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GEOLOGICAL CLASSIFICATION OF CANADIAN GOLD DEPOSITS

K.H. Poulsen, F. Robert, and B. Dubé

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Cover illustration

This intriguing pair of specimens from the Dome mine at Timmins, Ontario clearly shows the marks where the steel drill bit cut into the gold and quartz. The drill bit became plugged with gold, making it inoperable. Dome Mines Ltd. presented these to the Royal Ontario Museum in 1958. Photograph by Calvin Nicholls. ©Earth Science Department, Royal Ontario Museum

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GEOLOGICAL CLASSIFICATION OF CANADIAN GOLD DEPOSITS

Abstract

Classifications of ore deposits provide essential frameworks for designing exploration strategies, evaluating prospects, and performing resource assessments of selected areas. This paper proposes a geological classification of lode gold deposits, based largely on the nature of the ore and on the geological settings of the deposits. Sixteen common types of bedrock gold deposits are distinguished and their main geological attributes summarized. They do not correspond to an equal number of genetic types: many of these deposit types represent different components of larger hydrothermal systems and are genetically related. An important emerging point is that the majority of lode gold deposit types identified here are represented by at least one large example (>100 t Au); the search for large gold deposits must therefore rely on a multiplicity of models.

Résumé

Les classifications de gites minéraux constituent un cadre essentiel pour élaborer des campagnes d'exploration, évaluer les prospects et évaluer le potentiel minéral de régions choisies. Ce document propose une classification géologique des gîtes d'or primaires qui s'appuie principalement sur la nature de la minéralisation et sur le cadre géologique du gîte. Seize types de gîtes d'or encaissés dans le substratum rocheux sont ainsi définis et un sommaire de leurs principales caractéristiques géologiques est présenté. Ces types ne correspondent pas à un nombre équivalent de modèles génétiques : plusieurs types de gîtes identifiés représentent des composantes distinctes de systèmes hydrothermaux de plus grande dimension et sont apparentés génétiquement. Un point important mis à jour est que la majorité des types de gîtes d'or primaires ainsi définis sont représentés par au moins un exemple (>100 t d'or); conséquemment, la recherche de gros gîtes doit tenir compte d'une multiplicité de modèles.

SUMMARY

Classification of ore deposits is much more than a textbook exercise: it provides an essential framework for resource-assessment studies, for designing exploration strategies (e.g. what type of deposit to look for, where, and how?), and for evaluating prospects. In particular, there is a need for a coherent classification of gold deposits that takes into account massive amounts of new information resulting from the renewed focus on gold mining and exploration in the last 15 to 20 years. The main objectives of this report are to review the geology of significant Canadian gold deposits in light of commonly accepted models for gold deposits, and to propose a scheme for their geological classification.

This report is restricted to bedrock gold deposits, also commonly referred to as 'lode' gold deposits. Deposits considered to be 'gold deposits' in the context of this report are those that contain more than 1 t of gold, that are composed mostly of material grading greater than 1 g/t gold, and in which the value of contained gold exceeds that of co-commodities.

Contrasting classifications have been arrived at historically depending on whether they were approached from genetic, geochemical, economic, or tectonic points of view (Emmons, 1937; Boyle, 1979; Cox and Singer, 1986; Bache, 1987). Despite the diversity of approaches to gold deposit classification and the problems associated with each, there are three important unifying aspects to all classification schemes. First, there is a recognition that there are a finite number of well known gold deposit types. The actual number is not fixed, but is in the range of 8 to 20. Second, some deposit types (e.g. skarns, paleoplacers) are recognized universally and differ only in name from scheme to scheme. Third, attached to each deposit type is some form of model to distinguish it from other types.

The classification presented is first and foremost *geological* in scope. It is based mainly, but not exclusively, on the nature and mesoscopic attributes of the ore, and on the geological settings of the deposits: genetic connotations are secondary. Different deposit 'types' need not correspond to distinct genetic types of deposits and may have formed by similar processes. In addition, individual deposits may possess characteristics, to different degrees, of more than one deposit type, so that the classification scheme is not meant to rigidly 'pigeon-hole' deposits. It is better used to illustrate the diversity of types of lode gold deposits that can be encountered in a particular geological environment. It can also be used as a tool to assess the nature, significance, or potential of a showing or a prospect, even at an early stage of an exploration or drilling program, because it is based on information that is generally available or easily obtainable.

SOMMAIRE

La classification des gîtes d'or n'est pas un exercice de style. Elle constitue le cadre essentiel à toute étude portant sur l'estimation des ressources, sur la conception de stratégies d'exploration (comme, par exemple, la détermination du type de gîte recherché, le lieu où il se situe et les méthodes d'exploration) et sur l'évaluation des prospects. Il existe en premier lieu la nécessité de classer les gîtes d'or avec cohérence en tenant compte de la masse de nouvelles données fournies par le regain d'intérêt dans l'exploration et l'exploitation de l'or ces 15 à 20 dernières années. Le présent rapport a pour principaux objectifs de passer en revue la géologie des gîtes d'or importants du Canada à la lumière de modèles de gîtes d'or généralement reconnus et de proposer une classification basée sur leurs caractéristiques géologiques.

Le présent ouvrage porte uniquement sur les gîtes d'or encaissés dans le substratum rocheux, appelés communément «gîtes d'or primaires». Dans le cadre de ce rapport, on entend par gîtes d'or les gîtes renfermant plus d'une tonne d'or composé principalement de minerai dont la teneur est supérieure à 1 g/t d'or et dont la valeur de l'or contenu excède celle des autres matières premières associées.

Dans le passé, certains chercheurs ont proposé des classifications divergentes selon qu'elles étaient basées sur des données génétiques, géochimiques, économiques ou tectoniques (Emmons, 1937; Boyle, 1979; Cox et Singer, 1986; Bache, 1987). Malgré la diversité des méthodes de classification utilisées et les problèmes qui en découlent, ces diverses classifications ont trois éléments en commun. En premier lieu, leurs auteurs admettent généralement que le nombre de types de gîtes d'or notoirement connus est limité. Leur nombre actuel n'est pas fixe; il se situe entre 8 à 20. En second lieu, certains types de gîtes (comme les skarns et les paléoplacers) sont universellement reconnus et seule leur désignation diffère d'une classification à une autre. Enfin, à chaque type de gîte se rattache un modèle quelconque qui le différencie de tous les autres types.

La classification présentée dans le présent ouvrage est essentiellement d'ordre *géologique*. Elle est fondée principalement, mais non exclusivement, sur la nature et les propriétés mésoscopiques du minerai, ainsi que sur les cadres géologiques des gîtes. Les caractéristiques génétiques sont accessoires. Ainsi, les divers types de gîtes ne présentent pas forcément des caractéristiques génétiques distinctes et peuvent avoir été formés par des processus similaires. En outre, un gîte peut posséder, à divers degrés, des traits caractéristiques de plus d'un type. Par conséquent, un système de classification ne doit pas être conçu dans l'optique de «cataloguer» rigoureusement les gîtes. Il est utilisé à meilleur escient s'il illustre la diversité des types de gîtes d'or primaires susceptibles d'être présents dans un cadre géologique particulier. On peut également s'en servir comme outil d'évaluation afin de définir la nature, l'importance ou le potentiel d'un indice ou d'un prospect même dès la première phase de travaux d'exploration ou d'un programme de sondage, car il est fondé sur des données disponibles ou pouvant être facilement obtenues.

Gold deposit types

Sixteen well established gold deposit types can be considered to be of potential importance in Canada. Brief summary descriptions and discussions of each of these deposit types based on the authors' observations and a review of selected literature are presented.

The main points that emerge from this compilation of the characteristics of these deposit types are as follows:

1. The combination of geological environment, host rocks, nature of the mineralization, and hydrothermal alteration is unique for almost every deposit type. These geological attributes should represent the important discriminating criteria used in practical application of a deposit-classification scheme.
2. The deposit types have likely formed over a wide range of crustal depths in a variety of geological environments. Most of those thought to have formed in shallow to moderately deep crustal environments are commonly considered to be components (proximal or distal) of larger, intrusion-centred systems. These deposits have formed at convergent plate margins during plutonism and volcanism, marking stages of magmatic-arc development. Deposits formed at deeper crustal levels are generally considered to also have formed at convergent plate margins, but rather during deformation related to accretion and collision.
3. Despite the large number of geological types of deposits, it is clear that many of them correspond to different components of large, district-scale, hydrothermal systems and are in fact genetically related. This is the case for porphyry, skarn, breccia-pipe, carbonate-replacement, and high-sulphidation types of deposits, which are generally regarded as components of large, intrusion-centred hydrothermal systems (Sillitoe, 1991a). Other deposit types may also be related to similar magmatic-hydrothermal systems, but their exact links are less well understood; this is the case for sediment-hosted micron gold, gold-copper, sulphide-rich vein, low-sulphidation, and submarine gold-rich massive-sulphide deposits.
4. Most types of lode gold deposits have at least one known world-class example (i.e. >100 t of contained Au), and several types have truly giant examples (i.e. >500 t Au) illustrating the point that large lode gold deposits are of many different geological types and they occur in different geological environments.

Types de gîtes d'or

Au Canada, seize types de gîtes d'or bien définis pourraient receler un potentiel important. Chaque type de gîte présenté est décrit brièvement et étudié à partir des observations des auteurs. Une documentation sélective pertinente est également passée en revue.

La compilation des caractéristiques des divers types de gîtes étudiés a fait ressortir les principaux points suivants :

1. Presque chaque type de gîte présente une combinaison cadre géologique, roches hôtes, nature de la minéralisation et altération hydrothermale qui lui est propre. Ces caractéristiques géologiques devraient constituer les principaux critères discriminatoires utilisés dans la mise en application d'une classification des gîtes.
2. Les divers types de gîtes se sont vraisemblablement formés à diverses profondeurs dans la croûte et dans des milieux géologiques différents. La plupart des gîtes qui se sont développés vraisemblablement dans des milieux peu profonds ou modérément profonds sont reconnus généralement comme étant des composantes proximales ou distales de systèmes plus importants reliés à un centre intrusif. Ils se sont formés aux frontières de plaques convergentes au cours d'épisodes plutoniques et volcaniques marquant des étapes de formation d'arcs magmatiques. Les gîtes qui se sont développés à plus grande profondeur dans la croûte se seraient également formés aux frontières de plaques convergentes, mais au cours d'une période de déformation liée à des phénomènes d'accrétion et de collision.
3. S'il existe de nombreux types géologiques de gîtes, bon nombre d'entre eux correspondent, de toute évidence, à diverses composantes de vastes systèmes hydrothermaux qui se sont mis en place à l'échelle d'un district et sont, en réalité, génétiquement associés. Ces types comprennent le type porphyrique, le type skarn, le type cheminée bréchique, le type à remplacement de roches carbonatées et le type épithermal acide. Ils sont généralement considérés comme étant des composantes de vastes systèmes hydrothermaux associés à un centre intrusif (Sillitoe, 1991a). D'autres types de gîtes, comme les gîtes dont l'or, de la taille du micron, est disséminé dans des roches sédimentaires, les gîtes d'or et de cuivre, les gîtes filoniens riches en sulfures, les gîtes épithermal neutre et les gîtes de sulfures massifs sous-marins riches en or, peuvent également être associés à des systèmes hydrothermaux magmatiques similaires. Cependant, leurs liens exacts avec ces systèmes ne sont pas très bien connus.
4. Pour la plupart des types de gîtes d'or primaires, il existe au moins un exemple de gîte de niveau mondial (renfermant plus de 100 t d'or contenu) et pour plusieurs types, il existe des exemples de gîtes immenses (contenant plus de 500 t d'or), ce qui confirme l'énoncé selon lequel les grands gîtes d'or primaires présentent une pluralité de types et de milieux géologiques.

Canadian gold deposit types

Gold deposits are distributed throughout the major orogenic belts of Canada. The most important ones occur in the Archean cratons of the Canadian Shield with fewer, and in most cases smaller, deposits in Proterozoic and Phanerozoic terranes. Selected gold deposits representing the major metallogenic epochs and major gold-bearing terranes in Canada are treated equally and are compared against the standard global gold deposit types identified.

Canadian Archean terranes contain an estimated 8125 t of gold, accounting for approximately 80% of the country's production and reserves. Archean gold deposits are largely restricted to the Superior and Slave provinces. The largest concentration of deposits occurs in the southern Superior Province. In both provinces, gold deposits are hosted mainly by supracrustal sequences and coeval intrusions. The majority of them occur within, or immediately adjacent to, greenstone belts, commonly in spatial association with crustal-scale fault zones marking major lithological boundaries (Card et al., 1989; Poulsen et al., 1992). Only a few deposits, such as those in central Slave Province, are hosted by sedimentary sequences (Padgham, 1992). The majority of deposits contain between 400 000 and 10 000 000 t of ore at grades between 4 and 12 g/t Au, corresponding to 3 to 100 t of contained gold, but 14 deposits contain more than 100 t of gold and are regarded as 'world class'.

A description summarizing key geological elements of several significant Canadian Archean gold deposits is presented. It emphasizes the timing relationships of mineralization to other geological events (deformation, metamorphism, etc.) and current genetic models are discussed, based both on the work of others, on the authors' own observations, and, where appropriate, on comparisons with the globally recognized deposit types described in the previous section, 'Gold Deposit Types'. The deposits are described in an order that reflects similarities among deposits and a range of ore styles from quartz vein, to disseminated sulphide, to massive sulphide. Quartz-vein-type deposits are further grouped according to their lithological settings (i.e. volcanic-hosted, sediment-hosted, and intrusion-centred quartz-vein arrays).

Although Archean gold deposits are dominant in the Canadian Shield, significant examples of Early Proterozoic deposits are present in the Churchill and Grenville provinces. Most of these deposits occur in the 1850–1800 Ma Trans-Hudson Orogen. The settings and types of Canadian Proterozoic gold deposits are generally similar to those of their Archean counterparts, with the exception that the Proterozoic examples are commonly found in rocks of the amphibolite facies rather than in the greenschist facies that so predominates the Archean gold belts.

Types de gîtes d'or au Canada

Les gîtes d'or sont répartis dans les principales ceintures orogéniques du Canada. Les plus importants se trouvent dans les cratons archéens du Bouclier canadien et quelques-uns, la plupart plus petits, se rencontrent dans les terranes protérozoïques et phanérozoïques. Les gîtes d'or sélectionnés représentant les grandes époques métallogéniques et les principaux terranes aurifères du Canada sont traités sur le même pied et sont comparés aux types de gîtes d'or connus à l'échelle planétaire.

Selon les estimations, les terranes archéens du Canada renferment 8 125 t d'or, ce qui correspond à environ 80 p. 100 de la production et des réserves du pays. Les gîtes d'or de l'Archéen sont pour la plupart situés dans les provinces du lac Supérieur et des Esclaves. La plus grande concentration de gîtes se trouve dans la partie méridionale de la Province du lac Supérieur. Dans l'une et l'autre province, les gîtes sont inclus principalement dans des séquences supracrustales et des intrusions contemporaines. La plupart se trouvent au contact de ceintures de roches vertes ou à l'intérieur de celles-ci. Ils sont généralement en association spatiale avec des zones de failles à l'échelle de la croûte terrestre qui définissent des frontières lithologiques majeures (Card et al., 1989; Poulsen et al., 1992). Seuls quelques gîtes, dont ceux de la partie centrale de la Province des Esclaves, sont encaissés dans des séquences de roches sédimentaires (Padgham, 1992). La majorité des gîtes contiennent entre 400 000 et 10 000 000 t de minerai dont la teneur varie de 4 à 12 g/t Au, soit de 3 à 100 t d'or contenu. Cependant, 14 gîtes renferment plus de 100 t d'or et sont considérés comme étant de «niveau mondial».

Une description sommaire énumère les principaux éléments géologiques de plusieurs grands gîtes d'or archéens du Canada. Elle fait ressortir les relations chronologiques entre la minéralisation et d'autres événements géologiques (tels que la déformation et le métamorphisme) et présente les modèles génétiques actuels en faisant référence aux travaux d'autres auteurs et à nos propres observations et, le cas échéant, en établissant des comparaisons avec des types de gîtes connus à l'échelle planétaire décrits dans la section intitulée *Gold deposit types*. Les gîtes sont décrits selon un ordre qui met en évidence leurs similarités et un éventail de styles de minéralisation allant des filons de quartz aux sulfures disséminés et aux sulfures massifs. Les gîtes de type filons de quartz sont ensuite regroupés en fonction de leurs cadres lithologiques (c.-à-d. filons encaissés dans des roches volcaniques ou sédimentaires et réseau de filons de quartz associés à un centre intrusif).

Bien que les gîtes d'or archéens soient dominants dans le Bouclier canadien, d'importants gîtes du Protérozoïque précoce sont présents dans les provinces de Churchill et de Grenville. La plupart d'entre eux se sont formés lors de l'orogène trans-hudsonien il y a entre 1850 et 1800 Ma. Au Canada, les cadres et les types de gîtes d'or du Protérozoïque sont généralement similaires à leurs homologues de l'Archéen, si ce n'est que les gîtes du Protérozoïque se rencontrent plus souvent dans les roches du faciès des amphibolites que dans les roches du faciès des schistes verts omniprésentes dans les zones aurifères de l'Archéen.

Although there has been production of historic interest, the Appalachian Orogen accounts for only a small percentage of Canadian gold endowment. Most significant are Hope Brook in the Avalon Terrane, Newfoundland; a cluster of deposits associated with an ophiolitic suture at Baie Verte, Newfoundland; and the turbidite-hosted veins of the Meguma Terrane, Nova Scotia. The gold deposits at each of these localities are of different geological types and ages, and related to different tectonic events in the Orogen, ranging from Late Proterozoic arc development in the Avalon to Devonian granitic magmatism in the Meguma Terrane.

Although small compared to the two main Archean cratons, gold production from the Cordilleran Orogen is third among major geological domains in Canada. Because the geological terranes of the Canadian Cordillera are natural extensions of adjacent geological units in the United States, gold deposits within them are most comparable to many well known deposit types that characterize the western United States. As in the American segment of the Cordillera, Mesozoic gold deposits in Canada occur both in the miogeoclinal rocks and in accreted volcanic-arc and oceanic terranes, whereas Tertiary deposits are superimposed on both continental and accreted crust.

