Major Gold Deposit Types and Exploration process

N. N. Singh
Indo Gold Mines Private Ltd,
68B Sect-9, HM; Udaipur, India 313001
singhnn@gmail.com

Gold occurs as primary commodity in a wide range of gold deposit types and settings. Three main clans of deposits are now broadly defined, each including a range of specific deposit types with common characteristics and tectonic settings. The orogenic clan has been introduced to include vein-type deposits formed during crustal shortening of their host greenstone, BIF IOCG (Iron oxide Copper-Gold). Deposits of the new reduced intrusion-related clan share an Au-Bi-Te-As metal signature and an association with moderately reduced equigranular post-orogenic granitic intrusions. Oxidized intrusion-related deposits, including porphyry, skarn, and high-sulfidation epithermal deposits, are associated with high-level, oxidized porphyry stocks in magmatic arcs. Other important deposit types include Carlin, Au-rich VMS and Witwatersrand deposits. The key geology features of the ore-forming environments and the key geologic manifestations of the different deposit types form the footprints of ore systems that are targeted in exploration programs. Important progress has been made in our ability to integrate, process, and visualize increasingly complex datasets in 2D GIS and 3D platforms. For gold exploration, important geophysical advances include airborne gravity, routine 3D inversions of potential field data, and 3D modeling of electrical data. Improved satellite-, airborne- and field-based infrared spectroscopy has significantly improved alteration mapping around gold systems, extending the dimensions of the footprints and enhancing vectoring capabilities. Conventional geochemistry remains very important to gold exploration, while promising new techniques are being tested. Selection of the appropriate exploration methods must be dictated by the characteristics of the targeted model, its geologic setting, and the surficial environment. The application of exploration technology is an important aspect of any exploration program. The use of advanced exploration technology is necessary because we now often work in complex geological settings where discovery of subsurface mineral deposits is commonly based on subtle surface manifestations. Applying the advanced technology effectively may enable exploration of large target areas within restricted budgets. Advancements in exploration technology have progressed especially quickly in countries like Canada and Australia, where an evolved mineral exploration industry has already found the obvious deposits and more specialized techniques are required to detect the increasingly subtle indications of subsurface mineral deposits.

INTRODUCTION

Gold deposits worldwide display diverse ore-genetic associations and their petrogenesis is widely debated, especially in the context of the nature and source(s) of the ore-forming fluids. Significant progress has been made in the fields of exploration geochemistry, geophysics, and data integration, providing better tools to assist the discovery of new gold deposits. The objectives of this paper are to provide an update on gold deposit models, and what new approaches and techniques can now be used to discover gold deposits. Gold occurs in a wide range of deposit types and settings. Exploration is mainly preoccupied with defining the footprints of known gold deposits and with integrating various techniques with geology for their efficient identification and detection. Accordingly, the first part of the paper reviews the main types of gold deposits and the key elements of their footprints, defined here as the combined characteristics of the deposits themselves and of their local to regional settings. The second part deals with the techniques and approaches that can now be used for the recognition and detection of these footprints.

Much has been published on gold deposits in the last decade, leading to (1) significant improvement in the understanding of some models, (2) the definition of new types or sub-types of deposits, and (3) the introduction of new terms. However, significant uncertainty remains regarding the specific distinction between some types of deposits. Consequently, specific giant deposits are ascribed to different deposit types by different authors. In this paper, the most accepted nomenclature used in important reviews published in the last decade (e.g. Hagemann and Brown, 2000; Sillitoe and Hedenquist, 2003) have been used.

As represented in Figure 1 and compiled in Table 1, thirteen globally significant types of gold deposits are presently recognized, each with its own well-defined characteristics and environments of formation. Minor types of gold deposits are not discussed in this paper. As proposed by Robert et al. (1997) and Poulsen et al. (2000), many of these gold deposit types can be grouped into clans, i.e. families of deposits that either formed by related processes or that are distinct products of large-scale hydrothermal systems. These clans effectively correspond to the main classes of gold models, such as the orogenic, reduced intrusion-related, and oxidized intrusion-related ones (Hagemann and Brown, 2000). Deposit types such as Carlin, Au-rich VMS, and low-sulfidation are viewed by different authors either as stand-alone models or as members of the broader oxidized intrusion-related clan. They are treated here as stand-alone deposit types, whereas high- and intermediate- sulfidation and alkalic epithermal deposits are considered as part of the oxidized intrusion-related clan. Witwatersrand deposits are still controversial and viewed either as modified paleo placer or as orogenic deposits.

