

## Models and Exploration Methods for Major Gold Deposit Types

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### ABSTRACT

*Gold occurs as primary commodity in a wide range of gold deposit types and settings. In the last decade, significant progress has been made in the classification, definition and understanding of the main gold deposit types. 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 or clastic sedimentary rock sequences. 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, low-sulfidation epithermal, 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. Both greenfield and brownfield exploration contributed to the discovery of major gold deposits (>2.5 moz Au) in the last decade but the discovery rates have declined significantly. Geologists are now better equipped than ever to face this difficult challenge, but geological understanding and quality field work were important discovery factors and must remain the key underpinnings of exploration programs.*

### INTRODUCTION

Significant progress has been made on the classification and understanding of gold deposits since the Exploration 1997 conference. Perhaps even more substantial 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 find gold deposits. Gold occurs in a wide range of deposit types and settings, but this paper is concerned with deposits in which gold forms the main economic commodity or a co-product. Deposits in which gold occurs only as a by-product are not considered, including IOCG deposits.

Cu-Au porphyries and Au-rich VMS deposits are not discussed because they are the object of separate papers in this volume, as well as the Witwatersrand-type gold deposits, which are more than adequately reviewed in recent literature (Frimmel et al., 2005; Law and Phillips, 2005).

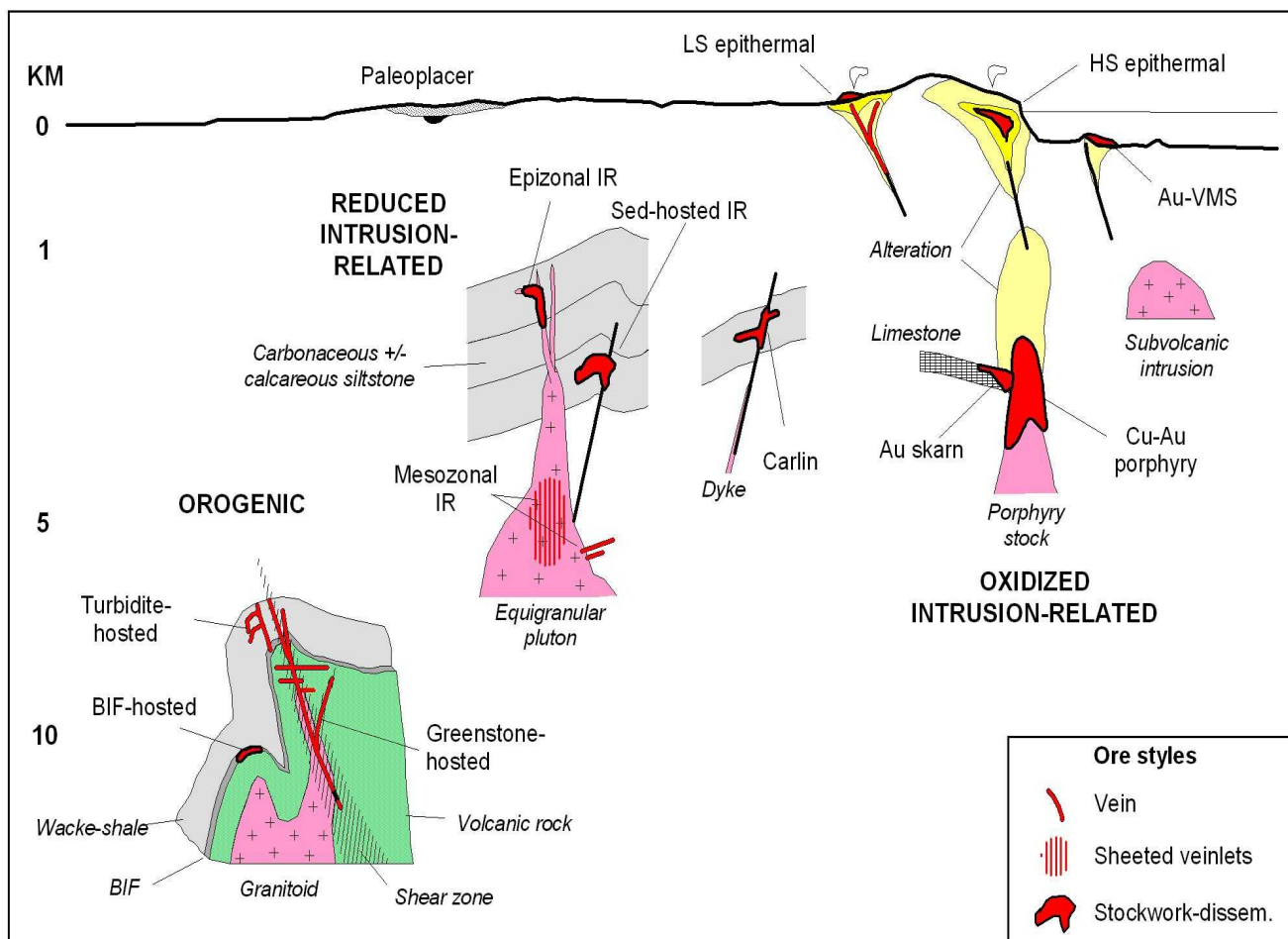
Exploration is mainly preoccupied with defining the footprints of known gold deposits and with integrating various techniques with geology for their efficient identification and detection. Accordingly, the first part of the paper reviews the main types of gold deposits and the key elements of their footprints, 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.

**OVERVIEW OF GOLD SYSTEMS**

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, we have adopted the most accepted nomenclature and models used in important reviews published in the last decade (e.g. Hagemann and Brown, 2000; Sillitoe and Hedenquist, 2003).

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 paleoplacer or as orogenic deposits.



**Figure 1:** Schematic cross section showing the key geologic elements of the main gold systems and their crustal depths of emplacement. Note the logarithmic depth scale. Modified from Poulsen et al. (2000), and Robert (2004a).

### Main deposit types and clans

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 transpressional 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). As discussed in more detail below, a confusing issue is that greenstone belts also contain gold deposit types that don't fit the orogenic model as defined here (Groves et al., 2003; Robert et al., 2005). There is no consensus on the origin of these atypical deposits.

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 siliciclastic 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).

The *oxidized intrusion-related* clan (OIR) includes the well known porphyry and high-sulfidation epithermal gold deposit types, as well as skarn and manto type deposits, formed in continental and oceanic convergent plate settings. These deposits are best regarded as components of large hydrothermal systems centered on high-level, generally oxidized, intermediate to felsic porphyry stocks (Figure 1; Table 1). In the last decade, the genetic connection between porphyry and high-sulfidation epithermal deposits has been more firmly established (Heinrich et al., 2004), and it has been suggested that the largest deposits of this clan form in compressional arcs (Sillitoe and Hedenquist, 2003). The characteristics and settings of the alkalic end-member of porphyry deposits have also been refined, as has their

possible connection with low-sulfidation alkalic epithermal systems (Jensen and Barton, 2000).

*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 stand alone 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). The recognition that some Au-rich VMS deposits are effectively submarine equivalent of high-sulfidation deposits (Sillitoe et al., 1996) puts them in the oxidized intrusion-related clan of deposits and has significant exploration implications. Finally, the controversy remains concerning the origin of the unique Witwatersrand gold deposits, with both modified paleoplacer 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.

Table 1: Compilation of key elements of selected types of gold deposits

Clan	Deposit Type	Key Features of Ore-Forming Environments		Key Manifestations of Deposits (By increasing proximity)	Type Examples	Selected References
		Regional Scale	Local Scale			
Orogenic	Greenstone-hosted deposits	<ul style="list-style-type: none"> <li>- Volcanic- or sediment-dominated greenstone belts</li> <li>- Crustal-scale shear zone</li> <li>- Conglomeratic rocks</li> </ul>	<ul style="list-style-type: none"> <li>- Shear zones, especially with bends and intersections</li> <li>- Rheological heterogeneity</li> <li>- Fe-rich lithologies</li> <li>- Felsic porphyry intrusions</li> </ul>	<ul style="list-style-type: none"> <li>- Zoned carbonate alteration, with proximal sericite-pyrite</li> <li>- Concentrations of gold-bearing veins or zones of dissem. sulfides</li> <li>- Au&gt;Ag, As, W signature</li> </ul>	Dome, Norseman, Mt Charlotte, Sigma Lamaque	Groves et al. (2003) Goldfarb et al. (2005) Robert et al. (2005) Dubé and Gosselin (2006a)
	Turbidite-hosted veins	<ul style="list-style-type: none"> <li>- Folded turbidite sequence</li> <li>- Granitic intrusions</li> <li>- Crustal-scale faults</li> <li>- Greenschist grade</li> </ul>	<ul style="list-style-type: none"> <li>- Culminations of anticlines</li> <li>- High-angle reverse faults</li> <li>- Cross-structures</li> </ul>	<ul style="list-style-type: none"> <li>- Fe-Mg-carbonate alteration (spotting)</li> <li>- Concentrations of Au-quartz veins</li> <li>- Au&gt;Ag, As signature</li> </ul>	Bendigo, Stawell, Alaska-Juneau	Hodgson (1993) Bierlein et al. (1998) Goldfarb et al. (2005)
	BIF-hosted	<ul style="list-style-type: none"> <li>- Volcanic- or sediment-dominated greenstone belts containing thick iron formations</li> <li>- Folded and metamorphosed</li> </ul>	<ul style="list-style-type: none"> <li>- Fold hinge zones</li> <li>- Faults or shear zones intersecting iron formation</li> <li>- Some stratiform controls</li> </ul>	<ul style="list-style-type: none"> <li>- Sulfidation of iron formation</li> <li>- Chlorite-carbonate or amphibole alteration</li> <li>- Au&gt;Ag, As signature</li> </ul>	Homestake, Lupin Cuiaba, Hill 50	Caddy et al. (1991) Kerswill (1996) Goldfarb et al. (2005)
Reduced intrusion-related	Intrusion-Hosted Mesozonal	<ul style="list-style-type: none"> <li>- Reduced siliciclastic sequences</li> <li>- Belts of moderately reduced intrusions</li> <li>- Common association with W-Sn+/-Mo belts</li> </ul>	<ul style="list-style-type: none"> <li>- Equigranular multiphase moderately reduced granodiorite-granite stocks and batholiths</li> </ul>	<ul style="list-style-type: none"> <li>- Early K-feldspar and later sericite-carbonate alteration</li> <li>- Occurrences of sheeted veins and veinlets</li> <li>- Au&gt;Ag, Bi, As, W, Mo signature</li> <li>- Au :Bi correlation</li> </ul>	Fort Knox, Vasilkovskoe	Thompson and Newberry (2000) Lang and Baker (2001) Hart (2005)
	Intrusion-Hosted Epizonal	<ul style="list-style-type: none"> <li>- Reduced siliciclastic sequences</li> <li>- Belts of moderately reduced intrusions</li> <li>- Common association with W-Sn+/-Mo and/or Sb belts</li> </ul>	<ul style="list-style-type: none"> <li>- High level dykes, sills, domes of generally reduced character</li> <li>- Major structures</li> </ul>	<ul style="list-style-type: none"> <li>- Pervasive clay and veinlet selvage serpy</li> <li>- Occurrences of sheeted veins and veinlets</li> <li>- Au&gt;Ag, As, Sb +/- Hg signature</li> </ul>	Donlin Creek Kori Kollo Brewery Creek	Lang and Baker (2001) Goldfarb et al. (2004)
	Sediment Hosted Intrusion Related	<ul style="list-style-type: none"> <li>- Faulted and folded reduced siliciclastic sequences</li> <li>- Granitic intrusions</li> <li>- Crustal-scale faults</li> </ul>	<ul style="list-style-type: none"> <li>- Folds and faults</li> <li>- Less permeable cap rock</li> <li>- Nearby temporally and spatially associated moderately reduced intrusions</li> </ul>	<ul style="list-style-type: none"> <li>- Early K-feldspar alteration, later sericarbonate</li> <li>- Sheeted veinlets, stockwork disseminated, vein swarms</li> <li>- Au&gt;Ag, Bi, As, W, Mo signature</li> </ul>	Murantau Kuntor Telfer	