Examination of the geological characteristics of Canadian hydrothermal gold deposits reveals a significant diversity in style of mineralization and timing of emplacement that requires consideration of multiple models. The different styles of mineralization represented by Archean and Proterozoic deposits in Canada include, in approximate order of decreasing importance (number of deposits), the following: quartz-carbonate veins related to shear zones and folds (Dome, Pamour, Hollinger–McIntyre, San Antonio, Kerr Addison, Kirkland Lake, Sigma–Lamaque, Con–Giant, parts of Lupin, Meliadine); zones of disseminated sulphide minerals±stockworks around porphyry bodies (Hemlo, Malartic, Harker–Holloway); massive-sulphide lenses (Horne, Bousquet No. 2–LaRonde, parts of Lupin, Montauban); sulphide-rich veins, stockworks, and disseminated sulphide minerals (Doyon, Bousquet No. 1); carbonate±quartz veins (Campbell–A.W. White); and disseminated sulphide minerals in vuggy silica (Hope Brook). The first of these styles typifies what most authors consider to be 'mesothermal' vein deposits (*see* Hodgson, 1993); the rest, however, have little in common with such vein deposits and rather, are compatible with totally different origins. Some deposits combine more than one style of mineralization of a single or different ages: quartz-carbonate veins overprinting copper-molybdenum±gold stockwork sulphide minerals at Hollinger–McIntyre, and quartz veins and massive-sulphide layers at Lupin. The presence of auriferous sulphide clasts in Timiskaming Group conglomerate at Dome and Pamour (Hutchinson, 1993) provides further evidence for multiple stages of gold mineralization in some deposits.

Bien que l'orogène des Appalaches ait été le siège de productions historiques, elle ne représente qu'un infime pourcentage de la richesse en or du Canada. Les gîtes les plus significatifs sont ceux de Hope Brook dans le terrane d'Avalon, à Terre-Neuve, un groupe de gîtes associés à une suture ophiolitique à Baie Verte, également à Terre-Neuve, et les filons encaissés dans des turbidites dans le terrane de Meguma, en Nouvelle-Écosse. Dans ces régions, les gîtes d'or sont d'une variété de types et d'âges. Ils sont associés à des événements tectoniques différents dans l'orogène, allant à la formation d'arcs au Protérozoïque tardif, dans le terrane d'Avalon, au magmatisme granitique au Dévonien, dans le terrane de Meguma.

La production d'or de l'orogène de la Cordillère, bien que petite comparativement à celle des deux principaux cratons de l'Archéen, se classe troisième parmi les principaux domaines géologiques du Canada. Les terranes géologiques de la Cordillère canadienne étant les prolongements naturels des unités géologiques limitrophes situées aux États-Unis, les gîtes d'or qui s'y trouvent sont pour la plupart comparables à de nombreux types de gîtes connus caractérisant la partie occidentale des États-Unis. Tout comme dans la partie américaine de la Cordillère, les gîtes d'or du Mésozoïque au Canada se trouvent à la fois dans des roches miogéoclinales et dans des terranes d'arc volcanique d'accrétion et des terranes océaniques, alors que les gîtes du Tertiaire sont superposés à la croûte continentale et à la croûte d'accrétion.

L'examen des caractéristiques géologiques des gîtes d'or hydrothermaux canadiens met en évidence une diversité remarquable de styles de minéralisation et de chronologie de mise en place qui nécessitent la prise en considération de multiples modèles. Les divers styles de minéralisation représentés par les gîtes de l'Archéen et du Protérozoïque sont, dans un ordre d'importance décroissant approximatif (nombre de gîtes), les suivants : filons de quartz-carbonates associés à des plis et à des zones de cisaillement (Dome, Pamour, Hollinger–McIntyre, San Antonio, Kerr Addison, Kirkland Lake, Sigma–Lamaque, Con–Giant, parties de Lupin, Meliadine); zones de sulfures disséminés ± stockwerks adjacent à des massifs porphyriques (Hemlo, Malartic, Harker–Holloway); lentilles de sulfures massifs (Horne, Bousquet n° 2–La Ronde, parties de Lupin, Montauban); filons riches en sulfures, stockwerks et sulfures disséminés (Doyon, Bousquet n° 1); carbonates avec ou sans filons de quartz (Campbell–A.W. White); sulfures disséminés dans de la silice résiduelle vacuolaire (Hope Brook). Le premier de ces styles est caractéristique de ce que la plupart des auteurs qualifient de gîtes filoniens «mésothermaux» (*voir* Hodgson, 1993); les autres styles ont cependant peu de chose en commun avec ce type de gîte et sont compatibles avec des gîtes d'origines complètement différentes. Certains gîtes comportent plus d'un style de minéralisation d'un seul âge ou de divers âges, tels les filons de quartz-carbonates superposant des stockwerks à sulfures et cuivre-molybdène±or (Hollinger–McIntyre) et les couches de sulfures massifs et de filons de quartz (Lupin). La présence de clastes de sulfures aurifères dans le conglomérat du Groupe de Timiskaming aux gisements de Dome et de Pamour (Hutchinson, 1993) constitue une indication additionnelle que la minéralisation aurifère s'est effectuée en multiples étapes dans certains gîtes.

The diversity of styles of mineralization among deposits also correlates with differences in composition of ore (Au:Ag ratios and metal associations), in associated hydrothermal alteration, and in lithological or structural associations. Differences in hydrothermal alteration are particularly important: the spectrum of such highly contrasted types of alteration as carbonatization-sericitization at many quartz-carbonate vein deposits, K-feldspar alteration at Hemlo, aluminous alteration (advanced argillic) at Bousquet, and massive silicic alteration at Hope Brook, require that different types of hydrothermal fluids be involved in the formation of these deposits. This conclusion is also consistent with significant differences in composition of the ores.

Furthermore, deposits corresponding to the different styles of mineralization have formed at different stages in the evolution of their host terranes. For example, massive-sulphide lenses at Horne, sulphide-rich veins at Doyon and Bousquet No. 2–LaRonde, carbonate-chert veins at Campbell–A.W. White, and disseminated sulphide minerals at Hemlo all predate the main stage(s) of deformation. They likely formed during stages of *construction* of volcano-plutonic edifices, at relatively shallow crustal depths. In contrast, shear-zone-related quartz-carbonate veins have formed later in the tectonic evolution, either during D_2 at Sigma–Lamaque and San Antonio, or after post-D_2 folding of fluvial-alluvial sedimentary rocks at Dome, Pamour, Kirkland Lake, and Kerr Addison. Such quartz-carbonate vein deposits have formed during stages of *deformation* of volcano-plutonic edifices, in deeper crustal environments (Hodgson, 1993).

The geological attributes of many Archean and Proterozoic gold deposits in Canada point to a significant diversity among these deposits and several models have been proposed for Precambrian gold deposits in general. A number of authors emphasize deep sources of gold and fluids, and deposition of gold in a continuum of crustal levels (Colvine, 1989; Cameron, 1993; Groves et al., 1995), although there is considerable debate as to whether the ore fluids are ultimately of magmatic (Spooner, 1991) or metamorphic (Kerrich and Cassidy, 1994) origin. On the other hand, other authors have suggested that most, if not all, Archean gold deposits have a shallow-crustal magmatic origin and have merely been buried to be deformed at different crustal levels (Mason, 1992; Mason and Helmstaedt, 1992). Multistage models have also been proposed, with the common concept that gold is recycled either from early formed, perhaps subecononmic gold deposits (Hutchinson, 1993) or from gold-rich district-scale reservoirs that resulted from earlier increments of gold enrichment (Hodgson, 1993). Each of those models has merit and is certainly applicable to specific deposits, or groups of deposits. In many cases, however, the models have been portrayed as accounting for most, if not all, Archean and Proterozoic gold deposits, reflecting a unifying approach deemed too restrictive given the diversity of deposit types documented here.

La diversité des styles de minéralisation d'un gîte à un autre est en corrélation également avec les différences dans la compositions du minerai (rapports Au/Ag et associations de métaux), dans l'altération hydrothermale associée et dans les associations lithologiques ou structurales. Les différences dans l'altération hydrothermale sont particulièrement importantes : une gamme aussi contrastée de types d'altération que la carbonatation et la séricitation dans de nombreux gîtes de filons de quartz-carbonates, l'altération en feldspath potassique (Hemlo), l'altération alumineuse (argileuse acide) (Bousquet) et l'altération en silice massive (Hope Brook), implique nécessairement que divers types de fluides hydrothermaux ont joué un rôle dans la formation de ces gîtes. Cette conclusion est également cohérente avec les différences significatives constatées dans la composition des minerais.

En outre, les gîtes correspondant aux divers styles de minéralisation se sont formés à différentes étapes dans l'évolution de leurs terranes encaissants. Ainsi, les lentilles de sulfures massifs au gisement de Horne, les filons riches en sulfures aux gisements de Doyon et de Bousquet n° 2–La Ronde, les filons de carbonates-chert aux gisements de Campbell–A.W. White et les sulfures disséminés au gisement de Hemlo sont tous antérieurs aux principaux épisodes de déformation. Ils se sont vraisemblablement formés au cours des étapes de *construction* des édifices volcano-plutoniques, à des profondeurs relativement faibles dans la croûte. À l'opposé, les filons de quartz-carbonates associés à des zones de cisaillement se sont développés plus tard au cours de l'évolution tectonique, soit durant la déformation D_2 aux gisements de Sigma–Lamaque et de San Antonio, soit après le plissement postérieur à la déformation D_2 des roches sédimentaires alluviales et fluviatiles aux gisements de Dome, de Pamour, de Kirkland Lake et de Kerr Addison. De tels gîtes de filons de quartz-carbonates se sont formés au cours des étapes de *déformation* des édifices volcano-plutoniques, à de plus grandes profondeurs dans la croûte (Hodgson, 1993).

Au Canada, les caractéristiques géologiques de nombreux gîtes d'or de l'Archéen et du Protérozoïque font ressortir une importante diversité entre ces gîtes. Plusieurs modèles ont été proposés pour illustrer les gîtes d'or du Précambrien. Un certain nombre d'auteurs mettent l'accent sur les sources profondes de l'or et des fluides et la mise en place de l'or dans un continuum de niveaux crustaux (Colvine, 1989; Cameron, 1993; Groves et al., 1995). Cependant, il existe une grande controverse à savoir si les fluides minéralisateurs sont d'origine magmatique (Spooner, 1991) ou métamorphique (Kerrich et Cassidy, 1994). En outre, selon d'autres auteurs, la plupart, sinon la totalité des gîtes d'or de l'Archéen sont d'origine magmatique, se sont formés à de faibles profondeurs dans la croûte et ont tout simplement été enfouis et déformés à divers niveaux de profondeur dans la croûte (Mason, 1992; Mason et Helmstaedt, 1992). Des modèles à étapes multiples ont également été proposés selon le concept communément admis que l'or est recyclé à partir de gîtes d'or, possiblement subéconomiques, de formation plus ancienne (Hutchinson, 1993) ou à partir de réservoirs riches en or de l'échelle d'un district, provenant d'un enrichissement antérieur d'or (Hodgson, 1993). Chaque modèle est valable en soi et est sans conteste applicable à des gîtes ou à des groupes de gîtes donnés. Dans de nombreux cas, cependant, les modèles ont été décrits comme englobant la plupart, sinon tous les gîtes d'or de l'Archéen et du Protérozoïque. Ce concept d'unicité est jugé trop restrictif, compte tenu de la diversité des types de gîtes compris dans la présente classification.

As in the older terranes, Canadian Phanerozoic deposits display considerable diversity in setting and style of mineralization. There has been a tendency to divide these deposits into 'epithermal' and 'mesothermal' groups (Nesbitt et al., 1986), and further to recognize that there are transitional types between these two extremes (Panteleyev, 1991). There is also a natural tendency to compare the gold metallogeny of the Canadian segment of the Cordillera and Appalachians with that of the United States to the south (e.g. Poulsen, 1996). The geological history of the Cordillera records accretion of arc terranes in the Late Paleozoic and Mesozoic to the western miogeoclinal margin of North America, and that of the Appalachians records accretion of Late Proterozoic and Early Paleozoic terranes to the eastern miogeocline. In both cases, the high-level epithermal groups of deposits are either pre- or post-collisional, whereas the mesothermal deposits tend to be related more closely with compressional deformation.

Classification scheme for gold deposits

There are recurring parameters that geologists have used for decades in attempts to apply their particular classification schemes. These include geological environment, host rocks, ore types, and hydrothermal signatures as expressed by ore and alteration mineralogy and chemistry. These parameters have therefore been used to construct a logical 'decision tree' or classification chart to explain how the globally recognized deposit types can be distinguished from one another. The classification scheme relies on four of the time-honoured parameters which geologists instinctively take into consideration when studying gold deposits: 1) Are the supracrustal rocks in and around the deposit mainly volcanic or sedimentary, and to what major tectonic environment can they be assigned? 2) What is the main host for ore? 3) What is the form of the ore? 4) What is the hydrothermal signature of the deposit as expressed by chemical composition and mineralogy of both ore and hydrothermal alteration products? Despite the limitations of each of these parameters, they can be combined in such a way as to illustrate how the commonly recognized types of gold deposits can be distinguished from one another even though they were defined at different times using different principles.

The classification chart, as constructed, reflects the following aspects of gold deposits:

1. Deposits are arranged into 'clans' on the basis of the broadly defined tectonic environments represented by the host rocks. Thus, terms like 'intrusion-related', 'epithermal', and 'greenstone gold' all retain a meaning in that they refer to a group of deposit types, possibly genetically related, that reflect a particular environment.

Tout comme dans les terranes plus anciens, les gîtes phanérozoïques du Canada présentent une pluralité considérable de milieux et de styles de minéralisation. Certains auteurs ont eu tendance à les répartir en groupes «épithermaux» et «mésothermaux» (Nesbitt et al., 1986) et à admettre par la suite qu'il existe des types transitionnels entre ces deux extrêmes (Panteleyev, 1991). Certains chercheurs sont portés tout naturellement à établir une comparaison entre la métallogénie de l'or de la portion canadienne de la Cordillère et des Appalaches et celle des États-Unis au sud (p. ex. Poulsen, 1996). L'histoire géologique de la Cordillère fait état d'une accrétion des terranes d'arc au cours du Paléozoïque tardif et du Mésozoïque sur la marge miogéoclinale occidentale de l'Amérique du Nord alors que l'histoire des Appalaches comporte une accrétion des terranes du Protérozoïque tardif et du Paléozoïque précoce sur le miogéoclinal oriental. Dans les deux cas, les groupes de gîtes épithermaux de haut niveau sont antérieurs ou postérieurs à la collision, alors que les gîtes mésothermaux sont généralement associés plus étroitement à la déformation par compression.

Classification des gîtes d'or

Les géologues ont utilisé, pendant des décennies, des paramètres récurrents dans une tentative de mettre en application certaines classifications. Ces paramètres sont, entre autres, le cadre géologique, les roches hôtes, les divers types de minerai et les signatures hydrothermales telles que présentées par la minéralogie et la composition chimique des minerais et des produits d'altération. Par conséquent, ces paramètres ont été utilisés pour ériger une «structure arborescente» logique ou un diagramme de classification expliquant comment différencier les divers types de gîtes reconnus à l'échelle planétaire. Cette classification se fonde sur quatre paramètres immuables que les géologues prennent d'instinct en considération lorsqu'ils étudient les gîtes d'or : (1) Les roches supracrustales se trouvant dans ou autour du gîte sont-elles principalement volcaniques ou sédimentaires et à quel principal cadre tectonique peut-on les associer? (2) Quelle est la principale roche hôte du minerai? (3) Quelle est la forme du minerai? (4) Quelle est la signature hydrothermale du gîte exprimée par la composition chimique et la minéralogie du minerai et des produits d'altération hydrothermale? Malgré les limites de ces paramètres, ils peuvent être regroupés de telle sorte que l'on peut démontrer comment des types de gîtes d'or communément reconnus peuvent être différenciés les uns des autres même s'ils ont été définis à diverses époques à l'aide de principes différents.

Dans sa forme actuelle, le diagramme de classification fait ressortir les diverses caractéristiques des gîtes d'or, à savoir :

1. Les gîtes sont disposés en «clans», selon les milieux tectoniques, au sens large, représentés par les roches hôtes. Par conséquent, des termes comme «associé à une intrusion», «épithermal», «or des roches vertes» ont tous un sens en ce qu'ils font tous référence à un groupe de types de gîtes, possiblement apparentés génétiquement et correspondant à un environnement particulier.

2. Although there is an ideal correlation between environments and deposit types, there are some types that can occur across environments. A good example is afforded by porphyry deposits (and possibly skarns) which are well known to occur in both (mainly submarine) island-arc and (mainly subaerial) continental-arc environments.
3. The chart illustrates an element of transition from clan to clan and deposit type to deposit type. Thus the 'intrusion-related' and 'epithermal' clans merge from one into another in that these are groups that are commonly discussed in the same context. Similarly, 'epithermal' deposits are placed in transition to gold-rich volcanogenic massive-sulphide deposits (e.g. Hannington, 1993).

Several problems may be encountered in applying this classification scheme as discussed in Robert et al. (1997). First, it is fully acceptable that some deposits can be classified as being of more than one type, in that the existence of transitional deposit types, such as those found between the epithermal and porphyry environments, has been proposed by several workers (Giggenbach, 1992; Panteleyev, 1996). Second, overprinting of different ore styles, either due to telescoping of distinct components of hydrothermal systems (Sillitoe, 1994), or due to superposition of two or more hydrothermal systems, is documented in a significant number of deposits and may have played a key role in the formation of world-class and giant gold deposits. This may lead to dual classification of the deposit, depending which parameters are emphasized. However, the main problem in deformed and metamorphosed terranes such as greenstone belts is that the primary characteristics of gold deposits may have been largely obscured by overprinting, deformation, and metamorphism to an extent that they are difficult to recognize. For example, a near-surface gold-rich volcanogenic massive-sulphide or epithermal deposit following a normal pressure-temperature-time path will progressively be buried and deformed. The deposit will move successively into the intrusion-related and into the deeper greenstone quartz-carbonate environment before returning along a similar path to its near-surface position following erosion and uplift. During such an evolution at different crustal levels, there is much scope for such a deposit to be modified or superimposed on by other style(s) of mineralization, ending in a complex ore deposit. However, the most fundamental elements to take into account to deal with such complicating factors are 1) basic chronological field relationships, combined with 2) accurate U-Pb geochronology in order to establish the definite chronological evolution between mineralizing event(s) and deformation/metamorphism phase(s).

