separation into the original groups so that appropriate adjustments can be applied to the groups of data. To avoid the problems of censored distributions, different processes have been designed to estimate replacement values for the objectives of statistical calculations. On the other hand, if missing values are present, several methods can be provided to impute replacement values that have complete analyses.

The normal concentration of an element in non-mineralized Earth materials is referred to as background, which fluctuates around a mean value. It is more realistically viewed as a range of values rather than an absolute value because the distribution of any element in any particular Earth material is rarely uniform and varies considerably from one type of Earth material to another and from one location to another. The upper limit of the range of background values is called the threshold, and uni-element concentrations greater than the threshold are collectively called anomaly. Regarding the concept of threshold, it is possible that in the same exploration project, a lower threshold can be applied in regional exploration, whereas a higher threshold is selected to locate the best targets for further drilling campaigns. Anomalous uni-element concentrations that indicate presence of mineral deposits are called significant anomalies. Thus, the identification of a geochemical anomaly needs an implementation of a geochemical background, which in itself can be difficult to establish. As a rule, geochemical values that deviate too far from the background (values that are atypical) can be considered as anomalous.

In an exploration area, anomalies can be delineated once threshold values in individual uni-element data sets are determined. Analysis of frequency distributions of uni-element concentrations is commonly the easiest way to define the modeling of geochemical thresholds. To do that, there are many classical methods such as comparison of data from the bibliography, data comparison with results of an orientation geochemical survey, graphical discrimination from a histogram of the data, or estimation of thresholds as the sum of the mean and some multiples of the standard deviation of data.

A method of selecting threshold values that is still much used involves calculating the mean (m) and standard deviation (s) of the data set and «applying the classification of anomalous to those values that exceed the value of m + 2 s» (e.g., Hawkes and Webb 1962). This ancient definition was based on the assumption of normality of the data, and its application is no longer legitimated in many cases. In this sense, the introduction of computer-based methods for evaluating geochemical data has provided powerful tools to identify outliers and specimens that can be related to mineralization targets. As a result, the previous commented method of selecting thresholds with the calculation of the mean plus two standard deviations can be erroneous, and a better method is the use of percentiles, specifically 97.5 percentile.

Exploratory data analysis (EDA) is concerned with studying geochemical data to detect patterns or structures in the data. The methods of exploratory data analysis can be grouped in univariate, bivariate, and multivariate methods. Davis (2002) and previous editions of this classical book (the first edition was at 1973) offer an invaluable support to understand the application of these statistical techniques to geological sciences, especially in multivariate techniques. SPSS and Statgraphics are common statistical software packages used in this type of data interpretation.

Univariate Methods

Univariate methods relate to each element separately and with data for which only one variable is considered at a time. These types of methods are crucial in statistically oriented geochemical studies, in particular in the interpretation of results of multivariate methods because achievements derived from multivariate studies can be often predicted by a detailed univariate approach. Many of the exploratory and descriptive methods introduced in this section are recommended as routine ways of investigating properties of new data, even if the final analysis required is bivariate and/or multivariate.

Summary Statistical Tables (Descriptive Statistics)

These types of tables provide useful descriptions of data where quantitative measures are desired. Usually, they show listings of the minimum, maximum, arithmetic mean, median, mode, kurtosis, skewness, etc. Measures of dispersion, a measurement of the spread of data values, include variance, standard deviation, and coefficient of variation (CV). The latter parameter is useful because the mean divided by the standard deviation is expressed as a percentage and represents a relative measure for comparison of different elements.

Skewness means lack of symmetry. A distribution is symmetrical where the frequencies are symmetrically distributed about the mean. The mean, mode, and median coincide in such a type of distribution. Positively skewed distributions occur where the mean is greater than the median and the tail end is more to the right (high values). This is in contrast to negative skewed distributions, where the tail end is toward the left (low values) (◘ Fig. 3.40). Skewness is important as it indicates whether a distribution is described as normal or lognormal. The coefficient of variation is commonly used for this purpose: values of CV less than 0.5 indicate normal distribution whereas values greater than 0.5 indicate skewness and usually represent a lognormal distribution or a combination of distributions.

The analysis of percentiles allows handling of univariate geochemical data. In a data set, the first percentile corresponds to the value of the variable below which 1% of the entries lie. The 50th percentile (median) divides the data set into two

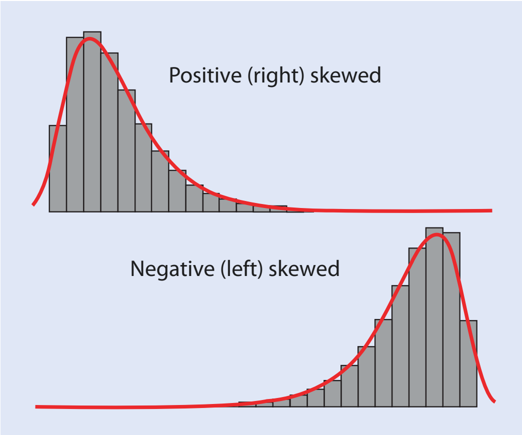


Fig. 3.40 Positive and negative skewness

equal parts. The 25th and 75th percentile are also typically used; they are known as quartiles and are used to calculate the interquartile range (IQR).

Summary tables are useful for the purpose of publishing actual values. However, as described below, graphical methods contribute to visualize the type of distributions and the relationships between observations. The values of a summary table are more easily interpreted where they are combined with graphical summaries.

Box (and Whisker) Plot

The box plot displays order statistics in a graphical form. Unlike the histogram, the shape of the box plot does not depend on a choice of interval. The box plot provides fast visual estimate of the frequency distribution and allows comparison of sets of data. Box plots are made of a rectangular box covering the central 50% of the data set. «Hinges» of the box are the 25th and 75th percentile values, respectively, and the median is marked by a line at the appropriate value (Fig. 3.41). The symmetry and skewness of the data are well reflected; if the data are symmetrically distributed, they are more central and closer to each other. Lines that extend beyond the box are called «whiskers,» whose lengths on each side of the box are indicative of the symmetry of the distribution.

Histograms

Histograms are formed of contiguous upright rectangles (Fig. 3.42). The width of the rectangles indicates the range of values for a particular

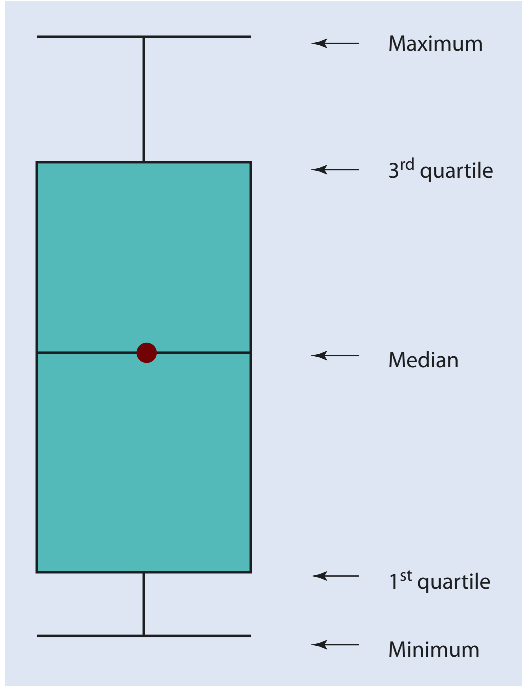


Fig. 3.41 Box and whisker plot

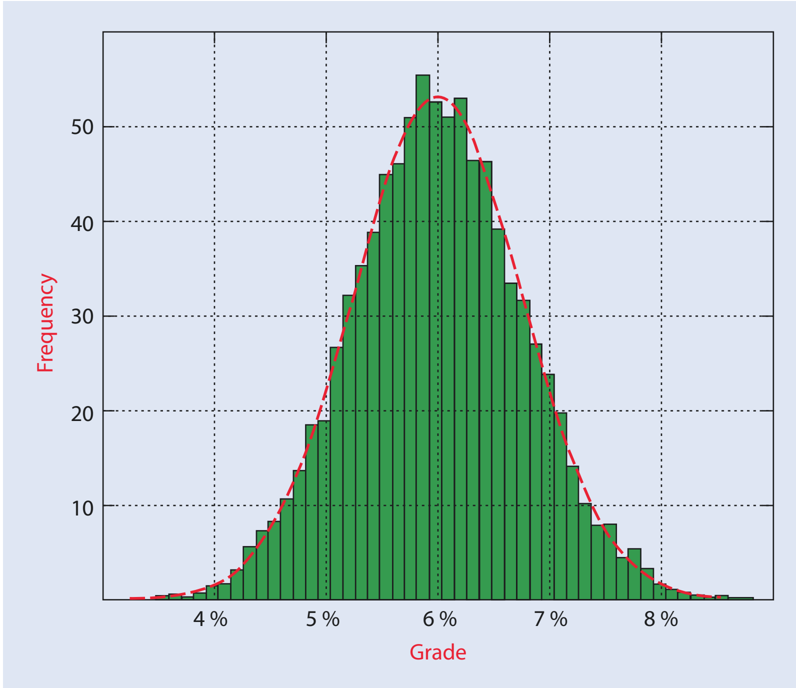
variable whereas the histogram height expresses the frequency of observations within that range. The scale of the height can be expressed either in number of observations or as a percentage of the total number of observations.

The histogram is a very popular graphical means for showing a distribution. At the initial stage of an investigation, histograms should be plotted for all variables, this helping in geochemical interpretations. Moreover, the histogram will suggest the procedure that can be applied in a further stage. Histograms can be directly drawn in spreadsheets such as Excel. The number of intervals must be clearly defined since too few intervals will avoid the representation of finer details of the distribution while too many intervals will result in a discontinuous distribution. Sturge's rule, which sets the number of intervals equal to $\log_2 n + 1$ (n is the number of observations), can be applied if the distribution is normal or close to normal.

Cumulative Frequency Plots, Probability Plots, and Q-Q Plots

Cumulative frequency diagrams show the percentage values that fall below a value plotted against that value. The shape of a cumulative frequency

Fig. 3.42 Histogram



curve representative of a normal distribution looks like «S.» A probability plot is a special adaption of that curve when the *Y* axis is scaled in such a way that a normal distribution plots as a straight line. In probability plots any deviations from normality can be quickly identified (Fig. 3.43). These plots have been applied in the splitting of univariate, polymodal geochemical populations into unimodal subpopulations as they help in the identification of anomalies. Cumulative frequency diagrams and probability plots are better than histograms in displaying data.

Equivalent to normal probability plots are quantile-quantile (Q-Q) plots. They also allow graphical comparison of a frequency distribution with respect to an expected frequency distribution (usually the normal distribution). In the Q-Q plots, the quantile values are calculated for the normal frequency distribution, and then they are plotted against the ordered observed data. The plot will be a straight line where the frequency distribution is normally distributed, but it will be curved or discontinuous for skewed frequency distributions or for polymodal populations.

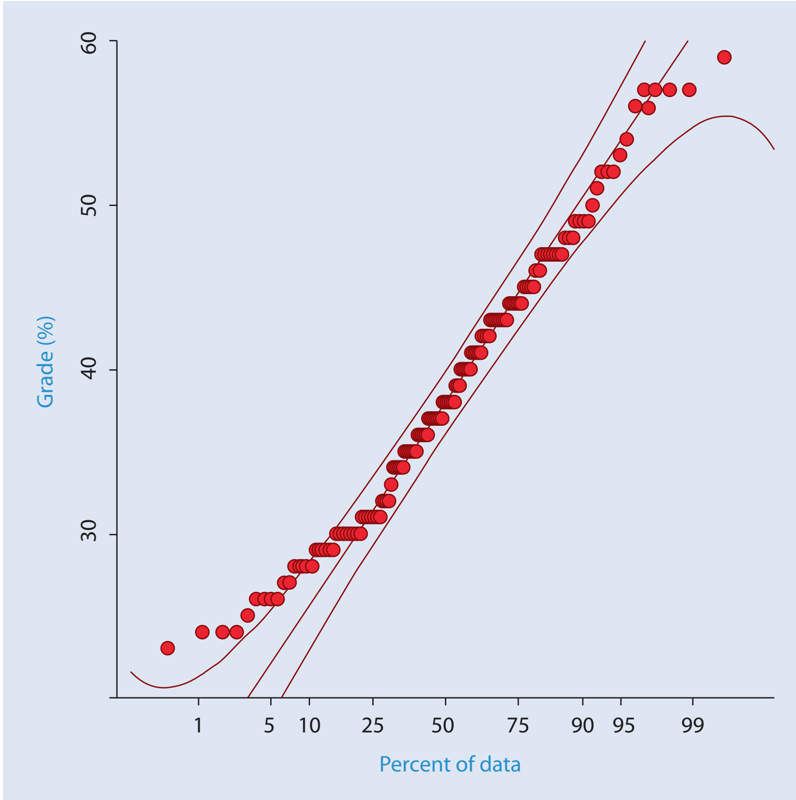
Geostatistical Techniques

Although geostatistics will be described in detail in the next chapter because this technique is mainly devoted to mineral resource/reserve evaluation, the use of geostatistical procedures provides quantification of the spatial variability of an element, for instance, by constructing a semivariogram. Semivariograms measure the average variance between sample points at specific distances (lags). Usually, the variance increases as distance increases between any pair of points. Thus, evaluation of the semivariogram allows assessing the spatial continuity of an element. The effectiveness of applying geostatistical methods relies on adequate sampling density to represent the variation of the data.

The effective use of geostatistical techniques requires knowledge and experience in order to model and extract information from spatial data. They permit better estimates of geochemical trends though geostatistical techniques must be used with the awareness of the problems with techniques of interpolation and the spatial behavior of the data (Grunsky 2010).

Contoured Plans and Profiles

Contour plots of both plans and sections can provide relevant information where variables are gradational in nature, and this gradational character exists between control points. Contours indicate trends, directions of preferred elongation and indications if more than one domain is needed. Since contouring



■ **Fig. 3.43** Normal probability plot

is made with computer software, it is important to get a clear understanding of the contouring criteria contained within a given software package (Sinclair and Blackwell 2002). Contouring routines use some kind of interpolation criterion to construct a regular grid of values that can be contoured easily. Interpolation algorithms include inverse distance weighting, nearest point, and triangulation or kriging, among others. This graphical expression of the data is commonly used not only for geochemical data but also in geophysical surveys.

Bivariate Methods

This section considers the analytical methods used if it is necessary to take in account simultaneously the variation of two variables where both are measured on each element in a sample. In addition to providing extra information about the frequency distribution of a sample, these methods generate information on the relationship between variables (Swan and Sandilands 1995). All the techniques of bivariate statistics can be regarded as ways of describing and analyzing the shape of the bivariate scatter.

X-Y Plots

In this method, the values of one variable are plotted against those of another variable determined in the same group of samples (■ Fig. 3.44). Normal distributions of the data are not assumed in *X-Y* plots, but log transformation can be used in scaling the data. The resulting plots supply better visual estimate of the relationship between two variables and can highlight clusters within the data. This can be improved by display in a scatterplot matrix that allows to represent *X-Y* plots for every variable against every other variable simultaneously.

Correlation Coefficients

Correlation is an exploratory technique used to examine if the values of two variables are significantly related. It means that the values of both variables change or are not together in a consistent way. There is no expectation that values of one variable can be predicted from the other or that there is any causal relationship between them (McKillup and Dyar 2010). Quantitative correlation and calculation of simple linear correlation coefficients

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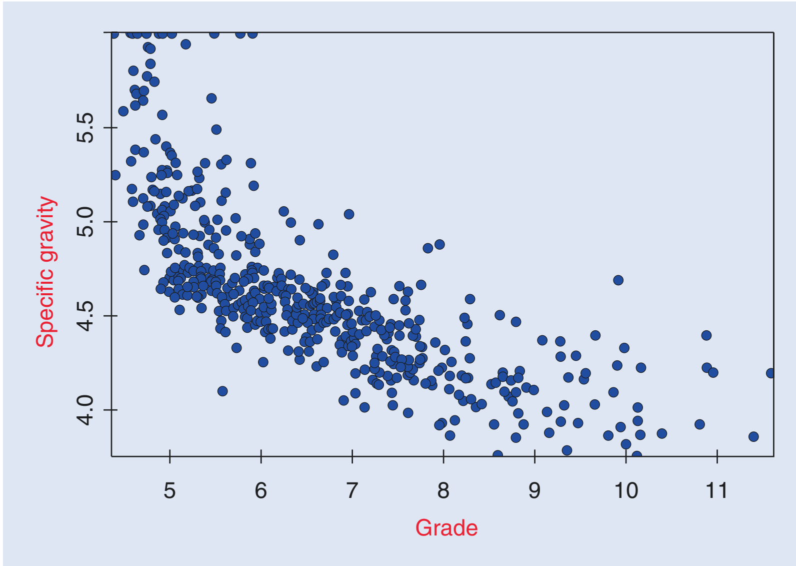


Fig. 3.44 *X-Y* plot

are useful tools for estimating the degree of interdependence between two variables. This can be of great importance provided that it can indicate that the variables are linked, directly or indirectly, in the underlying causative geochemical process.

The most common correlation coefficient used is the Pearson correlation coefficient (abbreviated to r). This coefficient is defined as the covariance of the two variables divided by the product of their standard deviations. As explained in a next section, the concept of R-mode factor analysis is based on the correlation coefficients among a large number of variables. Correlation coefficients are dimensionless. They range between +1.0 (perfect positive linear relationship) and −1.0, the latter value representing a perfect negative relationship (Fig. 3.45). Real data rarely lead to perfect, whether positive or negative, correlation. Like other summary statistics, the correlation coefficient can display abnormal values in the nature of the distribution. These must be always rectified before any important conclusions are drawn from the data or if the correlation coefficient is used as input to other statistical methods like factor analysis. A classic example is a low value of the correlation coefficient in a group of essentially random bivariate data, which increases excessively where a single outlier is introduced in the data set. It is important to remember that linear correlation will only detect linear relationship between variables. Sometimes two variables are clearly related, but their correlation coefficient is near zero, since this correlation is not linear.

Regression Analysis

The correlation coefficient measures the strength of the relationship between two variables. In contrast, regression analysis leads to express the nature of the relationship in quantitative terms. Thus, regression analysis is used to describe the functional relationship between two variables so that the value of one can be predicted from the other. Regression analysis is often preferred to measure the linear relationship between two variables because the nature of the bivariate relationship can be more precisely defined in the form of equation. Regression analysis is essential in geochemistry and geology since the derived equation can be used to describe and aid understanding of the geological process and permits predictions to be made (Swan and Sandilands 1995).

In the case of simple linear regression, a set of bivariate data, expressed graphically as *X-Y* plots, is fitted with a straight line, which can or cannot pass through the origin. This line represents a close relationship between the dependent variable (normally plotted on the *Y* axis) and the independent variable (*X* axis). Total deviation of the predicted values from the observed values is estimated. Moreover, the deviations are squared to remove the plus or minus effects so that the method is known as «least squares.» Sometimes, the values of dependent and independent variables are fitted with a curve, rather than a straight line, and it is called polynomial regression.