Table 1: Continued

Clan	Deposit Type	Key Features of Ore-Forming Environments		Key Manifestations of Deposits (By increasing proximity)	Type Examples	Selected References
		Regional Scale	Local Scale			
Oxidized Intrusion Related	Au-rich Porphyry	<ul style="list-style-type: none"> <li>- Calc-alkaline to alkaline magmatic arcs</li> <li>- Regional arc-parallel fault</li> <li>- Coeval volcanic cover not abundant</li> </ul>	<ul style="list-style-type: none"> <li>- Intersection with arc-transverse structures</li> <li>- Hornblende/biotite-bearing, magnetite-rich, steep-sided porphyry stocks</li> <li>- Hydrothermal breccias</li> </ul>	<ul style="list-style-type: none"> <li>- Advanced argillic (upper parts) or propylitic (around) alteration</li> <li>- Stockwork veinlets in altered rocks</li> <li>- K-silicate alteration with magnetite-bearing veinlets</li> <li>- Au-Ag, Cu signature</li> </ul>	Grasberg, Far Southeast, Cerro Casale, Batu Hijau	Sillitoe (2000a) Cooke et al. (2004) Seedorff et al. (2005)
	High (intermediate) sulfidation epithermal	<ul style="list-style-type: none"> <li>- Calc-alkaline to alkaline arcs; andesitic to dacitic arcs</li> <li>- Regional arc-parallel fault</li> <li>- Preserved volcanic cover</li> </ul>	<ul style="list-style-type: none"> <li>- Volcanic dome-vent complexes</li> <li>- Intersection with arc-transverse structures</li> <li>- Diatreme; hydrothermal breccias</li> </ul>	<ul style="list-style-type: none"> <li>- Advanced argillic alteration</li> <li>- Vuggy silica alteration</li> <li>- Au-Ag, As, Cu, Sb, Bi, Hg signature</li> </ul>	Yanacocha, Pierina, Veladero Pueblo Viejo Lepanto/Victoria	Hedenquist et al. (2000) Simmons et al. (2005)
	Low sulfidation epithermal Alkalic	<ul style="list-style-type: none"> <li>- Extensional settings related to island arcs and rifts</li> <li>- Alkalic magmatic belts</li> <li>- Regional faults</li> </ul>	<ul style="list-style-type: none"> <li>- Alkalic intrusive complexes</li> <li>- Regional faults intersecting intrusive center or caldera</li> <li>- Breccias (in some cases)</li> </ul>	<ul style="list-style-type: none"> <li>- Extensive carbonate alteration</li> <li>- Proximal inner sericite/Kfeldspar alteration</li> <li>- Concentrations of Au occurrences</li> <li>- Au&gt;Ag, Te, V, Pb, Zn signature</li> </ul>	Cripple Creek Porgera Emperor Ladolam	Jensen and Barton (2000)
	Low sulfidation epithermal Subalkalic	<ul style="list-style-type: none"> <li>- Intra-arc to back-arc, rift-related extensional settings</li> <li>- Subaerial bimodal volcanic suites (basalt-rhyolite)</li> </ul>	<ul style="list-style-type: none"> <li>- Extensional to strike-slip faults</li> <li>- Structural intersections</li> <li>- Rhyolite domes (in some cases)</li> </ul>	<ul style="list-style-type: none"> <li>- Propylitic to argillic alteration, grading inward to sericite/illite-adularia</li> <li>- Concentration of LS-type banded veins</li> <li>- Au&lt;Ag, Zn, Pb, Cu, As Hg signature</li> </ul>	Hishikari, Round Mountain, Pajingo, Cerro Vanguardia	Hedenquist et al (2000) Gemmeil (2004) Simmons et al. (2005)
Other deposit types	Carlin	<ul style="list-style-type: none"> <li>- Faulted and folded miogeoclinal sequences</li> <li>- Slope-facies lithologies (dirty carbonate)</li> <li>- Felsic magmatism</li> </ul>	<ul style="list-style-type: none"> <li>- Silty limestone</li> <li>- Less permeable cap rock</li> <li>- Anticlinal structures</li> <li>- Abundant high-angle faults, including deep-tapping ones</li> <li>- Felsic stocks and dykes</li> </ul>	<ul style="list-style-type: none"> <li>- Silicification (jasperoids) along reactive units and faults</li> <li>- Dissolution-type breccias</li> <li>- Occurrences of As, Sb and Hg minerals</li> <li>- Au&gt;Ag, As, Sb, Tl, Hg signature</li> </ul>	Goldstrike, Gold Quarry, Getchell, Jerritt Canyon	Hofstra and Cline (2000) Cline et al. (2005)
	Au-rich VMS	<ul style="list-style-type: none"> <li>- Rifted arcs and incipient back-arcs; greenstone belts</li> <li>- Mafic-felsic submarine volcanics</li> </ul>	<ul style="list-style-type: none"> <li>- Sub-volcanic felsic intrusion</li> <li>- Felsic volcanic rocks, including small domes</li> <li>- Syn-volcanic fault</li> <li>- Other VMS deposits</li> </ul>	<ul style="list-style-type: none"> <li>- Semi-conformable alteration and Na depletion</li> <li>- Footwall chlorite-sericite or argillic to advanced argillic alteration</li> <li>- Au&lt;Ag, Cu, Zn, As signature</li> </ul>	Horne, Bousquet 2, Henty, Eskay Creek	Huston (2000) Hannington (2004) Dubé and Gosselin (2006b)
	Paleoplacer	<ul style="list-style-type: none"> <li>- Very mature sediments in cratonic sedimentary basin</li> <li>- Foreland or back-arc basins</li> </ul>	<ul style="list-style-type: none"> <li>- Mature pebbly arenite</li> <li>- Unconformities</li> <li>- Alluvial to fluvial mainly channel facies</li> </ul>	<ul style="list-style-type: none"> <li>- Pyrophyllite-chloritoid alteration (perhaps overprint)</li> <li>- Gold in detrital pyrite bearing mature conglomerates and arenites</li> <li>- Au&gt;Ag, U signature</li> </ul>	Witwatersrand, Tarkwa	Frimmel et al. (2005) Law and Phillips (2005) Hirdes and Numoo (1994)

### Relative global importance of deposit types

From an exploration point of view, especially for large gold companies, efforts have to be focused on models that have the best chance of yielding large deposits. Table 2 shows the distribution of gold deposits among the types listed in Table 1 from a population of 103 deposits with an endowment of >10 Moz. Table 2 shows that nearly all deposit types are represented among the >10 Moz deposits. However some deposit types are clearly more abundant than others among this population of giants. For example, Au-rich porphyry deposits are by far the most abundant, followed by greenstone-hosted deposits (orogenic and atypical), and by Carlin deposits. The other key point highlighted by this compilation is that some deposit types tend to be larger than others, the largest being the individual Witwatersrand goldfields, followed by the sediment-hosted RIR deposits. Conversely, intrusion-hosted RIR, LS epithermal, and Au-rich VMS deposits are not abundant among the 10 Moz deposits and tend to be smaller, at <15 Moz on average.

**Table 2: Distribution of a population of 103 deposits >10 Moz among the different deposit types and clans discussed in this paper.**

Deposit Clans and Types	No of deposits >10 Moz	Contained Au (Moz)
<b>Orogenic</b>	<b>20</b>	<b>425</b>
Greenstone	14	285
Turbidite & BIF	6	140
<b>Reduced IR</b>	<b>13</b>	<b>434</b>
Intrusion-hosted	4	75
Sediment-hosted	8	359
<b>Oxidized IR</b>	<b>39</b>	<b>1104</b>
Porphyry (skarn)	27	739
HS-IS Epithermal	9	253
LS Alkalic	3	112
<b>Other Types</b>		
LS- Epithermal	7	91
Carlin	10	245
Au-VMS	2	20
Witwatersrand	8	1260
Greenstone atypical	5	113

### CHARACTERISTICS AND SETTINGS OF MAIN GOLD DEPOSIT TYPES

This section describes the key characteristics of selected, globally important types of gold deposits and their local to regional geologic settings. These characteristics form the basis

of the deposit footprints targeted by regional exploration programs, as discussed in the second part of the paper.

### Orogenic deposits

As indicated above, there remains ambiguity in the distinction between orogenic and RIR deposits. In a greenstone belt context, further ambiguity stems from the existence of additional styles of gold-only and gold-base metal deposits that are commonly overprinted by orogenic veins. These are interpreted either as different types and ages of deposits (Robert et al., 2005) or as depth variations on a single orogenic model with a few atypical gold-base metal deposits (Groves et al., 2003).

In this paper, the term orogenic is restricted to deposits composed of quartz-carbonate veins and associated wallrock replacement associated with compressional or transpressional geological structures such as reverse faults and folds, as depicted in the corresponding diagram of Figure 1. Three main types of orogenic deposits are distinguished based on their host-rock environment: greenstone-hosted, turbidite-hosted, and BIF-hosted types (Figure 1; Table 1). Atypical deposits encountered in greenstone belts are discussed separately.

Orogenic deposits of all three types share a number of additional characteristics. They consist of variably complex arrays of quartz-carbonate vein that display significant vertical continuity, commonly in excess of 1 km, without any significant vertical zoning. The ores are enriched in Ag-As+/-W and have Au:Ag ratios >5. Other commonly enriched elements include B, Te, Bi, Mo. The dominant sulfide mineral is pyrite at greenschist grade and pyrrhotite at amphibolite grade. Arsenopyrite is the dominant sulfide in many clastic-sediment-hosted ores at greenschist grade, and loellingite is also present at amphibolite grade. Orebodies are surrounded by zoned carbonate-sericite-pyrite alteration haloes that are variably developed depending on host rock composition. At the regional scale, a majority of deposits are spatially associated with regional shear zones and occur in greenschist-grade rocks, consistent with the overall brittle-ductile nature of their host structures.