2. Bien qu'il existe une corrélation idéale entre les milieux et les types de gîtes certains types peuvent être présents dans plusieurs milieux. Ainsi, les gîtes porphyriques (et probablement les skarns) sont présents à la fois dans des milieux (principalement sous-marins) d'arcs insulaires et dans des milieux (principalement subaériens) d'arcs continentaux.
3. Le diagramme met en évidence la présence d'un élément de transition d'un clan à un autre et d'un type de gîte à un autre. Ainsi, le clan «associé à une intrusion» et le clan «épithermal» fusionnent l'un dans l'autre, car ils sont communément présentés dans un contexte identique. De même, les gîtes «épithermaux» sont classés comme étant en transition avec les gîtes de sulfures massifs riches en or associés à des roches volcaniques (p. ex. Hannington, 1993).

Comme le signalent à juste titre Robert et al. (1997), la mise en application de cette classification fait apparaître plusieurs problèmes. Tout d'abord, il est tout à fait acceptable de classer certains gîtes dans plus d'un type. En effet, plusieurs chercheurs ont montré l'existence de types de gîte de transition comme les gîtes qui se sont formés entre les milieux épithermal et porphyrique (Giggenbach, 1992; Panteleyev, 1996). Deuxièmement, la sur impression de différents styles métallogéniques, attribuable soit au télescopage des composantes distinctes des systèmes hydrothermaux (Sillitoe, 1994), soit à une superposition de deux ou plusieurs systèmes hydrothermaux, est vérifiable dans un nombre important de gîtes et a pu joué un rôle clé dans la formation des gîtes d'or immenses et de niveau mondial. Cet état de fait peut conduire à l'élaboration d'une classification double des gîtes en fonction des paramètres retenus. Cependant, le principal problème soulevé par les terranes déformés et métamorphisés, comme les ceintures de roches vertes, réside dans la possibilité que la surimpression, la déformation et le métamorphisme peuvent avoir masqué les caractéristiques primaires des gîtes d'or à tel point qu'il est difficile de les reconnaître. Ainsi, un gîte de sulfures massifs riches en or associés à des roches volcaniques formé à faible profondeur ou un gîte épithermal, qui a suivi un parcours pression-température-chronologie normal, s'enfouira et se déformera progressivement. Il évoluera successivement dans un milieu associé à une intrusion et dans un milieu plus profond de roches vertes à quartz-carbonates avant de revenir dans un milieu superficiel similaire à son milieu d'origine à la suite d'épisodes d'érosion et de soulèvement. Au cours d'une telle évolution à diverses profondeurs dans la croûte terrestre, il y a de fortes chances qu'un tel gîte ait été modifié par d'autres styles de minéralisation ou superposé à d'autres styles de minéralisation pour devenir finalement un gîte complexe. Cependant, les éléments les plus fondamentaux que l'on doit prendre en ligne de compte lorsque l'on est confronté à des facteurs aussi intriqués sont les suivants : (1) les relations chronologiques de base observées sur le terrain associées à (2) une géochronologie U-Pb exacte permettant de définir l'évolution chronologique précise des événements minéralisateurs et des phases de déformation et de métamorphisme.

Conclusion

The proposed classification chart presented provides a first-order way of assessing if a deposit can be ascribed to one of sixteen known types of lode gold deposit or not; i.e. being typical or atypical. If a deposit is identified as being atypical, possible explanations for its atypical character are 1) a hybrid deposit produced by overprinting styles of mineralization; 2) a transitional deposit type with components of more than one type, such as those found between the epithermal and porphyry environments; 3) a deformed and metamorphosed deposit to the extent that its primary characteristics have been obscured; 4) a new geological type of gold deposit.

The task of developing an adequate classification of gold deposits is far from complete. There remains nonetheless an immediate need to categorize deposits for exploration and resource assessment. Despite imperfections in the method, such a classification chart can be used as a template for tackling the problem of identifying the main characteristics of a gold deposit at an early stage of development even if it is poorly exposed or incompletely documented. The chart can also be used to guide the generation of alternative targets in previously explored areas containing conventionally recognized deposits. It could also be used as a starting point for more rigorous analysis of gold deposits using modern digital technology.

Conclusion

La classification proposée se veut être une méthode de premier ordre permettant d’associer un gîte à l’un des seize types de gîtes d’or primaires connus, c’est-à-dire de déterminer si un gîte donné est typique ou atypique S’il est reconnu comme étant atypique, les raisons peuvent en être les suivantes : il peut s’agir (1) d’un gîte hybride produit par des styles de minéralisation surimprimés, (2) d’un type de gîte transitionnel renfermant des composantes d’un ou de plusieurs types de gîtes, tels que les gîtes situés entre les milieux épithermal et porphyrique, (3) d’un gîte ayant subi un déformation et un métamorphisme d’une intensité telle que ses caractéristiques originelles ont été masquées, ou (4) d’un nouveau type géologique de gîte d’or.

L’élaboration d’une classification pertinente des gîtes d’or est loin d’être définitive. Il reste néanmoins l’urgence de classer les gîtes à des fins d’exploration et d’évaluation des ressources. Malgré les imperfections de la méthode proposée, une telle classification peut servir de modèle pour traiter des problèmes liés à l’identification des principales caractéristiques d’un gîte d’or au début d’un projet de mise en valeur, même s’il est mal exposé ou s’il n’est que partiellement documenté. Elle peut être utilisée également comme guide de recherche d’autres cibles dans des régions précédemment explorées et renfermant des gîtes traditionnellement reconnus. Enfin, elle peut également être le point de départ d’une analyse plus rigoureuse des gîtes d’or, basée sur une technologie numérique de pointe.

THE PROBLEM OF CLASSIFICATION OF GOLD DEPOSITS

Introduction

From time to time, the Geological Survey of Canada has reviewed the main types of gold deposits that occur in Canada and abroad (Cooke, 1946; Boyle, 1979). These reviews not only provided descriptions of individual deposits and districts, but also contained discussions of how gold deposits should be classified. Classification of ore deposits is much more than a textbook exercise: it provides an essential framework for resource-assessment studies, for designing exploration strategies (e.g. what type of deposit to look for, where, and how?), and for evaluating prospects. In particular, there is a need for a coherent classification of gold deposits that takes into account massive amounts of new information resulting from the renewed focus on gold mining and exploration in the last 15 to 20 years. The purpose of this report, therefore, is to present a workable geological classification of gold deposits that occur globally (Fig. 1) and to discuss how it can be applied to selected Canadian examples (Fig. 2).

Acknowledgments

This report is a synopsis resulting from nearly 15 years of study by the authors, including visits to a large number of gold deposits in Canada and throughout the world. Such an undertaking would not have been possible without the kind co-operation of an even greater number of company, government, and university geologists who freely gave of their time and information. In particular, the authors would like to thank their provincial and territorial survey colleagues in Canada who contributed to a better understanding of individual districts and deposit types. The authors wish to thank D.F. Sangster for pointing out that gold deposit classification is, at first glance, irrational when compared to that for other commodities. D.F. Sangster, I. Jonasson, and C.W. Jefferson critically read the manuscript and Julie (Blondé) Jakop prepared most of the figures.

Scope

This report is restricted to bedrock gold deposits, also commonly referred to as 'lode' gold deposits. Following an introductory overview of the problem, geological classification of these deposits is approached in three main steps:

1. A compilation of generally recognized and accepted geological types of lode gold deposits and their most significant attributes is presented in'Gold Deposit Types'. These types of deposits must be ultimately represented in any classification scheme. In doing this, we have used existing models and terminology as much as possible, rather than defining new types or models.
2. Selected Canadian gold deposits are described and discussed in'Canadian Gold Deposit Types' against the backdrop of the deposit types identified in the previous section. This illustrates both the strengths and weaknesses of synthetic models when compared to specific, commonly complex, individual deposits.
3. A 'decision tree', or classification chart, is presented in'Application of Gold Deposit Models' in an attempt to rationalize existing geological models of gold deposits in the context of their broad geological settings, host rocks, relations to intrusions, structural styles of mineralization, and hydrothermal aspects such as geochemical signature and alteration type. The advantage of the decision

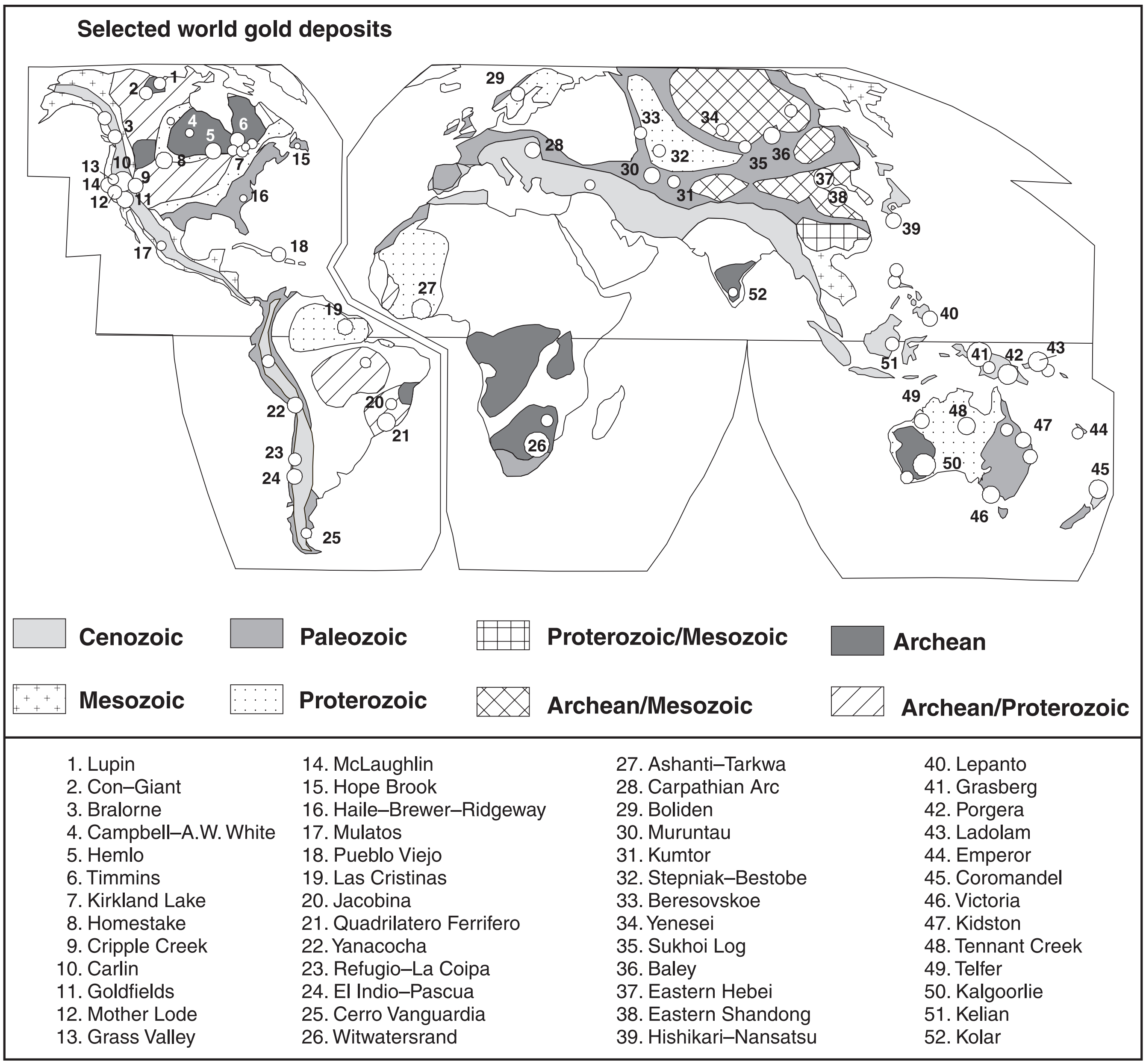
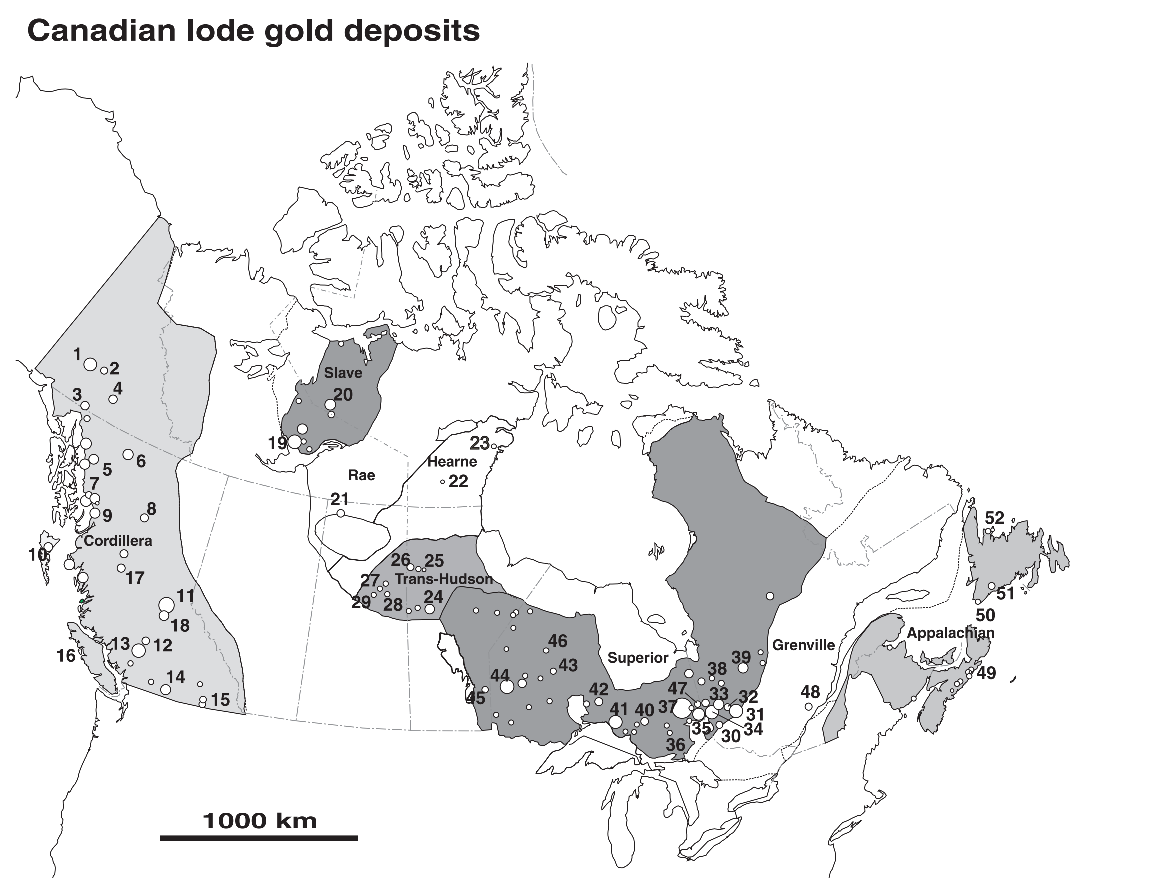


Figure 1. *Major gold deposits of the world. The circles qualitatively represent the size of total gold content in the deposit or district.*

tree is that it is equally applicable to individual, perhaps unique, deposits as it is to synthetic geological models representing groups of deposits of a more conventional type. It can also be used to pose questions about potential deposit types that have yet to be recognized or that are represented by rare examples, and to illustrate what types of deposits might be expected in specific geological settings.

Some parts of this report have been published elsewhere by the authors in the form of journal papers. In particular, the parts of 'Canadian Gold Deposit Types' dealing with selected 'world-class' Archean deposits can also be found in an article published by the Australian Journal of Earth Sciences (Robert and Poulsen, 1997). Parts of 'Gold Deposit Types' and 'Application of Gold Deposit Models' were published as a thematic paper in the Proceedings of Exploration '97 (Robert et al., 1997). The contents of both of these papers have been integrated into this more comprehensive report with minor modifications to text and figures.



Cordilleran Orogen
1. Brewery Creek
2. Dublin Gulch
3. Mount Skukum
4. Ketza River
5. Muddy Lake
6. Cassiar
7. Eskay Creek
8. Toodoggone
9. Premier–Stewart
10. Cinola
11. Cariboo
12. Blackdome
13. Bridge River
14. Hedley
15. Rossland
16. Zeballos
17. Equity Silver
18. QR

Slave Province
19. Con–Giant
20. Lupin

Rae Province
21. Box

Hearne Province
22. Cullaton Lake
23. Meliadine River

Trans-Hudson Orogen
24. New Britannia
25. Farley Lake
26. MacLellan
27. Star Lake
28. Seabee
29. Contact Lake

Superior Province
30. Belleterre
31. Val D'Or
32. Cadillac–Malartic
33. Doyon–Bousquet
34. Noranda
35. Kirkland Lake–Larder Lake
36. Matachewan
37. Timmins
38. Agnico–Eagle
39. Chibougamau district (Norbeau)
40. Renabie
41. Hemlo
42. Geraldton
43. Pickle Lake
44. Red Lake
45. Bissett
46. North Caribou Lake
47. Harker–Holloway

Grenville Province
48. Montauban

Appalachian Orogen
49. Meguma
50. Cape Ray
51. Hope Brook
52. Baie Verte

Figure 2. *Major gold deposits of Canada.*

The classification of gold deposits, as presented herein, has been approached with a full appreciation that there are many difficulties associated with classification of ore deposits in general. In the case of lode gold deposits, contrasting classifications have been arrived at historically depending on whether they were approached from genetic, geochemical, economic, or tectonic points of view (Emmons, 1937; Boyle, 1979; Cox and Singer, 1986; Bache, 1987). Geological classification of lode gold deposits is often further hampered by the following factors:

1. A significant number of large deposits result from the superposition of two or more systems, or superposition of distinct components of hydrothermal systems due to telescoping (Sillitoe, 1994): this can lead to apparently hybrid or composite deposit types.