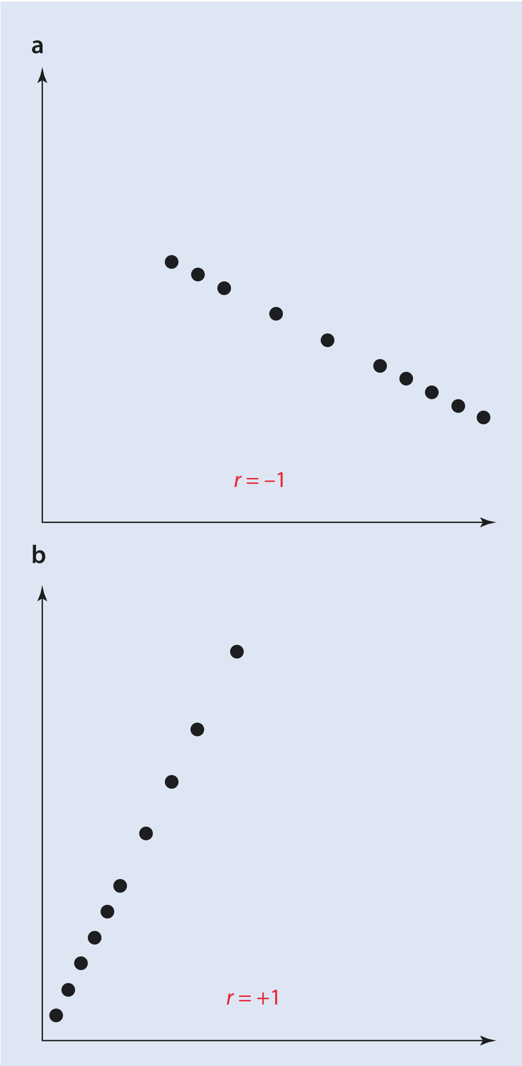


Fig. 3.45 Correlation coefficient of: **a** maximum negative = −1; **b** maximum positive = +1

Multivariate Methods

Multivariate statistics relate several elements to each other and facilitate the geochemical interpretation of multi-element data. Multivariate methods are important because virtually all geochemical data are inherently multivariate. Leaving aside some methods such as triangular diagrams, multiple linear regression, or multi-element indices, multivariate data analysis techniques simplify the variation and data relationships in a reduced number of dimensions or groups, which can commonly be tied to specific geochemical/geological processes. Many specific texts, (e.g., Davis 2002), include basics of multivariate data analysis techniques. The multivariate methods most commonly employed in studying and quantifying multi-element associations in exploration geochemical data include principal components analysis (PCA), factor analysis (FA), cluster analysis (CA), and discriminant analysis (DA). PCA and FA are useful in studying inter-element relationships hidden in multiple uni-element data sets, CA is utilized for studying inter-sample relationships, whereas RA and DA are useful for studying inter-element as well as inter-sample associations (Carranza 2009). It is important to note that multivariate analysis requires large samples: in the same way that two observations on a pair of variables are sure to give a correlation coefficient of 1; multivariate data with few observations on many variables will give misleading results.

Triangular Diagrams

Triangular or ternary graphs are used routinely to display relative compositions of samples in terms of three variables. In cases where metal abundance differs by several orders of magnitude, multiplication of one or two of the elements by an appropriate factor is common practice, this resulting in spreading of the plotted points over much of the triangular field. This procedure leads to strong distortion of the ratio scales in the diagrams. In the triangular diagram, each apex represents 100% of one of the elements and the coordinates are numbered for one element on each side in a clockwise direction. It is only necessary to know the percentages of two of the three variables to plot the point.

Multiple Linear Regression

Multiple linear regression is a straightforward extension of simple linear regression. Where there is no single variable sufficiently closely related to the variable being estimated, several variables can be taken together and the estimate of the derived variable will be satisfactory. For example, the sediment yield of a river can be dependent on its drainage area plus other factors such as topographic relief, precipitation, and flow rate (McKillup and Dyar 2010).

Multi-element Indices

Methods exist for dealing with multi-element data that strictly do not involve multivariate statistics. The calculation of multi-element indices is an example of how element associations can be

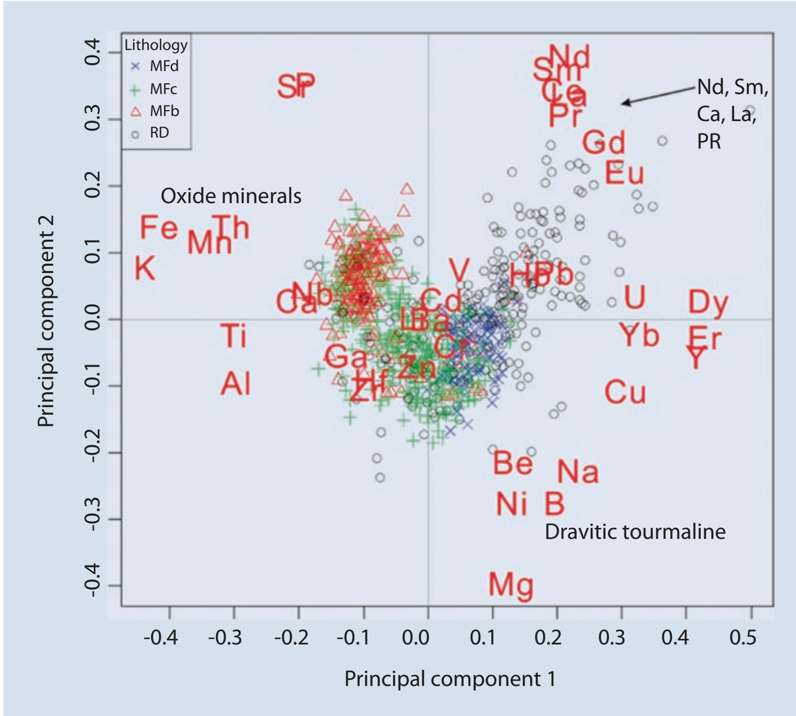


Fig. 3.46 Example of a graphic representation of principal component samples and variable scores (Chen et al. 2015)

applied to optimize features such as types of mineralization or lithologies. Under certain circumstances, some elements are deserving of greater weighting in such an index because of their greater importance as pathfinders for the deposit type sought. If detailed multivariate analysis cannot be achieved because of time limitation, the calculation of multi-element indices provides a way of combining the tendency of certain elements to be enriched in mineralization.

Principal Components Analysis

Principal components analysis, one of the oldest multivariate techniques, is a multivariate procedure to reduce the dimensionality of a data set with a large number of variables while retaining the variation in the variables. This is achieved by forming linear combinations of the variables (principal components) that describe the distribution of the data. In fact, PCA uses the redundancy within the data set to reduce the number of variables, although it does not exclude variables. Instead, PCA identifies variables that are highly correlated with each other and combines these to construct a reduced set of new variables that still describes the differences among samples.

The linear combinations are derived from some measure of association such as correlation or covariance matrix. Principal components are chosen in such a way that the first principal component accounts for most of the variation in the data set and subsequent components for decreasing amount of variation. The interpretation of PCA results points to geological/geochemical interpretation on the element loadings comprising the components. Ideally, each principal component might be interpreted as describing a geological process (e.g., crystal fractionation, mineralization processes, or weathering). Figure 3.46 shows an example of a graphic representation using principal component samples and variables.

Factor Analysis

The term R-mode factor analysis is given to several related techniques that try to identify a limited number of controls on a much greater number of observational variables. It is called R-mode because it is based on r, the correlation coefficient, and deals with relationships between variables. On the opposite, Q-mode factor analysis deals with relationships between samples instead of variables. They are designed as linear

Table 3.4 Factors are linear combinations of variables

Factor	Factor 1	Factor 2	Factor 3	Factor 4	Communality
Ba	*0.92*	0.06	−0.08	−0.09	0.863
Ce	*0.59*	0.01	0.34	*0.62*	0.855
Cr	*0.81*	−0.24	0.26	0.41	0.947
Fe	−0.07	*0.87*	−0.08	−0.00	0.766
K	0.31	0.04	*0.75*	−0.28	0.746
Mn	−0.06	*0.94*	0.04	−0.08	0.902
Ni	*0.79*	−0.38	−0.42	0.20	0.977
Ra	*0.67*	0.49	−0.03	0.17	0.730
Rb	0.21	*0.69*	−0.13	0.46	0.746
Sr	*0.82*	−0.31	0.21	−0.15	0.833
Th	0.05	−0.02	*0.79*	0.07	0.629
Ti	−0.39	*0.75*	0.49	0.09	0.962
U	0.10	−0.41	−0.13	*0.62*	0.579
Zn	−0.18	−0.08	0.00	*0.83*	0.734
Zr	−0.49	0.40	*0.63*	0.29	0.886
Eigenvalue	5.38	2.80	2.30	1.68	
% Var. expl.	36	18	15	11	
Cum. % var.	−36	54	69	80	

combinations, or «factors,» of those variables (Table 3.4). Where geochemistry is considered, such factors will be related to the processes acting on the environment, and furthermore they can correspond to geochemical relationships. R-mode factor analysis allows to condensate a large number of geochemical variables into a smaller number of linear combinations of those variables that account for most of the total data variance. The number of factors is likely to be much smaller than the number of variables. The factors can be plotted and interpreted more easily than the full data set because more geochemical information can be summarized at each sampling point (Gocht et al. 1988). Since the method is based on the correlation coefficients between the variables, FA is quite sensitive to their variations. Therefore, it is crucial to calculate the correlation coefficient so that distortion by outliers can be avoided.

Cluster (Dendrogram) Analysis

Cluster analysis leads to grouping of points that represent individual geochemical samples in multi-element space. The procedure is performed without prior knowledge of the groupings or their compositional characteristics. Cluster analysis methods offer an excellent exploratory tool for analyzing groups of multi-element data, not clearly observable in simple scatter plots or by means of PCA. Thus, the main objective of clustering algorithm is to distinguish natural groupings within multi-dimensional data: it links the most similar pairs of observations or clusters in successive stages until all points are grouped.

Discriminant Analysis

Discriminant analysis is utilized to deal with problems of classification (Fig. 3.47). It is one of the most widely used multivariate procedures in Earth sciences. Discriminant analysis uses

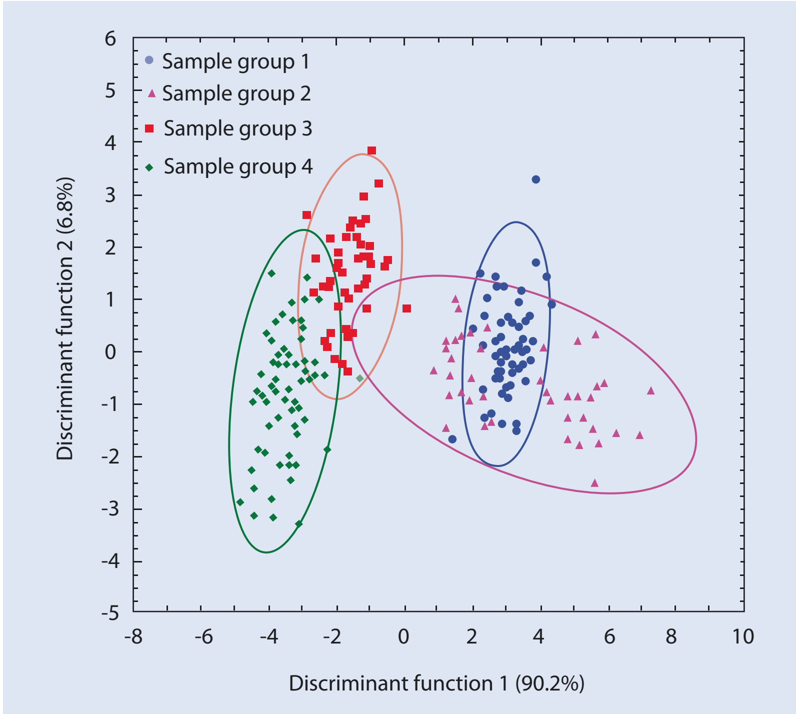


Fig. 3.47 Graphical representation of groups using discriminant functions 1 and 2

all of the analyses in a data set, being the objective to maximize the distinction between two or more previously defined groups. It enables the further allocation of samples of unknown origin based on analyses of the same elements. The objective is to find discriminant functions: these are vectors in the directions of optimal separation between the groups, and they transform the original set of measurements on a sample into a single discriminant score. The discriminant function provides not only the possibility of assigning samples of unknown association to one of these two groups but also of measuring the degree to which each of the variables contributes to the classification.

3.4.6 Drilling

Introduction

Where an anomaly is found, by using geophysical and/or geochemical prospection, the mining company will initiate a drilling program in order to test the extent of the mineralization. The density of drilling will be set up by the wanted level of geological confidence and project economics. The drill program searches to confirm the presence of the mineralization and must determine its shape and continuity by studying the samples collected from every drill target of the drill program. Mining requires drilling mainly for two different goals: (1) production drilling, making holes to place explosives for blasting (the holes drilled for this purpose are defined as blasthole and this topic will be covered in the exploitation chapter), and (2) exploration drilling, to estimate the amount and grade of a mineralization using the sample collections (Fig. 3.48). Likewise, drilling is a continuous process throughout the entire life of the mine to supplement reserve for the mined ore. This will increase the mine life and continue mining operation. Moreover, it also upgrades the categories of the reserves by using underground drilling. A strategically placed underground drilling program can even probe for new ore bodies in the neighborhood.

Drilling is the most frequently used technology in mineral exploration, and it is usually the most expensive because its expenditure can reach up to half of the costs of total exploration. In most cases, drilling locates and defines economic mineralization. The first objective of drilling is to safely obtain representative samples of the target mineralization in a cost-effective manner.

Fig. 3.48 Preparing samples after drilling (Image courtesy of Anglo American plc.)

The rock types are defined using the study of the samples, and portions of them are commonly chemically analyzed with the aim of further characterization of rock types and to search the existence of valuable minerals. Thus, the different methods of drilling are for diverse objectives at various phases of an exploration program. Studying drill core also allows for geotechnical/rock mechanics data, being logs gathered during surface drilling.

There are a large number of drilling techniques. This heading is centered on the three main types used in mineral exploration: reverse circulation (RC) drilling, rotary drilling using tricone roller bits, and diamond core (DC) drilling. Each drilling method has its own characteristics, which affect the quality of the collected samples. DC drilling generates a cylinder-shaped sample of the ground at an accurate depth. On the opposite, RC drilling and rotary drilling using tricone roller bits yield a crushed sample that includes cuttings from a precise depth in the drillhole.

Rock Drillability

Rock drillability is defined as the penetration rate of a drill bit into the rock. It is a feature that cannot be exactly defined by a single mechanical property of the rock. For this reason, drillability is a function of numerous rock properties such as mineral composition, grain size, texture, and weathering degree. Quartz is one of the commonest minerals in rocks. Since quartz is a very hard material, high quartz content in rock can make it very hard to drill and will certainly cause heavy wear, particularly on drill bits. On the other hand, a coarse-grained structure is easier to drill and causes less wear of the drill string than a fine-grained structure.

Drillability is not only decisive for the wear of tools and equipment but is, along with the drilling velocity, a standard factor for the progress of drilling works. Hoseinie et al. (2008) suggest that the most important rock mass parameters that affect the drilling are the following: the origin of the rock's formation, the Mohs hardness, the texture of the rock (shape and size of grains), porosity, density, abrasiveness, rigidity, P-wave velocity, elasticity and plasticity, UCS (point load index and Schmidt hammer), tensile strength, structural parameters of the rock mass (joints, cracks, and bedding), and RQD.

The factors that concern the drillability of rocks are numerous and can be classified into two main groups: controllable and uncontrollable parameters. Regarding the controllable parameters, these are bit type and diameter, rotational speed, thrust, blow frequency, and flushing. Rock properties and geological conditions are uncontrollable parameters (Yarali and Kahraman 2011). The drillability of rocks depends on not only their physical properties but also on the type of drill being used and drilling parameters such as rotation speed, feed rate, etc. The physical properties of rocks which have some effect on drillability are:

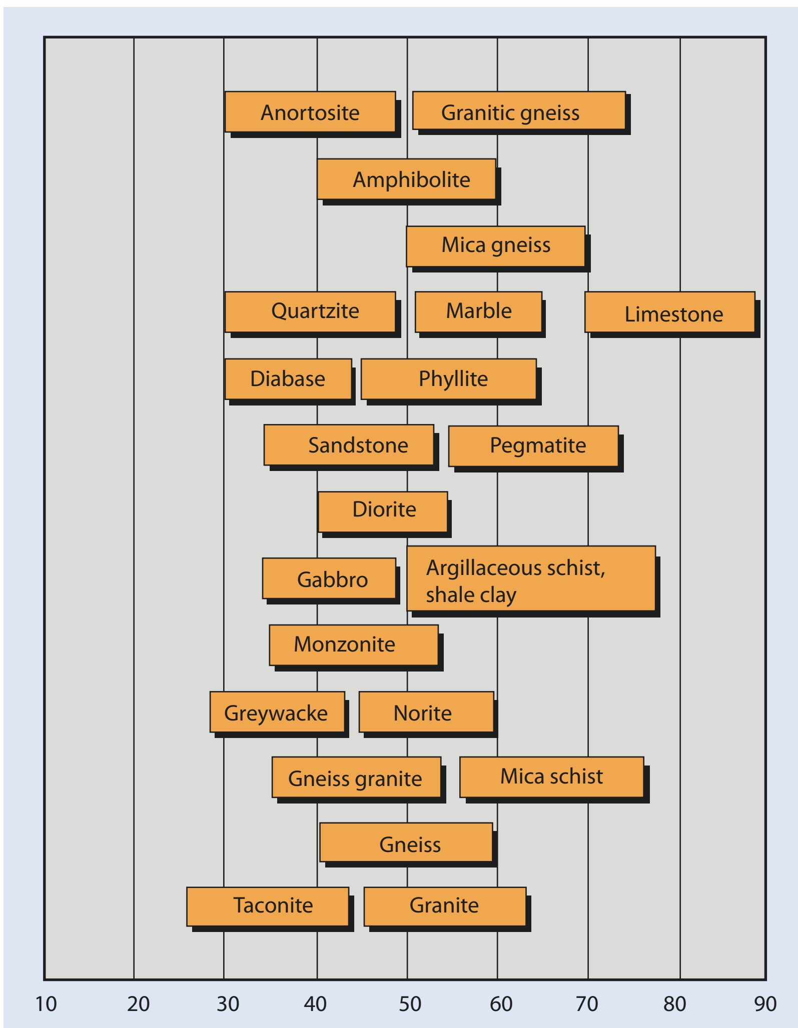
1. Crushing strength, defined as the pressure a rock sustains before breaking and related to grain hardness and strength, grain bond strength, porosity, and weakness planes.
2. Toughness, a measure of how difficult it is to pull a rock apart and related to grain shape and bond, fissibility, and tenacity.
3. Chip separation, this is how readily the cuttings are cleared from the face, and it is related to pore pressure and permeability.

4. Abrasiveness, the ability to wear downhole tools and related to grain hardness and shape (Hartley 1994).

The Norwegian Technical University has defined two methods to evaluate the rock drillability: the drilling rate index (DRI) and the bit wear index (BWI). The DRI describes how fast a particular drill steel can penetrate. It includes measurements of brittleness and drilling with a small, standard rotating bit into a sample of the rock. The higher the DRI, the higher the penetration rate, and this can vary greatly from one rock type to another (◘ Fig. 3.49). It should be noted that modern drill bits greatly improve the penetration rates in the same rock types. The BWI gives an indication of how fast the bit wears down, as determined by an abrasion test. The higher the BWI, the faster will be the wear. Thus, in most cases the DRI and BWI are inversely proportional to one another. However, the presence of hard minerals can produce heavy wear on the bit despite relatively good drillability. This is particularly the case of quartz, which has been shown to increase wear rates greatly. Certain sulfides in ore bodies are comparatively hard, impairing drillability (Samuelsson 2007). Other means of commonly used rock classification include the Q-system; rock mass rating (RMR) of Bieniawski, incorporating the earlier rock quality designation (RQD); and the geological strength index (GSI).

Selection of Drilling Method

Selecting the right technique or combination of techniques depends on many factors: speed, cost, actual conditions (surface or underground),



◘ **Fig. 3.49** Relationship between drilling rate index and various rock types (Samuelsson 2007)

Fig. 3.50 Rock chips and core samples (Image courtesy of Atlas Copco)

depths of the drillholes, type of rocks, required sample volume and quality, logistics, environmental considerations, and finally the preference of the geologist. Moreover, each of these factors depends in turn on many parameters. For example, drilling velocity is dependent on a lot of geological parameters such as jointing of rock mass, rock anisotropy (e.g., orientation of schistosity), degree of interlocking of microstructures, porosity and quality of cementation in clastic rock, degree of hydrothermal decomposition, and weathering of a rock mass, among others (Thuro 1997).

Modern core drilling rigs carry out fast and efficient core sampling of different diameters to very large length. There are many items to select the appropriate method of drilling: target, host rock, water presence, sample required, access, and politics (Hartley 1994). From a sampling viewpoint, there are two types of drilling methods in mineral exploration: drilling methods that originate rock chips and those that generate core samples (Fig. 3.50). A three-key-factor selection process can be established: the time needed, the cost of getting the job done, and confidence in the quality of the samples brought to the surface (Gustaffson 2010).