#### Greenstone-hosted deposits

Greenstone-hosted orogenic deposits are the most important of the clan and the best represented type among the >10 Moz deposits (Table 2), including Hollinger-McIntyre, Dome, Sigma-Lamaque, Victory-Defiance, Norseman, and Mt Charlotte. The quartz-carbonate veins in these deposits typically combine laminated veins in moderately to steeply dipping reverse shear zones with arrays of shallow-dipping extensional veins in adjacent competent and lower strain rocks (Figure 1). The reverse character of the shear-zone-hosted veins and shallow-dips of extensional veins attest to their formation during crustal shortening (Sibson et al., 1988; Robert and Poulsen 2001).

In greenstone belts, the significant vein deposits are typically distributed along specific regional compressional to transpressional structures. By virtue of their association with regional structures, these camps are also located at the boundaries between contrasted lithologic or age domains within the belts. Along these structures, the deposits commonly cluster in specific camps, localized at bends or major splay

intersections, and where deposits typically occur in associated higher-order structures (Goldfarb et al. 2005; Robert et al., 2005). The larger camps and deposits are commonly spatially associated with late conglomeratic sequences as exemplified by the Timiskaming polymict conglomerates in the Abitibi greenstone belt and the Tarkwaian quartz pebble conglomerates in the Birimian Shield. The deposits occur in any type of supracrustal rocks within a greenstone belt and, covering stratigraphic positions from lower mafic-ultramafic volcanic to upper clastic sedimentary stratigraphic levels. However, large deposits tend to occur stratigraphically near the unconformity at the base of conglomeratic sequences, especially if developed above underlying mafic-ultramafic volcanic rocks (Robert et al., 2005).

At the local scale, favorable settings for these deposits represent a combination of structural and lithologic factors (Groves et al., 1990; Robert, 2004b). Favorable structural settings are linked mainly to the rheologic heterogeneities in the host sequences. Shear zones and faults, universally present in these deposits, are developed along lithologic contacts between units of contrasting competencies and along thin incompetent lithologic units. Along these contacts and along incompetent rocks, deposits will preferentially develop at bends, and structural intersections. Competent rock units enclosed in less competent favor fracturing and veining. Common lithologic associations include Fe-rich rocks such as tholeiitic basalts, differentiated dolerite sills and BIFs, and with competent porphyry stocks of intermediate to felsic composition, whether they intrude mafic-ultramafic volcanic or clastic sedimentary rocks.

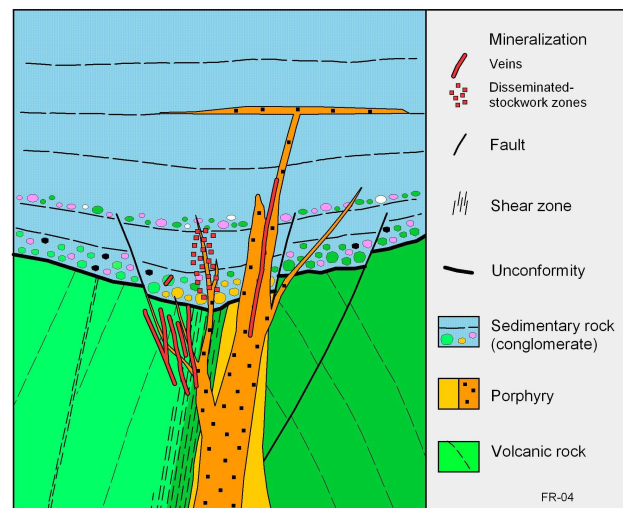
#### Atypical greenstone-hosted deposits

In the last decade, there has been an increased recognition that prolific greenstone belts contain gold-only and gold-base metal deposits that do not conform to the orogenic model (Robert et al., 2005). Selected examples of atypical deposits include Red Lake, Hemlo, Malartic, Doyon, Fimiston, Wallaby, Kanowna Belle and Boddington, and the well-documented Horne and LaRonde Au-rich VMS deposits (Dubé and Gosselin, 2006b). Although these atypical deposits display similar regional-scale controls and commonly occur in the same camps as orogenic deposits, they differ in styles of mineralization, metal association, interpreted crustal levels of emplacement, and relative age. Alteration associated with some atypical deposits is distinct in its aluminous mineral assemblages. These atypical deposits are important as they represent a significant proportion of the gold budget of greenstone belts (Table 2).

Ores of these deposits range from disseminated-stockwork zones at Wallaby and Kanowna Belle, to crustiform-textured veins with associated sulfidic wallrock replacements at Red Lake and Fimiston, to less common sulfide-rich veins (Robert et al., 2005). These different styles all show a close spatial association with high-level porphyry stocks and dykes. The ore textures and the common enrichments in Te, Sb, Hg are also suggestive of a high-level of emplacement of the deposits, many of which have indeed been classified as epizonal (Gebre-Mariam et al., 1995). The ores in many disseminated-stockwork and crustiform vein deposits are refractory.

Most atypical deposits occur near or above the unconformity at the base of conglomeratic sequences. Figure 2 illustrates the common settings of these disseminated-stockwork and crustiform vein styles of deposits, based on a model proposed by Robert (2001) for disseminated deposits in the Abitibi greenstone belt. From an exploration point of view, it is important to note that the most significant greenstone gold discoveries in the last decade are of the disseminated-stockwork style (Eleonore, Wallaby) and are hosted in the upper, sedimentary section of the stratigraphic column.

As argued by Robert et al. (2005) many of these atypical deposits have formed relatively early in the development of the greenstone belts, prior to the folding of their host units during the bulk of the shortening of their host belts, and are commonly overprinted by orogenic veins. Although still debated, the origin of many of these deposits is akin to that of alkalic, porphyry-style deposits of the oxidized intrusion-related clan. In fact many of the disseminated-stockwork deposits in the Yilgarn and Superior cratons have previously been interpreted as porphyry deposits (see Robert et al., 2005).



**Figure 2:** Geologic model for the setting of disseminated-stockwork and crustiform vein deposits in greenstone belts, showing their close spatial associations with high-level porphyry intrusions and unconformities at the base of conglomeratic sequences. Modified from Robert (2001)

#### BIF-hosted deposits

Only three BIF-hosted deposits contain >10 Moz Au (Homestake, Morro Velho, and Geita) but they are large and account for 90 Moz of gold, hence their attraction as an exploration target. The deposits consist mainly of sulfidic replacements of Fe-rich layers in magnetite or silicate BIF, adjacent to variably-developed quartz veins and veinlets. The intensely mineralized central parts of some deposits consist of nearly continuous wallrock replacements which can obscure their epigenetic character and can lead to ambiguities about the timing of mineralization (Caddy et al., 1991; Kerswill, 1996)

BIF-hosted deposits occur in greenstone belts that are either volcanic-dominated or sediment-dominated, where they are located stratigraphically near regional volcanic-sedimentary

transition, as is the case at Homestake and Morro Velho. A few deposits, like Lupin, also occur near the edges of large clastic sedimentary basins, in absence of significant mafic volcanic rocks. Magnetite BIF is the dominant host in greenschist grade rocks, whereas silicate BIF prevails at mid-amphibolite grade or higher (Kerswill, 1996).

At the local scale, BIF-hosted deposits are commonly associated with the hinges of folds, anticlines or synclines, and intersections of shear zones and faults. As a consequence, the deposits are commonly stratabound and plunge parallel to their host fold hinge or to the line of intersection of controlling shear zones with the BIF unit. In greenstone belts, many BIF-hosted deposits also contain concentrations of intermediate to felsic porphyry stocks and dykes.

#### Turbidite-hosted deposits

Orogenic turbidite-hosted (slate-belt-hosted) veins are common, but only three deposits contain >10 Moz Au, with Bendigo and Nataoka being the most important. They are well-understood and their regional to local settings and controls have been reviewed by Bierlein and Crowe (2000), among others. The classical examples of this deposit type consist of vertically stacked saddle reefs in anticlinal fold hinges linked by fault-fill veins in reverse shear zones and associated extensional veins.

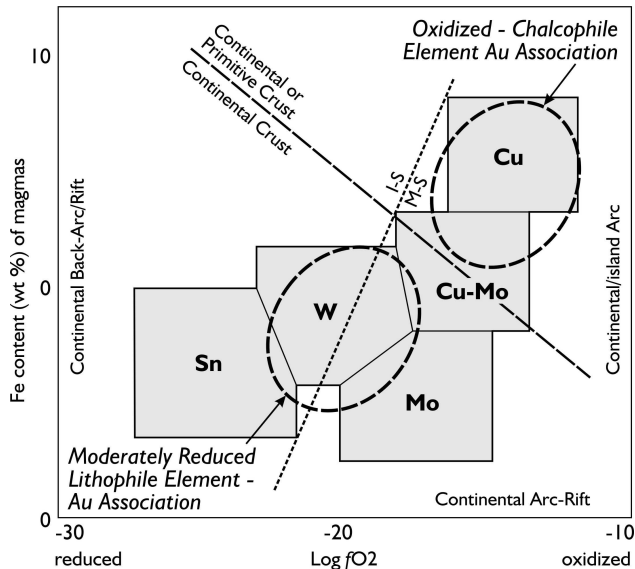
Deposits of this type occur in thick accretionary greywacke-mudstone sequences, intruded by granitic plutons and are in proximity to major crustal boundaries (Table 1). The presence of a hydrated oceanic substrate is considered to be favorable for the development of well-mineralized terranes (Bierlein et al., 2004). At the local scale, the deposits are typically associated with doubly-plunging, upright anticlines and high-angle reverse faults (Bierlein and Crowe, 2000). The deposit areas typically lack significant volumes of felsic intrusions, although lamprophyres dykes may be present.

Of significance to exploration is the recognition in the last decade of vein-scale to kilometer-scale ankerite-siderite spotting haloes around turbidite-hosted deposits of the Central Victorian Province in Australia, providing a significantly larger exploration footprint than the veins themselves (Bierlein et al., 1998).

#### Reduced Intrusion-Related Deposits

The last decade has seen the introduction, general acceptance, and progressive understanding of a group of gold-only deposits associated with moderately reduced intrusions. The terminology for this class of deposits has developed gradually, with various authors defining the class in different ways, which has resulted in some confusion over how best to classify these deposits (Hart 2005). Early work recognized the distinction from deposits related to highly oxidized, I-type, magnetite series intrusions that are typically associated with gold-rich "porphyry" deposits (McCoy et al., 1997, Thompson et al. 1999a, Lang et al, 2000). Thompson and Newberry (2000) defined the key distinguishing characteristics of these gold deposits and coined the term "reduced intrusion-related". Although the granitoids associated with these deposits are best described as "moderately reduced" (Baker 2003) and some are weakly oxidized, they are

significantly less oxidized than intrusions related to gold-rich or gold-only porphyry deposits (Hart, 2005). The RIR deposit clan is clearly distinguished from the oxidized intrusion-related clan in terms of degree of fractionation and oxidation state of associated calc-alkalic to alkalic magmas and of dominant metal assemblages (Figure 3).