2. Different geological environments are also commonly superimposed upon one another. For example, continental arcs are commonly found superimposed on sedimentary miogeoclines or older accreted volcanic arcs, making it difficult to determine which geological features are directly related to deposits and which are coincidental.

3. Geological attributes used to discriminate among deposit types should also be as diagnostic as possible to allow adequate classification of deposits that have been deformed and metamorphosed as opposed to deposits that simply occur in deformed and metamorphosed rocks. This is a particularly acute problem for deposits in Precambrian terranes.

The above caveats notwithstanding, the classification attempted here (in the sections 'Gold Deposit Types' and 'Application of Gold Deposit Models') is first and foremost *geological* in scope. It is based mainly, but not exclusively, on the nature and mesoscopic attributes of the ore, and on the geological settings of the deposits: genetic connotations are secondary. Different deposit 'types' need not correspond to distinct genetic types of deposits and may have formed by similar processes. In addition, individual deposits may possess characteristics, to different degrees, of more than one deposit type, so that the classification scheme is not meant to rigidly 'pigeon-hole' deposits. It is better used to illustrate the diversity of types of lode gold deposits that can be encountered in a particular geological environment. It can also be used as a tool to assess the nature, significance, or potential of a showing or a prospect, even at an early stage of an exploration or drilling program, because it is based on information that is generally available or easily obtainable.

The meaning of the term 'gold deposit'

Gold, as an element, occurs in a wide variety of ore deposit types. This inevitably leads to the question of what actually constitutes a 'gold deposit'. There are three factors to consider in answering this question:

1. *Concentration of gold in a deposit.* The natural abundance of gold in most rocks ranges from 0.001 to 0.005 g/t (Crocket, 1991). In the realm of ore deposits, however, gold is commonly found in concentrations ranging from 0.1 to 100 g/t in bodies that typically contain from 100 000 to 100 000 000 t of ore (Fig. 3). There is no precisely defined minimum concentration that defines a 'gold' deposit, but, at the present time, the vast majority of deposits that are mined principally for gold have grades exceeding 1 g/t, or at least contain a significant proportion of ore exceeding that grade.

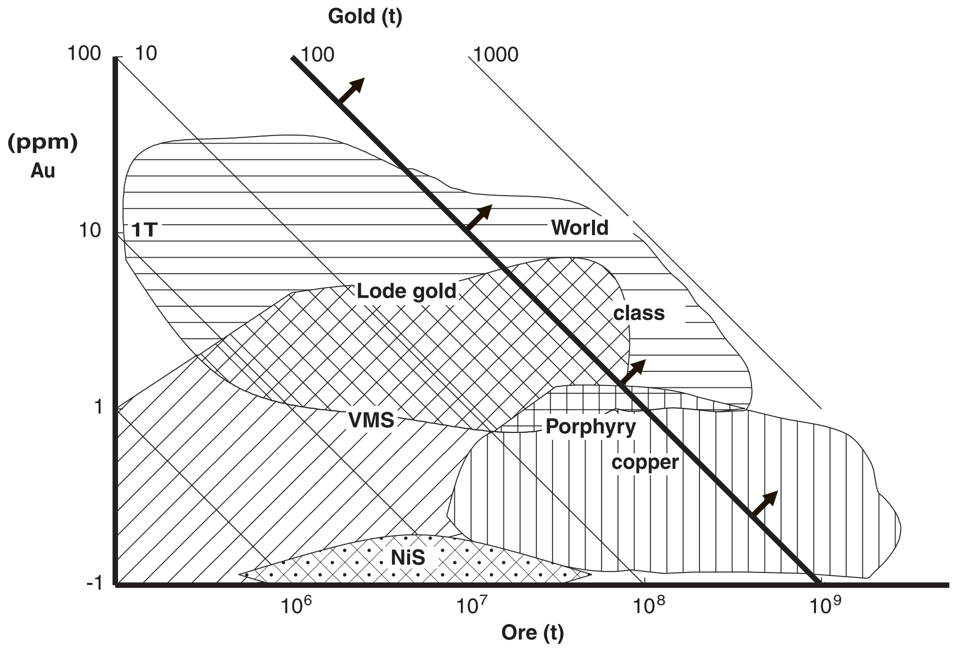


Figure 3.

Tonnage-grade diagram for gold in various deposit types. VMS – volcanogenic massive sulphide, NiS – nickel sulphide.

2. *Total amount of gold in a deposit.* The product of gold concentration times ore tonnage determines the total amount of gold in a deposit (Fig. 3). This amount ranges from 1 to 10 000 t of gold for economically viable deposits. A particular total can be achieved by low tonnage and high grade, by high tonnage and low grade, or by some intermediate combination. Therefore, certain types of large-tonnage deposits can contain a large amount of gold even though the concentration of the element is small. For example, the Bingham Canyon porphyry copper-molybdenum deposit represents a total resource of more than 800 t of byproduct gold at a concentration of 0.45 g/t and the Kidd Creek massive-sulphide deposit contains approximately 13 t of gold at a concentration of 0.1 g/t (M. Hannington, pers. comm., 1996). Compared to many gold-only deposits, Bingham Canyon and Kidd Creek would classify therefore as 'gold' deposits on the basis of contained gold even though they may fail on the basis of gold concentration.

3. *Relative amount of gold in a deposit*. A compositional continuum exists between relative abundance of gold and other metals (Ag, Cu, Mo, Zn, Pb) in a number of widely recognized types of ore deposits such as volcanic-associated massive-sulphide, porphyry, skarn, and epithermal (Fig. 4a–d). One defining characteristic of 'gold' deposits is therefore a gold content (in ppm) exceeding that of base metals expressed in weight per cent base-metal–copper equivalent. Such a limit corresponds to ore compositions where gold and copper-equivalent base metals have approximately equal dollar value, or for which gold is an important co-product, based on the long-term prices of these metals. A simple time-independent index for base metals equal to (4 x (%Ni) + 2 x (%Mo) + (%Cu) + 0.5 x (%Zn) + 0.25 x (%Pb)) is used here as a weighted average for the 'copper equivalent' in favour of one using actual variable metal prices. Gold deposits also display considerable variations in gold-to-silver ratios (Fig. 4d), and deposits at the silver-rich end of the spectrum with silver-to-gold ratios of greater than 50:1 are silver deposits in an economic sense. Note that only the hypogene components of the ores are considered using these criteria, although supergene processes may turn a gold-bearing base-metal deposit into an economic gold deposit according to the above definition.

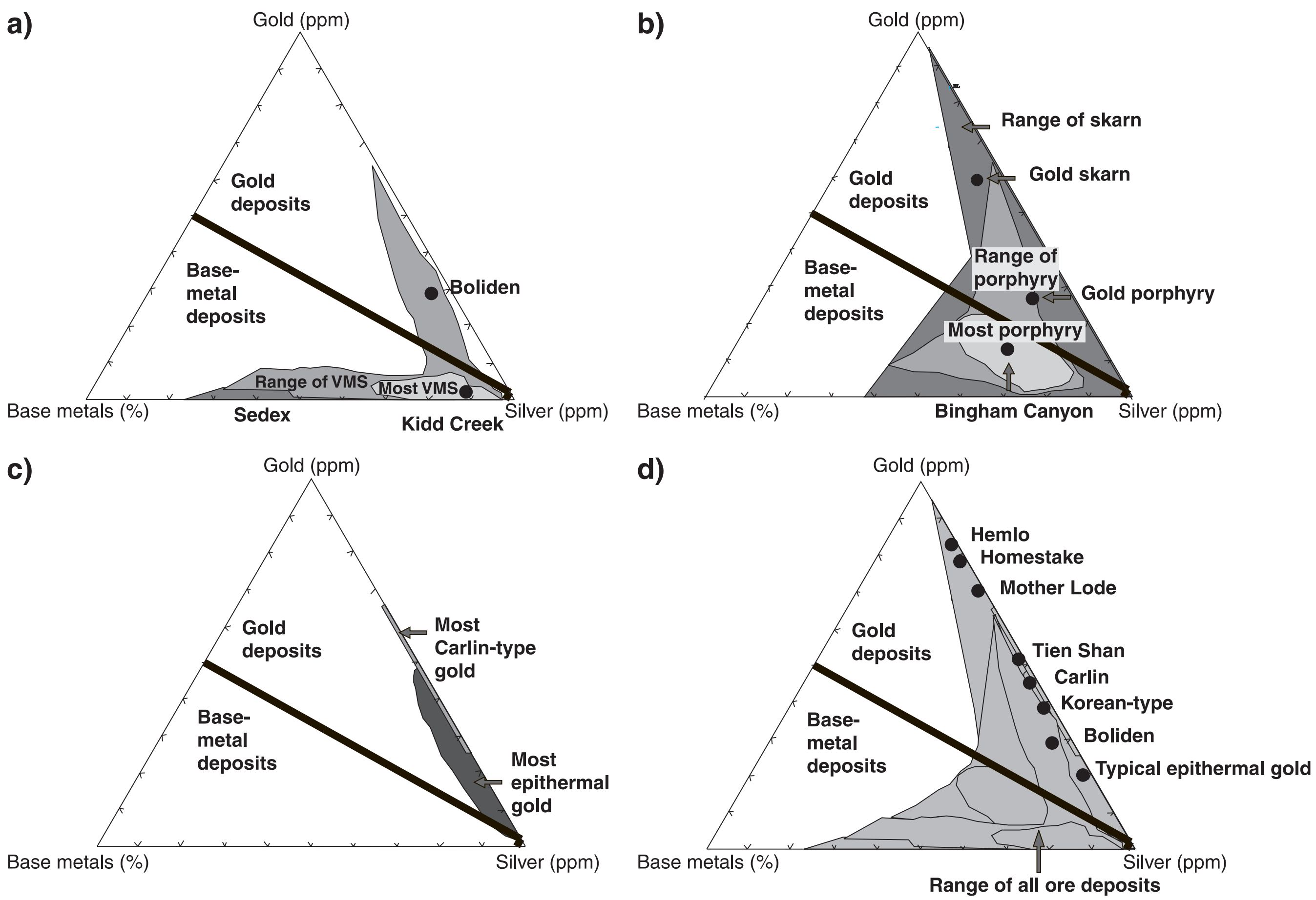


Figure 4. *Ternary diagrams illustrating the estimated compositions of ores for selected ore deposit types and for examples of individual deposits. See text for further explanation.*

A working definition of what constitutes a gold deposit should therefore take into account all three of the above factors. Deposits that contain more than 1 t of gold, that are composed mostly of material grading greater than 1 g/t gold, and in which the value of contained gold exceeds that of co-commodities, are considered to be 'gold deposits' in the context of this report. One of the resulting implications for geological classification is that, for some gold deposits, there is a continuum with deposit types dominated by another commodity (e.g. porphyry and massive-sulphide deposits). Therefore, due care must be taken to establish terminology that is compatible with classification schemes relating to these other deposit types.

Historical precedents

Table 1 summarizes some well known examples of classification schemes for lode gold deposits, and additional subdivisions for more specific portions of the broad spectrum of gold deposits are shown in Table 2. These tables illustrate the range of existing terminology that must be accommodated and some of the guiding principles that, historically, have been considered important in classifying gold deposits.

Genetic classifications

Geologists have long recognized that knowledge of the mode of formation of ore deposits has predictive value in making new discoveries, and therefore elements of genesis are hard to escape in most classification schemes. The point of departure for any discussion of gold deposits is undoubtedly the genetic classification (Table 1) of Emmons (1937). Based on the broader classification of ore deposits by Lindgren (1933), Emmons explicitly stated that the origin and the physical conditions at the time of deposition were the main considerations in his scheme, and that subsequent metamorphism, deformation, or weathering should not alter the assignment of a deposit to a particular type. The time-honoured concepts of mineralogical depth zoning are also very much a part of this classification scheme to which we owe (and to some degree are burdened with) terms such as 'epithermal', 'mesothermal', and 'hypothermal'. One approach in modern classification is to attempt to accommodate or modify these terms in line with current knowledge. Examples include the common retention of the term 'mesothermal' for deposits in metavolcanic and metasedimentary terranes (e.g. Hodgson, 1993; Safonov, 1997), subdivision of epithermal gold deposits into subtypes (e.g. Cox and Singer, 1986; Heald et al., 1987; Sillitoe, 1993), the proposal of a parallel set of baric types (Table 1) for Archean epigenetic deposits (Groves, 1993; Gebre-Mariam et al., 1995; Groves et al., 1995), and the recognition of environments and deposits that are 'transitional' between epithermal and mesothermal (Panteleyev, 1991). This approach is advantageous in that links with existing nomenclature are preserved, but it also suffers from the basic problem that, despite decades of research, there are no easily applicable criteria that allow one to state with confidence the physical conditions at the time of ore deposition. Modification of the original terminology can also lead to discrepancies that obscure links between the original and modified forms. For example, Lindgren (1933) assigned depths of 1.5 km, 1.5 to 3 km, and greater than 3 km to his epithermal, mesothermal, and hypothermal categories, respectively, but the figures proposed by Groves et al. (1995) for the equivalent baric types shows that it would be possible to find gold deposits (e.g. Kalgoorlie) that are 'hypothermal' (Table 1) yet 'mesozonal' (Table 2).

Another approach to genetic classification of gold deposits stems from the recognition that many mineral districts represent large hydrothermal systems, and that gold deposits represent individual components of such systems. The separation of deposits into types is therefore often an exercise in correctly identifying the components rather than the systems. Although the components may differ in detail according to their physical characteristics, relative time of deposition, and mode of formation, their relationship to one another within the context of larger systems is a unifying theme. The best examples of genetic classification in this sense are those deposits described by Bache (1987) as "post-orogenic plutonic"(Table 1) and by Sillitoe (1991a) as "intrusion-related" (Table 2). Few workers would dispute that most of the deposit types in question deserve to be linked in this way, but at the same time some discrepancies in classification can arise for deposits of uncertain genesis for which a judgment must be made as to their likely origin. For example, some carbonate-hosted gold deposits (e.g. those of 'Carlin type') are viewed by some to be linked to the intrusive environment by Sillitoe (1991a), whereas they are assigned, along with epithermal deposits, to a subaerial felsic-mafic extrusive environment by Cox and Singer (1986).

Host-rock classifications

One of the greatest strengths of genetic classification of gold deposits is that the effect of local variations due to host-rock controls is minimized. Nonetheless, it is much easier for most geologists to recognize the host rocks at a deposit than it is to instinctively know the deposit's genesis. Furthermore, as advocated by Boyle (1979), host rocks have a profound influence on the structural form and, through fluid-rock interaction, on the geochemistry of gold deposits. The classification schemes of Boyle (1979), Cox and Singer (1986), Bache (1987), Bonham (1989), and Safonov (1997) all have strong recurring elements of host-rock classification. They typically use sedimentary, volcanic, and plutonic hosts as discriminating features (Table 1) and their strength is the ease with which they can be applied to those deposits having strong lithological affiliations (e.g. skarns, carbonate-hosted polymetallic replacements, auriferous iron-formation, quartz-pebble conglomerate, massive-sulphide, and porphyry deposits). The weakness of these classification schemes, however, comes in their application to vein deposits which are not host-rock specific, and to metamorphic terranes which are themselves composed of volcanic, sedimentary, and plutonic rocks and where it is not clear whether their auriferous nature is due to metamorphic history or to prior volcanic, sedimentary, or plutonic processes.

Table 1. Examples of classification schemes for gold deposits.