Time Factor

For any exploration drilling, the sample is the most important goal result. RC drilling generates continuous drilling with high penetration rate and can offer three times the productivity of core drilling. Thus, significant timesaving can be obtained using RC. When the ore body is located, driller can decide to continue with RC drilling or switch to diamond core drilling to extract cores. In so doing, RC drilling and classical core drilling are perfectly combinable. The logistics of the drilling program have clear influence on the number of meters drilled per shift and thereof it is a time factor.

Cost Factor

Costs are mainly related to the time factor, except that investment in RC rigs and equipment is higher compared to core drilling. For shallow exploration applications, time and costs are in favor of RC drilling. For deeper exploration applications, shallow subsoil water and rocky terrain, core drilling is still the only practical alternative. Technical developments in drilling tools and rig technology have resulted in lower drilling costs.

Confidence Factor

The third variable in the equation is the confidence factor. In an evaluation with positive results, a program of core drilling is the common way to drill for the purpose of bringing the project to a resource/reserve status because geologists need dry and representative samples to carry out optimum evaluations. Therefore, core drilling remains the only viable method in these situations. The core helps the geologist to calculate the cost of extracting the

Fig. 3.51 Reverse circulation drilling machine (Image courtesy of Atlas Copco)

mineral from the ore. Moreover, cores also yield geotechnical data; for instance, data about slope stability can be of the highest significance. Finally, the geologist plays an extremely important role in finding an intelligent and balanced choice between the two methods.

Reverse Circulation Drilling

RC drilling technique (Fig. 3.51) starts its utilization in searching mineral deposits since the early 1970s in Australia. It can be used in unconsolidated sediments or for drilling rock. Since this method is clearly less expensive than core drilling, it is the selected method for most preliminary mineral exploration work. The advantages of using this method to collect rock chippings are that all the sample is collected, the method is very fast, up to 200–300 m per day is common at drilling rates exceeding 10 m per hour, and there is very little contamination. RC sample content ranges from dust to 25 mm chips. Often, reverse circulation drillholes are of larger diameter than common diamond drillholes, but it can be hard to acquire sound geological descriptions because the material is obtained/recovered in the form of broken rock chips.

The RC method uses dual wall drill rods that include an outer drill rod with an inner tube situated inside the drill rod (Fig. 3.52). The inner tube affords a continuous pathway with sealed characteristic for the drill cuttings to be translated to the surface. High-pressure air is the common way to define the drill flushing medium. Water can also be injected to reduce dust and to assist in transporting cuttings to the surface. At the surface, the cuttings are derivated to a cyclone for collection and bagging.

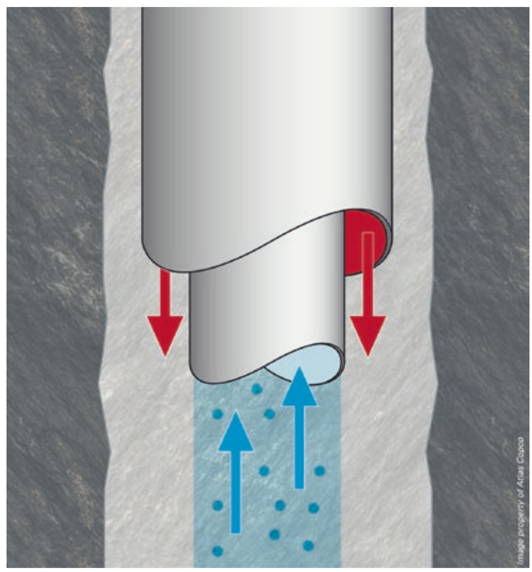


Fig. 3.52 RC system (Illustration courtesy of Atlas Copco)

There are many different drill bit types, each of them designed for different drilling conditions (e.g., rock type). Drill bits are chosen given the underground rock formations expected to be encountered since to change bits can be a long process. The most classical method utilized is the reverse circulation hammer because it drills almost all geological formations. RC hammers are designed with an inner sample tube that extends through the center and into the top of the hammer bit.

RC drill rigs typically reach depths up to 500 m, although it can exceed that depth. The method is undergoing continuous technical development that will result in RC drilling being applied to deeper drillholes and more difficult geological conditions. In a comparison between RC drilling and core drilling, RC drilling presents two main issues. First, most of the RC drill rigs actually used have a depth constraint of about 500 m. Second, RC drilling offers obviously less information regarding the geological structure of the ore body. It is important to bear in mind that this aspect is very important when estimating the cost of extracting mineral from ore. Regarding the sampling process, RC drilling is mostly led to obtain mineral samples for analysis, so correct sampling equipment and practices are necessary when undertaking this type of drilling.

There are two main components to the sampling system: the cyclone (◘ Fig. 3.51) and the splitter. The cyclone serves mainly to separate the sample from the air, thus allowing it to be recuperated. A good cyclone will usually gather more than 99% of the sample, being the sample interval normally 1 or 2 m of drillhole. As one sample has been collected, another is being drilled and incorporating to the cyclone. The other mentioned component is the splitter. The purpose of this instrument is to cut the sample to a smaller size, which accurately represents the complete sample. The sample from 1 m drillhole is about 50 kg. This sample is currently in a bag that is sent to a laboratory for subsequent analysis.

Rotary Drilling

Rotary drilling using tricone bits is a noncoring method, being usually utilized for drilling through soft to medium hard rocks such as limestone, chalk, or mudstone. Rotary drilling uses different type of rotary bits although the most typical rotary bit is probably the tricone or roller rock bit (◘ Fig. 3.53) that is made with tungsten carbide insets. As the drill string is rotated, the bit cones roll along the bottom of the borehole and the rock chips are flushed to the surface by

◘ **Fig. 3.53** Tricone bit (Image courtesy of Atlas Copco)

the drilling fluid for examination; in this method, advances of up to 100 m per hour are possible. It requires minimal air volume, and downhole costs are low. For this reason, it is a very economical method of drilling. Tricone bits are used in many drilling industry sectors. It is commonly applied to oil industry, with large diameter holes (>20 cm) and several 1000 ms depth.

Diamond Core Drilling

In diamond core drilling, a cylinder of solid rock, the core, is extracted from depth. It is commonly 27–85 mm in diameter (◘ Fig. 3.54), but larger diameters (up to 200 mm) are most useful but much more costly. The most common sizes used today for exploration drilling are 75 mm hole diameter. Due to the common hardness of the rocks and the time involved in translating the core from depth, the penetration in diamond core drilling is much slower than other drilling methods. Thus, diamond drilling is clearly more expensive than reverse circulation drilling.

◘ **Fig. 3.54** Different core diameter sizes

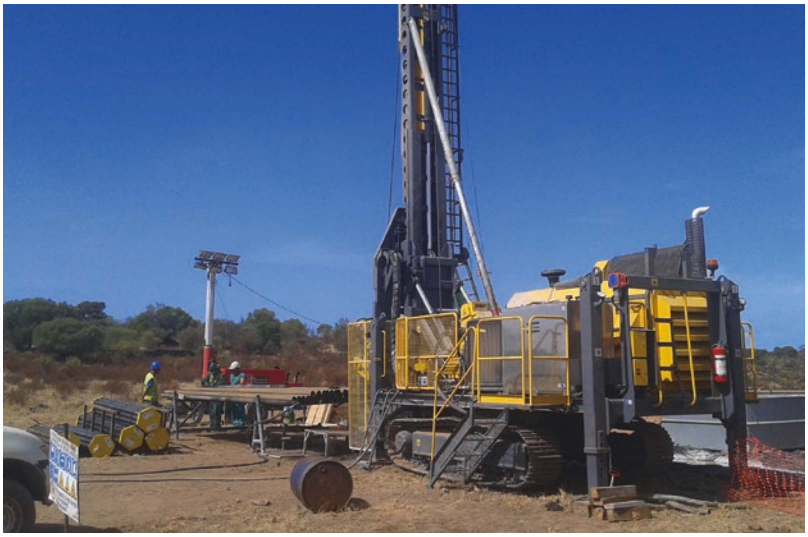


Fig. 3.55 Diamond core drilling operation (Image courtesy of Atlas Copco)

However, if core recovery is good, it has the benefit of carrying undamaged rock to the surface. Therefore, diamond drilling is usually accounted to offer the best quality of sample. Most advanced exploration uses a combination of diamond and reverse circulation drilling. In general, diamond drills are the most essential tool in the final exploration and evaluation of mineral projects because the study of the drill core yields a three-dimensional geologic picture of ore and host rock and the samples from drill core provide samples for chemical analysis, mineral recovery tests, and rock stability tests.

Nowadays, typical drilling operation includes a truck-mounted rig and a support truck to carry items such as the rods, casing, fuel, and water (Fig. 3.55). The method requires significant site preparation and rehabilitation. Diamond drilling machines utilized in mineral exploration commonly reach depth of up to 3000 m and extraordinarily up to 6000 m. In these situations, casing is installed in the upper levels to protect the walls from collapse. The rate of advance will depend of many factors (type of drill rig, type of bit, hole diameter, the depth of drillhole, and the rock type being drilled, among others). Drilling advance rates of up to 10 m an hour are common. The costs can range from USD 40 to USD 90 a meter in drillholes up to 300 m long and from USD 75 to USD 160 a meter for length up to 1000 m.

The quality and continuity of the core are crucial in the assessment of a potential mine, making the core bit a key component of a core drilling rig. The diamond drill bit comprises a cutting head using diamonds as the cutting medium. A variety of core bit types is available according to the diamond cutting elements used in their construction. In softer rocks (e.g., sedimentary formations), other cutting elements such as tungsten carbide and polycrystalline diamond compacts can be used. Diamonds used are fine to micro-fine industrial grade diamonds that are set within a matrix of varying hardness, from brass to high-grade steel. Other options include tungsten carbide (TC) and polycrystalline diamond composite (PDC) bits. TC core bits are utilized for drilling in non-consolidated formations and in overburden and for cleaning drillholes. PDC bits are an alternative to TC bits and surface set diamond bits when drilling in non-consolidated and medium hard rock formations (Black 2010).

As the drill bit advances, a cylindrical core of rock progressively fills a tube core barrel immediately above the drill bit. Core barrels are classified by the length of core they contain. They are usually from 1.5 to 3.0 m in length but can be as long as 6 m. It is important to note that to recover the core the barrel must be removed from the hole by pulling the entire length of drill rods to the surface, which is a time-consuming process. For this reason, the wireline system is now a standard practice (Box 3.7: Wireline System). Water is used in diamond core drilling as lubricant fluid and to remove crushed and ground rock fragments from the bit surface. Water can be used in combination with various clays or chemicals (Fig. 3.56).

Fig. 3.56 Chemical products used with water in diamond core drilling (Image courtesy of AMC)

Box 3.7

Wireline System

The Boart Longyear company introduced the wireline core retrieval technology to the mineral exploration industry in 1958. By the late 1960s, it was in almost universal use. Wireline core drilling is a special type of core drilling, most commonly used in mineral exploration. Before wireline drilling, the whole string of rods had to be pulled from the ground in order to recover core from each advance of the drill. Thus, in conventional rock coring, the entire drill stem and core barrel must be removed after each core run. This is a time-consuming operation on deep core holes, in addition to creating an inherent risk for collapse of the rock into the unsupported borehole. Moreover, as the average depth of hole continues to increase, the time and money saved by not having to remove the drill pipe in order to obtain a core is substantial. Consequently, wireline system is designed to recover rock core without removing the drill stem from the borehole after each core run (Fig. 3.57). Besides reduced tripping time and decreased cost, wireline core drilling system has the main following advantages: (1) with improved core recovery and quality, the purpose of the drilling project can be better satisfied; (2) logging instruments can be lowered by utilizing internal flush drill rod; (3) inner tube structure can be changed in accordance with the variation of rock layer; and (4) labor intensity of the operators can be reduced.

To obtain a core after the core bit is in place, the core barrel assembly is forced down the inside of the drill pipe using drilling mud pressure. When the core barrel assembly reaches the lower end of the drill stem, a locking device holds the barrel in place. The core barrel assembly consists of a cutter head, core catcher, core barrel, vent or inside pressure relief, locking device, and a retrieving head. During coring operations, the circulating fluid passes between the core barrel assembly and the drill collar. After the core has been cut, the core barrel assembly with its core is retrieved by lowering an overshot through the drill pipe (McPhee et al. 2015), or overshot, which is designed to engage the upper end of the core barrel. As the overshot is lowered over the upper end of the assembly, the locking devices are released,

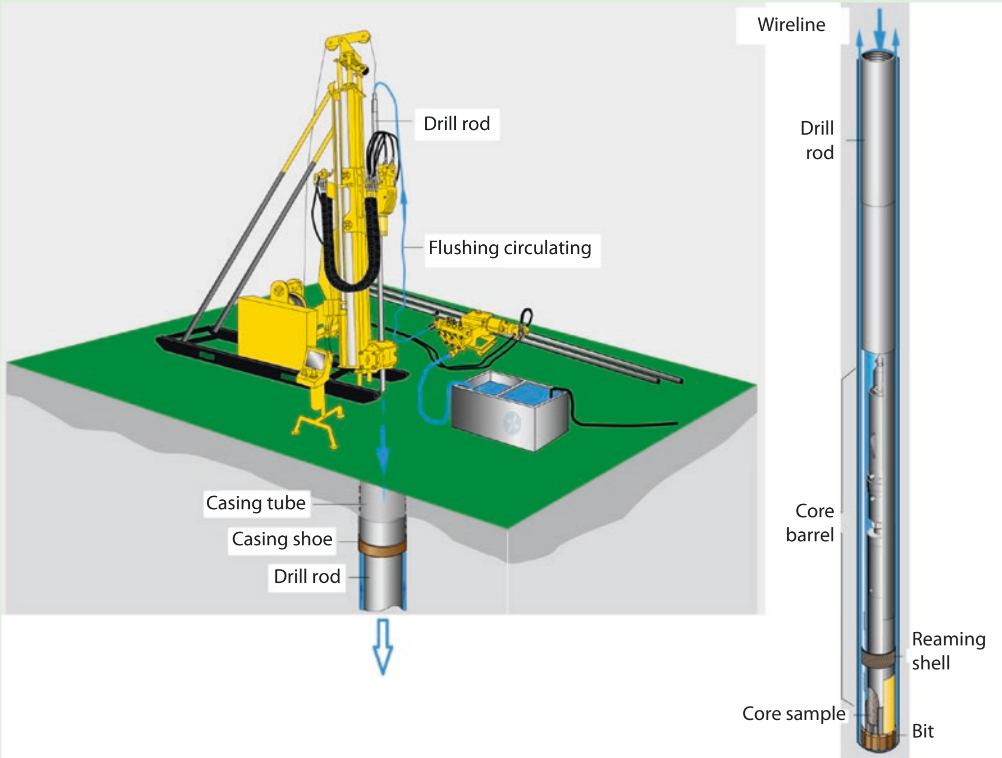
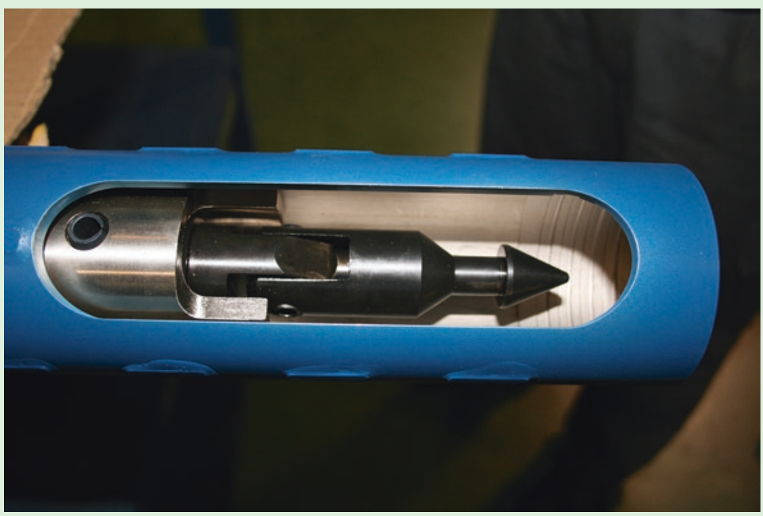


Fig. 3.57 Wireline system

Fig. 3.58 Head assembly inside the overshot (Image courtesy of TECSO)



permitting removal of the entire assembly. Thus, overshots are a key component of wireline coring systems. In this method, the inner barrel containing the rock core is rapidly brought to the surface, leaving the outer core barrel and drill rods sill in position within the borehole. While the core sections are being removed from the inner tube and placed in special core boxes, a replacement inner tube is lowered into the hole so that drilling can recommence. The commonly used standard core diameters for wireline drilling are AQ = 27 mm; BQ = 36.5 mm; NQ = 47.6 mm; HQ = 63.5 mm; and PQ = 85 mm. Figure 3.58 shows the head assembly and the overshot attached.

Core recovery is essential in diamond drilling. This is a quantifiable measurement defined as the total linear amount of physical core sample extracted over the total linear advance in a borehole, expressed as a percentage. Low core recovery impedes quantitative interpretation of important properties, such as ore grade and ore boundaries. For example, Henley and Doyle (2005) reported an important bias in ore grade at Las Cruces (Spain) as a result of core loss. The problem was related to the presence of chalcocite in the mineralization as a friable and unconsolidated form. Very often, core recovery of more than 90% is stipulated with drilling contractors. Other strict rules must be agreed, such as careful extraction of the core and its packing in properly labelled core boxes and marking individual core runs. In this sense, drilling should be supervised by experienced geologists. Proper storage of core is needed for the duration of the project if the prospect is rejected and for the whole life of the resulting mine, if the deposit is feasible (◘ Fig. 3.59). Although onerous, storage is much cheaper than repeat drilling (Pohl 2011).

It is important to note that diamond core drilling is also carried out in underground mining development (◘ Fig. 3.60). Thus, underground core drilling is mainly accomplished to characterize new ore reserves and for the safety of the mines in establishing the position of possible gas or water intersections.

Other Drilling Methods

Other drilling methods used in mineral exploration include auger drilling and sonic core drilling, the latter being the most recent improvement in drilling technology (◘ Box 3.8: Sonic Drilling). Regarding auger drilling, rock is cut and broken with a simple blade bit that is mounted on the end of a rotating string of rods (◘ Fig. 3.61). The drill stem is shaped like a helical screw and is driven rotationally into the ground. Auger drilling is a useful method for quickly and cheaply collecting geochemical samples. On the other hand, this method is usually utilized to take samples in the reconnaissance stage of mineral exploration. Regarding the rate of penetration, it depends on the type of formation being drilled but commonly can reach depths of around 20 m. Obviously, augers are not capable of penetrating hard or consolidated rock. Auger drilling uses either a handheld power auger or one mounted on a small vehicle. Augers are available in various sizes. Thus, small augers mounted on trucks are often used for reconnaissance exploration projects while large augers are utilized for construction purposes.

◘ **Fig. 3.59** Proper storage of core (Image courtesy of Matsa, a Mubadala & Trafigura Company)

Fig. 3.60 Diamond drill underground exploration station (Canada) (Image courtesy of North American Palladium Ltd.)

Fig. 3.61 Auger drilling at Burkina Faso (Image courtesy of SEMAFO Inc.)

Borehole Surveying

In a drillhole, the orientation is fairly established by its azimuth (direction) and dip (inclination). It is common that borehole deviates away from the original direction because of many factors (Fig. 3.64). Borehole deviation is commonly defined as the angular change from vertical during the course of drilling. Some authors also call this process as borehole deflection. However, it is possible to distinguish clearly between deviation and deflection (Hartley 1994). Deviation indicates how the borehole changes path naturally whereas deflection points out where the driller deliberately changes this natural deviation by inserting some mechanical device or changing the rod string. The reasons to change artificially the borehole path can be various: (a) to create daughter boreholes to enable several intersections from the same collar, (b) to enhance or depress natural deviation to ensure the target is intersected, (c) to bypass difficult drilling conditions, (d) to obtain second intersection for improved recovery, and (e) to force the borehole path to those otherwise inaccessible locations.

Box 3.8

Sonic Drilling

Sonic drilling is a unique technology that generates vibrational frequencies, usually between 50 and 180 Hz (cycles per second), transferring the vibrations down the drill pipe to its tungsten carbide bit while rotating the pipe at the same time. This frequency range falls within the lower range of sound vibrations that the human ear is capable of hearing. Thus, the term «sonic drill» has been applied to this class of rotary-vibratory drilling machine. Sonic drilling technology was first applied over 40 years ago in Canada. In mineral exploration, sonic drilling (◘ Fig. 3.62) is typically used to provide continuous core samples of softer or even harder rock formation of mineral deposits. Instead of using a diamond bit rotating at the end of a drill rod, the sonic drill head sends high-frequency vibrations throughout the length of the entire drill pipe and onto the bit (◘ Fig. 3.63).