**Figure 3:** Schematic plot showing degree of fractionation (shown by Fe-content) versus oxidation state associated with differing metal-enrichment in magmatic-hydrothermal systems. Relationship between ilmenite-series (I-S) and magnetite-series (M-S) also shown, in addition to generalized tectonic setting (from Thompson et al., 1999a)

The key characteristics of RIR deposits have recently been summarized by Hart (2005; see also Table 1). Mineralization typically has low sulfide content, mostly <5 vol %, with a reduced ore mineral assemblage that typically comprises arsenopyrite, pyrrhotite and pyrite and lacks magnetite or hematite. Metal assemblages combine gold with variably elevated Bi, W, As, Mo, Te, and/or Sb but low concentrations of base metals. The deposits also display restricted and commonly weak proximal hydrothermal alteration.

RIR deposits are spatially and temporally associated with meta-aluminous, subalkalic intrusions of intermediate to felsic composition that span the boundary between ilmenite- and magnetite-series. A key element of the model is that the deposits are coeval with their associated, causative intrusion. At the regional scale, these deposits are associated with magmatic provinces best known for their tungsten and/or tin deposits. They also occur in tectonic settings well inboard of inferred or recognized convergent plate boundaries.

Deposits of the RIR clan can be subdivided into three types based on variations in style relative to depth of formation and proximity to the causative intrusions, similar to what is observed within OIR "porphyry" systems (Lang et al., 2000; Hart, 2005; Figures 1 and 4; table 1). Differences in deposit types among the RIR clan are further reflected in alteration, style of mineralization, and metal association (Table 1). The first two types of deposits are intrusion-hosted and have formed in the epithermal and mesothermal depth environments, and here



referred to as epizonal and mesozonal intrusion-related deposits (Figure 1). The third type of deposit is hosted in clastic sedimentary rocks and has a more tenuous link to reduced intrusions; it is designated sediment-hosted intrusion-related (Figure 1, Table 1). These deposits consist of zones of stockwork-disseminated gold mineralization and share many of the characteristics of RIR deposits, notably metal associations and spatial and temporal relationships with moderately-reduced intrusions (Wall 2000, 2004; Yakubchuk 2002). This type of deposit is of high exploration significance, as it includes giant deposits such as Muruntau (Wall, 2004), Kumtor (Mao et al. 2004), and Telfer (Rowins, 2000). The inclusion of these deposits in the intrusion-related clan, however, remains controversial and other authors rather include them in the orogenic clan (Goldfarb et al., 2005).

Mesozonal Intrusion-Hosted Deposits

The mesozonal intrusion-hosted deposits have been well studied in the Yukon and Alaska and the model for these is well advanced and generally accepted (Figure 5, Hart 2005). The largest of these are typically characterized as low grade bulk mineable sheeted vein deposits such as Fort Knox (8 Moz) and Vasilkovskoe (12 Moz). Gold in these deposits is generally free milling, non-refractory and associated with bismuth minerals (Flanigan et al. 2000). Tellurium and tungsten are also common element associations. These sheeted vein deposits are generally located on the margins or roof zones of small elongate equigranular granodioritic to granitic plutons. These intrusions are typically metaluminous to weakly peraluminous, calc-alkalic, and subalkalic with inferred oxidation states straddling the boundary between ilmenite-series and magnetite series (Lang et al. 2000). Hart (2005) suggests that pluton phases likely to evolve mineralizing hydrothermal fluids display a number of the following characteristics: porphyritic textures, presence of aplite and pegmatite dykes, quartz and tourmaline veins, greisen alteration, miarolitic cavities, and unidirectional-solidification textures. It is also noticeable that in regions where mesozonal deposits dominate, coeval volcanic rocks are rare or absent because of their depth of emplacement.

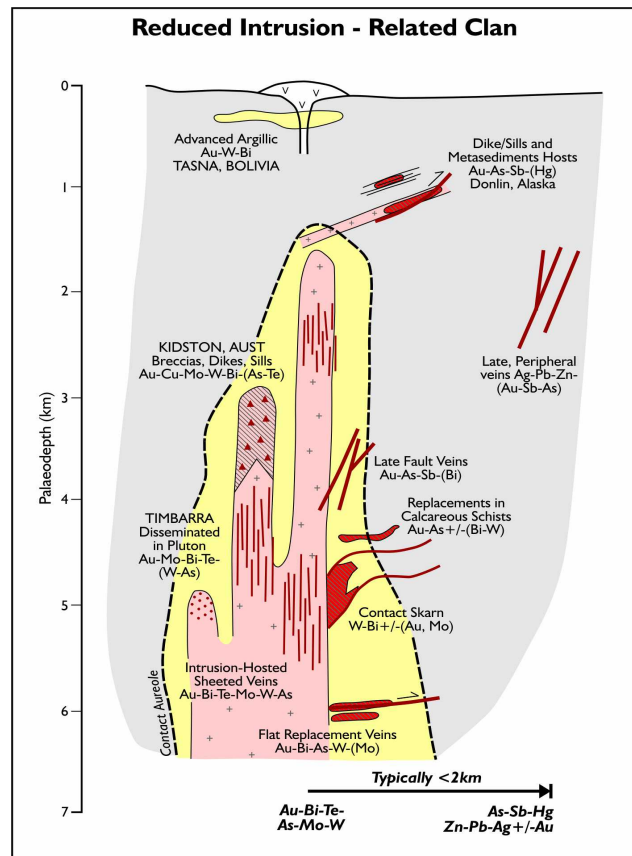


Figure 4: Diagram showing exploration zoning model for intrusion-related gold systems, with an emphasis on systems in Yukon-Alaska but including variations from other intrusion-related gold systems provinces. Modified from Lang et al. (2000).

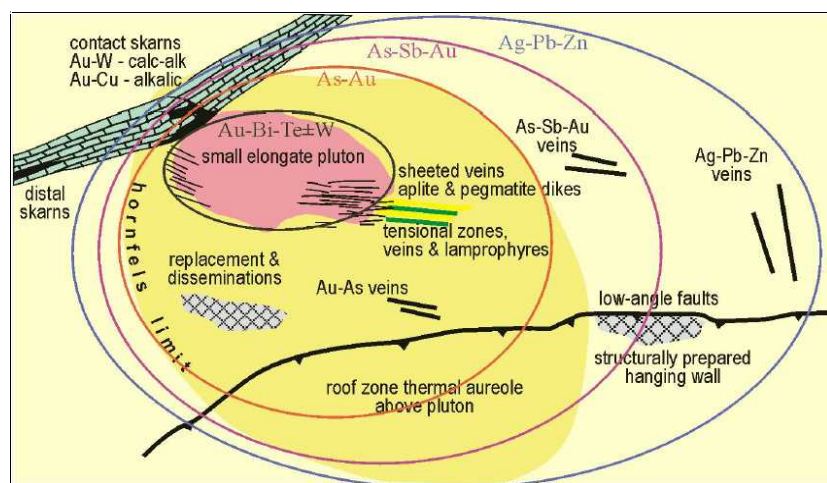


Figure 5: Generalized plan-view model for reduced intrusion-related gold systems from the Tintina Gold Province. Note the wide range of mineralization styles and geochemical variations that vary predictably outward from a central pluton (modified from Hart 2005).

These deposits do not commonly have extensive hydrothermal alteration systems surrounding them and are typically restricted to narrow sericite-carbonate-feldspar alteration halos on the quartz veinlets. However peripheral deposits and occurrences and hornfels zones in the mesozonal environment can display a predictable distribution pattern (Figure 5). This pattern significantly expands the exploration footprint of these deposits. Most of the deposits found outside of the intrusions either as skarns, mantos, or polymetallic veins are small (<3 Moz) with only a few exceptions (Pogo). Significant deposits of disseminated (Timbara) and breccia hosted mineralization (Kidston) in the vicinity of reduced granitoid stocks have also been noted (Lang et al., 2000).

#### Epizonal Intrusion-Hosted Deposits

Epizonal intrusion-hosted deposits, such as Kori Kollo, Brewery Creek, and Donlin Creek, consist of stockwork veinlets, disseminated sulfide or sheeted vein mineralization in dyke-sill complexes or volcanic domes. Host intrusions have similar characteristics to those described for the mesozonal deposits, but with evidence of shallower emplacement such as aphanitic groundmass in porphyritic dyke-sill intrusions. Donlin Creek is the largest of these deposits and has been shown by Baker (2002) and Goldfarb et al. (2004) to have formed at depths of less than 2 km. These deposits may show characteristic shallow level vein textures such as abundant drusy quartz-lined cavities, banded, crustiform, cockade and bladed textures (Goldfarb et al. 2004). In the regions of these deposits, age equivalent volcanic rocks are often present.

Hydrothermal alteration associated with these epizonal intrusion-hosted deposits typically has a component of clay alteration and/or veinlet scale alteration halos of carbonate and sericite (Baker, 2002). These deposits more commonly are characterized by refractory gold and associations with Sb and Hg in contrast to their mesozonal counterparts (Table 1).

#### Sediment-Hosted Intrusion-Related Deposits

Some authors have linked reduced intrusions in space and time to large sediment-hosted deposits, such as Muruntau, Kumtor, and Telfer as well as several other smaller examples (Goldfarb et al. 2005). These deposits have complex multi-stage mineralization paragenesis, with at least one stage that consists of stockwork-disseminated or sheeted veinlet zones, and have associated metal suites consistent with the mesozonal reduced-intrusion related deposits.

Hydrothermal alteration in these deposits usually has an important component of feldspathic alteration. Sericitization, carbonatization, and biotization have also been noted and may extend for considerable distances around ore. Muruntau is the largest deposit of this class (> 200 Moz) and main-stage gold mineralization consists of sheeted quartz-feldspar veins and is associated with As, W, Sb, Bi, and Mo (Wall et al., 2004). It is located in the thermal aureole above the roof zone of a syn-mineralization buried intrusion (Wall et al., 2004). Mao et al. (2004) firmly establish the mineralization at Kumtor, within the same broad belt as Muruntau, at the same age as post-collisional granites in the area.

The post-collisional granite suite in the Muruntau-Kumtor region contains Sn-Be, REE-Nb-Ta-Zr, U, and minor W deposits

of skarn and greisen type (Mao et al., 2004). The metal associations are indicative of an associated reduced intrusion suite. These deposits have important structural controls and commonly are located in the core of anticlines cut by high-angle faults. As noted by Wall et al. (2004), the presence of impermeable cap rocks may be important in the formation of Muruntau and other deposits of this type.