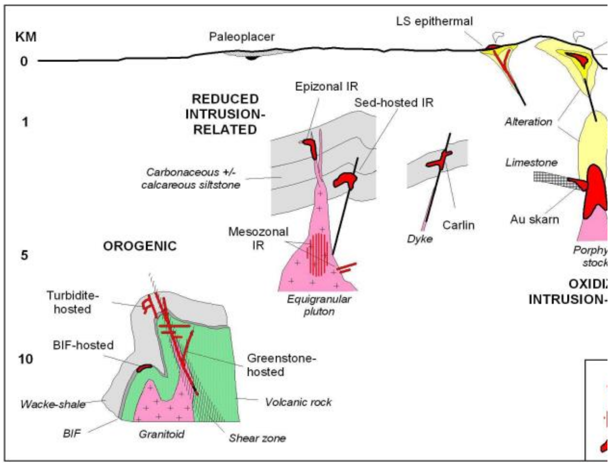


Figure 1: Schematic cross section showing the key geologic elements of the main gold systems; Modified from Poulsen et al. (2000), and Robert (2004a).

Types of Gold deposits

The term *orogenic* has been originally introduced by Groves et al. (1998) in recognition of the fact that quartz-carbonate vein gold deposits in greenstone and slate belts, including those in BIF, have similar characteristics and have formed by similar processes. Originally, the orogenic model applied strictly to syn-tectonic vein-type deposits formed at mid-crustal levels in compressional or transgressional settings, i.e. syn-orogenic deposits. However, the term has been progressively broadened to include deposits that are post-orogenic relative to processes at their crustal depth of formation. This has led to significant ambiguity in the definition of the boundary between the orogenic and reduced intrusion-related deposit models, with many type examples being ascribed to one model or the other by various authors (Thompson and Newberry, 2000; Goldfarb et al., 2001). In this paper, as illustrated in Figure 1, the orogenic clan is defined to only include the syn-tectonic quartz-carbonate vein-type deposits and their equivalents, formed at mid-crustal levels. Specific deposit types in this clan include the turbidite- hosted and greenstone-hosted vein deposits, as well as the BIF- hosted veins and sulfidic replacement deposits (Figure 1; Table 1). The *reduced intrusion-related* model (RIR) has been better defined in the last decade (cf. Lang et al., 2000). Deposits of this clan are distinguished by a Au-Bi-Te-As metal association and a close spatial and temporal association with moderately-reduced equigranular granitic intrusions (Table 1; Thompson and Newberry, 2000). These deposits occur mainly in reduced siliciclasic sedimentary rock sequences and are commonly orogenic deposits. A range of styles and depths of formation has been documented for RIR deposits, including intrusion-hosted deposits of mesozonal to epizonal character, and more distal, sediment-hosted mesozonal equivalents (Figure 1, Table 1). Deposits of the sediment-hosted type correspond to the initial sediment-hosted stockwork-disseminated type of Robert et al. (1997), as well as to the pluton-related thermal aureole gold (TAG) deposits of Wall (2000) and Wall et al. (2004). Several deposits of the sediment-hosted IR deposits have also been ascribed to the orogenic clan by Goldfarb et al. (2005).

Other types of globally important gold deposit include low and intermediate-sulfidation epithermal, Carlin, Au-rich VMS, and Witwatersrand type deposits (Figure 1). Epithermal deposits are now subdivided into low-, intermediate- and high-sulfidation categories on the basis of mineralization and alteration assemblages (Sillitoe and Hedenquist, 2003). Intermediate- sulfidation deposits, like high-sulfidation ones, are interpreted to be a component of large OIR systems, as is the case for the Victoria veins in the Far Southeast-Lepanto system and at Kelian. These deposits were initially singled out as carbonate- base-metal Au deposit type by Corbett and Leach (1998), and are characterized by a pyrite, low-Fe sphalerite and Mn carbonate ore assemblages accompanied by dominant illite alteration. Mineralization can consist of veins and breccia bodies and commonly display a larger vertical continuity than their low- or high-sulfidation counterparts.

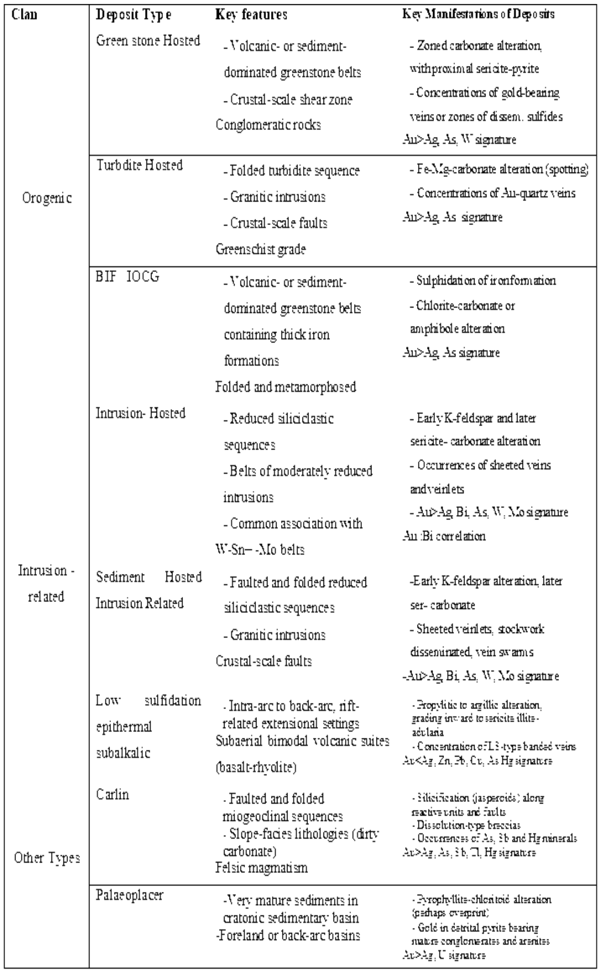
Carlin-type deposits have been regarded either as being distal parts of large OIR systems (Sillitoe and Bonham, 1990) or as standalone deposits (Cline et al, 2005). Distinction has also been made between Carlin-type deposits proper and distal-disseminated deposits, which occur peripheral to a causative intrusion and have a distinct Ag-rich metal association. However, controversy remains as to whether the two groups of deposits are fundamentally different (Muntean et al., 2004).