Emmons (1937)	Boyle (1979)	Cox & Singer (1986), Orris and Bliss (1992)	Bache (1987)
1. Magmatic segregations — orthomagmatic deposits (e.g. Waaikraal, South Africa; Golden Curry, Utah)	1. Auriferous porphyry dykes, sills and stocks; auriferous coarse-grained granitic bodies, aplites and pegmatites (e.g. Waaikraal, South Africa; Dartmoor, England)	E. Felsic intrusive environment — porphyro-aphanitic intrusions 19. Calcareous wall rocks a. Polymetallic replacement (e.g. Tintic, Utah) 20. Coeval volcanic wall rocks c. Porphyry Cu-Au (e.g. Ok Tedi and Panguna, Papua New Guinea)	I. Pre-orogenic volcanic-sedimentary 1. Polymetallic sulphides (+gold) a. Calc-alkaline (e.g. Horne, Quebec) b. Ophiolitic (e.g. Cyprus) c. Sedimentary (e.g. Cobar, Australia)
2. Pegmatites (e.g. Gold Hill, Utah; Natasmine, southwest Africa)	2. Auriferous skarn-type deposits (e.g. Hedley, British Columbia; Suian, Korea)	22. Igneous and sedimentary rocks b. Au-Ag-Te veins (e.g. Cripple Creek, Colorado; Emperor, Fiji)	2. Auriferous iron-formation (e.g. Homestake, South Dakota)
3. Pyrometasomatic deposits (e.g. Cable, Montana; Dolcoath, Montana)	3. Au-Ag and Ag-Au veins, stockworks, lodes, mineralized pipes and silicified bodies in fractures, faults, shear zones, sheeted zones, and breccia zones essentially in volcanic terranes (e.g. Yellowknife, Northwest Territories; Mother Lode, California; Kalgoorlie, Australia; Brad, Romania; Waihi, New Zealand)	G. Mafic-felsic extrusive environment — subaerial 25. Volcanic-hosted a. Hotspring Au-Ag (e.g. Round Mountain, Nevada) b. Creede epithermal veins (e.g. Creede, Colorado; Pachua, Mexico)	3. Discordant volcano-sedimentary deposits (e.g. Kalgoorlie, Australia; Mother Lode, California; Bendigo and Ballarat, Australia; Lamaque, Quebec; Cam and Motor, Zimbabwe)
4. Hypothermal deposits — considerable depth and high temperature (e.g. Porcupine, Ontario; Homestake, South Dakota; Morro Velho, Brazil; Kalgoorlie (Australia)	4. Au veins, lodes, sheeted zones, and saddle reefs essentially in sedimentary terranes; also replacement tabular and irregular bodies near faults and fractures in chemically favourable beds (e.g. Ballarat and Bendigo, Australia; Meguma, Nova Scotia; Telfer, Australia; Muruntau, Uzbekistan)	c. Comstock epithermal veins (e.g. Comstock, Nevada; Republic, Washington) d. Sado epithermal veins (e.g. Sado, Japan; La Libertad, Mexico) e. Epithermal quartz-alunite Au (e.g. Goldfield, Nevada; El Indio, Chile) 26. Sediment-hosted Au (e.g. Carlin, Nevada)	II. Post-orogenic plutonic-volcanic 4. Copper (+gold) porphyry a. Continental-arc Cu-Mo-Au (e.g. Bingham, Utah); b. Island-arc Cu-Au (e.g. Panguna, Papua New Guinea)
5. Mesothermal deposits — intermediate depth and temperature (e.g. Sierra Nevada, California; Nova Scotia, Canada; Victoria, Australia; Charters Towers, Australia)	5. Au-Ag and Ag-Au veins, lodes, stockworks, silicified zones, etc. in a complex volcanic, sedimentary, and intrusive environment (Kirkland Lake, Ontario; Grass Valley California; Juneau, Alaska)	G. Felsic-mafic extrusive environment — marine 28a. Kuroko massive sulphide (e.g. Kuroko, Japan)	5. Carbonate-replacement deposits a. Polymetallic (e.g. Tintic, Utah) b. Skarn Au-Cu (e.g. Hedley, British Columbia) c. Disseminated Au (e.g. Carlin, Nevada)
6. Epithermal deposits — shallow depths or low temperature (e.g. Comstock and Goldfield, Nevada; El Oro, Mexico; Brad, Romania; Waihi, New Zealand)	6. Disseminated and stockwork Au-Ag in intrusive volcanic and sedimentary rocks a. in igneous intrusive bodies (e.g. Lamaque, Quebec) b. in volcanic flows and volcaniclastic rocks (e.g. Goldfield, Nevada); c. in tuffaceous rocks and sedimentary beds (e.g. Homestake, South Dakota) d. in chemically favourable sedimentary beds (e.g. Carlin, Nevada)	K. Regionally metamorphosed environment 36. Eugeosynclinal a. Low-sulphide Au-quartz veins (e.g. Ballarat, Australia; Mother Lode and Grass Valley, California; Meguma, Nova Scotia; Chugach, Alaska) b. Homestake Au (e.g. Homestake, South Dakota; Passagem, Brazil; Dome, Hollinger and Kerr, Ontario; Agnico–Eagle, Quebec)	6. Intrusion-centred vein deposits a. Cu-Au (e.g. Butte, Montana) b. Pb-Zn-Au (Idaho Springs, Colorado) c. Au-Ag (e.g. Rossland, British Columbia) d. Ag-Au (e.g. Sunnyside, Colorado)
7. Deposits formed by cold solutions (no significant examples)	7. Au in quartz-pebble conglomerates and quartzites (e.g. Witwatersrand, South Africa)	H. Sedimentary environment 29. Clastic a. Quartz pebble conglomerate Au-U (e.g. Witwatersrand, South Africa)	III. Detrital 7. Ancient placers (e.g. Witwatersrand, South Africa; Tarkwa, Ghana)
8. Sedimentary Deposits (e.g. widespread gold placers)	8. Placers a. Elluvial including those in karst terranes (e.g. Omai, Guyana); b. Alluvial (e.g. Klondike, Yukon Territory) c. Fossil eluvial and alluvial (e.g. Otago, New Zealand)	M. Surficial environment 38. Residual g. Laterite-saprolite Au (e.g. Boddington, Australia) 39. Depositional	8. Modern placers
	9. Miscellaneous sources — (e.g. massive-sulphide and porphyry deposits)	a. Placer Au-PGE (Sierra Nevada, California; Victoria, Australia)	

Table 2. Examples of partial classification schemes for gold deposits.

Intrusion-related Au deposits Sillitoe (1991a)	Bulk mineable Au deposits Bonham (1989)	Epithermal Au deposits Heald et al. (1987); Berger and Henley (1989)	Epigenetic Archean Au deposits Groves et al. (1995)
Intrusion-hosted deposits a. Porphyry Au and Cu-Au (e.g. Lepanto, Phillipines; Ok Tedi, Papua, New Guinea) b. Intrusion-hosted stockwork / disseminated (e.g. Gilt Edge, South Dakota; Zortman–Landusky, Montana)	Porphyry-related deposits a. Cu-Au stockworks (e.g. Bingham, Utah; Robinson, Nevada) b. Alkalic porphyry Cu-Au (e.g. Copper Mountain and Galore Creek, British Columbia) c. Calc-alkalic porphyry Au (e.g. Bald Mountain, Nevada) d. Deposits associated with alkalic porphyries (e.g. Zortman–Landusky and Golden Sunlight, Montana) e. Gold-bearing skarn and metasomatic deposits (e.g. Fortitude and McCoy, Nevada)	Acid-sulphate (alunite-kaolinite) type (e.g. Goldfield, Nevada; Summitville, Colorado)	Epizonal deposits — less than 6 km depth (e.g. Wiluna, Australia; Ross, Ontario)
Carbonate-hosted deposits a. Skarn (e.g. Fortitude, Nevada; Hedley, British Columbia; Suan, Korea) b. Carbonate-replacement deposits (e.g. Barney's Canyon, Utah; Foley Ridge, South Dakota)	Sediment-hosted Deposits a. Carlin type (e.g. Carlin and Cortez, Nevada)	Adularia-sericite type (e.g. Creede, Colorado; Pachua, Mexico)	Mesozonal deposits — 6 to 12 km depth (e.g. Kalgoorlie, Australia; Kirkland Lake, Ontario; Sigma, Quebec)
Stockwork, disseminated, and replacement deposits in non-carbonate rocks (e.g. Porgera, Papua New Guinea; Muruntau, Uzbekistan)	Metamorphic-hosted deposits a. Mother Lode type (e.g. Carson Hill and Jamestown, California) b. Mesquite type (e.g. Mesquite and Picacho, California)		Hypozonal deposits — greater than 12 km depth (e.g. Norseman, Australia; Red Lake, Ontario)
Breccia-hosted deposits (e.g. Kidston, Australia; Golden Sunlight, Montana)	Volcanic-hosted deposits a. Low-sulphur (e.g. Creede, Colorado; Pachua, Mexico) b. High-sulphur (e.g. Goldfield, Nevada; Chinkuashi, Taiwan) c. Alkalic (e.g. Cripple Creek, Colorado; Vatukoula, Fiji)		
Vein-type deposits (Charters Towers, Australia; Zhaoyuan, China)	Hotspring deposits (e.g. McLaughlin, California; Hog Ranch, Nevada)		

Geochemical/mineralogical classifications

The mineralogy and geochemistry of gold deposits are undoubtedly reflections of their hydrothermal history with a strong buffering by host rocks, and therefore are parameters which commonly 'fingerprint' deposits to some degree. Geochemical affiliations (silver and base metals) of gold in ore figure prominently in the classifications of Boyle (1979) and Bache (1987), and are implicit in the depth categories of Emmons (1937). Geochemical subdivision of plutonic and volcanic suites into calc-alkalic and alkalic types are commonly used to distinguish types of porphyry-related (Bonham, 1989) and epithermal deposits (Bonham, 1989; Sillitoe, 1993). Another important manifestation of hydrothermal processes that is commonly considered in the classification of gold deposits is wall-rock alteration. This has been used particularly to distinguish porphyry deposits from other intrusion-hosted stockwork and disseminated deposits (Sillitoe, 1991a), and to subdivide epithermal deposits into adularia-sericite (low-sulphidation, quartz adularia) and acid-sulphate (high-sulphidation, alunite-kaolinite, quartz-alunite) subtypes (Cox and Singer, 1986; Heald et al., 1987; Berger and Henley, 1989; Sillitoe, 1993).

Tectonic classifications

Tectonic parameters are implicit in most classification schemes based on genetic, host-rock, or geochemical parameters, but are explicit in the classifications of Cox and Singer (1986) and Bache (1987). There are two aspects to consider: tectonic environment and tectonic sequence. The first is addressed to some degree by Cox and Singer (1986) who used subaerial versus marine volcanic environments, clastic versus carbonate sedimentary environments, and the presence or absence of particular types of intrusions to classify deposit types (Fig. 5) and by Bache (1987) to distinguish continental from island-arc environments (Table 1). Such classifications along with host-rock parameters are of considerable value in their application to resource assessment where more information may be available on tectonic environments and sequences than on mineral deposits. The recognition that deposits form at different stages of an orogenic cycle is much more difficult to apply in a practical way. Bache (1987) proposed that hydrothermal gold deposits can be classified into pre- and postorogenic categories (Table 1). The difficulties with such a scheme are that it doesn't allow for a synorogenic designation which other authors (e.g. Groves et al., 1995) apply to many of the deposits in Bache's group of preorogenic "discordant volcanic-sedimentary deposits", nor does it readily allow that postorogenic deposits of one cycle can be themselves deformed and metamorphosed at a later stage. Nonetheless, it is instructive to consider that different types of gold deposits, particularly those in Precambrian greenstone belts, may have formed at different times and be of pre-, syn-, or postorogenic timing, and that this may be reflected in their physical characteristics. Recognition of this possibility might avoid the classification of all gold deposits of an orogenic belt into a single type.

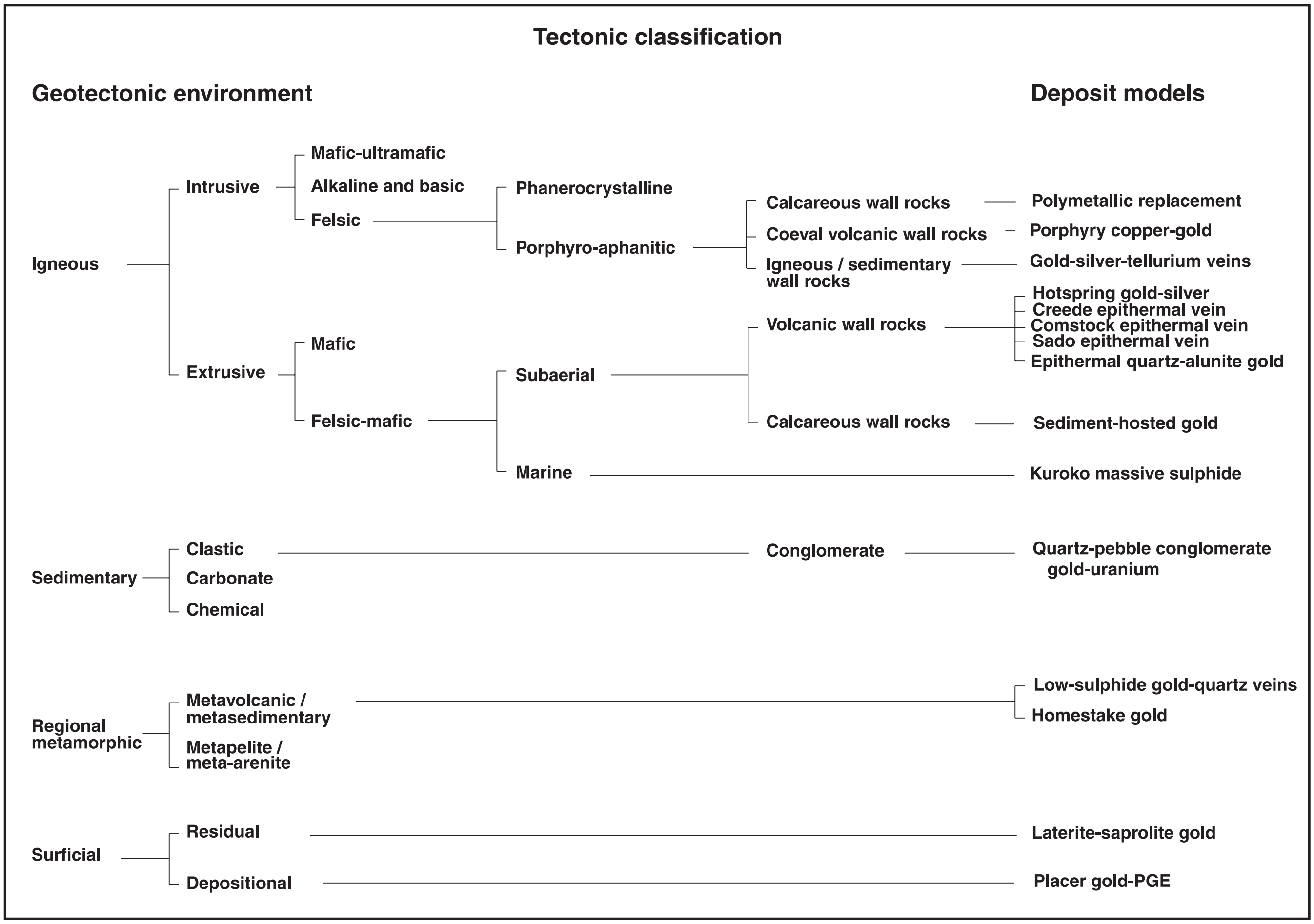


Figure 5. *Decision tree which classifies gold deposit models according to geotectonic environment (after Cox and Singer, 1986).*

Prototype classifications

A common practice in classifying gold deposits (Table 1, 2) is to name them according to prototype examples (e.g. Carlin-type, Homestake-type, Mother Lode–type, and Creede-type deposits). In addition, most classification schemes (Table 1) include partial lists of typical deposits to illustrate the spectrum of conditions that the classifiers have in mind. There is certainly some merit to classifying deposits by their resemblance to large, well known, and well studied benchmarks with which to compare a more poorly known deposit, but there are also pitfalls in doing so. The first is that the prototype, although large, may not have the most typical characteristics of the intended group: this is tantamount to calling all birds 'ostrich-type' when perhaps 'robin-type' would be more appropriate. For example, Singer (1995) analyzed world metal production and concluded that approximately 50% of the gold in Canadian deposits come from those of 'Homestake-type' as defined in Table 1 even though only a handful of Canadian deposits (representing at most 5% of Canada's gold resources) have geological characteristics strongly resembling those of the Homestake deposit in South Dakota. The second related problem is that there are no clear rules for deciding when a deposit sufficiently resembles a prototype to be classified with it, or when the deposit departs sufficiently in characteristics to warrant creation of a new prototype. Informal use of terms such as 'Hemlo-type' or 'Bousquettype' in Canada is an example of this problem. Certainly it would not be totally incorrect to classify many Canadian deposits as 'Homestake-type' (Table 1), for example, if one were to add a qualifier as to the degree of belonging to the class. The Agnico–Eagle deposit could therefore be classified as being 50% similar to the Homestake deposit whereas the Dome mine might be said to be a 'Homestake-type' deposit to a lesser degree. The problem with this approach, however, is that it allows all gold deposits to be of any type to a certain degree and that it doesn't give any guidance as to what to do with important large deposits like Hemlo or Bousquet that don't really resemble the prototype at all.

Economic classifications

Historically, classification of gold deposits has been mainly an academic matter, but in recent times economic measures have also been incorporated into classification schemes. Therefore terms such as 'bulk mineable' (Bonham, 1989) and 'world class' (Singer, 1995) have become acceptable forms of classifying deposits. This affects classification in several ways. First it illustrates that the form of the deposit should be considered as a significant practical factor in classification. Currently, large deposits in which gold occurs as wall-rock disseminations or in extensive stockworks are preferred as exploration targets over smaller deposits composed of narrow quartz veins. Second, it reinforces the tradition that 'prototype' deposits, which inevitably are large, have a strong influence on deposit classification: smaller, unusual deposits gain less study and are not accounted for in most classification schemes. Third, the use of economic criteria in classification raises the fundamental question as to whether large deposits have other geological characteristics which distinguish them from smaller ones.

Conclusions

Despite the diversity of approaches to gold deposit classification (Table 1, 2) and the problems associated with each, there are three important unifying aspects to all classification schemes. First, there is a recognition that there are a finite number of well known gold deposit types. The actual number is not fixed, but is in the range of 8 to 20. Second, some deposit types (e.g. skarns, paleoplacers) are recognized universally and differ only in name from scheme to scheme. Third, attached to each deposit type is some form of model to distinguish it from other types. The model may be simply a list of important attributes (e.g. Cox and Singer, 1986) or a perceived mode of genesis (e.g. Emmons, 1937), but in most cases also implies a particular geological setting at a particular crustal level.

GOLD DEPOSIT TYPES

Introduction

Some of the deposit types that have been identified historically (Table 1, 2) are not known to be significant in a Canadian context and are not considered further in this paper. Examples include gold-rich pegmatite deposits, magmatic deposits in layered intrusions (although such deposits are known in Greenland), and eluvial lateritic deposits. Others, like placer deposits, are mainly of historic importance in Canada, have been well studied in their own right, and are not discussed herein. Among the rest, however, 16 well established gold deposit types (Table 3) can be considered to be of potential importance in Canada. The following pages contain brief summary descriptions and discussions of each of these deposit types based on the authors' observations and a review of selected literature. They are numbered to correspond with their designations in Table 3, and Figures 6 and 84.