### Epithermal deposits

Epithermal deposits were originally defined by Lindgren (1922) as precious or base metal deposits forming at shallow depths and low temperatures. The currently accepted definition, while not rigorous, includes precious and base metal deposits forming at depths of <1.5 km and temperatures of <300° C in subaerial environments within volcanic arcs at convergent plate margins and in intra- and back-arc as well as post-collisional extensional settings (Table 1). Epithermal systems can be grouped in to high-, intermediate- and low-sulfidation types based on variations in their hypogene sulfide assemblages (Sillitoe and Hedenquist, 2003). Most epithermal gold deposits are Cenozoic in age, but some older deposits are known, although none of the giant ones are older than Cretaceous.

#### High sulfidation deposits

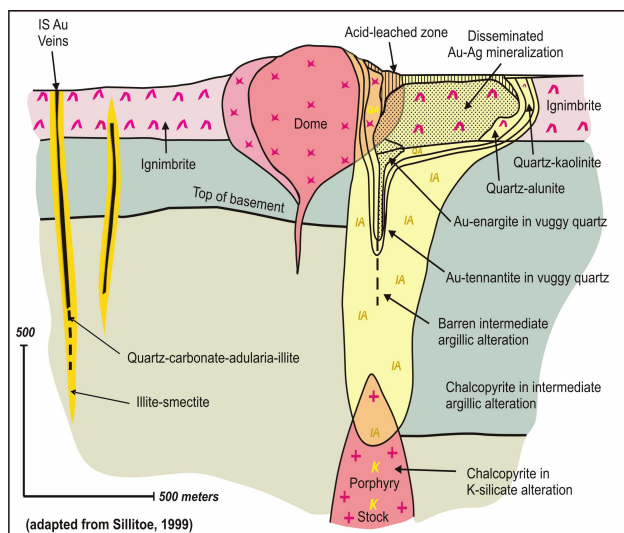
High sulfidation (HS) gold systems are widely distributed in volcanic arcs worldwide. Deposits range from structurally controlled and deeper seated examples, such as El Indio, to shallow host-rock or breccia controlled examples such as Yanacocha, Pierina, and Pueblo Viejo (Figure 6; Sillitoe, 1999). At the regional scale, HS systems lie within calc-alkaline volcanic arcs dominated by andesitic volcanism. They form in the upper parts of Cu (Au, Mo) porphyry systems, which themselves do not necessarily contain economic mineralization. The giant HS deposits of northern Peru and the central Andes of Argentina and Chile are all Mid- to Upper-Miocene in age, and are inferred to have formed above flat or flattening subduction zones, and temporally coincident with compression and shortening in the upper crust. As with porphyry systems, the giant HS systems appear to be localized at intersections of arc-parallel with arc-transverse crustal-scale structures.

Locally, giant HS systems are associated with felsic subvolcanic or volcanic rocks, often within igneous centers showing prolonged activity. They can be hosted either in volcanic rocks, as at Yanacocha and Pierina, or in their basement, as at Veladero, Pascua-Lama, and Alto Chicama, the latter case reflecting compression-driven uplift. The HS deposits lie within large volumes of advanced argillic alteration formed through the mixing of acidic magmatic vapors and groundwater above mineralized porphyry intrusives (Hedenquist et al., 1998). Typically these advanced argillic alteration zones show characteristic zoning from proximal vuggy silica through advanced argillic assemblages containing alunite, pyrophyllite, dickite and kaolinite to distal argillic alteration. The central siliceous alteration zones are the main hosts to ore. The nature of the host rock can produce variations from these typical alteration assemblages and zoning patterns.

Mineralization in HS deposits comprises pyrite-rich sulfide assemblages including high sulfidation-state minerals like enargite, luzonite and covellite. Mineralization post-dates the formation of the advanced argillic lithocap described above. The mineralizing fluid is much less acid than the fluid responsible for forming the advanced argillic alteration zones which host mineralization (Jannas et al., 1990; Arribas, 1995). Fluctuations from enargite to tetrahedrite-tennantite are a common feature during the evolution of HS deposits and indicate changes in sulfidation state and pH of the mineralizing fluid during the life of the hydrothermal system (Sillitoe and Hedenquist, 2003, Einaudi et al., 2003). Minor gold can occur with early enargite mineralization but most gold is introduced with paragenetically later tennantite-tetrahedrite-low Fe sphalerite mineralizing events (Einaudi et al., 2003).

The giant systems comprise disseminated Au-Ag mineralization often in mushroom-shaped ore bodies with narrower structural roots (Figure 6). Permeability contrasts between aquitards and permeable lithologies can be important controls on the distribution of gold. Additionally, breccias are usually abundant and host ore in some systems. Phreatomagmatic breccias are present in all giant HS deposits underlining the genetic connection with an underlying intrusive. Mineralization can occur over vertical intervals of 100s of meters below the paleosurface, from disseminated Au-Ag immediately below surficial steam-heated alteration to deeper structurally controlled Au-enargite at depth.

Supergene oxidation, often to considerable depths in permeable silicified rock, generates oxide gold mineralization amenable to recovery by cyanide leaching.



**Figure 6:** Schematic model of a dome-related HS system above an underlying parent porphyry system. Alteration and Cu sulfide mineral assemblages vary with depth below the paleosurface, which is marked by acid-leached rock of steam-heated origin. Adapted from Sillitoe (1999).

#### Intermediate sulfidation deposits

Intermediate sulfidation (IS) gold systems also occur in mainly in volcanic sequences of andesite to dacite composition within calc-alkaline volcanic arcs. Large IS Au deposits are found in

compressional as well as in extensional magmatic arcs. Some Au-rich IS systems are spatially associated with porphyry systems (e.g. Rosia Montana, Baguio) while others adjoin coeval HS systems (Victoria, Chiufen-Wutanshan). Additionally, several larger Au-rich IS deposits are associated with diatremes which further emphasizes a magmatic connection.

At the deposit scale, mineralization occurs in veins, stockworks and breccias. Veins with quartz, manganiferous carbonates and adularia typically host the Au mineralization. Gold is present as native metal and as tellurides together with a variety of base metal sulfides and sulfosalts. Low-Fe sphalerite, tetrahedrite-tennantite and galena often dominate these assemblages. IS Au veins can show classical banded crustiform-colloform textures in the veins. Permeable lithologies within the host sequence may allow development of large tonnages of low-grade stockwork mineralization.

Alteration minerals in IS Au deposits are zoned from quartz  $\pm$  carbonate  $\pm$  adularia  $\pm$  illite proximal to mineralization through illite-smectite to distal propylitic alteration (Simmons et al., 2005). Breccias may be common and can show evidence for repeated brecciation events.

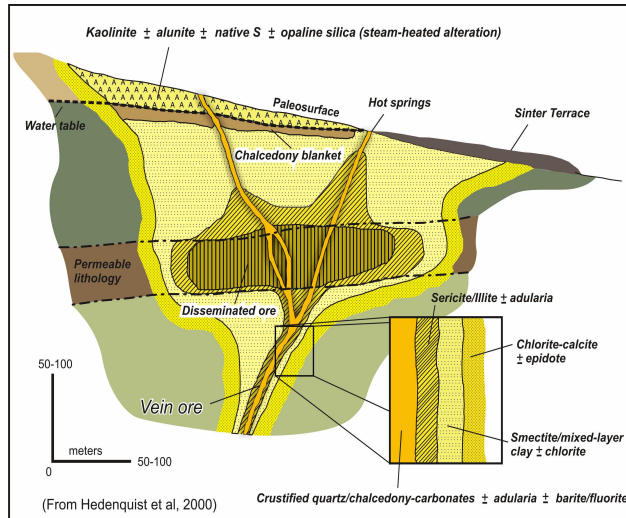
#### Low sulfidation deposits

Low sulfidation (LS) epithermal gold deposits of the alkalic and subalkalic subtypes share a number of characteristics (Table 1) and are described together. Differing characteristics of the less common alkalic LS deposits are highlighted where appropriate. Most LS gold deposits are found in intra-arc or back-arc rifts within continental or island arcs with bimodal volcanism (Table 1). Rifts may form during or after subduction or in post collisional settings. Additionally, some LS deposits are found in andesite-dacite-rhyolite volcanic arcs, but only in clearly extensional settings (Sillitoe and Hedenquist, 2003). Deposits of the alkalic subset of low sulfidation epithermal deposits are specifically associated with alkaline magmatic belts but share an extensional setting with their calc-alkaline counterparts (Table 1; Jensen and Barton, 2000).

At the deposit scale, LS gold deposits are typically hosted in volcanic units, but can also be hosted by their basement. Vein development in the basement does not reflect syn-mineral uplift, as is the case in HS and IS systems, but rather the intersection of the hydrothermal system with rheologically more favorable basement host rocks. Syn-mineral mafic dykes are common in these deposits (Sillitoe and Hedenquist, 2003). Both low-grade disseminated and structurally controlled high-grade deposits can form, such as Round Mountain and Hishikari, respectively (Figure 7). Calc-alkalic LS deposits have restricted vertical continuity, generally <300m, whereas alkalic LS deposits such as Porgera and Cripple Creek can extend in excess of 1 km vertically. Mineralization in subalkalic LS systems generally has high silver (Au:Ag ratio <1) and low base metal content and gold is associated with pyrite – high-Fe sphalerite  $\pm$  pyrrotite  $\pm$  arsenopyrite. In contrast, LS alkalic mineralization commonly contains abundant telluride minerals, has elevated Au:Ag ratios, and less voluminous quartz gangue (Jensen and Barton, 2000).

Alteration mineralogy in LS systems shows lateral zoning from proximal quartz-chalcedony-adularia in mineralized veins, which commonly display crustiform-colloform banding and platy, lattice-textured quartz indicative of boiling; through illite-

pyrite to distal propylitic alteration assemblages (Figure 7). Vertical zoning in clay minerals from shallow, low temperature kaolinite-smectite assemblages to deeper, higher temperature illite have also been described (Simmons et al., 2005). As with HS and IS systems, host rock composition can also cause variations in the alteration mineral zoning pattern in LS systems. Alteration assemblages in alkalic LS deposits commonly contain roscoelite, a V-rich white mica, and abundant carbonate minerals (Jensen and Barton, 2000).



**Figure 7:** Schematic section showing typical alteration and mineralization patterns in a low sulfidation system. Modified from Hedenquist et al. (2000).

#### Paleosurface features

By definition, epithermal systems form close to the paleosurface and therefore each of the systems described above may lie beneath steam-heated alteration blankets formed above the paleowater table (Figure 7). As the name indicates, this alteration is formed by the acidification of cool meteoric waters by acidic vapors derived from boiling, ascending hydrothermal fluids. Steam-heated alteration typically comprises fine-grained, powdery cristobalite, alunite and kaolinite and has a morphology which mimics the paleotopography. Massive opaline silica layers mark the water table. Siliceous sinters can also form, marking outflow zones where the paleowater table intersected topography, but sinters will only form above or lateral to LS systems where the upwelling fluid has near-neutral pH (Simmons et al., 2005).