In sonic drilling, the head contains the mechanism necessary for rotary motion, as well as an oscillator, which causes a high-frequency force to be superimposed on the drill string. The drill bit is physically vibrating up and down in addition to being pushed down and rotated. These three combined forces allow drilling to proceed quickly through most geological formations including most types of rock. The operator is able to vary the frequency and drill bit weight to match the material he/she is going through, ensuring the best penetration rate and most accurate sampling are obtained.

The sonic drilling method can produce almost completely undisturbed core samples from both solid and unconsolidated materials with high percentage of core recovery rates; it is commonly greater than 90%, which gives rise to extremely accurate estimates of mineral distribution in the ore body. Sometimes, core sampling can be accomplished without any drill fluids (dry coring), although the casing is usually installed by using water or mud to flush cuttings. Sonic drilling can collect samples up to 300 mm in diameter and can drill down to 250 m in a vertical or angled hole. The environmental impact from sonic drilling is typically less than other drilling methods. Thus, having a small footprint and lack of need to introduce fluid into the hole, this is an ideal drilling method where contamination is potentially a problem.

In soft materials, sonic drilling is a penetration technique that strongly reduces friction on the drill string and drill bit due to liquefaction, inertia effects, and a temporary reduction of porosity of the material. The entire drill string is brought to a vibration frequency of up to 200 Hz, which causes a very thin layer of soil particles directly surrounding the drill string and bit to loose structure. Instead of the stiff mass that requires torque and weight to penetrate, the soil behaves like a fluid powder (in an unsaturated zone) or as a slurry or paste in a saturated zone.

The liquefaction and inertia effects enable to collect very long and continuous samples. In addition, the drill string stays extremely straight due to the vertical high-frequency movement, with a diversion

◘ **Fig. 3.62** Sonic drilling in iron ore mining (Image courtesy of Sonic Drilling Ltd.)

◘ **Fig. 3.63** Sonic drill bit (Image courtesy of Sonic Drilling Ltd.)

of commonly a few centimeters over the full length of the borehole. It makes sonic drilling an optimal technology for installing instrumentation and monitoring equipment. In alluvial material, vertical vibrations are generally enough to drive down a drill string for many meters without the injection of any water or air. On the contrary, liquefaction cannot take place in hard formations. In such cases, it is necessary to combine vibration with rotation to allow the tungsten carbide buttoned ring bits to cut through the harder formations. Because a sonic drill bit actually impacts the rock face, if a diamond drill bit was used with the sonic drilling method, it would shatter, so tungsten carbide bits are used instead. In order to keep the temperature of the drill bit down and lift the cuttings, foam injection is the best solution, but water or air is possible.

Fig. 3.64 Borehole deviation

If the orientation of the borehole is not known, the location of the sample is similarly unknown. Large discrepancies between planned and true drillhole locations can occur. Since the location of a borehole is just as important as the information itself, the error in location of drillhole due to borehole deviation can impinge significantly on resource/reserve estimation. These errors are unfortunately common. Deviation is commonly cumulative, and the bottom of a deep hole can be many tens of meters away from its straight-line course. For instance, a 200 m drillhole whose plunge is off by only 5° will have the end of borehole moved horizontally by about 17.5 m from its intended position. Consequently, the use of the wrong value of the end of the borehole sample in estimation procedures can originate serious and intense errors of resource and/or reserve estimation.

Although it is difficult to assign an order of importance, there are a number of features that cause a drillhole to deviate both in azimuth and inclination. The more important are hardness of rocks, rock strength anisotropy, anisotropic strength index, active length of drill rods, barrel length, hole size, bit type, and direction of rotation and wedges (Hartley 1994). Regarding the rock strength anisotropy, which is exhibited by rocks with planar texture features such as foliation and bedding, drillholes will tend to deviate so as to make a greater angle with the dominant foliation (usually bedding or cleavage) of the rock unless the drillhole is already at a very low angle to that foliation, in which case the drillhole will tend to deflect along the foliation. However, the absolute magnitude of deviation is related not only to rock strength but also to the relative strength in different directions. Thus, drillholes in well-foliated schists deviate at a much greater rate than through a normal shale, which will be greater than granite. Regarding drillhole size, greater deviation occurs in smaller holes, probably a function of greater flexibility of rod string.

Surveying the path of a borehole is referred to as a borehole orientation survey or a deviation survey. Borehole surveying must be an integral component of all drill programs. Downhole orientation surveys are commonly carried out by moving a probe along the drillhole and checking the movement of the probe relative to a reference. The references can include the Earth's gravitational field, magnetic field, or other inertial reference. There are differences among the numerous boreholes surveying devices used. These are based on the ability to operate inside steel casing, time-consuming, and complexity to operate. In any case, none of them are clearly perfect.

In general, a survey of a borehole must supply an accurate estimation of the path of the drillhole in three-dimensional space (X, Y, and Z coordinates) of every point along the path that is known. It should be obvious that the greater the number of known data points, the less extrapolation required and the more accurate the survey. The coordinates of points are not measured directly but are computed from measurements of the dip, azimuth, and length along the drillhole.

At present, there is a great variety of instruments for measure deviation, and borehole surveys are carried out routinely in all drillholes of the exploration project. Commonly used measuring devices are based on photographs of a bubble ring and related to an original orientation, such as single or multishot photos, magnetometer/accelerometer based tools, and/or small gyroscope devices, from which azimuth and dip measurements are taken. The probe is lowered into the hole, taking azimuth and dip measurements at prespecified intervals, typically every 20–50 m down the hole, and the data values are transmitted to the surface for processing. The measurements are later used to determine the X, Y, and Z location of each sample. Calculation of corrected positions at successive depths is a straightforward mathematical procedure, if both the location of the top of the drillhole and the initial drillhole inclination are known. In borehole geometry probe, the verticality section includes a triaxial magnetometer and three accelerometers and data from these are combined.

If the surveying is carried out in mostly non-magnetic rocks and in open hole, then the standard magnetometer/accelerometer system is useful. On the contrary, a non-magnetic gyroscopic device must be necessary if magnetic anomalies are present. For instance, it is the case in ironstone mineralizations, ore with massive pyrrhotite, etc. This instrument uses an inertial navigation system to define the borehole path as it moves.

Logging

Considering the high costs of drilling, a maximum of information must be extracted. Thus, intense geological logging of core and drill cuttings is a common practice. Drillhole information is produced from many sources such as core, chips, down-the-hole geophysical measurements (e.g., caliper, natural gamma radiation, gamma-gamma density, magnetic susceptibility, or resistivity), data from instruments inside the hole such as MDW – measurements while drilling (e.g., pressure at the bit face, temperature, or rate of water flow) – and performance of the drilling machinery. All information related to each drillhole, including topography, drillhole deviation estimations, mapped geological features, and a copy of the data returned, should be available with a single folder for each drillhole (Rossi and Deutsch 2014).

Routine studies of drill cores consist of fracture spacing and orientation, core recovery (including the location of excessive core loss, >5%), lithological description (e.g., color, texture, mineralogy, rock alteration, and rock name), photographic documentation, description of the geological structures visible in the core, preliminary geological profile, rock properties for calculating geotechnical parameters (e.g., RQD), and content and distribution of mineral and ore components, including as possible in situ assaying of ore. Depending upon the objective of the site investigation, a secondary processing can include many other aspects such as the presence and content of clay minerals, total carbonate content, organic components, grain-size distribution, sediment matrix and cement, porosity, pore-size distribution, and many others. The description must be quantitative and systematic, avoiding as much as possible qualitative descriptions. Since structural features must be captured before split the core, the most useful way is to take photographs of the wet core previous the logging process with the objective of producing a permanent photographic record. In noncore drilling, descriptions must be again systematic and quantitative. The data from core and noncore observation are plotted on graphical core logs and utilized to help in interpreting the geology of the present and next holes to be drilled.

Regarding RQD, it is used as a standard parameter in drill core logging and forms a basic element value of the major mass classification systems such as rock mass rating (RMR) system and Q-system. In rock quality designation (RQD), the lengths of all sound rock core pieces that are greater than 100 mm in length are summed and divided by the length of the core run to obtain the final value in percentage. This parameter is commonly estimated where the rock has been altered and/or weakened by weathering. This procedure obviously penalizes if the recovery is poor, being useful since poor recovery commonly means poor quality rock.

Since geological logging is commonly a subjective process, this results in inconsistencies in the application of the logging codes. To solve the problem, it is desirable to use methods to objectively classify how mineralized is a sample, for instance, using portable XRF technology (Gazley et al. 2014). Thus, a clear, accurate, and standardized logging procedure is essential to promote uniformity of data through what is commonly a long data-gathering period. It is important to note that as geological information and concepts evolve with time, the context is likely to request the core be relogged (Sinclair and Blackwell 2002).

Although a great number of different logging methods are utilized in the industry, «there are three main logging forms for recording observations on drill core and cuttings: prose logging, graphical scale logging, and analytical spreadsheet logging» (Marjoribanks 2010). An interval is selected in prose logging, being identified by its downhole depth limits, and described in words. It is recommended that this type of logging must be only utilized in a special column (e.g., comments). Graphical scale log forms can include several mapping columns along with extra columns for recording digital data, sketches, verbal comments, etc. (Fig. 3.65). The important

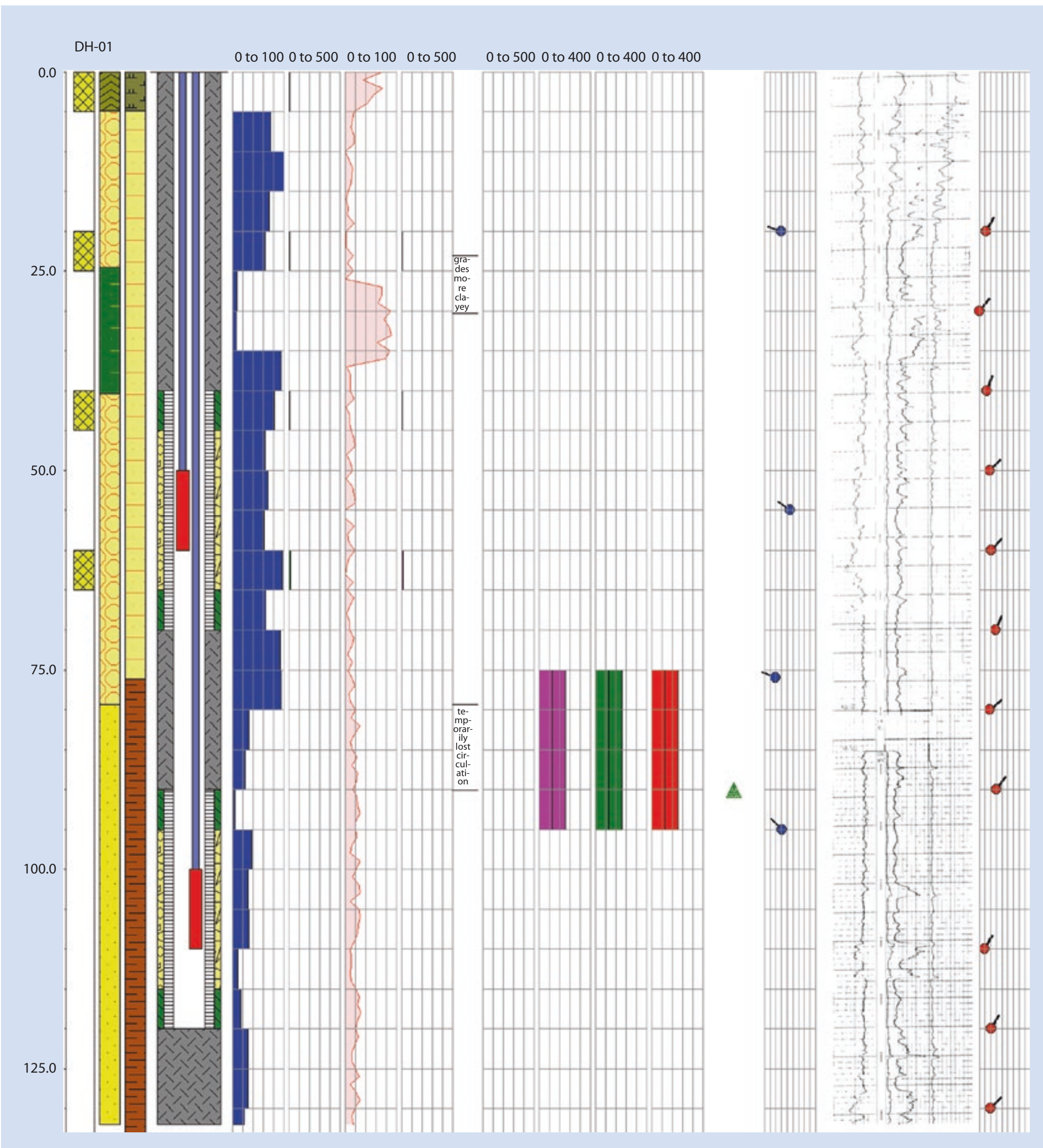


Fig. 3.65 Graphical scale log (Rockworks)

feature about all such logs is that they assemble many different types of geological observations on one form linked by a single down page scale. Finally, the use of spreadsheet logging is indicated in second-phase drilling programs (e.g., resource evaluation and definition) where the main geological problems associated with the ore body have been solved, and the aim of the logging is the routine recording of masses of reproducible data. Regarding the graphical scale logging form, it is usually separated into columns. The columns will be referred to in numbered order from left to right, for example, column 1 (hole depth), column 2 (core recovery), column 3 (sample no.), column 5 (assay results – it will be commonly necessary to devote several columns to insert all assay results), and so on.

3.5 Case Studies

■ Klaza Gold-Silver-(Lead-Zinc) Project Exploration: Courtesy of Rockhaven Resources Ltd.

The property lies 50 km due west of the town of Carmacks (Yukon, Canada), located 420 km from the year-round tidewater port at Skagway, Alaska (USA). Most of the property is underlain by mid-Cretaceous granodiorite. A moderately sized, late Cretaceous quartz-rich, granite-to-quartz monzonite stock intrudes the granodiorite in the southeast corner of the property and is thought to be the main heat source for hydrothermal cells that deposited mineralization along a series of northwesterly trending, structural conduits. The porphyry dykes are up to 30 m wide and commonly occupy the same structural zones as the mineralization. The dykes are coeval with or slightly older than the mineralization. Mineralization is dominated by gold-silver-rich structures associated with a zonation model ranging from weak porphyry copper-molybdenum centers, outward to transitional anastomosing sheeted veins, and lastly to more cohesive and continuous base and precious metal veins. The metals of primary interest at the property are gold and silver. These metals are intimately associated with lead, zinc, and copper in various forms and concentrations throughout the mineralizing system. The age of the mineralizing events is now considered to be Late Cretaceous. Depth of surface oxidation ranges from 5 to 100 m below surface, depending on fracture intensity, the type of mineralization, and local geomorphology.

The project exploration carried out by Rockhaven systematically advanced through soil geochemistry, followed by excavator trenching, geophysics (both magnetics and EM work very well), and finally through diamond drilling. Early soil sampling identified linear gold ± silver ± lead anomalies, which correspond to some of the known mineralized structural zones, and a large (2000 m by 3000 m) area of moderately to strongly anomalous copper-in-soil response, which partially defines the Kelly porphyry target in the southeastern corner of the property. Grid soil sampling performed from 2010 to 2012 expanded grid sample coverage to the west and north of the earlier grids and collected samples on a few contour-controlled lines in the northwestern part of the property. The grid to collect soil samples were established at 50 m intervals on lines spaced 100 m and oriented at 37°. Soil samples were obtained using a handheld auger and from 30 to 80 cm holes.

■■ Soil Sampling

Effectiveness of soil sampling is often limited by thick layers of organic material and overburden and in many areas by permafrost. Despite these limitations, soil sampling has been an essential and effective surface exploration technique for detecting trenching or drilling targets. Results for gold from historical surveys and Rockhaven's sampling are illustrated in ▣ Fig. 3.66.

Historically, excavator trenching in geochemically anomalous areas has been the most effective tool for identifying near surface but non-outcropping, mineralized zones. Within the main areas of exploration, overburden generally consists of 5–20 cm of vegetation and soil organics covering a discontinuous layer of white volcanic ash and 50–125 cm of loess and/or residual soil, which cap decomposed bedrock. Trenching of 22,366 m was performed in 84 trenches between 2010 and 2015. Where possible, trenches were excavated in areas that had previously been stripped of soil and vegetation. The trenches were aligned at about 30°, which is perpendicular to the anomalous trends of the main soil geochemical anomalies. All rock samples (chip sampling) collected from the property were taken from excavator trenches, because there are no naturally outcropping exposures of these zones. Continuous chip samples were collected along one wall of the trench as close to

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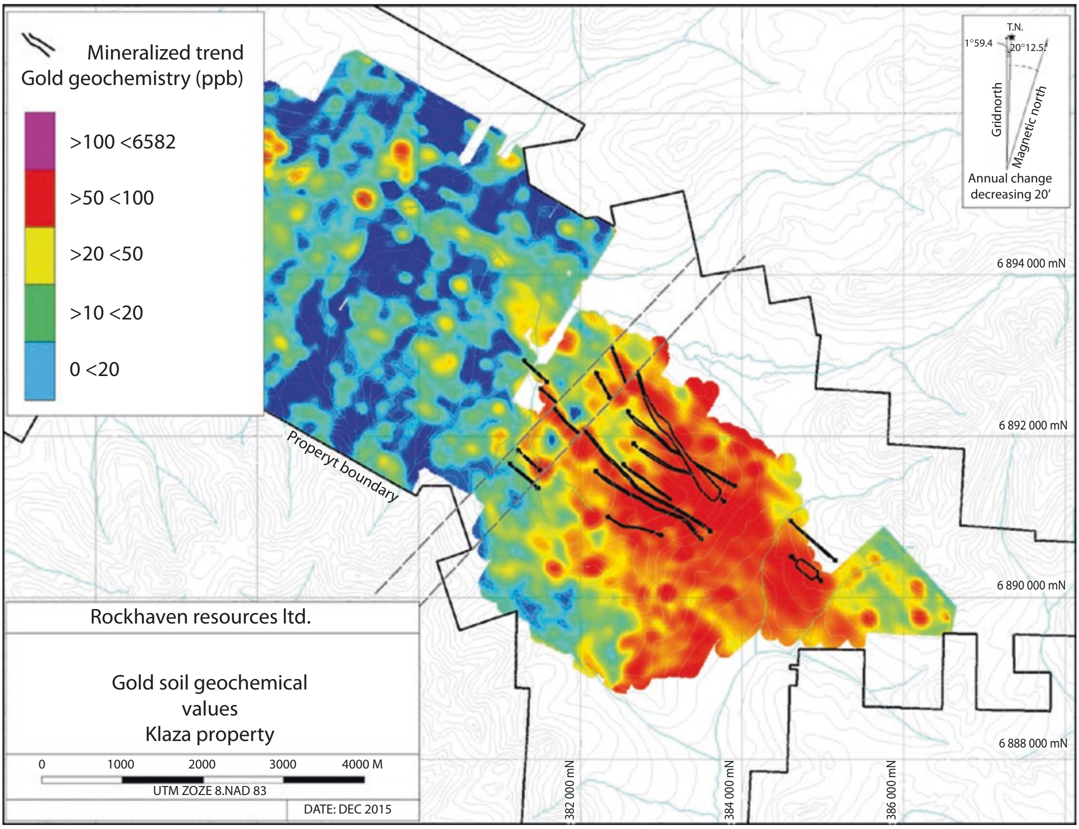

Fig. 3.66 Gold soil geochemical values in Klaza property (Data courtesy of Rockhaven Resources Ltd.)

the floor of the trench as slumping would allow using a geological hammer. Sample sizes averaged approximately 2 kg per linear meter sampled for intervals containing veins and about 1.5 kg per linear meter sampled for intervals comprised primarily of altered wall rock.