The deposit types have been named in as conventional a manner as possible, given that several have more than one precedent name. The main points that emerge from this compilation of the characteristics of these deposit types are as follows:

1. The combination of geological environment, host rocks, nature of the mineralization, and hydrothermal alteration is unique for almost every deposit type (Table 3). These geological attributes should represent the important discriminating criteria used in practical application of a deposit-classification scheme.
2. The deposit types (Table 3) have likely formed over a wide range of crustal depths in a variety of geological environments (Fig. 6). Most of those thought to have formed in shallow to moderately deep crustal environments are commonly considered to be components (proximal or distal) of larger intrusion-centred systems. These deposits have formed at convergent plate margins during plutonism and volcanism marking stages of magmatic-arc development. Deposits formed at deeper crustal levels are generally considered to also have formed at convergent plate margins, but rather during deformation related to accretion and collision.
3. Most types of lode gold deposits have at least one known world-class example (i.e. >100 t of contained Au), and several types have truly giant examples (i.e. >500 t Au) illustrating the point that large lode gold deposits are of many different geological types and they occur in different geological environments.

Paleoplacer deposits (1)

Paleoplacer deposits, like those of the Witwatersrand Basin in South Africa, consist of stratiform layers (blankets) of auriferous quartz-pebble conglomerate, pebbly quartz arenite, and crossbedded arenite, with thin carbonaceous seams locally enriched with gold. The deposits occur in mature fluviatile- to deltaic-facies rocks in extensive cratonic sedimentary basins. The most significant deposits of this type occur in Archean and Early Proterozoic sedimentary basins, perhaps reflecting an important control by an oxygen-poor atmosphere or a local oxygen-poor environment.

The ore and associated minerals consist of native gold and pyrite, in most cases of detrital origin, and the heavy minerals: magnetite, uraninite, ilmenite, and locally hematite. The ores are typically gold rich relative to silver (Au:Ag = 10:1). Hydrothermal alteration, mainly sericitization and chloritization, overprints some deposits and has been responsible for local redistribution of gold or for introduction of new gold. In addition, pyrite at some deposits is paragenetically late and may result from sulphidation of detrital oxide grains. Nevertheless, the detailed distribution of gold is controlled by primary sedimentary-facies variations.

It has been long recognized that the Witwatersrand Basin bears many lithological similarities to the Early Proterozoic Huronian sequence in central Canada (Fig. 7), which is noted more for its concentration of uranium than for gold (Mossman and Harron, 1983; Roscoe and Minter, 1993). S.M. Roscoe (Roscoe et al., 1989; Roscoe, 1990) also noted that certain quartz-arenite successions in the Archean Slave and Superior provinces are stratigraphically and temporally more comparable to the Witwatersrand than is the Huronian. He showed, however, that the gold concentrations of both the Huronian and

Table 3. Commonly recognized types of lode gold deposits and their main geological attributes.

	Deposit type	International examples	Canadian examples	Geological setting	Form of mineralization	Associated alteration	Metal association	Size & grade of deposits
1	Paleoplacer (Witwatersrand type)	Witwatersrand (S. Africa), Tarkwa (Ghana), Jacobina (Brazil)	rare: Huronian (Ontario), Sakami (Quebec)	Mature fluviatile- to deltaic-facies rocks in extensive cratonic sedimentary basins	Pyrite-bearing quartz-pebble conglomerate and quartz arenite	Overprinting sericitization and silicification	Au>Ag; U common Au:Ag typically 10:1	1–100 Mt of ore @ 1–10 g/t Au; some up to 1000 t Au
2	Submarine gold-rich massive-sulphide (VMS type)	Boliden (Sweden), Mt. Lyell & Mt. Morgan (Australia)	Horne, Bousquet, Agnico–Eagle (Quebec), Eskay Creek (British Columbia)	Mixed volcanic, volcaniclastic and sedimentary sequences in greenstone belts	Banded and stratiform massive-sulphide lenses and adjacent stockwork zones	Sericitization and silicification; common advanced argillic alteration	Ag, Au, Cu, base metals; typically Ag>Au	1–10 Mt of ore @ 3–10 g/t Au and 1–5% base metals
3	Hotspring (subtype of low sulphidation epithermal)	McLaughlin (California), Hasbrouk Mt., Buckskin Mt. (Nevada), Cherry Hill, Champagne Pool (New Zealand)	Cinola (British Columbia)?	Subaerial mafic and felsic volcanic centres and associated epiclastic rocks in volcano-plutonic belts	Disseminated sulphides in silicified and brecciated rocks; underlying quartz veins	Silicification, steam-heated argillic and advanced argillic alteration; adularia	Au, Ag, Hg, As, Sb, Tl, Ba; locally W; typically Ag>Au; strong vertical zoning	Typically <30 t Au; up to 20 Mt of ore @ 5 g/t Au
4	Low-sulphidation epithermal	Creede (Colorado) Hishikari (Japan), Cavnic (Romania), Round Mountain (Nevada)	Lawyers, Blackdome, Cinola (British Columbia), Skukum (Yukon Territory)	Subaerial inter-mediate to felsic volcanic centres and associated subvol-canic intru-sions in volcano-plutonic belts	Crustiform-colloform to brecciated quartz-carbonate-adularia veins	Smectite-illite/sericite-adularia; silicification; outward propylitic alteration	Au, Ag, As, Sb, Hg±Pb, Zn, Te; Au:Ag = 1:10 to 1:25; vertical zoning	<100 t Au but some >500 t Au; grades of 2–70 g/t Au
5	High-sulphidation epithermal	Goldfield (Nevada), El Indio (Chile), Pueblo Viejo (Dominican Republic), Nansatsu (Japan), Yanacocha (Peru)	Hope Brook (Newfoundland), Equity Silver (British Columbia)?	Subaerial intermediate to felsic volcanic centres and associated subvol-canic intrusions in volcano-plutonic belts	Disseminated sulphide in vuggy silica zones, veins, breccias and stockworks	Silicic and alunite-bearing advanced argillic alteration, grading outward into argillic or propylitic	Au, Ag, As, Cu, Sb, Bi, Hg, Te, Sn, Pb Au:Ag 1:2 to 1:10;	10–150 t Au but up to 600 t Au; grades of 1–8 g/t Au, averaging 4–5 g/t
6	Porphyry gold	Lepanto Far South East (Philippines), Grasberg (Indonesia), Lobo (Chile), Refugio (Chile), Yu-Erya (China), Fort Knox (Alaska)	Dublin Gulch (Yukon Territory), Young-Davidson (Ontario), Douay, Troilus (Quebec)	Calc-alkalic to alkalic, subaerial intermediate volcanic centres and associated subvolcanic intrusions in volcano-plutonic belts	Intrusion-hosted (in part) quartz-pyrite stockwork zones	K (±Na)-silicate alteration; common argillic and advanced argillic overprint; hyrdrothermal magnetite	Au, Cu, Ag± Bi-Te; Au:Ag>1:1	50–100 t Au, up to 400 t; grades of 0.5–2 g/t Au and <0.8% Cu
7	Breccia pipe	Kidston (Australia), Montana Tunnels (Montana), Cripple Creek (Colorado)	Sunbeam Kirkland (Manitoba), Chadbourne, Berrigan Lake (Quebec)	Mafic to felsic volcanic centres and associated subvolcanic intru-sions in volcano-plutonic belts	Mineralized discordant breccia bodies	Sericite-carbonate alteration; variable silicification	Au, Ag, Pb, Cu, Zn; Au:Ag <1:1	6–60 Mt of ore @ 1–2 g/t Au; some up to 100 t Au
8	Skarn	Fortitude (Nevada), Red Dome (Australia), Suan (Korea)	Hedley & Tillicum (British Columbia), Marn (Yukon Territory), Akasaba (Quebec)	Carbonate platform sequences over-printed by volcano-plutonic arcs	Disseminated to massive-sulphide lenses and veins cutting skarn	Al-rich prograde skarn assem-blages; retro-grade alteration common	Au, Ag, As, Bi, Te; Au:Ag variable	1–10 Mt of ore @ 3–10 g/t Au, <1% base metals; <100 t Au

Archean sequences are, on average, two orders of magnitude less than that of the Witwatersrand, even though the Huronian and Witwatersrand show comparable ranges of uranium concentrations. Roscoe (Roscoe et al., 1989) argued that these differences likely reflected different metal sources during sedimentation. The question as to the relative importance of sedimentological versus hydrothermal processes in the formation of the paleoplacer gold deposits is both complex and controversial (Phillips and Myers, 1989; Minter, 1991), and well beyond the scope of this report.

Submarine gold-rich massive-sulphide deposits (2)

This type, as exemplified by the Horne deposit, Quebec (Kerr and Mason, 1990) and Boliden deposit, Sweden (Grip and Wirstam, 1970; Bergman-Weihed et al., 1996) consists of banded and locally concordant massive lenses and adjacent discordant stockwork zones, but significant syntectonic sulphide veins are also present in deformed and metamorphosed deposits. Deposits occur in mixed submarine volcanic, volcaniclastic, and sedimentary sequences in greenstone belts of all ages, typically metamorphosed to greenschist and lower amphibolite facies. Ore is composed mainly of pyrite

Table 3 (cont.)

	Deposit type	International examples	Canadian examples	Geological setting	Form of mineralization	Associated alteration	Metal association	Size & grade of deposits
9	Carbonate replacement (manto-type)	Ruby Hill (Nevada), Mammoth (Utah)	Mosquito Creek–Island Mountain (British Columbia), Ketza River (Yukon Territory)	Carbonate platform sequences overprinted by volcano-plutonic arcs	Concordant to discordant massive-sulphide bodies in carbonate rocks	Silicification of limestone; sericitization of clastic rocks	Au, Ag, As, Bi, Hg±Pb, Cu, Zn; typically Au<Ag	Typically <3 Mt of ore @ 5–20 g/t Au & 1–5% base metals; up to 65 t Au
10	Sediment-hosted micron gold (Carlin-type)	Carlin (Nevada), Mercur (Utah), Golden Reward (South Dakota), Guizhou (China)	possibly Golden Bear (British Columbia), Brewery Creek (Yukon Territory)	Carbonate and impure carbonate-argillite facies of continental shelves overprinted by volcano-plutonic arcs	Disseminated sulphides in discordant breccia bodies and stratabound zones	Decalcification and silicification of carbonate rocks	Au, Ag, As, Sb, Hg typically Au<Ag	1–10 Mt of ore @ 1–10 g/t Au; some up to 500 t Au
11	Noncarbonate-hosted stockwork and disseminated	Andacollo (Chile), Porgera Stage I ore (Papua New Guinea), Muruntau (Uzbekistan)	East Malartic, Beattie (Quebec), Hemlo(?), Holt-McDermott (Ontario), QR (British Columbia)	Siliclastic, turbiditic, and volcaniclastic facies in common association with felsic to intermediate stocks and dykes	Stockwork, sheeted veins, and disseminated stratabound to discordant zones	K-metasomatism (K-feldspar, roscoelite, biotite) or albite commonly accompanied by carbonate	Cu, As, Bi, Te +/-W, F, B	1–20 Mt of ore @ 2–5 g/t Au; some greater than 500 t Au
12	Au-Cu sulphide-rich vein	Tennant Creek (Australia)	Rossland (British Columbia), Red Mountain (British Columbia), Mouska, Cooke, Copper Rand, Doyon #3 zone (Quebec)	High-level intrusions and associated dykes in volcano-plutonic arcs and greenstone belts	Quartz-sulphide veins (>20% sulphide)	Sericitization and chloritization	Au, Ag, Cu± Pb, Zn typically Au<Ag	Mostly <5 Mt of ore at 3–15 g/t Au; some >100 t Au
13	Batholith-associated quartz vein (Korean-type)	Chenoan (Korea), Linglong (China), Charters Towers (Australia)	Zeballos, Surf Inlet (British Columbia), Venus (Yukon Territory)	Tectonic uplifts containing metamorphic basement rocks and abundant granitoid batholiths	Quartz veins in brittle to brittle-ductile faults	Sericitization and chloritization	Au, Ag±Cu, Pb, Zn Au:Ag variable	1–10 Mt of ore @ 1–10 g/t Au
14	Greenstone-hosted quartz-carbonate vein (Mother Lode–type)	Mother Lode–Grass Valley (California), Mt. Charlotte, Norseman, Victory (Australia)	Sigma–Lamaque (Quebec), Con–Giant (Northwest Territories), Contact Lake (Saskatchewan), San Antonio (Manitoba), Dome, Kerr Addison (Ontario)	Greenstone belts; spatially associated with major fault zones	Quartz-carbonate veins associated with brittle-ductile shear zones	Carbonatization and sericitization	Au, Ag, W, B± As, Mo Au:Ag = 5:1 to 10:1 no vertical zoning	1–10 Mt of ore @ 5–10 g/t Au; mostly 25–100 t Au, but many >250 t Au
15	Turbidite-hosted quartz-carbonate vein (Bendigo-type)	Victoria Goldfields (Australia); Ashanti (Ghana), Otago (New Zealand)	Camlaren (Northwest Territories), Little Long Lac (Ontario), Meguma (Nova Scotia), Cape Ray (Newfoundland)	Deformed turbidite sequences	Quartz-carbonate veins in folds and brittle-ductile shear zones	Minor sericitization and silicification	Au, Ag, As±W Au:Ag = 5:1 to 10:1	Mostly <5 Mt or ore @ 6–15 g/t Au; some >500 t Au
16	Iron-formation-hosted vein + disseminated (Homestake-type)	Homestake (South Dakota), Jardine (Montana), Cuiaba (Brazil), Hill 50 (Australia)	Lupin (Nunavut), Farley (Manitoba), Central Patricia and Cockshutt (Ontario), Nugget Pond (Newfoundland)	Mixed volcanic, volcaniclastic, and sedimentary sequences in greenstone belts	Banded stratabound disseminated to massive-sulphide lenses and discordant quartz veins	Sulphidation of pre-existing iron-formation facies; chlorite-carbonate alteration	Au, Ag, As Au:Ag = 5:1 to 10:1	1–10 Mt of ore @ 3–20 g/t Au; some >500 t Au

and base-metal sulphide minerals, but commonly contains complex high-sulphidation assemblages, including minor phases such as bornite, sulphosalts, arsenopyrite, and tellurides. It therefore contains considerable iron, a few per cent combined base metals (Cu, Pb, Zn) and gold concentrations (in ppm) exceeding the percentage of base metals. Locally high concentrations of arsenic, antimony, mercury, and silver, generally exceeding that of gold (Au:Ag = 1:2 to 1:10), are common features of these deposits.

The deposits occur in districts containing subvolcanic intrusions and other volcanogenic massive-sulphide deposits which contain proportionately less gold. They are hosted mostly by felsic volcanic tuff and derived schist near their interface with basalt or sedimentary strata. The host rocks are typically sericitized and chloritized, with local massive silicic alteration, and some deposits are enveloped by zones of andalusite-bearing aluminous alteration resulting from extreme alkali depletion (Fig. 8). The latter may be another distinguishing feature of gold-rich massive-sulphide ores and is thought to result from boiling of ore-forming fluids (Hannington et al., 1998). This further suggests that shallow-water sequences showing a transition to subaerial conditions (Bergman-Weihed et al., 1996) may be more favourable environments than other massive-sulphide environments (Sillitoe et al., 1996).

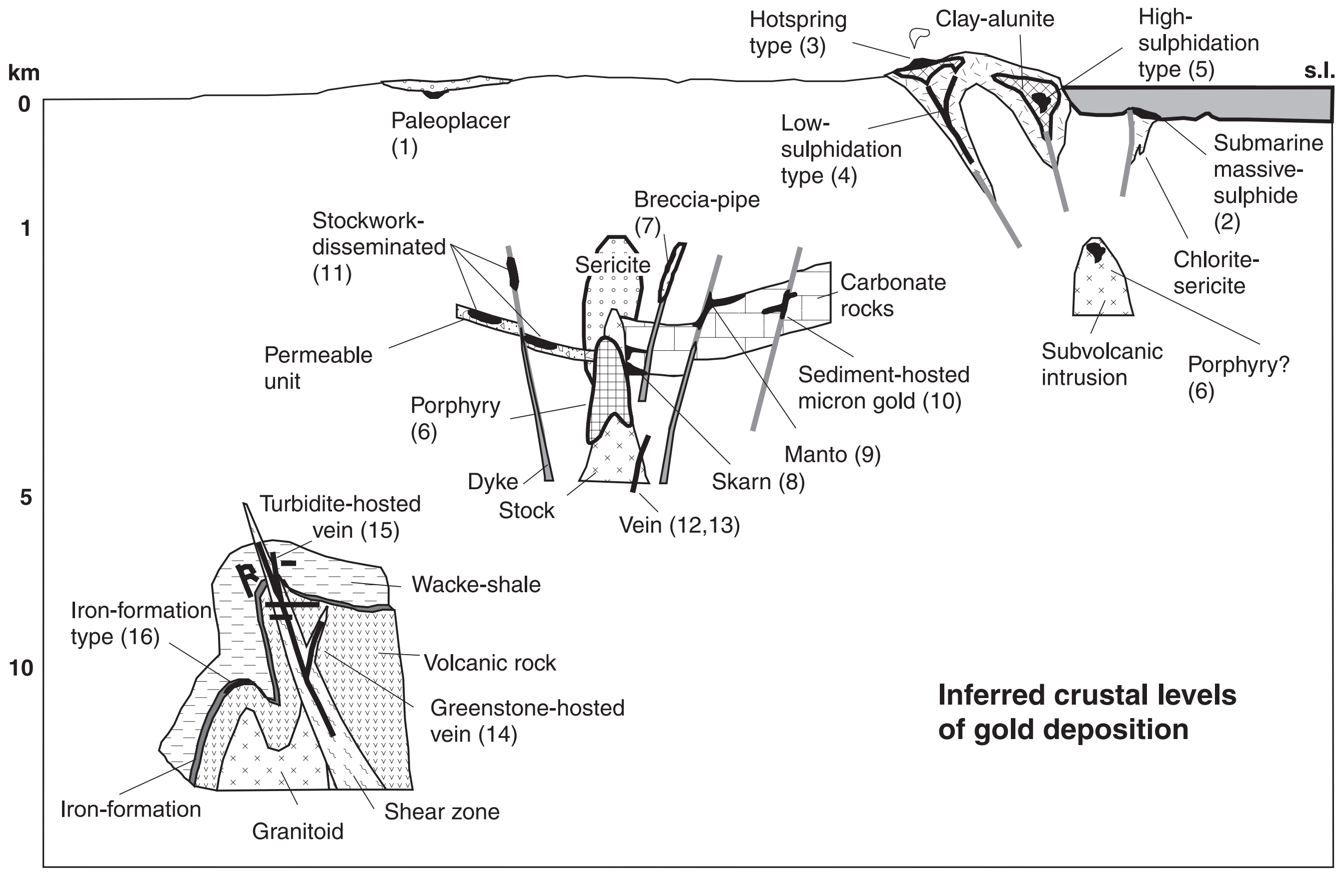


Figure 6. *Crustal settings of major gold deposit types. Numbers correspond to deposit types in Table 3, and Figure 84.*

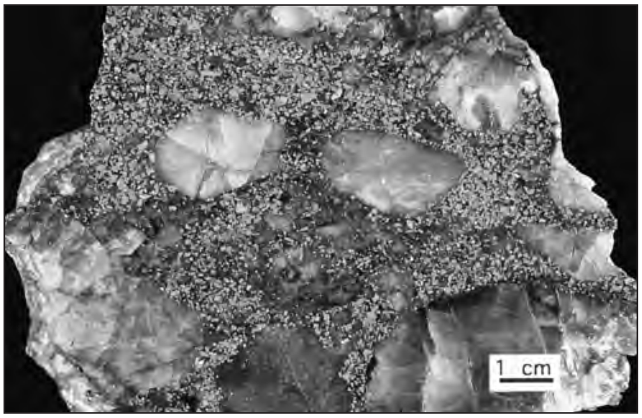


Figure 7.