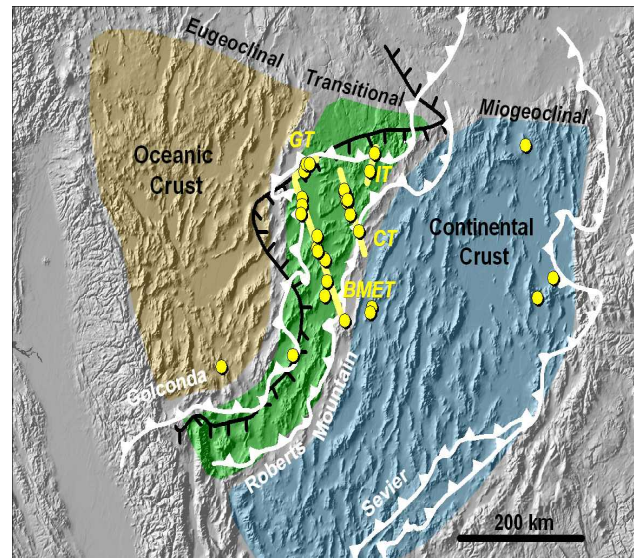
#### Carlin-type deposits

The term Carlin-type (CT) was first used to describe a class of sediment-hosted gold deposits in central Nevada following the discovery of the Carlin mine in 1961. Carlin-type mineralization consists of disseminated gold in decalcified and variably silicified silty limestone and limy siltstone, and is characterized by elevated As, Sb, Hg, Tl, Au:Ag ratio > 1, and very low base metal values (Hofstra and Cline, 2000; Muntean,

2003; Table 1). Main ore-stage mineralization consists of gold in the lattice of arsenical pyrite rims on pre-mineral pyrite cores and of disseminated sooty auriferous pyrite, and is commonly overprinted by late ore-stage realgar, orpiment and stibnite in fractures, veinlets and cavities (Hofstra and Cline, 2000; Cline, et al., 2005). The largest and most significant known Carlin-type deposits and districts are located in Central Nevada. Significant advances have been made during the last decade in understanding their age, geologic setting, and controls.

At the regional scale, they occur within a north-trending band of favorable Paleozoic slope-facies carbonate turbidites and debris flows within the North American continental passive margin (Figure 8). These slope-facies carbonate rocks form a lower plate to Paleozoic deep water siliciclastic rocks that have been repeatedly over thrust from the west during late Paleozoic through Cretaceous orogenic events, resulting in the development of low-angle structures and open folds. The region has been overprinted by Jurassic through Miocene magmatic events related to shallow east-dipping subducting slabs, and dissected by a series of north-trending high-angle faults accommodating Cenozoic extension (Hostra and Cline, 2000).

Carlin-type deposits and the districts in which they cluster are distributed along well-defined, narrow trends (Figure 8) that are now understood to represent deep crustal breaks extending into the upper mantle. The main trends are oblique to the early Paleozoic passive continental margin and possibly represent deep crustal structures related to the Neoproterozoic break up of the continent (Tosdal et al., 2000).



**Figure 8:** Map of Central Nevada showing the location of Carlin-type deposits and trends, relative to the leading edge of major Paleozoic thrusts (white) and boundary between continental and oceanic crust in the basement (yellow, defined by  $87\text{Sr}/86\text{Sr}(i)=0.706$ ; from Tosdal et al., 2000). CT = Carlin Trend, BMET = Battle Mountain Eureka Trend, GT = Getchell Trend, IT = Independence Trend. Colored background represents the dominant Paleozoic depositional environment, with favorable, slope-facies (transitional) environment represented in green.

Direct dating of ore-related minerals and associated dykes at the giant Getchell, Twin Creeks and Goldstrike deposits has shown that gold mineralization was deposited in a narrow time

interval between 40 and 36 Ma, at a time of transition from compressional to extensional tectonics in Central Nevada (Arehart et al., 2003; Cline et al., 2005; Ressel and Henry, 2006). Recent work using apatite fission-track thermochronology has further documented a district-scale thermal event at approximately 40 Ma over the northern Carlin trend, probably representing the thermal footprint of the mineralized system (Hickey et al., 2005a).

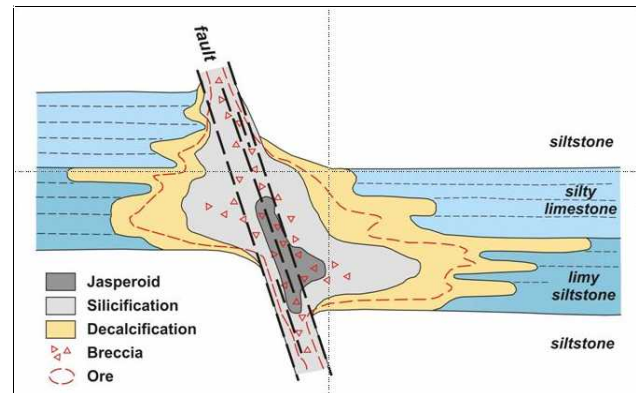
The largest deposits and districts, Getchell, Cortez and Goldstrike, are spatially associated with pre-mineral Mesozoic plutons considered to have acted as structural buttresses during subsequent tectonic events, resulting in enhanced faulting and fracturing, and increased permeability of the sedimentary host rocks for later mineralizing fluids. In these districts, deep-tapping high-angle normal faults are important controls of mineralization, especially those that represent basement faults reactivated during basin inversion (Muntean, 2003). The presence of thrust plates of siliciclastic rocks is also considered important as district-scale aquaculdes that promote lateral dispersion of mineralized fluids into reactive host rocks. Recent application of carbonate sequence stratigraphy to the Great Basin has shown that favorable host rocks in most districts occur at 3rd order low-stand sequence boundaries in carbonate slope facies environments (Cook and Corboy, 2004). During the low stand (low sea level) cycle, the carbonate slope environments become unstable and shed coarse turbidite sequences and debris flows which form the most favorable carbonate stratigraphic horizons for disseminated CT mineralization.

Reconstruction of the paleogeography of the Eocene erosional surface along the Carlin Trend has established that the depth of formation of CT deposits is probably 1 to 3 km (Hickey et al., 2005b). A shallow depth of formation for Carlin-type deposits is also supported by hypabyssal textures and glassy margins observed in Eocene dykes that have overprinted mineralization at the Deep Star and Dee mines in the Carlin Trend (Heitt et al., 2003; Ressel and Henry, 2006).

Most deposits consist of structurally fed strata-bound zones of disseminated-replacement mineralization in specific limy siltstone horizons or of fault-controlled high-grade silica-sulfide breccia bodies (Figure 8; Hofstra and Cline, 2000; Teal and Jackson, 2002). Anticlinal structures and the presence of cap rocks such as sills and moderately-dipping dykes are particularly favorable for the development of replacement-type mineralization (Muntean, 2003; Table 1). Other deposits can also consist of fracture-controlled mineralization in the shattered hanging wall of major structures, or of disseminated mineralization in felsic and mafic intrusive rocks. Associated alteration consists of widespread decalcification of the host rocks and multistage but more proximal silicification (Figure 9). Intense decalcification leads to large scale dissolution and development of collapse breccias, which can form a very favorable site for mineralization. Alteration mineral zoning includes illite+ kaolinite+dickite and smectite within the decalcified zones with late kaolinite and powdery silica+zeolites on fractures within the silicified zones (Kuehn and Rose, 1992).

Primary gold mineralization in Carlin-type deposits is refractory but is amenable to autoclave and roasting extraction technologies. However, deep oxidation, considered to be supergene even though it forms irregular shapes and sometimes occur underneath carbon/sulfide zones, makes many previously

carbonaceous and sulfidic ores amenable to conventional cyanide leaching.



**Figure 9:** Schematic diagram showing discordant structurally controlled and strata-bound mineralization with respect to silicified and decalcified zones in receptive limestone host rocks in a CT system.

## EXPLORATION METHODS

### Exploration strategies

The last decade has seen a significant decline both in the number of major gold deposits discovered (>2.5 Moz Au) and the amount of gold contained in these deposits, compared to the early to mid '90s (Metals Economics Group, 2006). Of the 44 major gold discoveries in the last decade, 32 were made during 1996-2000 and only 12 during 2001-2006. Of these 44 major gold discoveries, 31 were attributable to greenfield exploration and only 13 to brownfield exploration, but the near mine discoveries have not declined at the same rate as greenfield discoveries. Such data attest to the continued value of regional exploration and to the importance of near-mine exploration in the strategy of any mid- to large-size gold producer. In addition to declining discovery rates, future success will have to be achieved in a context of increasing costs, increasing pressure for yearly replacement of reserves/ resources, and increasing minimum size of deposits that really impact the bottom line in larger companies.

A review of the main discovery methods of gold deposits found in the last 10 years indicates that geological understanding was the key element in the discovery process in both the greenfield and brownfield environments (e.g. Sillitoe and Thompson, 2006). Geochemistry in support of geology plays an important role in cases particularly where deposits are exposed, and geophysics aided discovery in some cases where the discoveries were concealed (Sillitoe and Thompson, 2006). A clear lesson from this analysis is that geology should remain an important underpinning of future gold exploration programs.

Accordingly, a key element of success for the explorationist will be to understand and detect the different types of gold deposit and their favorable geologic settings and controls at the regional to local scales, and increasingly in covered terrains. So is an understanding of erosion levels relative to depth of formation of the explored systems, of the environments where

they can be best preserved. Another element will be the wise application of proven and emerging detection techniques, in close integration with geology. The successful strategy should emphasize as much the detection of geological features typical of favorable settings, as that of hydrothermal manifestations of deposits, such as alteration and mineralization, and their dispersion products in the surficial environment. In addition, the exploration approach also needs to take the unusual and unique into account so that deposits which do not conform closely to current models or that occur in unusual settings, are not overlooked (e.g. Sillitoe 2000b).

Exploration is now supported by a variety of advanced data integration and processing tools, from advanced 2D GIS platforms, which have the ability to display drilling data, to full blown 3D data modeling, processing and visualization packages. 3D packages are more suited to near mine or data rich environments, whereas 2D GIS platforms have become an essential tool in regional exploration. However, any approach should focus on detecting a footprint, or elements of a footprint of a mineralized system, at both regional and local scales.

Finally, people are the backbone of any good exploration approach. Not only do team members need to have ability and experience, they must also understand the characteristics of the gold deposits they are searching for and be given sufficient field time to adequately test their targets. Other factors such as an excellent understanding of proven exploration methods, effective use of technology, enthusiastic and responsible leadership, confidence in corporate direction, and attracting and training young professionals, are also important.