Work on the modern seafloor has provided additional insight into the formation of Au-rich VMS deposits, with the identification of a number of favorable settings (Huston, 2000; Hannington, 2004). Finally, the controversy remains concerning the origin of the unique Witwatersrand gold deposits, with both modified paleo placer and hydrothermal origins being proposed (Frimmel et al., 2005; Law and Phillips, 2005).

Although many of the giant deposits conform to one of the models outlined above, many of them have unique characteristics and are not easily classifiable in the scheme presented in Figure 1 (Sillitoe, 2000b). It is therefore likely that the next big discovery could be of a different style or mineralization, or perhaps located in an unexpected geologic setting, a fact that obviously has to be taken into account in regional exploration programs. A good example is the discovery of the Las Lagunas Norte deposit in the Alto Chicama district of northern Peru, where high-sulfidation epithermal mineralization is hosted in clastic sedimentary rocks rather than in volcanic rocks, as favored by the classical model.

Gold deposit types by clan is placed below:

Table 1



Clan	Deposit Type	Key features	Key Manifestations of Deposits
Orogenic	Green stone Hosted	- Volcanic- or sediment-dominated greenstone belts - Crustal-scale shear zone Conglomeratic rocks	- Zoned carbonate alteration, with proximal sericite-pyrite - Concentrations of gold-bearing veins or zones of dissem. sulfides Au>Ag, As, W signature
	Turbdite Hosted	- Folded turbidite sequence - Granitic intrusions - Crustal-scale faults Greenschist grade	- Fe-Mg-carbonate alteration (spotting) - Concentrations of Au-quartz veins Au>Ag, As signature
	BIF IOCG	- Volcanic- or sediment-dominated greenstone belts containing thick iron formations Folded and metamorphosed	- Sulphidation of ironformation - Chlorite-carbonate or amphibole alteration Au>Ag, As signature
Intrusion - related	Intrusion- Hosted	- Reduced siliciclastic sequences - Belts of moderately reduced intrusions - Common association with W-Sn- -Mo belts	- Early K-feldspar and later sericite- carbonate alteration - Occurrences of sheeted veins and veinlets - Au>Ag, Bi, As, W, Mo signature Au :Bi correlation
	Sediment Hosted Intrusion Related	- Faulted and folded reduced siliciclastic sequences - Granitic intrusions Crustal-scale faults	-Early K-feldspar alteration, later ser- carbonate - Sheeted veinlets, stockwork disseminated, vein swarms -Au>Ag, Bi, As, W, Mo signature
Other Types	Low sulfidation epithermal subalkalic	- Intra-arc to back-arc, rift-related extensional settings Subaerial bimodal volcanic suites (basalt-rhyolite)	- Propylitic to argillic alteration, grading inward to sericite illite-adularia - Concentration of LS-type banded veins Au<Ag, Zn, Pb, Cu, As Hg signature
	Carlin	- Faulted and folded miogeoclinal sequences - Slope-facies lithologies (dirty carbonate) Felsic magmatism	- Silicification (jasperoids) along reactive units and faults - Dissolution-type breccias - Occurrences of As, Sb and Hg minerals Au>Ag, As, Sb, Tl, Hg signature
	Palaeoplacer	-Very mature sediments in cratonic sedimentary basin -Foreland or back-arc basins	- Pyrophyllite-chloritoid alteration (perhaps overprint) - Gold in detrital pyrite bearing mature conglomerates and arenites Au>Ag, U signature

Exploration process

An exploration process evolves from a generative stage that result in a) identification of geological conducive area b) identification of target areas through geological in-put c) testing and evaluation of targets culminating in-to discovery of mineral occurrences d) definition and delineation of the deposit e) development of the deposit. The process involves an inherent risk at each stage that requires testing of large number of ventures or mineral occurrences to discover and delineate an economic deposit. The risk is related to the factors of uncertainty associated with the occurrence of mineral with respect to its location , size, shape, quality, depth and the exploration technology employed. The risk therefore, could be minimised within the given limitations by evolving an exploration strategy which judiciously combines sound geological concept with economic and commercial judgement at each stage of exploration and an environment friendly mining plan to maximize the expected return. Exploration process (Singh 2009) is provided at Table 2