Quartz-pebble conglomerate; Quirke mine, Elliot Lake, Ontario. GSC 1999-014A

Hotspring deposits (3)

Hotspring deposits (Nelson and Giles, 1985; Nelson, 1988; Bonham, 1989) are specific subtypes of epithermal deposits for which there is convincing geological evidence of a surface to near-surface origin. There is no general agreement as to whether these deposits should really be singled out from other epithermal gold deposits, particularly those of low-sulphidation adularia-sericite type, but the fact that they preserve evidence of the position of a paleosurface is a practical, geologically motivated reason for distinguishing them. Examples such as McLaughlin in California consist of siliceous sinter (Fig. 9) and geyserite formed at the paleosurface, but also include subsurface, funnel-shaped, hydrothermal and tectonic breccia, and quartz stockworks narrowing at depth into structurally controlled feeder zones. These deposits occur in belts of subaerial mafic and felsic volcanic centres and intervening clastic sedimentary rocks in subduction-related arc settings. They are mainly recognized in young volcanic belts, but, perhaps due to their poor chance of preservation, are not known to exist widely in older, deformed terranes. Nonetheless, some Paleozoic examples of this deposit type have been reported (Cuneen and Sillitoe, 1989).

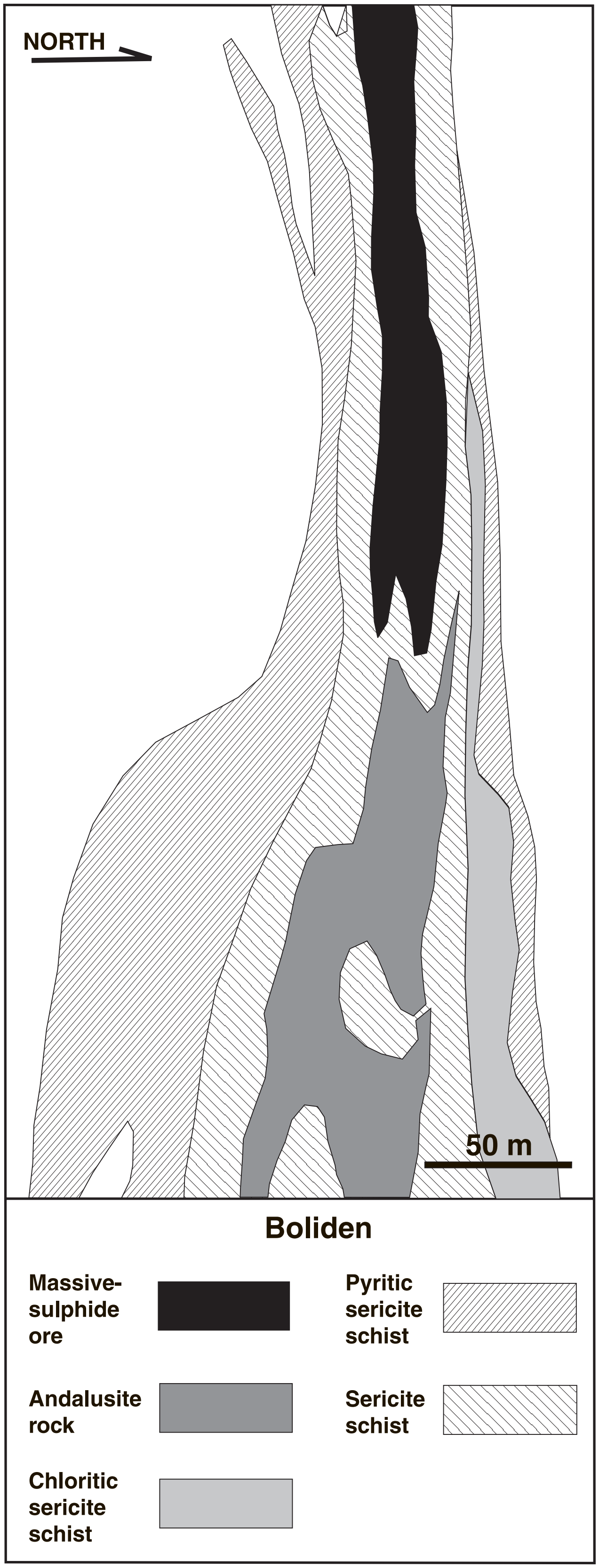


Figure 8. *Geological cross-section of the Boliden gold deposit, Sweden (after Grip and Wirstam, 1970).*

Ore in this deposit type is hosted by vent and hydrothermal breccia in volcanic or sedimentary rocks, as well as by subvolcanic porphyritic intrusions. The ore consists of micron-scale gold in zones of massive silicification, less commonly in sinter zones (which are nonetheless defining features), and in crustiform banded quartz±adularia and carbonate veins and stockwork zones. Thick deposits (5–50 m) of siliceous sinter (opal and chalcedony inverted from amorphous silica) typically form around hydrothermal vents. Micron-size native gold or electrum occurs with microcrystalline silica (brown hydrocarbon-bearing opal and chalcedony) and/or quartz and barite. Calcite, dolomite, siderite, and magnesite are common gangue minerals. Ore contains up to 5% pyrite±marcasite, pyrrhotite, cinnabar, stibnite, realgar, and tellurides, with elevated concentrations of mercury, arsenic, antimony, and barium. It commonly displays a characteristic steep, vertical, metal zoning with near-surface enrichments in mercury, antimony, thallium, and arsenic, and increasing silver content with depth (Au:Ag from 1:1 near surface to 1:30 at depth) (White and Hedenquist, 1995). The strong vertical variations over tens of metres likely reflect shallow-level boiling, fluid mixing, and steep thermal gradients.

Associated alteration consists of massive silicification and adularization of breccia zones, grading outward into zones of steam-heated advanced argillic and argillic alteration (cristoballite, alunite, and kaolinite), and downward into narrower zones of adularia along vein margins and as replacements along hydrothermal conduits. These deposits are thought to represent the near-surface expressions of deeper low-sulphidation vein deposits with which they may be transitional (Fig. 6). Diagnostic features are the presence of siliceous sinter caps composed of amorphous silica with columnar growth structures perpendicular to laminations (Fig. 9c) and geyserite (rounded balls of concretionary silica which accumulate on rock fragments from the throat of the geyser interbedded with hydrothermal breccia) coupled with the common presence of mercury in the form of cinnabar.

Low-sulphidation epithermal deposits (4)

These deposits, also referred to as 'adularia-sericite' epithermal deposits, consist of subvertical banded and breccia veins with associated irregular stockwork and hydrothermal breccia zones and less common disseminations (Hedenquist et al., 1995). They occur in volcano-plutonic continental and island arcs at convergent plate margins, in association with subaerial, intermediate to felsic, calc-alkalic volcanic centres and related subvolcanic porphyritic intrusions, or, less commonly, with alkalic-shoshonitic igneous rocks and related sedimentary rocks. The deposits are hosted by extensional or transcurrent structures and are commonly associated with calderas. They commonly occur immediately above the basement to the host volcanic rocks, but also in basement rocks, and relatively impermeable rock types play an important ponding role in some deposits. Most significant deposits of this type are Cenozoic and Mesozoic.

Veins, stockworks, and hydrothermal breccia zones consist of crustiform-, colloform-, and cockade-textured chalcedonic quartz (Fig. 10a–d, *see* colour section) accompanied by adularia

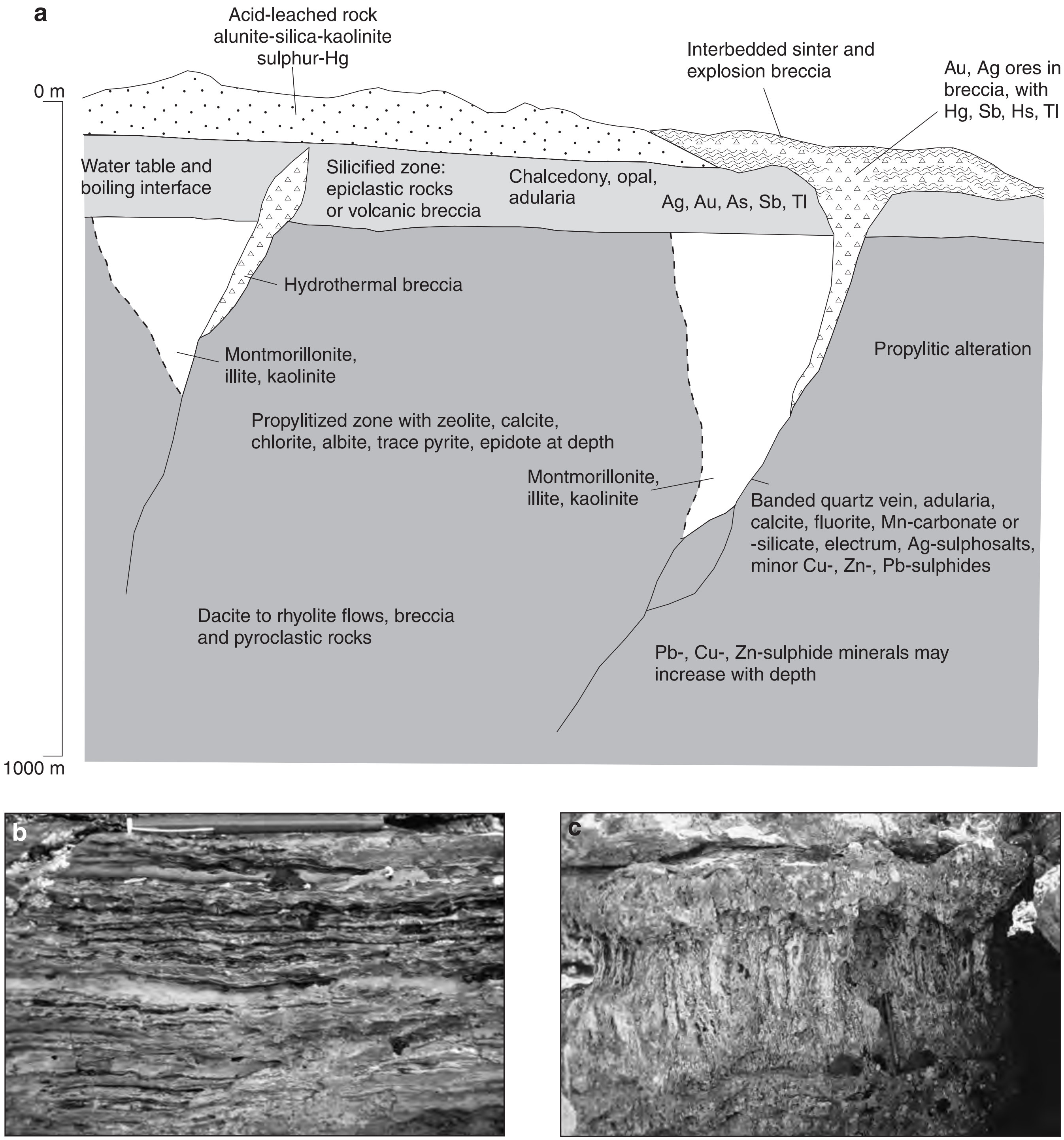


Figure 9. *Hotspring deposits.* ***a****) Schematic diagram of a hotspring-type deposit (after Bonham, 1988). Sinter textures:* ***b****) subhorizontal fine laminations in siliceous sinter containing approximately 1 g/t Au and 7 g/t Ag; La Josefina, Patagonia, Argentina (photograph by B. Dubé). GSC 1999-014B* ***c****) Columnar growth texture perpendicular to laminations in sinter; El Macanudo, Patagonia, Argentina (photograph by B. Dubé). GSC 1999-014C*

and Mn-carbonate with electrum, silver-sulphide minerals, and sulphosalts. The gold-silver±tellurium, lead, zinc ores are vertically zoned and grade downward over distances of tens to hundreds of metres into precious-metal-poor, base-metal-rich (Zn, Pb) ores with distinctive quartz textures (Dong et al., 1995). Ores are either base-metal-poor with gold-to-silver ratios of 10:1 to 1:10 , or base-metal-rich with gold-to-silver ratios of less than 1:25 (Sillitoe, 1993). Some veins within mining districts also show significant lateral zoning of metals over distances of several kilometres, as illustrated by the Jinchanggouliang district in northeast China (Fig. 11). Hydrothermal alteration adjacent to individual veins in deposits of this type grades outward from silicification, sericitization±fine-grained adularia near the veins, to a broader zone of propylitic alteration. Lattice-textured bladed calcite or barite (Fig. 10e, f, *see* colour section) pseudomorphed by silica is common and thought to be a direct product of boiling.

High-sulphidation epithermal deposits (5)

These deposits, also known as ‘alunite-kaolinite’ or ‘acid-sulphate’ types, are noted for their diagnostic high-sulphur-mineral assemblages and massive silicic and advanced argillic alteration containing hypogene alunite (Heald et al., 1987; Hedenquist et al., 1994, 1995; Arribas et al., 1995). They consist of disseminated replacement sulphide minerals in irregular, stratabound to mushroom-shaped, discordant, vuggy, silica-replacement zones, and less commonly in hydrothermal breccia zones, stockworks, and veins. They are associated with subaerial, calc-alkaline, andesite to rhyodacite volcanic centres and related subvolcanic porphyritic intrusions and sedimentary rocks in volcano-plutonic arcs at convergent plate margins of all ages. These high-sulphidation deposits are commonly hosted by volcanic dome-vent complexes, maar diatremes, and basaltic volcanic rocks (Pueblo Viejo, Dominican Republic) and volcaniclastic sedimentary rocks (La Coipa, Chile) above basement, or by underlying basement rock types, in association

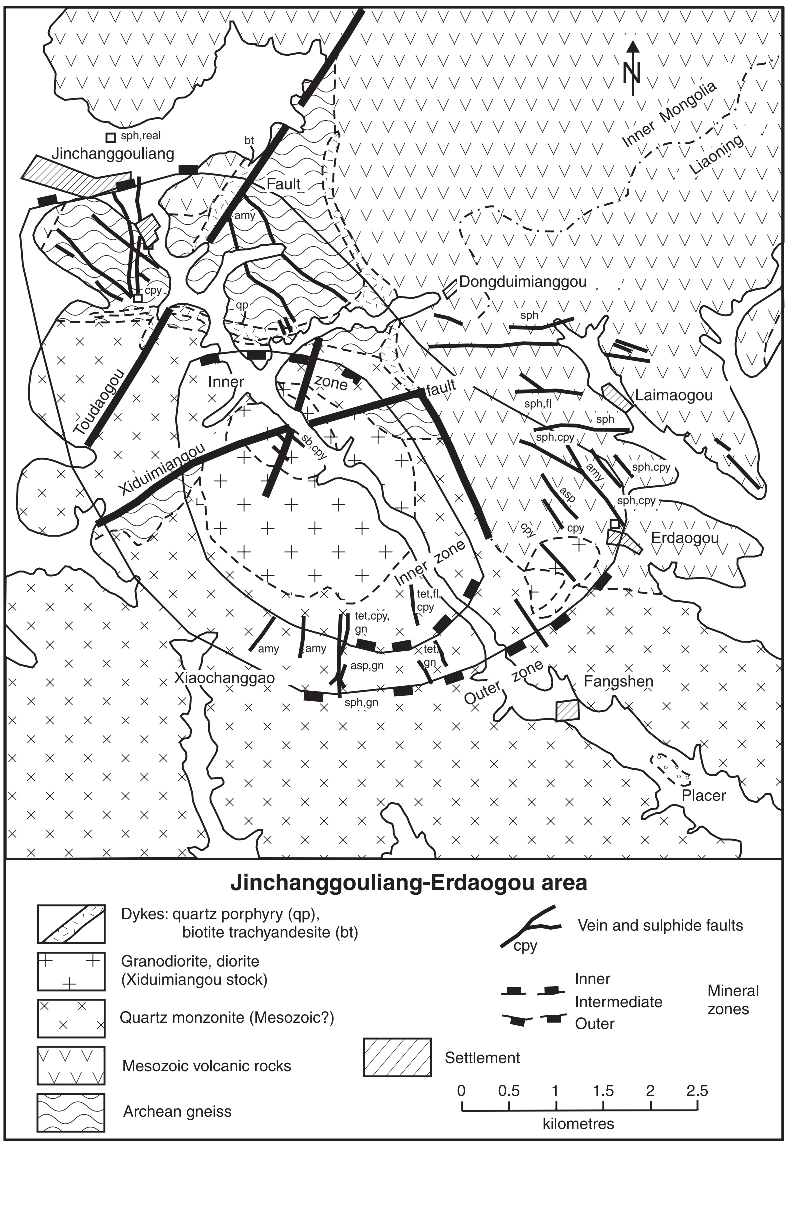


Figure 11.