### Advances in Exploration Techniques for Gold Deposits

#### Geophysics

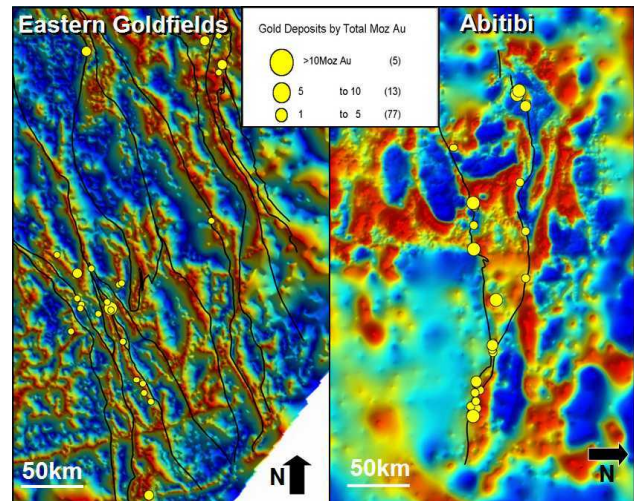
In the last decade, significant advances have been made on proven geophysical methods and on techniques to interpret and to visualize geophysical data. Such advances reach their full impact by appropriate consideration of physical properties of rocks in relation to the key manifestations of the different deposit types and the key features of their host environments (Table 1) manifestations of deposit types. As ore deposit models have developed, so have the amount of petrophysical data, collected via bore hole logging or hand sample analysis, and many recent studies (e.g. Australian Minerals and Research Organization (AMIRA) Project 685-Automated Mineralogical Logging of Drill Core, Chips and Powders, University of British Columbia (UBC) Mineral Deposit Research Unit Geophysical Inversion Facility (MDRU-GIF) Project - Building 3D models and AMIRA Project 740- Predictive Mineral Discovery Cooperative Research Center (PMD\*CRC)) have focused on petrophysical analysis of known ore systems. The petrophysical properties determine what geophysical techniques can best be used to target mineralization. For example Pittard and Bourne (2007) determined that the combination of magnetite and pyrite, rather than pyrite alone, caused the induced polarization response at the Centenary deposit (greenstone) in the Yilgarn, Western Australia. Historically, petrophysical data have also been used at the regional scale, for example, to look at the effects of metamorphism on the geometry and geophysical

response of greenstone belts (Bourne et. al., 1993) but is seeing renewed interest in recent time with the introduction of a priori geophysical inversion routines.

There are many examples of the gravity technique being used at all scales from the identification of prospective gold districts to that of gold-related hydrothermal alteration at a local scale. More recently the development of airborne gravity gradient systems (eg BHP Billiton-Falcon, Bell Geospace-Air FTG), have seen the gravity technique grow in application. Areas are now being flown where ground access was previously not possible and where rapid acquisition is required. Gradient systems are now achieving the equivalent of 0.4mGal/ 500m resolution. Airborne gravimeters are used for regional surveys and have resolutions approaching 0.8mGal/ 2.5km. Ground surveys are still the most cost effective at station spacing less than 1km (access permitting) and can be resolved down to 0.01mGal/ <1m.

Gravity is an effective technique for defining the geometry and structure of greenstones belts at a regional scale, as illustrated in Figure 10. Experience at Barrick shows that gravity has also proven effective in mapping intrusions in sedimentary and volcanic terrains for Carlin, OIR and RIR systems Structure and alteration can also be mapped, either directly by gravity in weathered environments or inferred in terrains where geological units of different density are offset and/or altered.

Magnetic and radiometric methods are considered to be more mature exploration techniques, but nevertheless still very important. Incremental improvements continue to be made, namely better sampling or using multiple sensors to measure gradients which can assist in interpolation of information between flight lines.

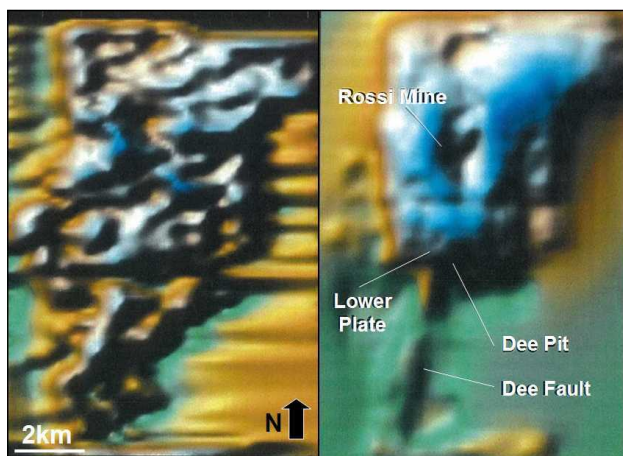


**Figure 10:** Bouguer gravity (2.67g/cc) response of the Eastern Goldfields, Australia (left) and the Abitibi Greenstone Belt, Canada (right) with regional structures and the location of large gold deposits. Eastern Goldfields data from Geological Survey of Western Australia; Abitibi data from Geological Survey of Canada.

One of the most significant recent advance in geophysics is the routine 3D inversion of potential field data (magnetic and gravity). Progress in computer power has allowed inversions to be applied to a variety of problems, from modeling discrete

targets to regional geology. There are many good examples of 3D inversions being used to map alteration associated with gold systems, for example by Coggon (2003) at Wallaby, Western Australia, and by Wallace (2007) at Musselwhite, Canada. However, the lack of petrophysical and geological constraints, and the drive to view data in 3D have also lead to inappropriate application of 3D inversion techniques.

The popularity of inversion of potential field data has lead to a renewed push for the inversion of electrical data. Although many times more computationally intensive, electrical techniques are just beginning to be modeled in 3D. Magnetotelluric (MT) data, for example, has traditionally been acquired and processed in 2D (Petrick, 2007). The best solution for solving real exploration problems is to acquire data capable of being processed in 3D. A recent example of the benefits of processing data in 3D, rather than 2D, from the Dee-Rossi Carlin deposit in Nevada is shown in Figure 11.

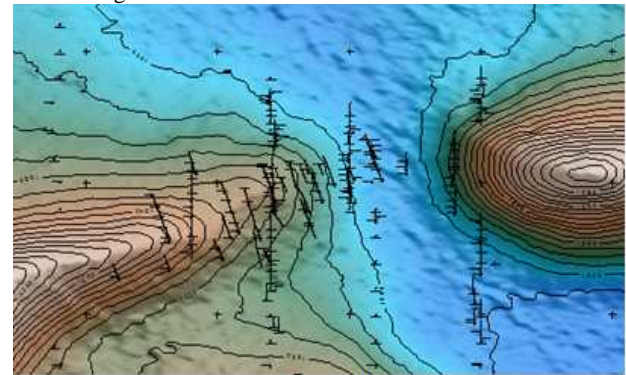


**Figure 11:** Subsurface conductivity distribution at a depth of 450m obtained from stitching together 2D-TM (left) inversions and 3D inversions (right) of magnetotelluric data over the Dee-Rossi region, Nevada (after Petrick, 2007). Tick spacing is 1km.

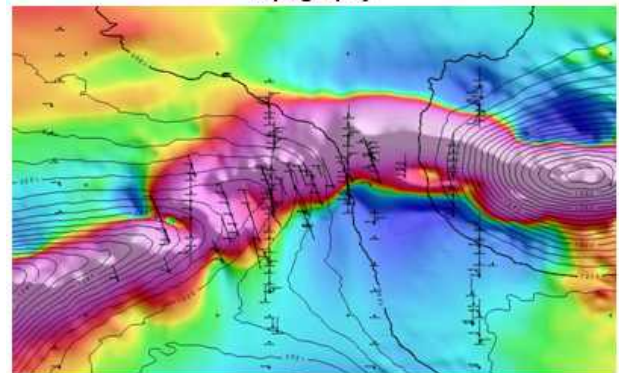
The ability to model data in 3D has just started to promote the acquisition of electrical data (resistivity and induced polarization) in various 3D arrays which can capitalize on new inversion techniques. The new array style acquisition results in data which are difficult to check for validity in the field and no doubt will be the focus of future development.

Resistivity techniques are dominantly used in sedimentary environments, where there is a contrast between carbonaceous and non-carbonaceous terrigenous sediment. In sedimentary environments, intrusions and silica alteration zones are usually more resistive than their host rocks. Commercially available helicoptertime-domain electromagnetic systems with in-loop receivers are increasingly applied in gold exploration e.g Newmont-NEWTEM and Geotech-VTEM. These systems have a fixed geometry which allows them to be flown closer to the ground, leading to higher resolution and making the data easier to interpret. In addition, the early-time reading capability is improving, making the systems better for mapping and for identifying near surface resistors and/or hydrothermal alteration. As an example, Figure 12 shows the response of disseminated

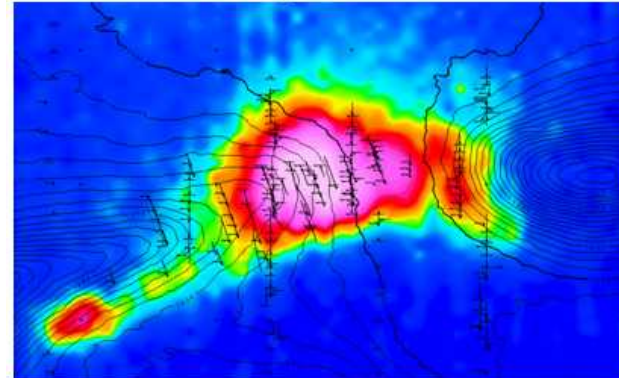
sulfides associated with gold mineralization in a magnetite-BIF unit in the greenstone belt environment.



**Topography**



**Magnetics**



**HEM - Late Time (6msec)**

**Figure 12:** Topographic, magnetic and late time helicopter EM response data from a disseminated sulfide deposit, Lake Victoria Goldfields, Tanzania. Width of image is ~2.5km.

Seismic surveys are not widely applied to gold exploration in hard rock terrains. This is largely due to the complicated 3D geometry of lithologic contacts and their often steeply dipping nature and the high cost of acquisition compared to other geophysical techniques. In recent years, seismic surveys have nevertheless been used at local (Stoltz et. al., 2004) and regional scales to map stratigraphy and structure in the appropriate geological settings.

As the understanding of gold models progresses, so do geophysical methods and techniques to interpret and visualize

the data. One of the largest steps forward in the last decade is the acquisition and application of petrophysical data to solve geological problems. This approach can lead the discovery of gold mineralization via the association of a geophysical response to different rock types or to alteration.

#### Geochemistry

In regional exploration, stream sediment geochemistry, in the form of conventional fine fraction, BLEG (Bulk Leach Extractable Gold), cyanide leach, or pan concentrate sampling, continue to be important tools in gold exploration. At a more local scale, geochemical techniques such as soil, lag, and rock-chip sampling are usually effective in defining anomalies associated with outcropping or sub-cropping deposits. Combinations of elements characterizing the metallogenic associations of the various deposit models (Table 1) can be used together to prioritize anomalies according to model types.