Geophysical Surveys

To date, four types of geophysical surveys have been completed on the property: (1) ground-based VLF-EM and magnetic surveys, (2) gradient array induced polarization survey, (3) high-sensitivity helicopter-borne magnetic and gamma-ray spectrometric surveys, and (4) high-resolution induced polarization surveys. The magnetic surveys identified a number of prominent, linear magnetic lows on the property. Subsequent trenching and drilling have shown that many of the northwesterly trending lows coincide with mineralized structural zones, while northeasterly trending breaks in the magnetic patterns correspond to cross faults. These relationships are consistent with the low magnetic susceptibility results that returned from core samples within the altered structural zones compared to higher values from surrounding unaltered wall rocks. Several of the magnetic lows extend outside the main areas of exploration and have not yet been tested by drilling or trenching. Figure 3.67 shows the first vertical derivative of the magnetic data overlain with the interpreted surface traces of the structural zones. Elevated potassic radioactivity is evident in the general area of the main zones in the eastern part of the property but does not specifically coincide with individual mineralized zones. Numerous porphyry dykes and frost boils containing porphyry fragments lie within this area, and they are the probable source of the elevated radioactivity.

The gradient array and pole-dipole IP survey covered a 1800 m by 1450 m area in the east-central part of the property. Readings were collected at 25 m intervals along lines spaced 100 m apart. This survey identified two main anomalies, both of which feature elevated chargeability with coincident resistivity lows. The most prominent anomaly is located in the southeastern corner of

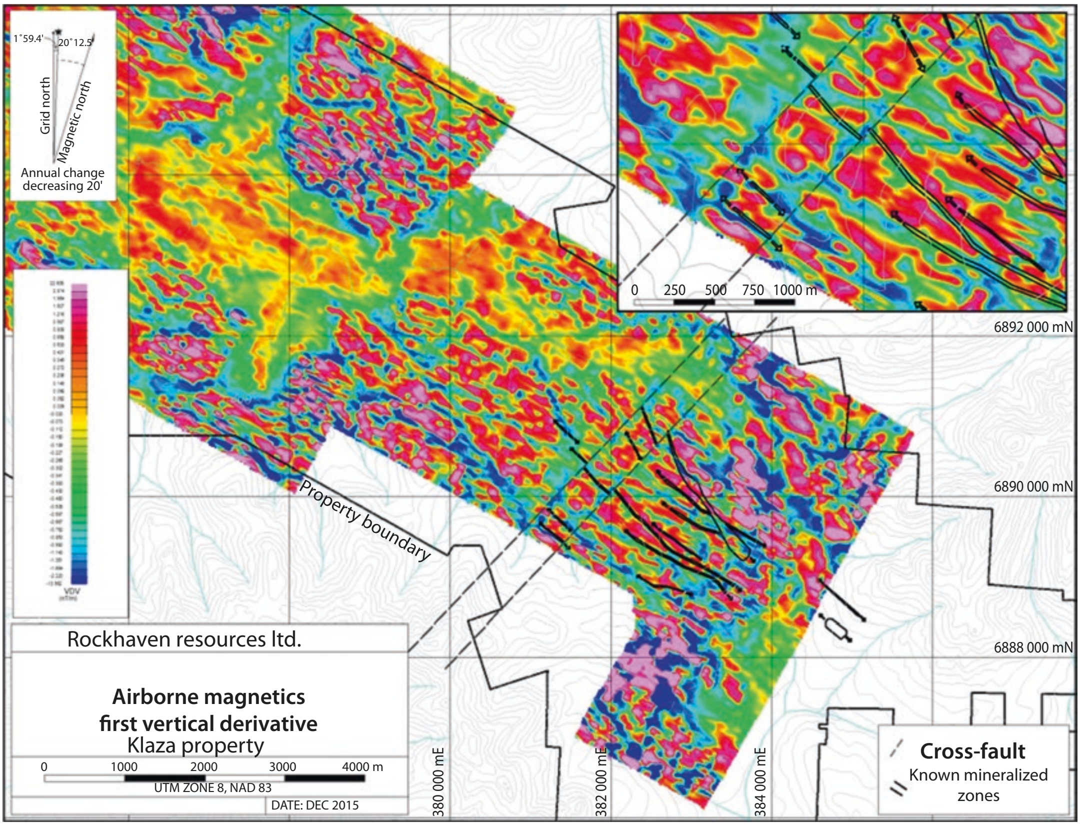

Fig. 3.67 First vertical derivative of the magnetic data in Klaza project (Illustration courtesy of Rockhaven Resources)

the grid and coincides with an area of weak to strong gold-in-soil geochemistry (25–100 ppb) and strong copper geochemistry (>200 ppm) as well as porphyry style mineralization that is part of the Kelly zone. The mineralized vein and breccia zones tested by geophysical surveys show up as resistivity lows that coincide with chargeability highs.

Drilling

Regarding drilling program, a total of 70,099.72 m of exploration and definition drilling was done between 2010 and 2015 in 295 diamond drillholes on the property. All diamond drillholes were collared at dips of −50°, and most of the holes had azimuths of 30–35° (north-northeast). Drilling was completed on section lines spaced roughly 50 m apart. Some of the 2015 drilling was done in part for geotechnical and environmental purposes. To monitor seasonal water levels and frost variations, vibrating wireline piezometers were installed in four holes and a thermistor was installed in one hole. Five diamond drillholes totaling 308.76 m were drilled vertically, peripheral to the mineral resource areas as water monitoring wells. In general, core recovery was good, averaging 95%, excluding the near surface portions of the holes where core recovery was poor. Final hole depths within the Klaza zone averaged 251.49 m, which included a maximum hole depth of 550.77 m. To determine the deflection of each drillhole, the orientation was measured at various intervals down the hole. Measurements taken and recorded were inclination, azimuth, temperature, roll angle (gravity and magnetic), as well as magnetic intensity, magnetic dip, and gravity intensity.

As an example of the results obtained in the main mineralized zones, the host rock of the mineralization in the central Klaza zone is an extensive complex of steeply dipping veins, breccias, and sheeted veinlets. The strongest veins are typically found along dyke margins. Pyrite, arsenopyrite, galena, and sphalerite are the main sulfide minerals in this subzone. Excellent results from

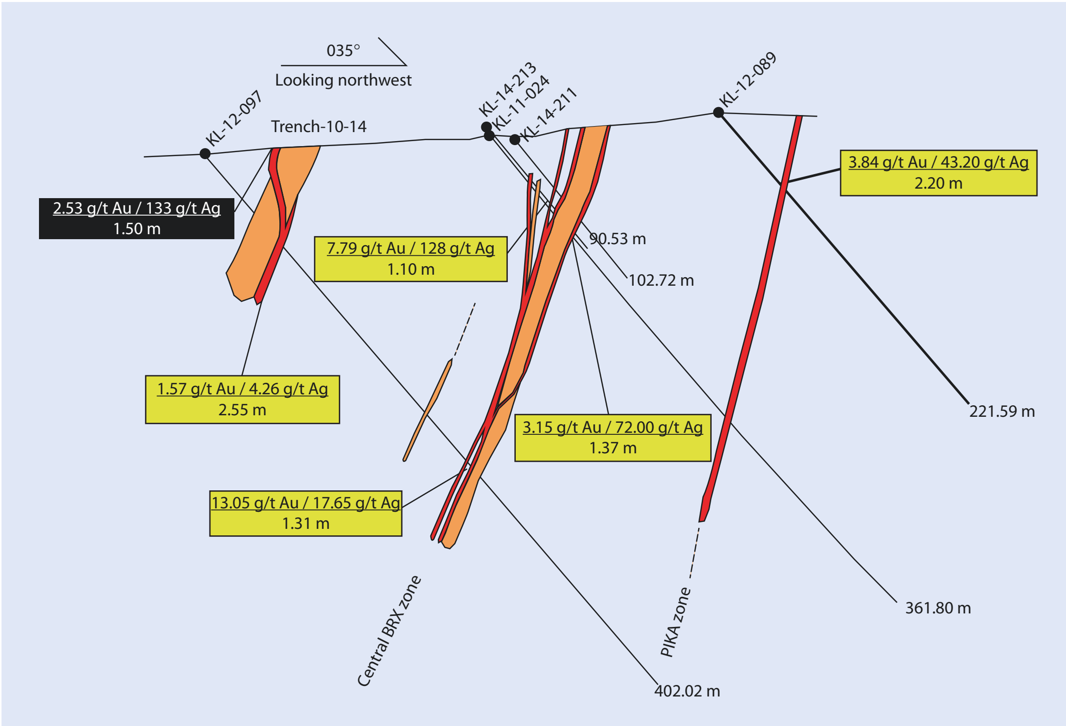

Fig. 3.68 Type section depicting the geometry of the mineralized veining relative to the dyke and the gold and silver grades values obtained in the samples (Illustration courtesy of Rockhaven Resources Ltd.)

this part of the Klaza zone were reported from an interval in KL-10-07, which graded 7.10 g/t gold and 259 g/t silver over 15.25 m, and an interval in KL-12-133, which graded 11.85 g/t gold and 5.24 g/t silver across 6.65 m. Figure 3.68 shows the results of central Klaza zone. Finally, a geotechnical log was carried out previous to geological logging and included determinations of core, rock quality designations (RQD), hardness, and weathering. In 2015, fracture frequency, joint sets, and joint set roughness, shape and infill were also recorded.

Ekati Diamond Project Exploration: Courtesy of Dominion Diamond Corporation

The Ekati diamond mine is located in northwest Canada, 200 km south of the Arctic Circle. Cold winter conditions are predominant in the region for most of the year. The area is a wildlife habitat, where human activities are limited to hunting and fishing. The geology of the Ekati project area consists mainly of Archean granitoids, intruded by metagreywackes and transected by Proterozoic mafic dykes. Bedrock is overlain by less than 5 m thick quaternary glacial deposits. The 45–75 Ma kimberlites of the Lac de Gras kimberlite field intrude both the granitoids and metagreywackes. The kimberlites are mostly small pipe-like bodies controlled by tectonic fissures and typically extend to depths of several 100 m below the land surface. The mineralization is mostly limited to olivine-rich resedimented volcaniclastics and primary volcaniclastics. Diamond grades from the kimberlites range from less than 0.05 cpt to more than 4 cpt.

Diamond exploration in the area started with heavy mineral sampling from fluvial and glaciofluvial sediments, which was followed by mapping of geomorphological features and field observations. Till sampling coupled with ground geophysics pinpointed the Point Lake kimberlite pipe, which was later investigated by core drilling and confirmed as diamondiferous kimberlite. Approximately 15,000 till samples were taken during the project exploration phase. They were also used to search for airborne geophysical anomalies. The extent and chemistry of the indicator minerals dispersion trains were evaluated to pinpoint drill targets.

Indicator Mineral

Kimberlite indicator mineral (KIM) compositions were outstanding in the exploration program leading to the development of the Ekati mine. Discovery of the first kimberlite at Point Lake was followed by the identification of over 150 kimberlite bodies within the Ekati areas. The use of KIM geochemistry was adopted to prioritize likely high-grade phases for follow-up bulk sampling and/or diamond drilling programs. The method involved selecting representative samples from the drilling and recovering a full suite of KIM's from each sample. The recovered grains (garnet, chromite, ilmenite, clinopyroxene) were analyzed by electron microprobe for major elements and by inductively coupled plasma mass spectrometry (ICPMS) for nickel.

Geophysical Surveys

The Ekati area was explored using helicopter-borne total field magnetic (TFM), electromagnetic (EM), and very low-frequency electromagnetic (VLF) surveys. Final exploration sweeps were carried out using an improved airborne EM system with tighter line spacing, reduced sensor height, and airborne gravity gradiometer (Fig. 3.69).

The ground geophysical surveys were used to gather more precise kimberlite/non-kimberlite target discrimination and estimates of pipe size. The surveys were completed on both the majority of the drill targets and all of the pipes with reported mineral resource estimates. A small core hole seismic survey was designed in the Koala pipe, this searching for detailed spatial information of the kimberlite body. The data proved that the borehole seismic technique could augment drillhole pierce points with seismically determined pipe wall contacts.

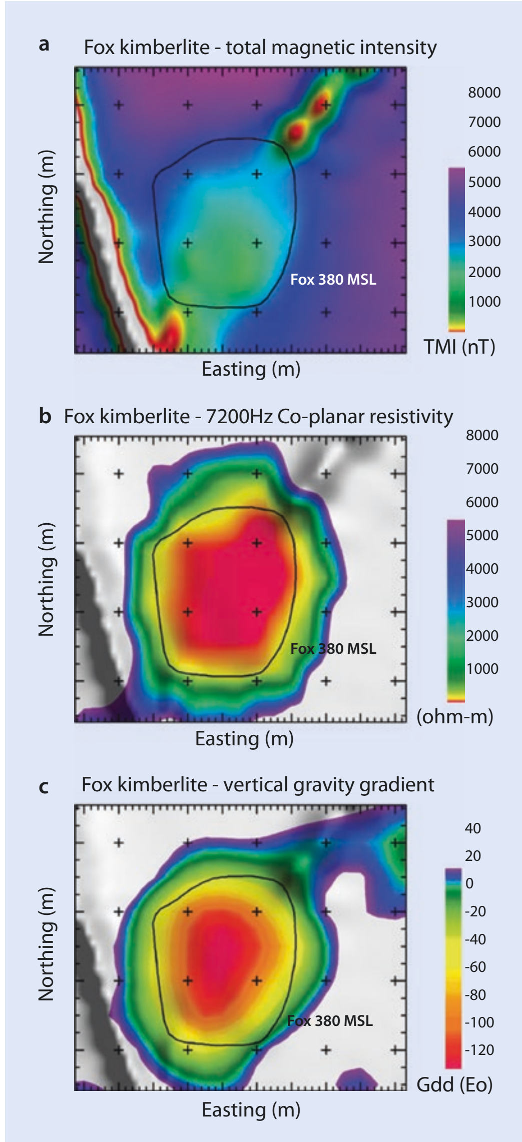

Fig. 3.69 Fox kimberlite airborne geophysical response; the Fox kimberlite has a weak and normal magnetization **a**, a strong conductive response **b**, and a very strong gravity response **c** (Illustration courtesy of Dominion Diamond Corporation)

Drilling

Drilling lasted from 1991 until 31 July 2016 and included 1389 core holes (254,490 m), 111 sonic drillholes (2596 m), and 513 RC holes (106,547 m). Core drilling using synthetic diamond-tipped tools and/or carbide bits contributed to define the pipe contacts, wall-rock conditions, and internal geology. Prior to 1995, the diameter of drillholes ranged from 27 to 71 cm; from 1995 to 2008, the holes' diameter was standardized to between 31 and 45 cm. In order to obtain larger samples, drillholes' diameters for the 2015 and 2016 programs ranged from 45 to 61 cm. Core drilling was also used for gathering geotechnical and hydrogeological data. Figure 3.70 shows the location of the drillholes. Forty kimberlite occurrences were subsequently tested for diamond content using reverse circulation (RC) drilling and/or surface bulk samples.

Sonic drilling was used to core both soil and bedrock in Ekati. The primary objective of sonic drilling was to characterize the nature and

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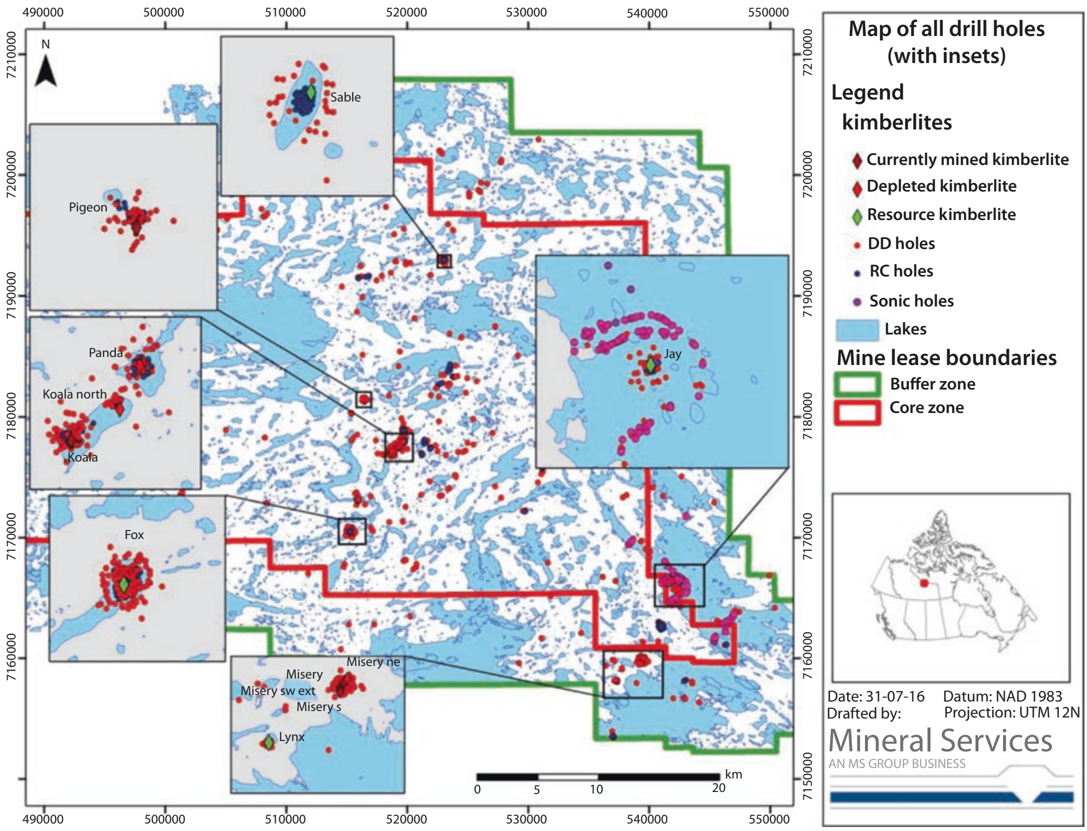

Fig. 3.70 Map showing location of all drillholes with insets for pipes with reported mineral resources for the Ekati project area; approximately 350 geophysical and/or indicator dispersion targets were drilled, with a total of 150 kimberlites discovered (Illustration courtesy of Dominion Diamond Corporation)

variation of the soil layers to determine the depth to bedrock. In addition, recovered soil was logged and geotechnical laboratory testing was performed on selected samples. After reaching the final depth of investigation at each borehole location, in situ hydraulic conductivity testing was carried out.

Since core recovery was largely a function of the hardness of the kimberlite, recoveries of 95–100% for both core and RC drillholes were common within wall rock. In kimberlite, the core recoveries were as low as 20% and as high as 95% but were more typically in the 75–85% range. For RC drillholes, kimberlite recoveries ranged from 50% to over 100% in cases of in holes sloughing. All core and RC drillhole collars were surveyed with GPS instruments prior to and after drilling in order to ensure that the drillhole collar location error is minimal. For core holes, downhole surveys were done with industry standard instruments. Three tools, including the tool for gyroscopic deviation surveying, the three arm caliper, and the tool for conductivity induction and natural gamma readings, were used on all RC holes.

Oriented core was used for geotechnical investigation of the wall rocks but not in kimberlite. The following geotechnical parameters were determined for all core drillholes: (a) percentage core recovery, (b) rock quality designation (RQD), (c) fracture frequency, (d) point load strength index, and (e) joint condition and water.

Digital geological and geotechnical logging was completed and the core photographed before being stored in appropriate building. Color photographs were taken of delineation drill core and used to verify significant contacts and lithologies as well as provide a permanent record of the drill core. Geological logging used digital logging forms for both wall-rock lithology, kimberlite/wall-rock contacts, and internal kimberlite lithology. Kimberlite cores were examined macroscopically and using a binocular microscope to determine concentration of macrocrystic olivine, matrix composition, abundance and type of country rock xenoliths, approximate abundance of indicator minerals, rock fabric, color, and alteration. Samples were taken from core holes for determination of dry bulk density and moisture content of host rock and kimberlite. In the opinion of the responsible QPs, the quantity and quality of the lithological, geotechnical, density, collar, and downhole survey data collected in the drill programs were sufficient to support mineral resource and mineral reserve estimation.

Matawinie Graphite Project Exploration: Courtesy of Nouveau Monde Mining Enterprises Inc.