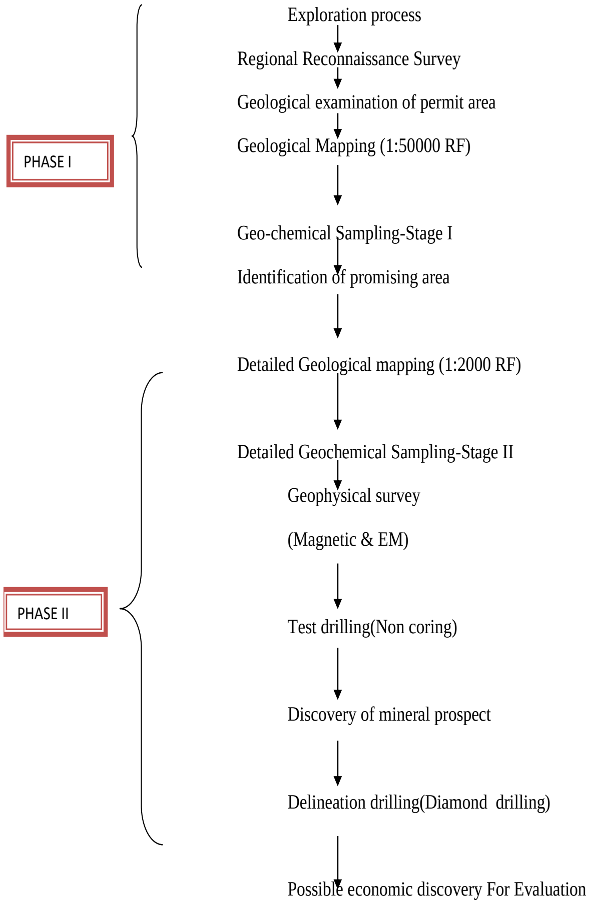


Table-2

Exploration technology:

Exploration in India has two scenarios - ground that has already been explored but merits re-evaluation in the light of new techniques and/or data and ground that has been subjected to limited exploration. The ground requiring re-evaluation needs to be assessed on the basis of revised geological models supported by modern theories of basin-analysis, geo-dynamic-study and revalidation of the acquired exploration data while, the areas requiring first-hand exploration have to be selected on the basis of regional geological map and integration of available exploration data. In both the cases modern exploration techniques have to be deployed judiciously as the selection of technology is a function of geological setting and characteristics of exploration environment.

It is the application of exploration technology that can pay huge dividends through the efficient application of an exploration budget. Technical up-gradation in the exploration technology has kept pace with time in countries like Canada and Australia where surface indications of the occurrence of a deposit are minimum if not negligible.

Major technological development in the field of exploration technology is as below:

Remote-sensing imagery: Remote sensing techniques have proved of considerable importance as they are more effective in reducing the time and cost factors in the strategy of mineral exploration and management. The mineral exploration planning usually involves four stages namely – (1) prospecting, (2) regional exploration, (3) detailed exploration, and (4) mine exploration. Remote sensing satellite data analysis enables us in delineation of potential locations for mineral exploration even in the inaccessible regions. The demarcation of mineral deposits in dense vegetation terrains requires development of special techniques. The remote sensing represents an advance stage in the exploration technique and is the next step above aerial photography. This technique has proved its immense significance by providing synoptic overview, repetitive coverage, capability to look beyond visible region of the electro-magnetic spectrum, cost effectiveness, time savings, distinct advantage of obtaining information of inaccessible areas and responsibility of data to digital image processing which has proved to be advantageous over conventional methods in earth science investigations.

The occurrence of some deposits is confined to a particular rock which may constitute a valuable lithological guide. The deposit may be syngenetic (sedimentary deposits - banded iron formation, bauxites, coal, phosphorites; igneous deposits - chromite, magnetite) or epigenetic (carbonates, volcanic flows, metapelites etc). The remote sensing data of adequate spatial and spectral resolution may be useful in location of the occurrence of lithological guides under favourable conditions, by virtue of synoptic overview and multi-spectral approach. Based on Landsat MSS data and supervised classification, likely extension of known strata-bound copper deposits in the Tertiary Totra sandstones of Bolivia, into adjoining territory of Peru has been located.

Geomorphological Guides: Geomorphological guides are significant in prospecting of mineral deposits resulted due to phenomena of sustained weathering and erosion. The geomorphological indicators such as hills, ridges, plateaus and valleys help in location of deposits formed by residual and supergene enrichment. All these deposits are confined to Quaternary terrain. The remote sensing data help in providing information pertaining to pattern of relief, drainage and slopes. The suitable sites of deposition and occurrence of placer deposits such as diamonds, gold, monazite etc. are better demarcated on the remote sensing data, e.g., in the case of fluvial placers, by identifying buried channels, abundant meander scars and scrolls.