The coarse free gold present in many gold deposits, especially in the RIR, orogenic, and some LS epithermal systems, results in the development of significant associated placer deposits in the appropriate geomorphological settings. Given gold's resistance to weathering, as documented in analyses of gold particles in heavy mineral concentrates from glacial or stream sediments, studies of the composition, shape, and inclusion content of the gold particles allows effective tracing of gold deposits to their sources. However, hypogene mineralization in atypical greenstone deposits of disseminated-stockwork type, Carlin, and HS epithermal deposits is often refractory and does not shed placers or significant coarse gold into their environment.

Non-conventional geochemical exploration methods are becoming increasingly important as exploration is progressing into areas of deeper cover. The past 10 years have seen the development of various new techniques which detect mainly far-field geochemical and biological features of mineral deposits as recently reviewed by Kelley et al. (2006). Newer detection methods include: reduction-oxidation potential in soils, microbial populations in soil, soil gas analysis, selective leaches, halogen concentrations, and isotopic compositions. Many of these techniques are in their infancy with few case studies but they may be promising techniques of the future with further research.

Various petrochemical criteria may be effective in defining favorable igneous suites for deposits in the OIR and RIR clans. For example, Sr/Y ratios in whole rock samples can be used to define fertile oxidized hydrous melts, and oxygen isotopes have been used to define fluid flow pathways at the Comstock epithermal gold deposit, USA (Kelley et al. 2006).

Apatite fission track studies in the Carlin district have outlined large thermal aureoles related to Carlin-type deposits (Cline et al., 2005; Hickey et al., 2005a). Definition of similar thermal anomalies elsewhere may be positive indicators of Carlin-type systems, or potentially of porphyry deposits (Cunningham et al., 2004).

Igneous suites and alteration zones of favorable age can now be more rapidly and economically identified with new dating techniques. Favorable ages in large prospective regions may also be potentially identified by techniques such as GEMOCs

TerraneChron™ in which zircons from regional heavy mineral concentrates are analyzed (O'Reilly et al., 2004).

Finally, various analytical improvements have also contributed to significant advances in the understanding of gold deposit types. Of particular impact are the Re-Os technique for direct dating of ore-related minerals and the laser-ablation ICP-MS technique for analyzing ore-fluid composition, or Au and other trace elements in pyrite.

#### Remote sensing and field-based infrared spectroscopy

Very significant technological advances have been made in the last ten years in the field of infrared spectroscopy for alteration mapping. Satellite multispectral systems such as ASTER and airborne hyperspectral sensors such as Hymap have improved spatial and spectral resolution, higher signal-to-noise ratio, and wider spectral range coverage. Field portable hyperspectral instruments such as Pima have become a standard tool for alteration mapping since it was first introduced to the mineral industry in mid-1990's. Since the late 90's, various field portable spectrometers manufactured by Analytical Spectral Devices have allowed data collection three times faster than PIMA, not only from core, chips, and pulps, but also remotely from outcrops, road cuts, trenches and open pit walls. CSIRO's lab-based hyperspectral systems Hylogger and Hychipper operate automatically and spectrally image over 700m of core/day and analyze up to 2000-3000 RC chip samples/day. A detailed review on these technologies is given by Agar and Coulter (2007, this volume).

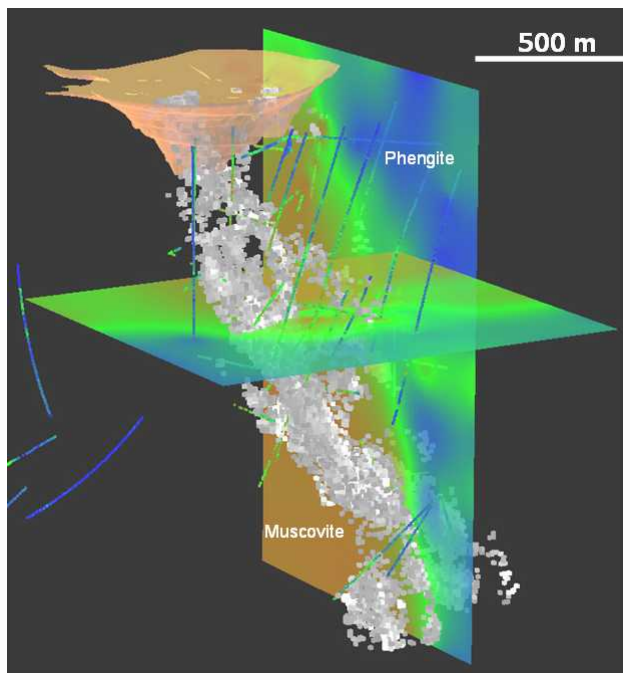
Such technical advances provide improved capability for mapping alteration, structure, lithology and regolith, especially at the district to deposit scales. Spectral-based alteration mapping has helped to construct alteration models for a number deposit types such as HS epithermal and greenstone belt deposits. Such mapping leads to a better definition of the alteration footprint and zoning of mineral assemblages, for example in HS systems where clay minerals are difficult to identify visually (Thompson et al., 1999). This approach also identifies subtle changes in mineral chemistry, especially in white mica (illite-muscovite) and chlorite (AusSpec, 1997), which provide enhanced vectoring capabilities. Furthermore, information on mineral chemistry of white mica and chlorite can be quickly extracted semi-automatically from the spectral data, allowing for routine determination of compositional information (Pontual, 2004).

For example, an integrated Pima, Hylogger, Hychipper, and mineralogical study at Kanowna Belle demonstrated for the first time zoning in mica composition extending for several kilometers outboard of this 7 Moz greenstone deposit in Eastern Goldfield Province, Western Australia (Halley, 2006). This study showed that gold mineralization is spatially associated with the transition zone between the V-bearing phengite and Barich muscovite (Figure 13). Similar zoning patterns, of similar spatial extent, have also been documented at other gold deposits in greenstone belts such as at St. Ives and Wallaby, in Western Australia and in the Timmins camp, in the Abitibi (Halley, 2006). Airborne hyperspectral systems such as Hymap have successfully mapped such mineral compositional zoning over large areas (Cudahy et al, 2000).



Spectral based mineral composition mapping provides new vectoring tools within large hydrothermal systems, and extends the alteration footprint beyond previously recognized limits. Such larger alteration footprint and enhanced mineral vectoring capabilities allow for a lower density of drilling for camp scale targeting, and particularly under cover.

The most commonly used regional to district scale alteration mapping tool in recent years has been ASTER. With this tool, geologists are able to quickly acquire useful surface mineralogical information for mapping alteration, lithology and structure, with more mineralogical resolution than was possible using the older Landsat TM imagery. In contrast to Landsat "FeOx - Clay" anomalies, the improved spectral resolution of the ASTER system allows recognition of specific alteration minerals and mineral groups. With critically positioned bands across the visible, near infrared, shortwave infrared, and thermal infrared regions, the spectral signatures from advanced argillic alteration, argillic alteration, and silicification associated with HS systems can readily be differentiated (Rowan et al, 2003). Through enhanced calibration, based on field data or on hyperspectral data such as Hyperion, ASTER may successfully map illite and illite-smectite alteration associated with low sulfidation epithermal systems (Zhou, 2005) and phyllic alteration in porphyry systems (Mars and Rowan, 2007). In addition, the thermal infrared (TIR) bands of ASTER allow mapping of silica and/or quartz abundance and lithology (Rowan and Mars, 2003).

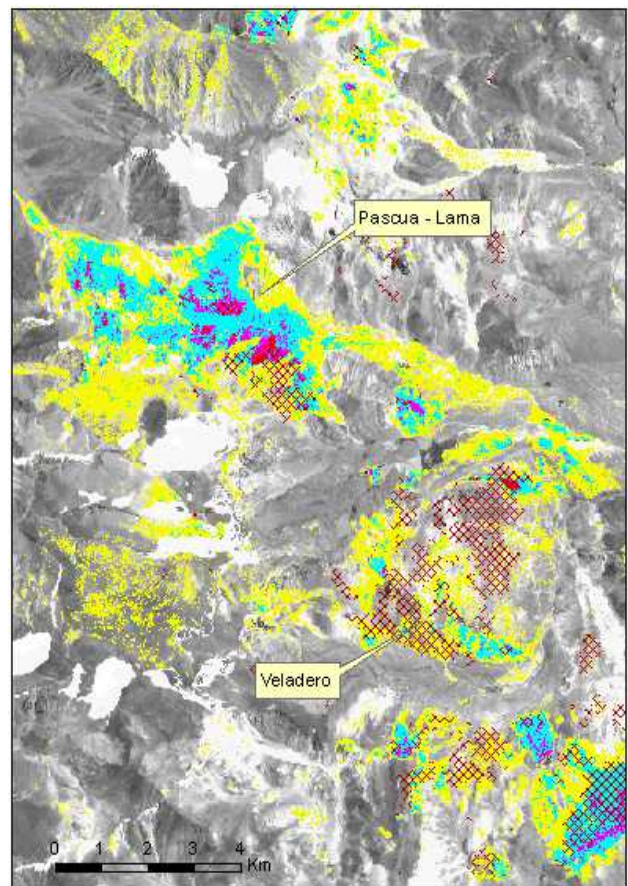


**Figure 13:** 3D model of gold mineralization (grey) and white mica chemistry (blue is phengitic, brown is muscovitic) at Kanowna Belle, Eastern Goldfields, Australia. Looking ENE. From Halley (2006)

Since its launch in 1999, ASTER has proven to be most effective in mapping exposed high sulfidation systems at district-regional scales in arid, semi-arid, and to less extent, vegetated terrains around the world. An example can be drawn

from the Pascua-Lama and Veladero world class HS epithermal deposits in Chile. Aster mapping clearly identifies the centers of silicification and advanced argillic alteration, and outboard to argillic alteration associated with these HS deposits (Figure 14). From a regional exploration point of view, such alteration information allows target prioritization and can efficiently guide field mapping and sampling.

However, like with any other technology, Aster has its limitations. For gold exploration, the 90 meter spatial resolution for the TIR bands is still a limiting factor for mapping silicification associated with quartz vein and stockwork style silicification in low sulfidation deposits, greenstone belt deposits and intrusion related deposits. Further more, Aster may not necessarily differentiate lithology related quartz vs. hydrothermal silicification; or hypogene advanced argillic alteration from steam heated alunite in high sulfidation systems or from supergene alunite in porphyry systems. As pointed out previously, calibration issues also hamper Aster mapping for white mica and white mica chemistry.



**Figure 14:** Aster alteration map of the Pascua Lama-Veladero district, Chile. Intense alunite alteration at the core of the system is shown in red to magenta, grading out to argillic alteration in cyan and yellow. Silicification is shown in dark red hatch.

## 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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