The Matawinie project is spread over an area of approximately 70 km by 50 km, being the center of the most important block (Tony Block) positioned approximately 120 km north of the city of Montréal (Canada). The Matawinie property lies in the southwestern portion of the Grenville geological province. The belt hosts the only currently producing crystalline flake graphite mine in North America. The area includes a great variety of rock types such as paragneiss and calc-silicates. Granitic and pegmatitic intrusions also occur and are located occasionally on the property. The graphite mineralization is hosted in paragneiss horizons and appears as disseminated graphite flakes. The graphitic paragneiss occurs as layers a few centimeters to several meters thick and can often be followed along strike over tens to hundreds of meters. This rock type visually contains approximately 0.5–3% disseminated crystalline graphite. The graphitic horizons are interbedded with garnet paragneiss units displaying low graphite content and ranging from a few centimeters to tens of meters in width. The mineralized zones are limited by garnet paragneiss on the exterior side of the main circular conductive anomaly while charnockite granitic gneiss (hypersthene granite) occupies the internal portion of the circular anomaly.

Geophysical Surveys

Given the contrasted physical properties of the graphite mineralization sought after, geophysics was the key component of the exploration program and in particular time domain electromagnetic techniques (TDEM). The exploration strategy was twofold. First, it implied large regional airborne surveys with a wide line spacing to detect pluri-kilometric conductors, which were then followed up with ground prospecting/sampling. Second, areas with mineralization of interest were then flown again at the local scale with a tighter line spacing to define areas with better potential for thick and continuous mineralized envelopes. These prioritized areas were then surveyed with ground-based TDEM technology to allow high-resolution delineation of the sub-outcropping parts of conductors. This information was used to quickly plan trenching and drilling for efficient sampling of the mineralization.

With graphite being significantly more conductive than host rocks, the first step in the exploration stage was to carry out an airborne time domain electromagnetic (TDEM) survey. Thus, a regional heliborne magnetic and TDEM survey was carried out over an area of 55 km × 72 km at a 1 km line spacing. Several anomalies were detected and ten local areas were selected for detailed surveying using the same configuration, but at a 100 m line spacing. The surveys were successful in outlining several large-size conductors (Fig. 3.71). In order to assess the multiple

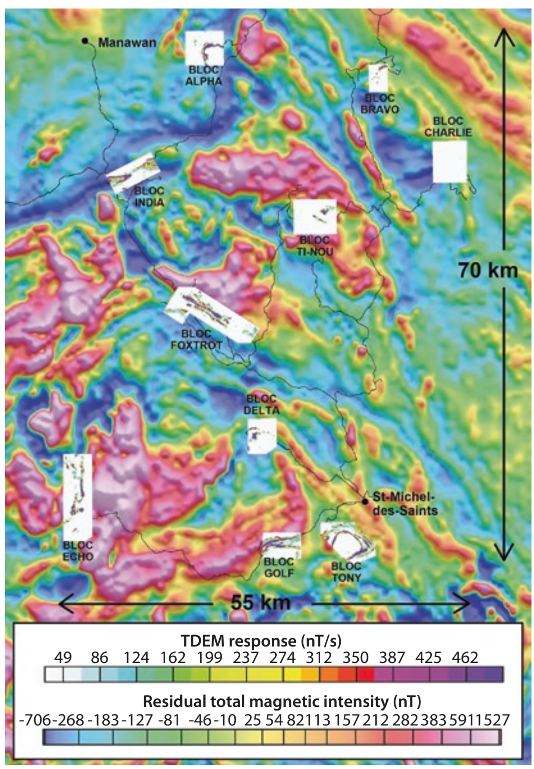

Fig. 3.71 Local areas flown with heliborne MAG-TDEM (Illustration courtesy of Nouveau Monde Mining Enterprises Inc.)

resulting targets in an efficient manner, a quick prospection campaign was deployed. It was supported by the use of a very small EM device with a penetration capability estimated at 1 m. This effort resulted in the collection of 35 grab samples grading between 5% and 17% graphitic carbon. Based on these preliminary results and the potential size of the conductors estimated from the airborne surveys, several areas were selected for further assessment.

In order to get an accurate image of the sub-outcropping portion of the conductors, a ground TDEM system was used. The system has a limited penetration depth estimated in the order of 10–15 m but offers high spatial resolution, being the unit equipped with an integrated GPS. The survey was carried out along existing roads and trails, along the 100 m spaced network of lines cut for other geophysical techniques, and finally along a local 20 m spaced set of lines specifically designed for this instrument. The overall results obtained with this system proved very useful to map the sub-outcropping conductors. This type of high-spatial-resolution information enables a significant gain for understanding the geometry of ore bodies close to surface. It served as a guide for strategically locating exploratory trenches and drillholes, especially in this geological area that underwent strong deformation. Everywhere a trench was dug or a hole drilled based on these results, graphite and/or sulfide mineralization was found and could explain the anomalies. The overburden encountered in the drillholes of the area varied from 0.4 to 5.5 m, with an average of 3.5 m.

Other classic geophysical techniques were used to better define the conductors. A horizontal loop EM (HLEM) survey was performed every 25 m with a 100 m cable using three frequencies. With its estimated penetration depth of 50 m, the information provided by this survey was especially useful at locating conductors with significant vertical extensions and those with their top located deeper than the penetration depth of the previous system. It also enabled some estimation of the dip, conductance, and depth to top of conductors. A resistivity/induced polarization (IP) survey was also carried out at a 12.5 m station spacing (for increased resolution) with ten receiving dipoles using the pole-dipole configuration (for increased penetration depth). The conductors identified with this electrical method conformed well with those detected using EM methods. Some poorer, more subtle, conductors were also outlined. Furthermore, the chargeability model highlighted some areas where disseminated graphite and/or sulfides may occur in addition of the conductive occurrences. In addition, the 2-D section models of the IP data were especially useful for drillhole planning.

Magnetic data was also gathered in an effort to try to discriminate weakly magnetic conductors, likely relating to low sulfide graphite occurrences, from strongly magnetic conductors for which higher sulfide concentration may occur (◘ Fig. 3.72). In one instance where a drillhole had intersected a graphite-rich horizon at a depth much greater than expected (85 m instead of about 20 m), a borehole Mise-À-La-Masse survey (MALM) was carried out with a 12.5 m spacing to verify which of the sub-outcropping conductors this deep intersection was connected to. The MALM survey proved that the deep graphite occurrence was connected to shallow conductive units further to the northwest rather than nearby, indicating some local discontinuities.

The 2014 and 2015 ground TDEM surveys delineated wide conductive areas over each of the targeted mineralized zones. As a result, four trenches were excavated in 2014 and five in 2015 (◘ Fig. 3.73). Trenches were oriented roughly perpendicular to the foliation of the paragneiss units and mineralized horizons with the exception of one trench, which was at about 45° to the foliation because of terrain constraints. In 2014, the trenching program aimed at sampling only mineralized material along the trenches in order to determine the potential of the mineralization, while in 2015 channel sampling usually started 2 or 4 m (1–2 sample lengths) outside the visible mineralized area and was collected in a continuous manner as to prevent any sample bias. Trenches were approximately 1.5 m in width and varied from 0 to 4 m in depth. In some instances, large boulders, the accumulation of water and prohibitive depth prevented the excavation and/or sampling of portions of the planned trenches.

Drilling

Drilling on the Tony Block targeted wide conductors on each of the main conductive areas outlined by the 2015 ground TDEM survey. A total of 70 holes were drilled for a total of 10,479 m. As an example, the drilling on the southeast zone of the south deposit consisted of nine holes for a

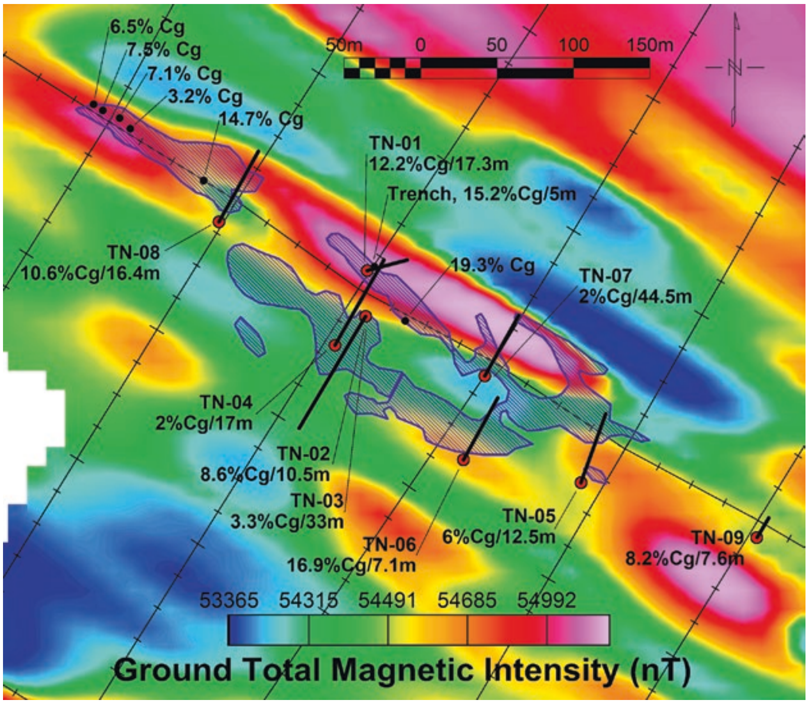

Fig. 3.72 Ground magnetic survey results (Illustration courtesy of Nouveau Monde Mining Enterprises Inc.)

Fig. 3.73 Part of a trench including a channel sampling (Image courtesy of Nouveau Monde Mining Enterprises Inc.)

total of 1552 m drilled. Mineralization was intercepted 13 times by drilling here resulting in the interpretation that the southeast zone is composed of two main mineralized horizons (S1 and S2). From Section S2600 to Section S2900 (300 m length), the mineralized horizon ranges from 116 to 159 m true width, with grade varying from 3.18% to 3.61% Cg. The drilling on the southwest zone of the south deposit consisted of 22 holes for a total of 2617 m drilled. Mineralization was intercepted 57 times by drilling here resulting in the interpretation that the southwest zone is composed of two main mineralized horizons (S1 and S2). The highlight of southwest zone is a first graphitic horizon (S1) about 29 m thick. It is followed by a mainly barren interval between 24 and 62 m thick and finally a second graphitic horizon (S2) around 40–50 m thick, with both graphitic horizons varying from 2.79% to 5.29% Cg.

Coringa Gold Project Exploration: Courtesy of Anfield Gold Corp.

The Coringa gold project is located in north central Brazil in the mining friendly state of Para, 65 km south of Novo Progresso. The area occurs in the southeastern part of the Tapajós mineral province where past production is estimated at 30 million ounces of gold. The claims are underlain by Proterozoic granites and rhyolitic volcanics, and the main structural trends are northwest and north-northwest. The Coringa shear-vein system (high-grade gold mineralization is hosted in a series of narrow quartz-sulfide veins that range in thickness from 0.15 to 4 m) is coincident with the north-northwest trend (345°) and dips 70–90° to the northeast. The main shear is 7 km long and five zones of vein mineralization occur along it. Many other mineralized structures are also present.

Geophysical Surveys

The exploration program initially focused on determining drilling targets. These targets were identified through artisanal workings, geological mapping, airborne geophysics, and ground IP surveys, along with rock and soil sampling. An airborne magnetic-gradiometric and gamma-ray survey was carried out during 2007. The airborne survey covered 549 km^2 with a 200 m grid spacing and at an altitude of 100 m. A 34 km line induced polarization (IP) dipole-dipole geophysical survey over two zones and a 70.7 km line IP (induced polarization) dipole-dipole geophysical survey over approximately 7.0 km of gold-bearing structures were later completed. A time domain electromagnetic geophysical survey of 860 km line was flown to cover all identified pan concentrate and gold-in-soil anomalies.

Rock and Soil Sampling

Rock and soil sampling were carried out in several phases. Gold and 34 other elements were assayed in the samples. Soil sampling was carried out using a 100 m by 25 m sampling grid together with 18 trenches. For soil sampling, a baseline was set up perpendicular to the soil line orientation. The topsoil (between 0.3 and 0.5 m deep) was removed and a 0.5–0.7 kg sample was collected from the following 0.5 m below the topsoil. Samples were placed in a plastic bag and tagged. A brief description that included color of the sample, percentage of gravel, sand, and silt was carried out. All field information was controlled by the geologist in charge of the soil survey and digitized into the data base before sending the sample to the laboratory for gold analysis. In trench sampling, a start point was located with a handheld GPS, and azimuth and trench length was estimated with a compass and tape. Trenches were hand dug to a depth of 1 m. In these trenches, approximately 2–3 kg chip-channel samples were collected at 1–1.5 m intervals. Finally, a stream sediment sampling program was also carried out, being collected a total of 756 samples.

Drilling

In drilling program, four drilling phases have been completed on targets identified at the project site for a total of 24,093 m of HQ core in 160 exploration holes. In the first phase of drilling, 1774 m in 22 holes was carried out for early stage exploration, being drilled under the main artisanal workings («garimpos») (Fig. 3.74). The second phase drilling includes 5032 m in 44 holes, and

Fig. 3.74 «Garimpo» or artisanal working (Image courtesy of Anfield Gold Corp.)

Table 3.5 Drilling summary by phase

Phase	Holes	Holes with downhole survey	Meters	Samples	Meters sampled
1	22	0	1774	1922	1717
2	44	42	5032	1711	1370
3	15	12	1979	434	333
4	79	66	15,308	5227	4752.83
Total	*160*	*120*	*24,093*	*9294*	*8172.83*

Data courtesy of Anfield Gold Corp.

Fig. 3.75 Sampling procedure (Images courtesy of Anfield Gold Corp.)

the aim was further defining of the resources in several blocks. Regarding the third phase, drilling was 1979 m in 15 holes; the main objective was to define the resource in one block and test two of the IP targets. Finally, the fourth phase of drilling covered 15,308 m in 79 holes), being the goal to test the continuity of the Mae de Leite structure at depth and along strike as well as the continuity of the Meio zone along strike to the north and south.

Table 3.5 summarizes the drillholes completed within each phase of drilling.

The sampling procedure in holes (Fig. 3.75) includes the continuous sampling of the core at intervals of approximately 0.5 m (mineralized zones) to 1 m (non-mineralized zones). In this process, a cutting/splitting guide line is marked on the core by the geologist to ensure that the mineralized structure is equally divided, each box is photographed to provide a visual record of the core, and then one-half of the core is returned to the core box, while the other half is placed in the numbered and tagged sample bag.

Atacama Copper Project Exploration: Courtesy of Arena Minerals Inc.

Atacama copper property consists of approximately 920 km^2 (92,000 hectares) in Chile's Antofagasta Region, approximately 40 km northeast from the city of Antofagasta. The property has been almost exclusively explored and exploited for industrial minerals, primarily iodine and/or nitrates. These industrial minerals are found within overburden covered areas and generally within 20 m from surface. As a result, the exploration activities within the property focused on shallow exploration methods, ranging from trenching to short RC drilling in more recent years, which targeted sedimentary layers within the overburden. Most of the Cu porphyry deposits of the region belong to the Paleocene-Early Eocene world-class Cu-Mo porphyry belt which extends from southern Peru to northern Chile for a distance of over 1300 km. Mineralization is associated with a complex of granodioritic to quartz-monzonite stocks with accompanying Paleocene dykes dated at 57 million of years.

A basic outline of the exploration program in place is as follows: (1) data compilation; (2) desktop analysis and target selection; (3) initial ground work and prospecting; (4) prospect generation and selection; (5) follow-up ground work, including additional geology, geochemistry, and ground geophysics; and (6) drill program design, RC drilling in two phases: 2 km grid drilling followed by 1 km grid infill based on results. Thus, the exploration program during 2013–2014 started with an initial phase of target selection using satellite imagery (ASTER) to identify exposed alteration zones and main structural features and trends. This work was combined with regional geological and geochemical data to provide a selection of priority targets for field follow-up with prospecting and sampling. Twenty-nine target areas were selected of which 11 have exposed alteration of various compositions read from the ASTER images. The other targets that do not have surface alteration detectable by ASTER imaging lie under cover or have only small outcrop expressions (less than the 25 m pixel limit). These areas were selected based on their copper-molybdenum geochemical anomalies from the short RC exploration holes carried out by SQM while looking for industrial minerals, known reported or inferred lineaments forming structural corridors and other geological information.

The initial target selection was reviewed again once the company acquired regional airborne magnetic and radiometric data that had been flown as part of a multi-client survey in 1999 (Fig. 3.76). The reinterpretation of this database led to the identification of an additional 23 targets that had not been selected during the initial selection process. The remaining 17 of the reinterpreted magnetic/radiometric targets correspond with previously selected ASTER/geochemical targets.

All alteration zones or mineralized outcrops were systematically sampled, and a preliminary geological map was made of all areas of interest. A total of 1450 rock chip samples were collected during this phase of exploration, and several areas with potential for both copper porphyry and epithermal gold mineralization were identified for additional ground follow-up surveys. Based on the results of the initial fieldwork, five areas were selected for ground magnetics coverage: Cerro Barco, Cerrillos, Quebrada Honda, La Paloma, and Paciencia. A total of 3647 line km of surveying was completed by this survey. Following the ground geophysics, additional mapping and in some cases multispectral analysis were done on selected alteration areas to get a better definition of the targets and define trenching and drilling targets.

The ground magnetic surveys were conducted on north-south lines with a line spacing of 100 m. Readings were carried out with an approximate station spacing of approximately 0.5–1.5 m. A checkpoint was measured twice daily with all the magnetometers. Repeatability of the corrected magnetic readings was within 1 nT, and the GPS UTM coordinate repeatability was within 2 m of the average value. In summary, several large anomalies that may be indicative of large hydrothermal alteration systems were observed, being the magnetic data effectively mapping lithology.

Regarding the exploration results and interpretation, the comparison between the smoothed analytical signal data and what is known of the local geology from either the regional map sheets or the arena mapping allowed for a definition of a set of characteristics for the different lithologies, subject to variations caused by things like burial

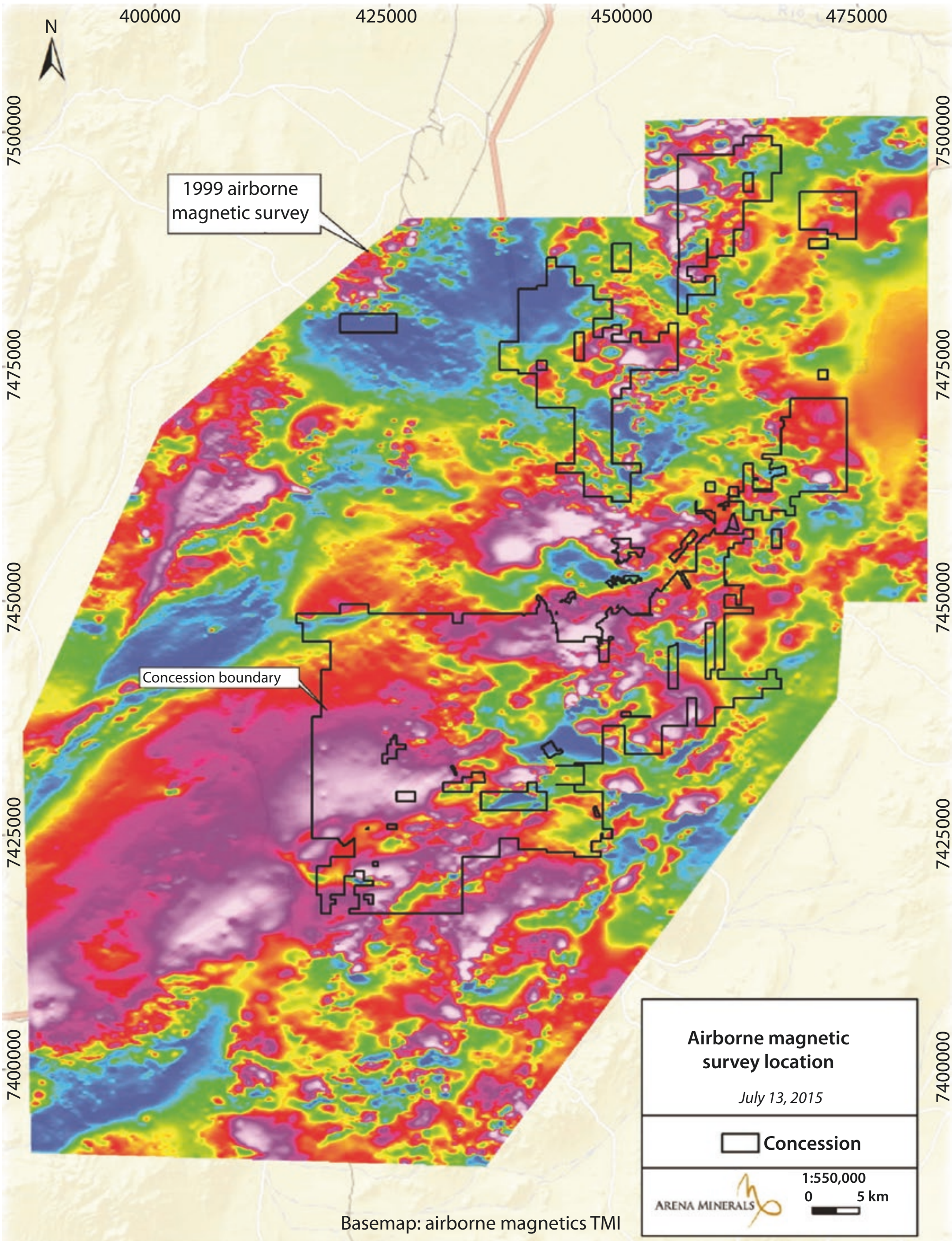

Fig. 3.76 Airborne magnetic survey location (Illustration courtesy of Arena Minerals Inc.)

depth and well-known magnetic characteristics of igneous and sedimentary rocks. Typically, mafic intrusives are more magnetic than mafic and intermediate volcanics that have been subject to oxidation, and in turn, these are more magnetic than granites. In several locations, the lithologies were revised based on magnetic characteristics where the regional mapping indicated lithologies (e.g., Cretaceous granites) that are not consistent with high magnetic gradients measured in the

Fig. 3.77 Crustiform quartz from Paciencia prospect (Image courtesy of Arena Minerals Inc.)

new survey and where the geological map sheet shows Holocene cover and an absence of outcrop.