Structural Guides

The structural guides in mineral exploration are of various dimensions and scales. The structure may control : (a) the distribution of metallogeny provinces within orogenic belts or platforms, (b) the distribution of ore-bearing regions and fields within the metallogeny provinces and (c) the localization of ore deposits in a particular ore field (Kreiter, 1968). The remote sensing data can provide useful information regarding the relationship of global, mega and minor structural features with ore deposits

The information regarding localization of mineral deposits by geological structural belts, shear zones, faults, fractures, contacts, folds, joints or intersections of specific structural features is of immense importance in the planning of exploration. The identification of lineaments from satellite imagery has provided useful information for mineral exploration. However, some difficulties in integration of lineament maps with mineral exploration models have been observed which could be assigned to following reasons : (a) some of the features mapped as lineaments may not be structural-geologic nature, and (b) it may not be possible to distinguish between the post-mineralization and pre-mineralization structures. Aster image showing structural interpretation is shown in **Fig 2.**

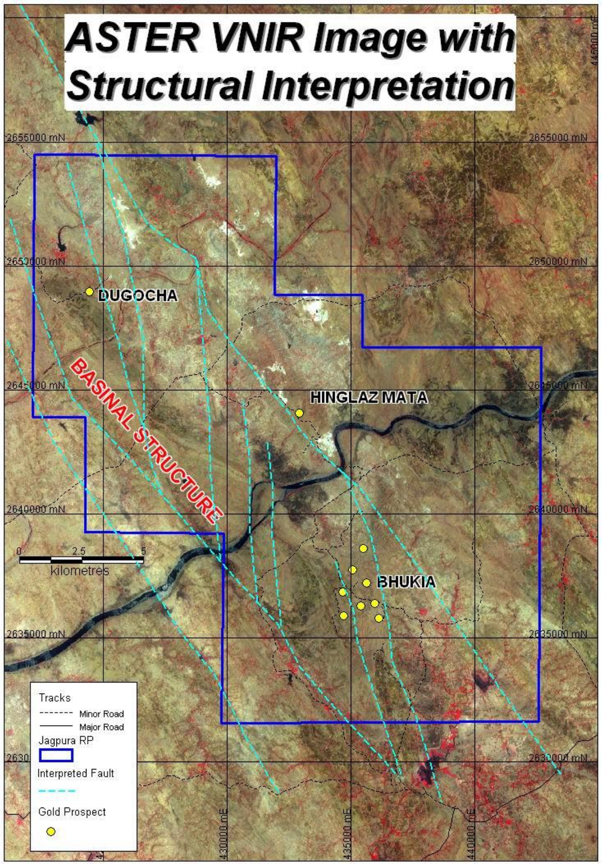


Fig: 2 Satellite imagery showing structural interpretation

Remote sensing satellite data analysis has proved its immense significance in the mineral resource exploration and management. Most of the mineral deposits are detected with the help of various mineral guides as observed on satellite imagery. The LANDSAT - TM and RADAR images are used to map fracture pattern and distinctive spectral features that help in strategy of mineral exploration

Aerial photographs as well as imagery, obtained by remote sensing using aircraft or spacecraft as platforms, have applicability in various fields. By studying the qualitative as well as quantitative aspects of images recorded by various sensor systems, like aerial photographs (black-and-white, black-and white infrared, color and color infrared), multiband photographs, satellite data (both pictorial and digital) including thermal and radar imagery, an interpreter well experienced in his field can derive lot of information. Image interpretation is defined as the act of examining Image to identify objects and judge their significance. An interpreter studies remotely sensed data and attempts through logical process to detect, identify, measure and evaluate the significance of environmental and cultural objects, patterns and spatial relationships. It is an information extraction process.

Application of remote sensing data is useful because:

1. It represents a larger area of the earth from a perspective view and provides a format that facilitates the study of objects and their relationships.
2. Certain types of imagery and aerial photograph can provide a 3-D view.
3. It provides the observer with a permanent record/ representation of objects at any moment of time.
4. In addition, data is real-time, repetitive and, when in digital form, is computer compatible for quick analysis.

For many types of earth- resource analysis, the use of the convergence system by image interpretation of varying background is likely to produce a more accurate and thorough analysis than could be achieved by a single image interpreter working alone.

Hyperspectral Technology

Traditional remote sensing is based on the Landsat Thematic Mapper (TM). The coarse spectral resolution of the data serves only to detect mineral groups and prevents reliable discrimination of other features with similar spectral characteristics. The recent commercialization of airborne hyper spectral remote sensing-systems, with its ability to accurately map individual minerals, marks the beginning of a new era in geological mapping and mineral exploration. It has been well documented that reflectance and emission spectroscopy (the measurement of light as a function of wavelength) of minerals is sensitive to specific chemical bonds caused by electronic and vibration processes between elements

As a result, individual minerals may be fingerprinted by their spectral responses.

Effective mineral exploration applications require a system that can acquire spectral information in the Short Wave Infrared (SWIR) . Fig 3.

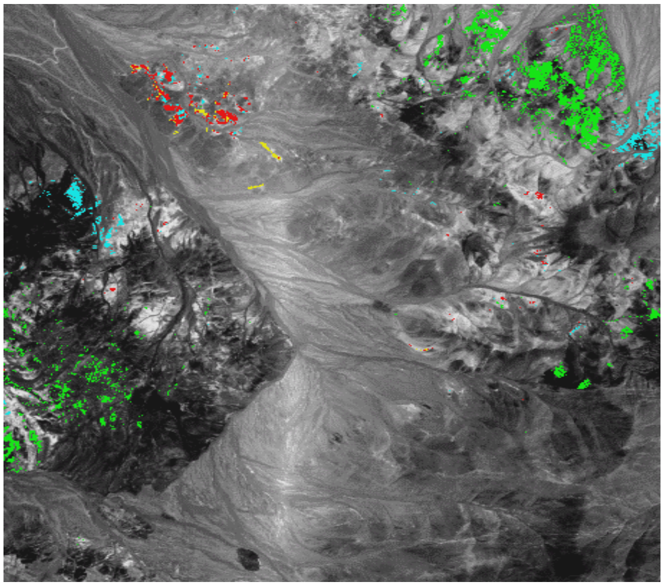


Fig 3: Hyperspectral Remote sensing Image

Airborne geophysics:

To see beyond the ground surface in to depth dimension is the objective of modern geophysical technique. Acquiring airborne geophysical data of a quality suitable for visualisation using image-processing technique is complex. The first and foremost development in data acquisition is for 'Positioning', which was originally, achieved with the help of maps and aerial photographs. The navigation aids were added by Global positioning system based on dedicated Satellite to provide precise position of data – capture location. At present, receivers used in Airborne surveys can achieve an accuracy of ± 15-50m in stand-alone mode and ± 5m in differential.

Airborne electro-magnetic has also witnessed an advanced configuration system both in frequency and time domains. The application of the system has lead to considerable increase in the bandwidth of both helicopter-borne FDEM and fixed wing TDEM system. The frequency range of FDEM systems has extended higher by an order of magnitude so that shallow targets can be accurately mapped. Similarly, the frequency range of TDEM systems has also extended higher for exploration of highly conductive or deeply buried mineral targets with lower base frequency (e.g. 25 H_z) and longer pulse width (e.g. 4-6 ms). In India there has been the introduction of GEOTEM airborne geophysical technology for exploration of large prospecting license areas of HZL-BHPM JV in Southeast Rajasthan and HZL areas in Ajmer (Kala 2000) , **Fig 4**. These provide base for integrated ground surveys and drilling to locate possible mineralized zones.

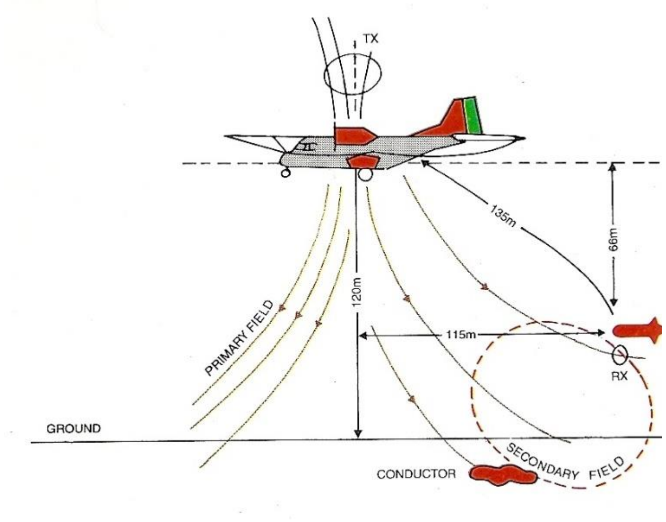


Fig 4: GEOTEM System Geometry

The EM data processing after synchronisation with navigation data and noise reduction etc generates products like vertical and horizontal synthetic sections from conductivity depth transformation algorithms for each flight line, channel amplitude maps, amplitude weight decay index maps, multi-parameter profile plots, stationary current image etc. Similarly, the magnetic data processing and interpretation, after synchronisation, diurnal levelling, generates magnetic profiles and contours and images **(Fig 5)**.