Pampa Paciencia prospect results, as an example of the exploration program, are the following. The Pampa Paciencia prospect is located approximately 10 km north and northeast of the Sierra Gorda and Spence mines, respectively. The detailed magnetic survey has allowed the interpretation to refine the position of the faults and to recognize that most of the lithologies are fault-bounded in a broadly north-south elongation direction. Two distinct mineralized areas, approximately 2 km apart, have been discovered within altered dioritic and granodioritic intrusive rocks. The mineralization consists of quartz vein outcrops and subcrops of angular quartz fields that align with east-west to west-northwest lineaments. The quartz vein material exhibits well-developed crustiform-colloform textures (Fig. 3.77) and is associated with gold, silver, and base metals anomalies.

The epithermal quartz field consists of a 500- to 800-m-long area of quartz float concentrated along a west-northwest axis immediately south of a large granodiorite outcrop. Several quartz chip samples taken from this area originated anomalous values of gold up to 6.82 g/t of gold. Seventeen other samples from this zone also generated anomalous values ranging from 0.5 to 3.85 g/t of gold. The second area of interest is located 2 km southwest of the epithermal quartz field, consisting of veins with associated quartz-amethyst. Anomalous gold values from chip sampling range from 0.3 to 2.07 g/t and are associated locally with anomalous base metal values in copper (up to 0.12%), lead (up to 0.41%), zinc (up to 0.15%), and silver (up to 154 g/t). The next stage of work on this target should comprise of trenching, sampling, and mapping of the two vein areas prior to exploration RC drilling.

Preston Uranium Project Exploration: Courtesy of Skyharbour Resources Ltd.

The Preston uranium property is located in northwestern Saskatchewan, Canada. The property comprises 121,148 ha and is approximately 32 km long in a northerly direction. Outcrop exposure is limited, generally 5%. Vegetation, weather conditions, and seasons are typical of northern Saskatchewan. The Preston uranium project is located 30 km southwest of the southwest margin of the Athabasca Basin, which is interpreted to have been filled over a 200 Ma period in four major depositional sequences coalescing into a single basin. No significant zones of uranium mineralization have been identified on the property to date but the Athabasca Basin arguably hosts the world's largest and richest known uranium deposits.

Airborne Geophysical Surveys

A 5162 line km combined versatile time domain electromagnetic (VTEM^{plus}) and aeromagnetic survey was completed over six blocks of the Preston property. The survey areas were flown at 200–300 m line spacings with tie lines at 1000 m. Over 300 km of conductor segments, some approaching 10 km in length, occur in the combined eastern blocks of the Preston VTEM coverage. Basement aeromagnetic trends in the furthest western block are oriented northwest-southeast, while those of the eastern blocks are E-NE which is similar to the dominant basement strike orientation at Fission's Patterson Lake South high-grade uranium discovery area. Cross-cutting structural features and flexures affecting the conductor traces were identified to be of particular interest as prospective follow-up targets.

A Goldak high-resolution radiometric survey was flown to locate uranium boulder trains, in situ uranium mineralization and alteration associated with uranium mineralization. The airborne radiometric, magnetic, and VLF-EM survey was flown over one large block extending up to 60 km east-west and up to 36 km north-south flown at 50 m above surface. A total of 8273 line-km on 200 m line spacing was flown on lines at 155°/335°. The airborne radiometric spectrometer coverage mapped a significant number of enhanced radioactive locations that were classified into contributions from uranium, thorium, and potassium sources. Interpretation of the radiometric data identified areas with elevated uranium counts that can be correlated along and between multiple lines potentially indicating the presence of radioactive boulder trains or in situ uranium mineralization. These radiometric features, particularly when coincident with prospective EM conductors, were given high priority for follow-up ground work.

Geological outcrop mapping and identification of boulders and/or boulder terrains were completed over geochemical survey grids (at 200 m line spacing) and on prospecting traverses while ground truthing geophysical anomalies. Geological traversing and mapping and sampling of the various rock types were aided by ground radiometric surveying. Areas with high topography were chosen for geological mapping traverses based on coinciding airborne radiometric anomalies and strong EM conductors. Geological outcrop and structural mapping was completed at a scale of 1:5000 in selected areas. The dominant lithology was moderately to steeply dipping, northeast trending, weakly to moderately foliated granite. Further to the northeast, to the extent of the Preston tenure boundary, diorite-to-gabbro and granite-to-granodiorite outcrops are mapped along the same intermediate airborne magnetic northeast trend. Radioactive pegmatites (>2000 cps) intrude granite to granodiorite to the northeast.

Water, Sediment, and Soil Sampling

Lake-bottom water and sediment sampling were regularly collected together at the same site. Samples of lake sediment were collected using a tubular steel instrumentation, fitted with a butterfly valve that opens an impact with the sediment and closes as the sample is retrieved, and trapped the containing sediment. The sampler is designed so that once retrieved, it can be inverted and the contained sediment poured into a sample bag. Sample control was by GPS with sub 5 m accuracy. Thematic plotting was completed for As, Au, Co, Cu, Li, Mo, Pb, U, Th, Y, and Zn and assessed for spatial associations with known geological, radon, and geophysical features. Statistics for select elements of interest are tabulated in Table 3.6. For

Table 3.6 Select lake sediment statistics

n = 260	U_ppm	Pb_ppm	Pb206_ppm	Co_ppm	Au_ppb	Y_ppm
Max	*2.60*	*19.74*	*4.66*	*42.90*	*7.30*	*39.49*
Min	0.05	0.55	0.13	0.50	0.10	0.65
Average	0.63	3.31	0.83	8.10	0.50	8.01
Stdev	0.46	2.31	0.57	6.47	0.78	7.09
50‰	0.50	2.81	0.70	6.20	0.30	5.66
78‰	0.80	4.02	1.03	11.01	0.70	11.08
90‰	1.20	5.35	1.40	16.19	1.10	16.84
95‰	1.71	6.60	1.62	20.98	1.51	22.47
99‰	2.20	12.66	3.12	29.42	3.30	33.79

Data courtesy of Skyharbour Resources Ltd.

the uranium lake-bottom sediment results, a total of 7 out of 260 samples collected in 2013 are above the 99th percentile. This cluster of samples is also strongly anomalous in Co, Cu, Nb, Y, and Zn.

Regional soil sampling grids were completed, for the most part, between 200 and 400 m line spacing and 100–200 m sample spacing orthogonal to EM conductors and/or radiometric anomalies. Over 700 B-horizon samples were collected with sampling generally avoiding muskeg. The soil profile comprises 0–15 cm of moss or pine needles covering a thin 0.1–1 cm organic humus layer, then into a generally beige- to white-colored unconsolidated pebbly sand. The B-horizon selected for sampling was identified in the field as an abrupt transition from the above beige or white sand to a brown or orange sand typically occurring between 15 and 85 cm depth. Thematic plotting was completed for Ag, As, Au, Ce, Co, Cu, Li, Mo, Pb, U, Th, Y, and Zn and assessed for spatial associations with known geological, radon, and geophysical features. Uranium anomalies in soils are generally limited to one or two adjacent station anomalies. Two of the most significant multi-station soil anomalies in the north-west to north central fin area are spatially associated with mapped granitoid outcrops with significant topographic relief. The highest U value for 2013 came from the west central portion of the Swoosh target, adjacent to the projected map extension of pelitic sediments. This sample returned 7.90 ppm U with >95th percentile values for Cu and Y and greater than 80th percentile As and Pb and positive Pb isotope systematics.

■ ■ Biogeochemical Sampling

Regional biogeochemical sampling was completed on geochemical survey grids in conjunction with soil sampling. Black spruce was selected as the preferred vegetation medium due to its proven ability to concentrate many elements and widespread availability in both well-drained and poorly drained areas. Previous studies also identified Jack pine as a suitable biogeochemical medium. These species was selected as a secondary target vegetation type, due to its widespread distribution in the property area. Thus, twigs with attached needles were collected from around the circumference of an individual tree within 20 m of each soil sampling site. Numerous field parameters were collected including tree height, twig length and diameter, soil moisture conditions, slope, aspect, and any other factors that would affect sample quality. The three different tree species have differing background values on an element by element basis, so it is critical that plots showing biogeochemical results be levelled to account for these differences.

■ ■ In Situ Radon-in-Soil

In situ radon-in-soil measurements were taken adjacent to the site of soil sample (hole). A hand-operated auger was used to drill a hole approximately 2.5 cm in diameter to a depth of approximately 65 cm. Net radon results are given in counts per minute (cpm). Radon-in-soil analysis was completed at a total of 181 sample sites, most of which have corresponding soil sampling completed for ICP analysis. Values for radon ranged between 0 and 26 counts per minute. In most areas, the spacing and sample density were too low to establish significant anomalies when viewing the radon-in-soil data alone. Other samples such as lake-bottom water samples were also collected and measured.

■ ■ Ground Gravity Surveys

The targets for land-based gravity surveying were selected based on favorable geology and structure, coincident geochemical survey (lake sediment, radon-in-water, radon-in-soil, and/or biogeochem), and airborne geophysical survey results from the 2013 exploration program. Prioritization was given to discrete sub-kilometric ovoid gravity lows potentially associated with desilicification, clay alteration, and other alteration typically found in uranium deposits. The 2014 ground-based gravity survey consisted of gravity stations collected on survey lines spaced at 400 m with a station spacing of 50 m. A horizontal loop electromagnetic survey (HLEM) was later carried out. The targets were selected for HLEM surveying to more accurately define airborne VTEM conductors of interest refined by the geological, geochemical, and gravity results.

■ ■ Drilling

Finally, two diamond drilling programs were carried out in 2014 and 2015. The drill core was descriptively logged by the geologist on site for lithology, alteration, mineralization structure, and other geological attributes with the pertinent data entered into a database. Handheld spectrometers were used to measure the radioactivity of the drill core and aided in the selection of zones for sampling. The core was sampled based on radioactivity, alteration, and structure of the core with sample intervals typically 0.5–1 m in length.

Ilovica-Shtuka Gold-Copper Project Exploration: Courtesy of Euromax Resources

The Ilovica property is located in the southeast of Macedonia, about 16 km to the border with Bulgaria. Ilovica is a porphyry copper-gold deposit, situated in a northwest-southeast striking Cenozoic magmatic arc that covers large areas of central Romania, Serbia, Macedonia, southern Bulgaria, northern Greece, and eastern Turkey. It is more or less 1.5 km in diameter, being associated with a badly exposed dacite-granodiorite plug and emplaced along the northeastern border of the northwest-southeast elongate Strumica graben. The exact location of the deposit is controlled by major north-south crosscutting faults and minor northwest-southeast faulting, parallel to the faulted border of the graben. Alteration related to tertiary magmatic activity at Ilovica is variably present over an area of approximately 8 km^2. Pervasive alteration is largely confined to a roughly 1.5 km^2 area in and adjacent to the main intrusive complex. Smaller areas of pervasive and structurally-controlled alteration extend somewhat asymmetrically to the south and east of the intrusive complex.

Regarding the mineralization, the main sulfide mineral at Ilovica is chalcopyrite followed by pyrite and secondary copper sulfides such as chalcocite, covellite, and bornite. Molybdenite, galena, and sphalerite are present in minor amounts, and occasional traces of sulfosalt minerals such as tetrahedrite-tennantite and tellurides of gold and silver are observed. High-temperature oxide mineralization, such as magnetite, dominates at depth associated with pyrrhotite and chalcopyrrhotite in what is interpreted as the core of the system. A variety of iron hydroxide group minerals are largely developed within the oxidation and cementation zones. Very occasionally gold nuggets are observed at the base of the oxidation zone.

Field Mapping, Rock Chip Sampling, and Soil Geochemistry Survey

Detailed geological mapping was completed on 1:2000 and 1:5000 scales and comprised observations with respect to petrology, style of alteration, and mineralization. Rock chip samples were collected from the outcrops which were identified as having potential to host mineralization.

In total, three phases of soil sampling have been undertaken on the property, resulting in a total of 540 sampling points arranged on a 100 m × 100 m grid. The total area covered by the soil geochemistry sampling was approximately 5000 m^2. The soil sampling targeted the subsoil horizon, which is generally at a depth of 20–30 cm (the «B» horizon of the soil profile), as this unit generally contains the accumulated minerals. The soil surveys were completed by initially removing the humus topsoil layer with a spade, before taking a 2–3 kg sample of the subsoil. The remainder of the soil was restored to the sampling location and rehabilitation of disturbed areas was performed.

Results of soil sampling over the property indicate significant copper anomalies (>200 ppm copper) to the northwest, southwest, and south of the mineralized intrusive (Fig. 3.78). These anomalies are believed to represent down slope dispersion of the copper from the central area of mineralization. In contrast, significant gold (>0.10 ppm) and to a lesser extent molybdenum (>20 ppm) show less down slope dispersion and more accurately delineate the underlying mineralization.

Geophysical Surveys

A total magnetic intensity survey was carried out and 24 east-west lines spaced 100 m apart were surveyed with readings taken every 10 m. The aim of the survey was to outline the lateral and vertical extension of stockwork zones with secondary magnetite enrichment intersected in several drillholes. Magnetic susceptibility measurements were taken at an average interval of about 10 cm on core from these holes using an electromagnetic inductance bridge. A high amplitude magnetic anomaly was outlined; the magnetic susceptibility measurements demonstrated that the only magnetic rocks in the area are the secondary magnetite enrichment stockwork zones that are the source of the magnetic anomaly. The magnetic models indicated that the magnetic stockwork zone trends north-northeast along an 800 m strike length and is approximately 300 m wide, though inherent ambiguities in the interpretation process may have underestimated the width of the body.

A high-resolution pole-dipole array survey was carried out using dipole lengths of 300 and 150 m and n spacings of 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, and 5.5 for the array with dipole length of 300 m and $n = 1, 2, 3, 4, 5, 6$, and 7 for the 150 m dipole length. The IP or resistivity survey identified a number of intense IP anomalies, interpreted to be related to sulfide and magnetite mineralization previously intersected in drillholes (Fig. 3.79). The resistivity

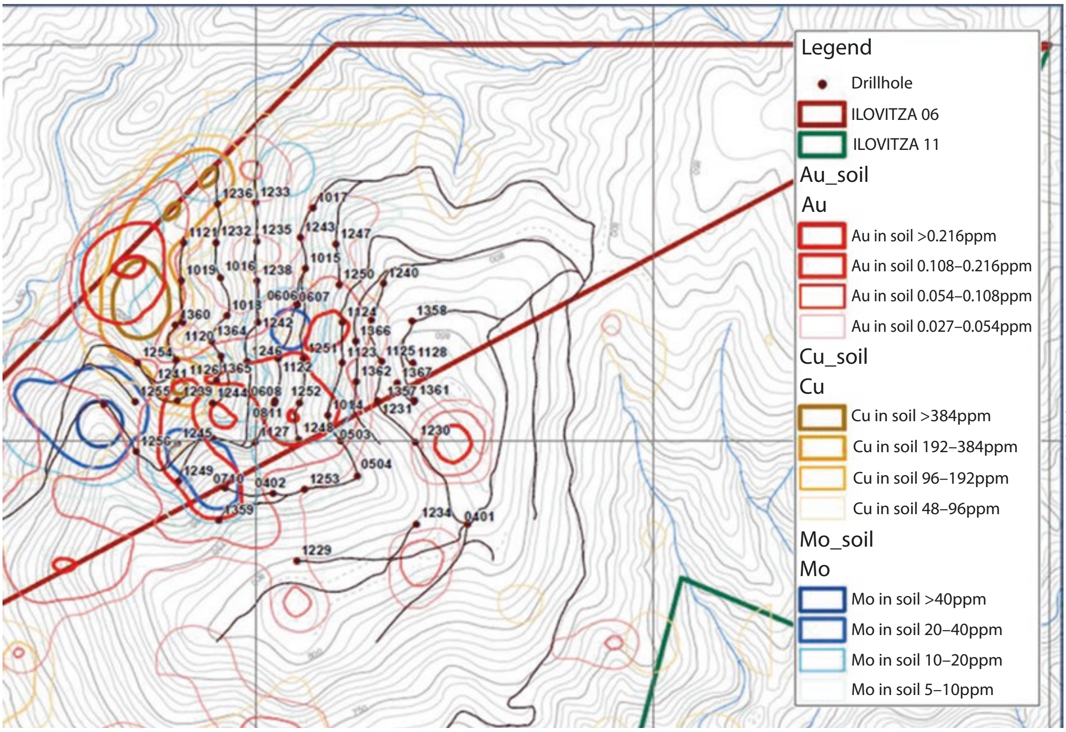

Fig. 3.78 Excerpt of the soil geochemistry anomalies map (Illustration courtesy of Euromax Resources)

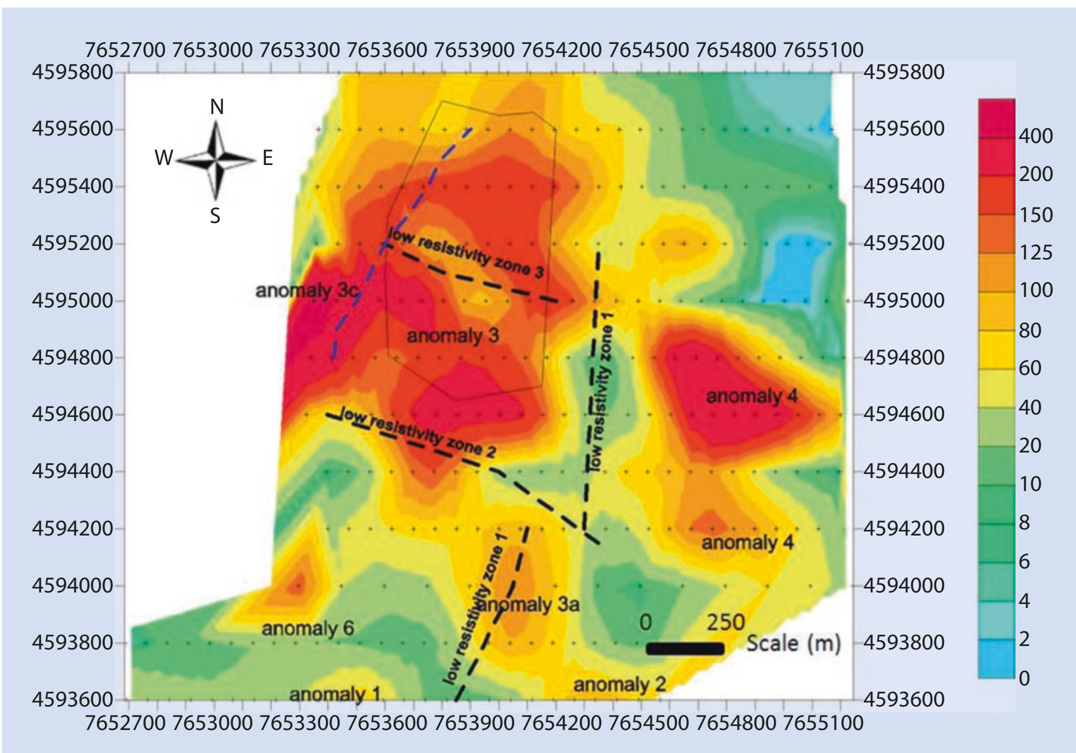

Fig. 3.79 2D IP Inversion model on level 350 m from surface (Illustration courtesy of Euromax Resources)

models revealed the presence of linear, almost vertical low resistivity features, interpreted as fault zones. The most prominent IP anomaly coincided spatially with the magnetic stockwork zone defined previously by the magnetic survey and tested by several drillholes. The high IP intervals correlated with high total sulfide values of up to 3–5%, though while the copper mineralization in drillholes coincides with high sulfide concentrations, it was not possible to distinguish between anomalies related to a barren pyrite halo and IP anomalies associated with porphyry copper mineralization.