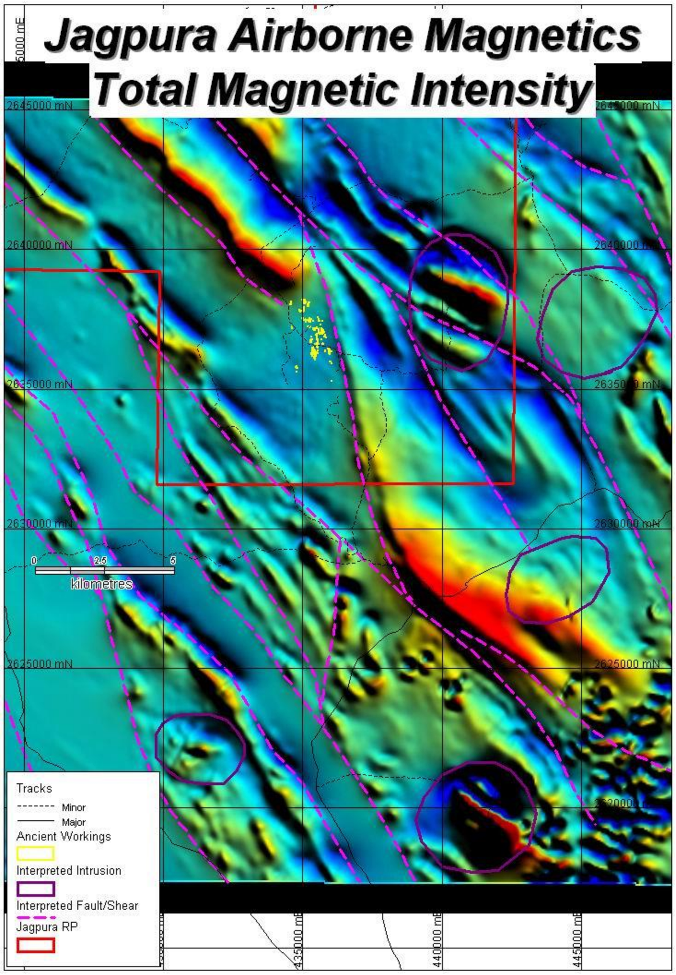


Fig 5: Airborne magnetics

The technology for airborne spectral remote sensing based on spectral properties has been developed. Spectral reflectance, emittance, and microwave remote sensing is in use for mineral exploration. This data is used in the primary or target generation stage of exploration to assess on a small-scale regional level. The reflectance spectra for most common rock-forming silicate, oxide, carbonate and sulphate minerals as well as a suite of hydrothermally altered rocks representing potassic, argillic alterations have been determined visible to SWIR (Short Wave Infrared). The information received through Spectral Remote sensing technique is integrated with all other available data such as geological, geophysical and geo-chemical and, interpreted within the context of a geologic model within a geographic information (GIS) environment.

Ground Geophysical survey:

Significant changes and improvements have occurred in Ground Electro Magnetic techniques. With regard to the effective EM systems that operate in the range of 10 to 100 Hz and which are generally used for mineral prospecting and geologic mapping, improvement has yielded EM instrumentation presently capable of detecting large conductive bodies to a depth of 500m or smaller, less conductive tabular galena / sphalerite / pyrite bodies such as Licheen deposit in Ireland to a depth of 300m.

Seismic reflection technique developed for Petroleum exploration has now been extended to the domain of hard rock application including mineral exploration. Recently Seismic reflection surveys have been attempted in hard rock mining environments in Canada such as Ni/Cu deposits at depth in Sudbury intrusive complex and volcanogenic polymetallic massive sulphide deposits in Matagami and Kidd Creek in Canada.

The application of borehole geophysical techniques to mineral exploration has become more wide spread in last decade. There have been a number of significant technological developments in hardware (probes, sensors, cables and winches), and software (modelling, interpretation and data display). The use of borehole EM techniques in base metal exploration has become routine. Several new three-component borehole EM systems have emerged and new advances have taken place in the area of orientation of the three-component probes and in borehole directional surveying. New generation three component magnetometer probes with orientation are available. Improved interpretation has led to increased requirements for physical property logs, especially magnetic susceptibility and resistivity/conductivity measurements. Logging for other physical rock properties is also receiving more attention in mining and mineral exploration. A multi-parameter approach to borehole geophysics provides the best data required for interpretation and for imposing constraints on models. Great strides have been made with respect to inverse modelling of surface data, and extensions of these inverse methods to the borehole environment are currently being developed.

GIS provides a computing environment of handling images, maps and data tables, with tools for data transformation, visualisation, analysis, modelling and spatial decision support (Bonham-Carter 97). Methods of integrating exploration data sets for mineral potential mapping are facilitated by GIS, and can be either knowledge-driven or expert-system –

driven, depending on the level of prior exploration.

Down hole Electromagnetic methods:

During the past decade, downhole electromagnetic (DHEM) has become a very important exploration method for conductive mineralization, particularly in areas where the ability of surface EM to define the target is limited either by large depths or by interfering conductive bodies such as overburden, surface sulphides and peripheral mineralised horizon. The power of DHEM is that the receiver is placed in the exploration drillhole, generally locating it closer to the target than to most of the interfering bodies **(Fig 6)**. From this position it can detect conductive bodies at distances greater than 100m from drillhole (depending on the size of target), at depths well over 1000m. However, to date the main problem with the application of DHEM has been inaccurate interpretation.