Several IP anomalies form a discontinuous annular zone around the interpreted core of the system, probably related to the pyrite halo. The resistivity model indicates the presence of near to horizontal low resistivity layers to the west of the core of the system interpreted to reflect the presence of intensive stockwork zones with copper mineralization. A further observation is that the area of low resistivity correlates with low-grade copper and gold in the Ilovica block model, and in fact, grade appears to increase as the higher resistivity zone is intersected.

Drilling

A total of 130 holes have been drilled over 10 campaigns (42,032 m): 20 were drilled for geotechnical investigation, 15 were carried out for hydrogeological investigation, and 95 were drilled for mineral resource determination. The drillholes are generally vertical or steeply dipping, with 95 of the drillholes being vertical and the remainder being between 55° and 75°. The drill locations are illustrated in Fig. 3.80. All of the holes were drilled using rotary diamond coring techniques. Drillholes were collared with PQ diameter (85 mm core) and then advanced with HQ (61.1 mm core) and then occasionally NQ (45.1 mm core) diameters. A wireline system was

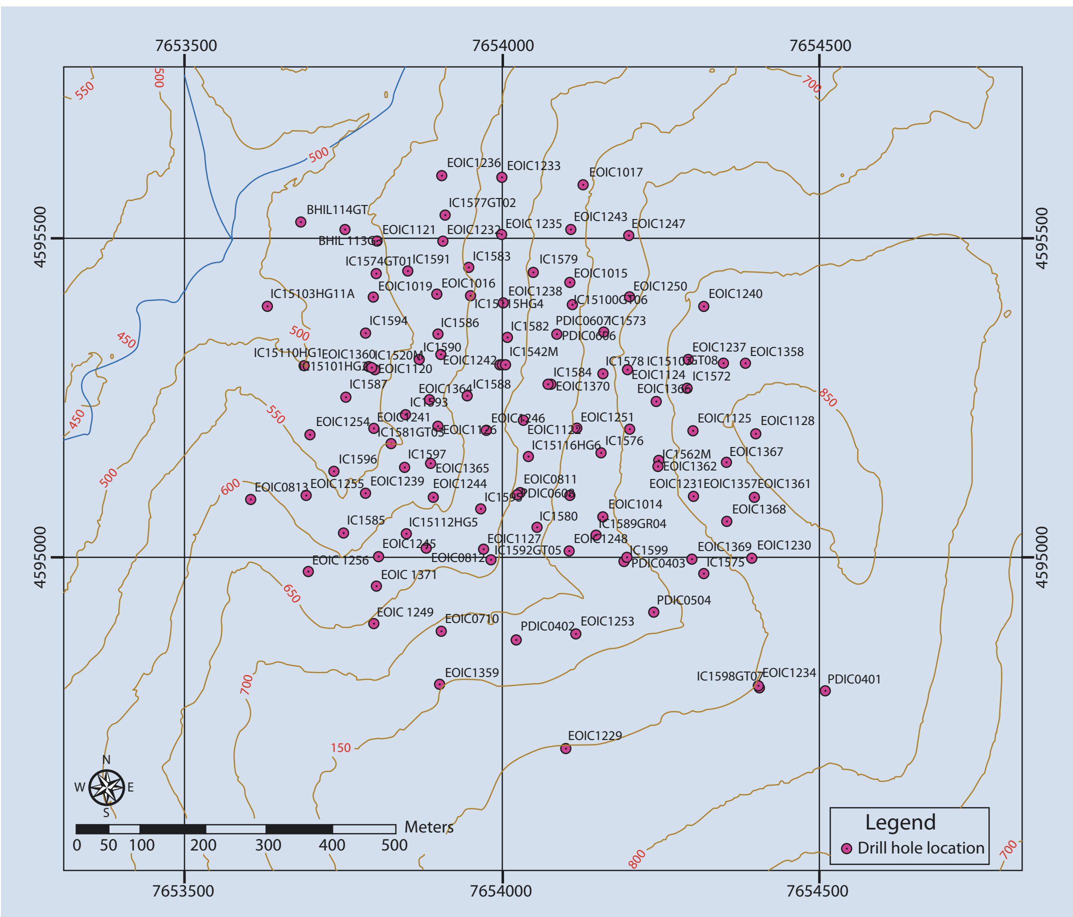

Fig. 3.80 Drillhole locations (Illustration courtesy of Euromax Resources)

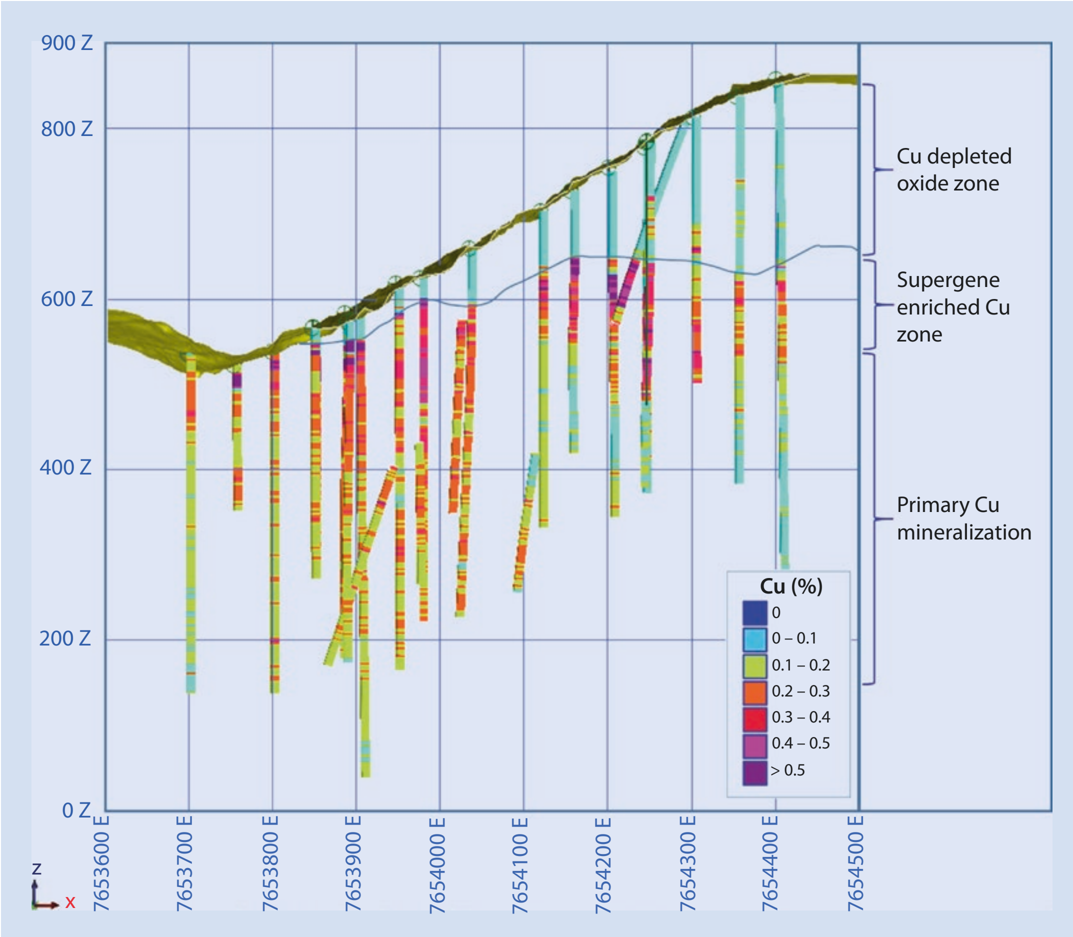

Fig. 3.81 Typical section with copper assays (%) (Illustration courtesy of Euromax Resources)

used to hoist the core tube to surface to allow the drill core to be extracted.

Logging included observations relating to lithology, alteration, mineralization, structure, recovery, and rock quality designation (RQD). Drill core recovery is very good, generally greater than 95%, throughout the deposit. Within the oxide zone, the core is general highly fractured, and as such the RQD is low; however the overall core recoveries remain high. Generally half of the core samples were taken and processed for analysis. Where density samples were taken, one quarter was collected for density determination and another quarter was taken for assaying. Downhole surveys were completed using a digital survey instrument (JKH-R magnetic single shot inclinometer) with readings taken every 50 m. Generally the drillholes show very low deviation from the planned hole paths; deeper holes show up to five degrees variance from design for both dip and azimuth. The cross section presented in Fig. 3.81 illustrates the interpretation of the drilling results in relation to copper depletion in the oxide materials and supergene enrichment beneath. The gold assays show a similar but less pronounced distribution.

Gold Springs Gold Project Exploration: Courtesy of TriMetals Mining Inc.

The Gold Springs gold project is an advanced exploration stage gold project located along the Nevada-Utah border in the USA. The project is situated in the southeastern portion of the basin and range physiographic province, which is characterized by northerly trending mountain ranges with closed internal drainage basins that resulted from extensional tectonism and associated volcanism during the tertiary period. The Gold Springs

Fig. 3.82 Stockwork veining (Image courtesy of TriMetals Mining Inc.)

project lies within the Indian Peak volcanic field, which is a broad tertiary volcanic field that straddles the Utah-Nevada border and contains several nested, collapsed calderas and resurgent dome features that formed as part of a major Oligocene-Miocene «ignimbrite flare-up cycle.» The oldest rocks in the region consist of Proterozoic through lower Mesozoic sedimentary sequence that became folded and thrust-faulted eastward during the Cretaceous Sevier orogeny and were subsequently overlain by tertiary sedimentary deposits.

Gold mineralization at Gold Springs is hosted by complex sheeted veins, breccias, and stockwork vein systems (Fig. 3.82) that are laterally extensive and locally form resistant ledges and ribs that protrude up to 10 m above the surrounding ground surface and surrounding areas of mineralized wall rock. The veins contain quartz, adularia, and bladed calcite with minor sulfides (<2%) and represent a low sulfidation, epithermal gold-silver vein system. Gold and silver mineralization are hosted in quartz and quartz-calcite veins, breccias, and stockwork/sheeted vein zones surrounding the main vein systems. True thickness of the mineralized zones reaches up to 150 m wide with the strike length of the vein systems extending up to several kilometers.

Sampling

The work program collected 2409 rock chip samples, 2964 soil samples, and 323 stream sediment samples. The majority of the samples were collected on a reconnaissance basis from both outcrop and float material. Sampling was also conducted within the target areas where outcropping mineralization was sampled perpendicular to structural trends where possible. Grab samples were collected to help define background geochemical levels within the various rock units and to evaluate metallic ion distribution and chemical zonation in areas of new exploration. Select samples were also collected from mine dumps and vein exposures to determine if there were any specific geochemical signatures and to characterize the ability of the system to contain high-grade gold values.

Rock chip results ranged from <5 ppb gold to a high of 145.68 g/t gold. Silver shows some correlation with gold and values ranged from <0.1 ppm to a high of 252.9 ppm. Gold geochemistry from the soil samples ranged from <0.5 ppb to a high of 1.3 g/t while silver ranges from <0.1 to 11.6 ppm. Results from the stream sediment sampling show a variation in gold values from a low of <5 ppb to a high of 1.28 g/t. Preliminary analysis of some of the downhole geochemical data suggests that there are at least two different signatures for the various target areas. Moderately anomalous arsenic and local molybdenum values are associated with gold mineralization with a surrounding zone that shows a relative depletion in calcium, potassium, and sodium.

Then, a detailed follow-up sampling and mapping were conducted on several of the target areas. This work included detailed structural analysis and channel sampling as well as detailed vein sampling in the main trenches. In addition, a series of channel sample lines were completed over the exposed vein zones. These channel sample lines generally consist of a series of 2 m long, continuous chip-channel samples across outcropping exposures of the various vein-stockwork zones.

Geophysics

A 470 line-km ZTEM and aeromagnetic helicopter survey was completed. Previous ground surveys revealed a positive correlation between the known epithermal gold systems and buried subvertically dipping high resistivity features. The ZTEM results correlated very well with known geology, in particular the presence of all the known epithermal centers. The helicopter-borne geophysical survey in Gold Springs project included a Z-axis Tipper electromagnetic (ZTEM) system and a cesium magnetometer. Ancillary equipment included a GPS navigation system and a radar altimeter. The survey was flown in an east to west (N 90° E azimuth) direction, with a flight line spacing of 200 m. Tie lines were flown in a north to south (N 0° E azimuth) direction, with a flight line spacing of 1900 m.

TD (total divergence) imaging converts the ZTEM tipper crossover data into peak responses which assists their interpretation in plan. TD low (conductive) areas signify areas with sulfides or possibly conductive clays, and the TD high (resistive) areas represent resistive rocks which show an excellent correlation with known gold occurrences as would be expected in the low sulfidation environment. Subsequent to the 2-D inversion, a 3-D inversion of both the ZTEM conductivity data and the magnetics was carried out. The resulting models for the ZTEM and magnetic inversions provided a 3-D conductivity model of the earth that honors the ZTEM and magnetic data to a specified level of fit. The modeling correctly considered 3-D topographic effects which can significantly influence the data. The inversion modeling was unconstrained by geologic and physical property information. The primary outcome of these studies was the development of a clear correlation with the location of surface gold mineralization and gold intersected in drillholes particularly with the margins of the high resistivity features. This correlation can be seen in the «depth-slice» presentation of the data (Fig. 3.83). Where the high resistivity is shallow, a strong correlation between the margins of the high resistivity and gold intersected in drillholes exists. Where the high resistivity is deeper, gold mineralization is found both at the margins and over the top of the resistivity features. This correlation is interpreted as relating to the heat source for the «hot spring» style mineralization seen at Gold Springs.

Drilling

The last exploration work in 2014 focused on completing a 38-hole RC and 4-hole core drill program. The four core holes were completed to collect material for metallurgical testing and to start to collect geotechnical data for rock quality designation (RQD), fracture analysis, and lithologic and alteration data. On the other hand, downhole surveys are conducted using a gyro deviation survey instrument at or near the termination of the hole. These surveys provide detailed downhole data on the azimuth and dip of the hole over the length of the hole.

The 2012–2014 drilling programs were conducted by wet reverse circulation drilling method. Emphasis was placed on quality control and the proper handling and numbering of all samples. The reverse circulation drill cuttings are collected as they come out of the drillhole from an industry standard rotary wet splitter provided by the drilling company, which delivers the material to three collection points. Samples are collected on 1.52 m intervals. Every 20 samples, standards and blanks are inserted into the numbering sequence of the drill cuttings. The material from the second sample point is retained as a duplicate sample for future testing if needed. The material from the third sample point is geologically logged on site and put into chip trays that are labeled with sample numbers and footage intervals from which the sample was taken.

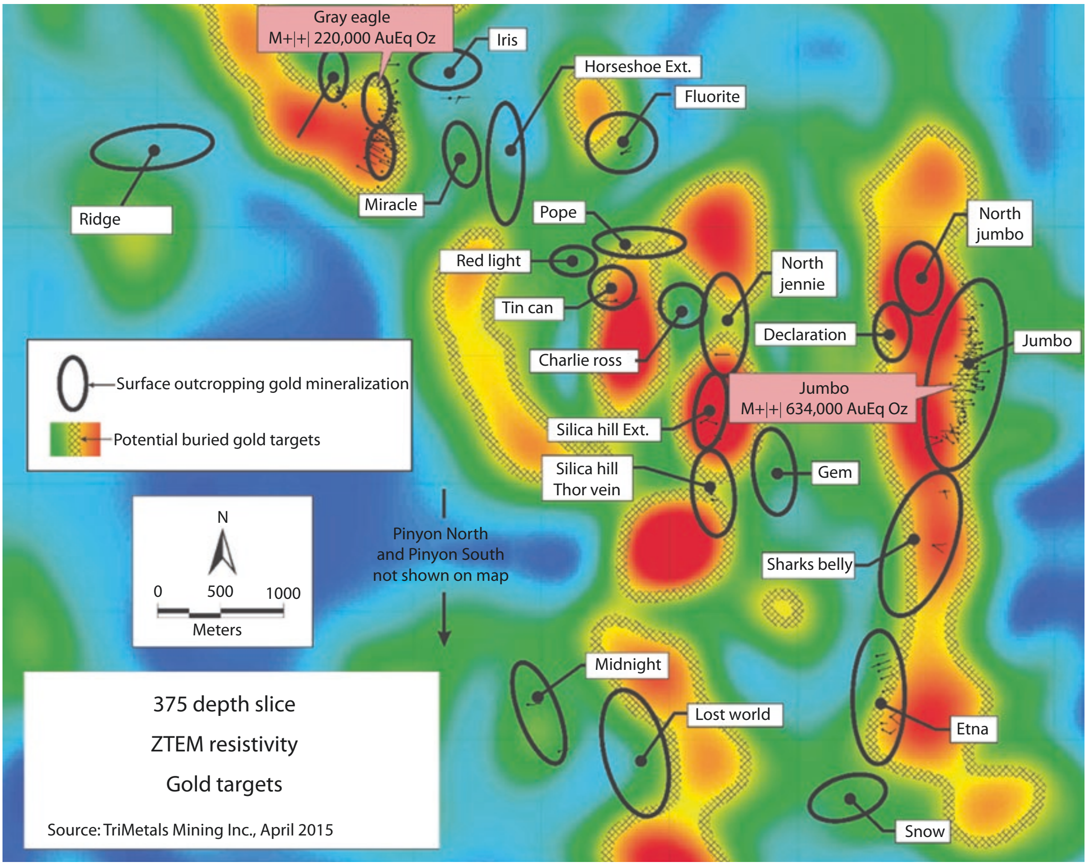

Fig. 3.83 ZTEM high resistivity and correlation with outcropping gold-bearing rocks in the Gold Springs project area (Illustration courtesy of TriMetals Mining Inc.).

3.6 Questions

Short Questions

- What is mineral exploration?
- Define the concepts of «juniors» and «majors» mining companies.
- What greenfield and brownfield exploration programs mean? Explain the advantages and disadvantages of both.
- What are the main mineral resource exploration stages? Explain briefly each stage.
- What is a mineral deposit model?
- What is the Landsat program?
- Explain the differences among diamagnetic, paramagnetic, and ferromagnetic minerals.
- What are the airborne geophysical surveys? List the main types of measurements carried out in these methods.
- Explain the importance of borehole geophysical logging.
- Explain the differences between primary and secondary halos in geochemical exploration.
- List the main types of multivariate statistical methods used in geochemical interpretation.
- Bring out the main disadvantage of reverse circulation drilling.
- What is the wireline system in diamond core drilling?
- Define the concept of borehole deviation. What is the difference between deviation and deflection?
- Explain the parameter RQD in logging and the method of calculation.

Long Questions

- Explain the three-key-factor process in selection of drilling methods.
- Describe the electrical methods used in mineral exploration.

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