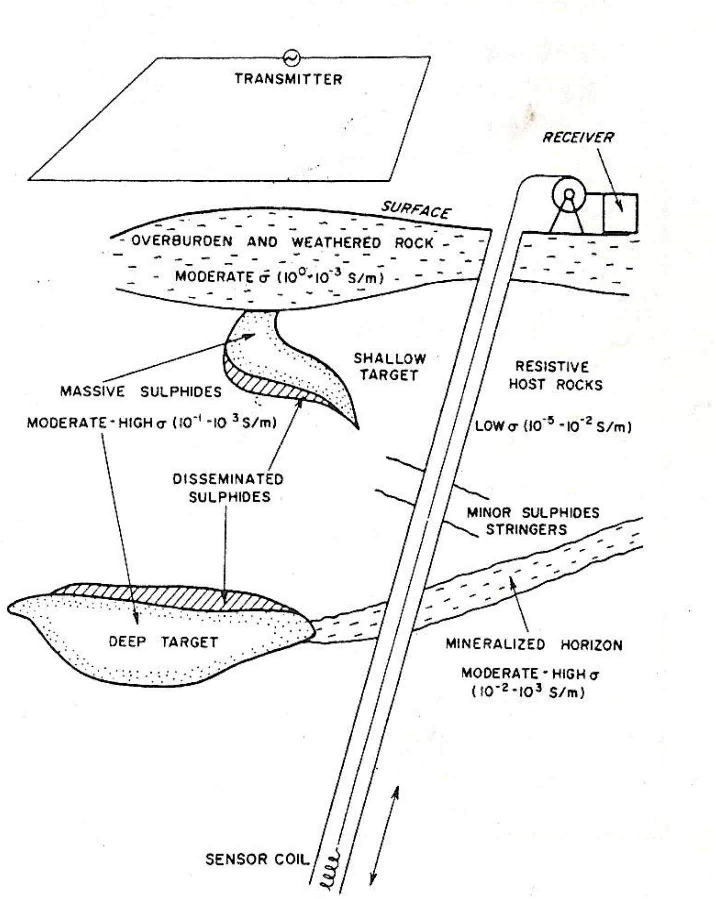


Fig: 6 The advantage of DHEM is that the sensor coil is located in the hole, closer to the target

Geo-chemistry

Geochemistry is an essential component in most modern integrated mineral exploration programs. It constitutes 10 to 25% of exploration budgets. Advances in the field include progressive improvements in mineral deposit models, conceptual models, ICP-ES and ICP-MS instrumentation and capabilities, partial extraction analysis, and computer-based data analysis and visualization techniques **(Fig 7)**.

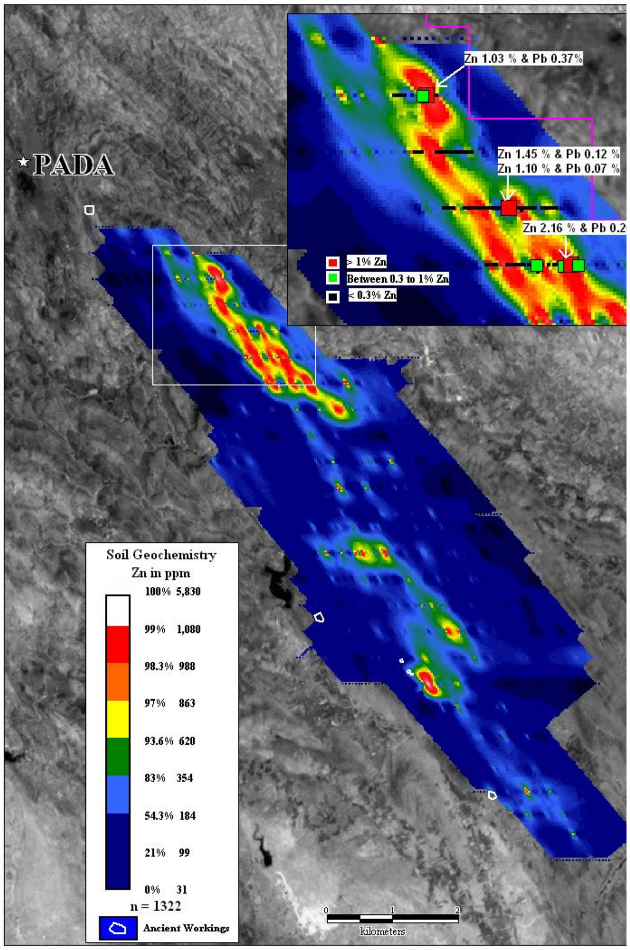


Fig: 7 Imagery of soil geo-chem plot

New and rediscovered developments include formulation of preliminary geoenvironmental mineral deposit models, and renewed interest in field-based, in situ geochemical analysis via soil gas, x-ray fluorescence and near-infrared spectrometric instruments. Geochemistry has the potential to make additional contributions to the mineral supply process through initial baseline and subsequent monitoring studies for environmental purposes and to the ore reserve estimation process. With the increasing use of geochemistry in all aspects of mineral resource development, there is concern that insufficient numbers of qualified people will be available to meet these needs.

CONCLUSIONS

There has been significant progress in the last decade in the understanding of the geology, settings and controls of the diverse types of gold deposits, including the recognition of new deposit types in new environments. Such progress has been paralleled with the development of data integration, processing and visualization techniques, and of advances in geophysical, geochemical and spectral detection techniques. Geologists are now better equipped than ever to face the increasingly difficult challenge of finding gold. However, one of the key lessons of the last decade, as reminded by Sillitoe and Thompson (2006), is that the exploration work needs to remain grounded in geology, especially in the field, and the elaborate detection techniques and tools available will only find their full power when closely integrated with a good geological framework.

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