Map of the Jinchanggouliang–Erdaogou area, western Liaoning and Inner Mongolia, China, as an example of a zoned low-sulphidation epithermal vein system (after Lin et al., 1991). Note the zonal distribution of ore minerals about the Xiduimiangou stock. The Inner zone is enriched in copper, the Outer zone in lead-zinc. Mineral abbreviations: amy - amethyst, fl - fluorite, tet - tetrahedrite, cpy - chalcopyrite, asp - arsenopyrite, sph - sphalerite, gn - galena, sb - stibnite, and real - realgar. The Erdaogou deposit is at lat. 42°56′N, long. 125°34′E.

with regional normal and transcurrent faults, or with diatreme ring faults. Most deposits like Goldfield, Nevada, are Cenozoic, with a few Mesozoic to Precambrian examples.

Ore in these deposits commonly consists of 'high-sulphidation' assemblages including phases such as pyrite, enargite-luzonite, chalcopyrite, tennantite-tetrahedrite, and gold in a gangue of massive or, more commonly vuggy, silica, or quartz±alunite assemblages in veins and breccia (Fig. 12a, d, e, *see* colour section). This ore assemblage occurs within zones of leached vuggy silica (Fig. 12c, *see* colour section) that overprint larger zones of earlier massive silicic alteration, above or grading outward into advanced argillic (Fig. 12b *see* colour section,), argillic, and/or propylitic alteration zones. The gold-to-silver ratio of the ore typically ranges from 1:2 to 1:10, and associated metals include mainly copper, arsenic, antimony, and locally, mercury, lead, and bismuth (White and Hedenquist, 1995). The high-sulphidation deposits commonly have limited vertical extent (<500 m) and lack significant vertical zoning. They are thought to occur above porphyry copper or copper-gold systems to which most authors have suggested that they are genetically related (Arribas et al., 1995).

Porphyry gold deposits (6)

Porphyry gold and gold-copper deposits (Sillitoe, 1991a, b) are irregular to pipe-like zones (Fig. 13) of quartz-sulphide stockwork, sheeted veins, and associated disseminated sulphide minerals confined to intrusions and their immediate wall rocks (Fig. 14, *see* colour section). They occur in volcano-plutonic belts in continental or island-arc settings, overlying a wide range of basement rock types. The deposits are associated with composite stocks of calc-alkaline (diorite, granodiorite, quartz-monzonite) and alkaline (monzonite, quartz syenite)

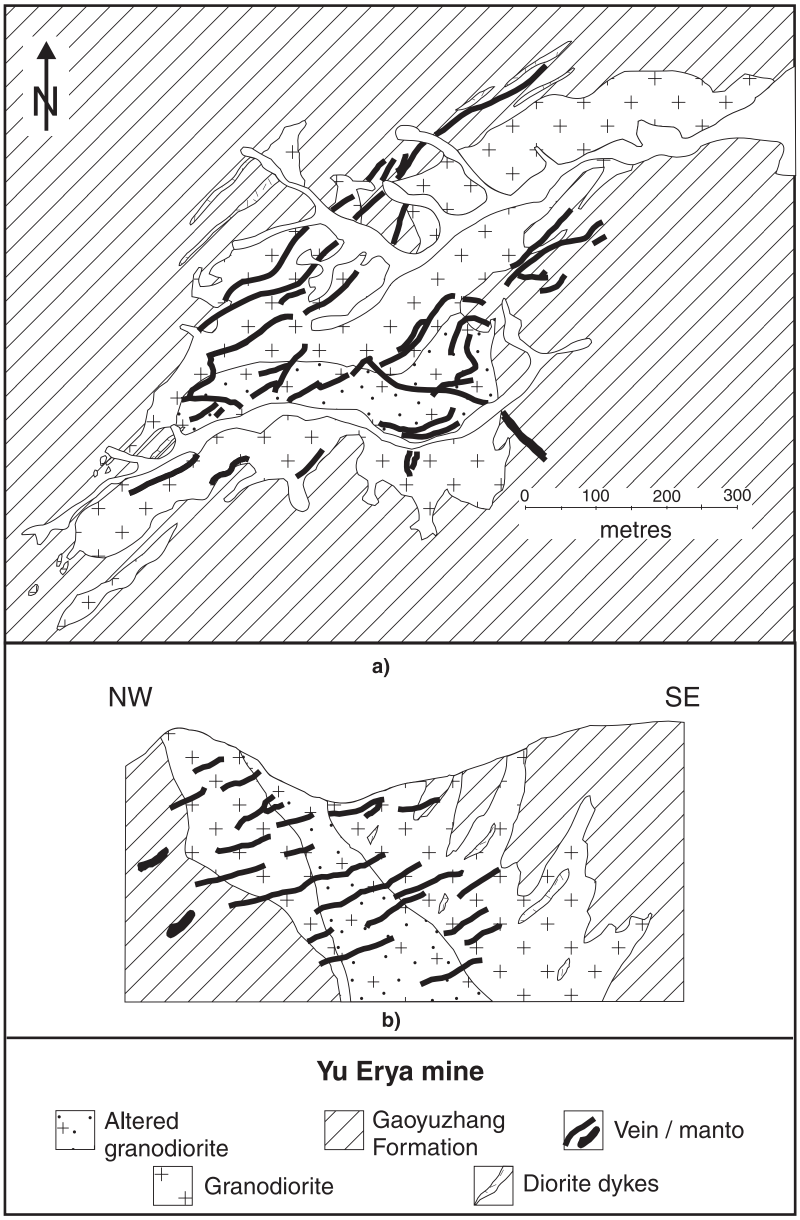


Figure 13.

Plan and schematic section of the Yu Erya mine, Eastern Hebei, China, as an example of a porphyry gold deposit (after Poulsen and Mortensen, 1993). The Yu Erya mine is at lat. 40°10′N, long. 118°19′E.

compositions, with locally preserved remnants of coeval volcanic rocks. The quartz stockworks are less well developed in deposits associated with alkalic intrusions.

Pyrite is the dominant sulphide mineral; its abundance ranges from 1–3 volume per cent in the ore zone to 5–10 volume per cent outside, and it is accompanied by up to 20 volume per cent hydrothermal magnetite±hematite, either in the stockwork ore or as wall-rock disseminations (Fig. 14d, e, *see* colour section). The ore typically contains more silver than gold (Au:Ag < 1), and associated metals include copper, bismuth, tellurium±molybdenum. Mineralization is coincident with potassium-silicate alteration, or albite and calc-silicate alteration in alkalic systems, grading outward into large zones of propylitic alteration. In some deposits, argillic or advanced argillic alteration overprint parts, or most, of potassium-silicate alteration.

Some porphyry-like gold deposits, like Fort Knox, Alaska (Bakke, 1995), and Yu Erya, China (Poulsen and Mortensen, 1993), differ substantially from the conventional calc-alkaline gold-copper porphyry deposits. As in the case of Yu Erya (Fig. 13), the host intrusions are not unduly porphyritic, much of the gold is in quartz veins (Fig. 14b, *see* colour section) and shear zones rather than in rarer stockworks and disseminations (Fig. 14c, *see* colour section), and they appear to have formed in deeper crustal environments than conventional porphyry deposits. These may represent a subtype of porphyry gold deposit related to ilmenite-series I-type magmas rather than the more familiar magnetite-series intrusions (J. Lang, pers. comm., 1997).

Breccia-pipe deposits (7)

Such deposits, as represented by Kidston, Australia, consist of mineralized, funnel-shaped, pipe-like, discordant breccia bodies and sheeted fracture zones in mafic to felsic, calc-alkaline volcanic environments in volcano-plutonic arcs and greenstone belts (Sillitoe, 1991a). They are often controlled by graben faults and ring complexes related to cauldron development. Ore can be hosted by a variety of breccia types, including magmatic-hydrothermal, phreatomagmatic, hydraulic, and collapse varieties. Breccia cement consists dominantly of quartz, carbonate (calcite, ankerite, siderite), with specularite and tourmaline at some deposits. Ore commonly contains pyrite, chalcopyrite, sphalerite, galena, and pyrrhotite, with minor molybdenite, bismuthinite, tellurobismuthite, and tetrahedrite, which occur either in the cement or in rock fragments. It is silver rich (Au:Ag = 1:10), with associated lead, zinc, copper±molybdenum, manganese, bismuth, tellurium, and tungsten, and a lateral (concentric) metal zoning is present at some deposits. A sericite-quartz-carbonate-pyrite alteration assemblage, along with variably developed silicification, is coincident with the ore zones and grades outward into propylitic alteration. An early-stage potassium-silicate alteration is present at some deposits. Breccia-pipe deposits are commonly associated with intrusion-related hydrothermal systems.

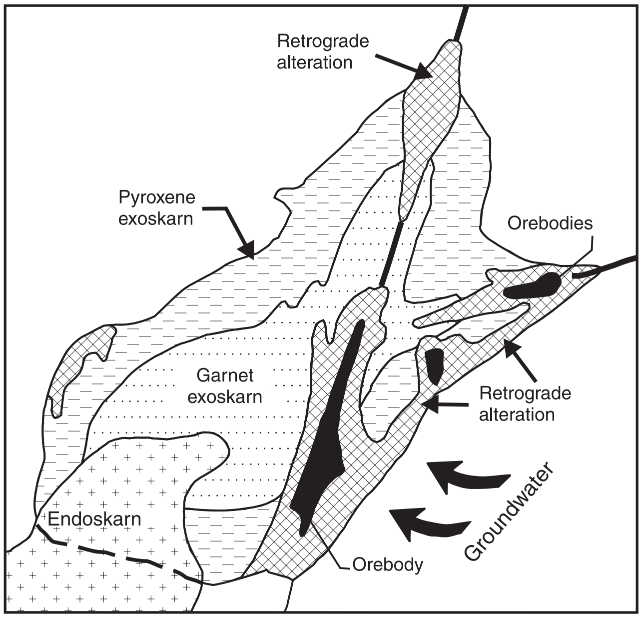


Figure 15. *Schematic model of a gold skarn deposit (after Ray and Webster, 1991).*

Skarn deposits (8)

Skarn deposits, as exemplified by Hedley, British Columbia, consist of disseminated to massive-sulphide lenses and cross-cutting veins in carbonate platform sequences overprinted by volcanic and/or plutonic arcs (Fig. 15). Mineralization is associated with aluminum-rich garnet-pyroxene skarn assemblages replacing limestone, calcareous siltstone, and carbonatized volcanic rocks adjacent to diorite or granodiorite stocks, dykes, or sills (Meinert, 1989; Ray and Webster, 1991). They occur in some districts along with porphyry copper-molybdenum mineralization and are usually associated with more mafic, hotter intrusions.

Orebodies are commonly composed of pyrite, pyrrhotite, arsenopyrite, and smaller amounts of telluride minerals. Ores contain locally high concentrations of arsenic, bismuth, and tellurium, and show wide variations in their gold-to-silver ratios (Au:Ag = 1:10 to 10:1). Retrogression of prograde skarn assemblages is common, and gold mineralization is considered to be related to such retrogression. Until recently, the retrogression was thought to result from ingression of meteoric fluids during the late stages of skarn development, but more recent studies (Meinert et al., 1997) suggested that the late-stage ores in skarns form from low-salinity ascending magmatic fluids which, unlike the prograde high-salinity fluids, have not undergone phase separation.

Carbonate-replacement (manto) deposits (9)

Carbonate-replacement gold deposits, such those at Ruby Hill, Nevada (Fig. 16), consist of discordant pipes or tabular concordant bodies of massive-sulphide minerals replacing

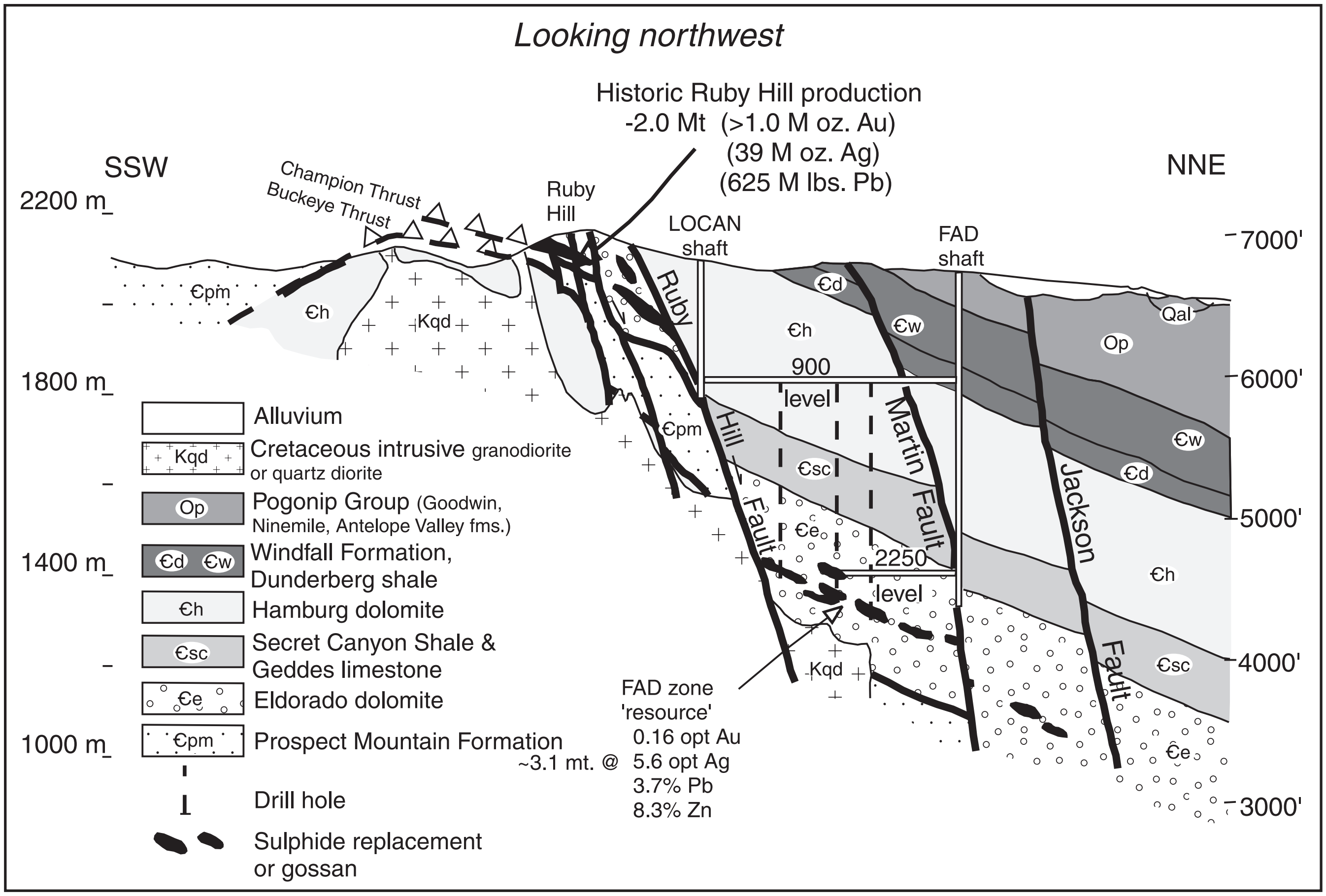


Figure 16. Geological cross-section of the Ruby Hill deposit, Nevada, showing the relationship between manto- and Carlin-type mineralization (after Dilles et al., 1996).

limestone or dolostone beds, commonly interlayered with calcareous quartzite, quartzite, and phyllite. Like the more common silver-lead-zinc mantos (Beatty et al., 1990), they occur in continental-platform, carbonate, sedimentary sequences superimposed by volcano-plutonic arcs. The deposits occur near a 'marble front' related to nearby intrusions (Sillitoe, 1991a), represented in some cases only by dioritic sills and dykes, but they are in many cases remote from intrusive rocks. Fault intersections are important in localizing discordant mineralized pipes.

Orebodies are composed largely of pyrite, and may contain variable amounts of pyrrhotite, galena, sphalerite, chalcopyrite, magnetite, and arsenopyrite. The ores are typically silver rich (Au:Ag < 1), with elevated concentrations of arsenic, bismuth, and mercury, and they may contain several per cent of combined lead, zinc, and copper. Associated hydrothermal alteration is generally restricted to the immediate vicinity of the orebodies and consists of silicified carbonate rocks and adjacent sericitized clastic sedimentary rocks.

Sediment-hosted micron gold deposits (10)

These deposits, also referred to as being of 'Carlin type' (Berger and Bagby, 1991; Arehart, 1996), are irregular, discordant breccia bodies and concordant, stratabound disseminated zones (Fig. 17) confined to particular stratigraphic units. They occur in carbonate and impure carbonate-argillite facies of continental platforms and shelves that have been overprinted by regional thrusting, extensional faulting, and felsic plutonism. The deposits are hosted mostly by impure carbonate rocks of Paleozoic age, but also by clastic sedimentary rocks, greenstones, and rarely granitoid stocks. They commonly occur near hornfels, skarn, or calc-silicate rocks, but typically outward from the edge of contact metamorphic aureoles. They coexist regionally with copper and/or molybdenum porphyry, copper or tungsten-molybdenum skarn, and silver-lead-zinc vein and manto deposits.

Mineralization consists of disseminated, very fine-grained pyrite overgrown by arsenian pyrite rims containing submicron-size gold inclusions. Orpiment, realgar, cinnabar, and stibnite are common accessory minerals at the deposit scale. The gold-to-silver ratios of the ores are highly variable, but typically less than one, and the ores contain locally high concentrations of arsenic, antimony, mercury, and thallium. Decalcified and silicified carbonate rocks, in the extreme case forming jasperoid (Fig. 18, *see* colour section), are typically associated with ore which also may be enveloped by zones of argillic and sericitic alteration. Despite common stratigraphic controls on many orebodies, high-angle faults are important ore controls for most of them, and deep, discordant breccia bodies host high-grade mineralization at some deposits.

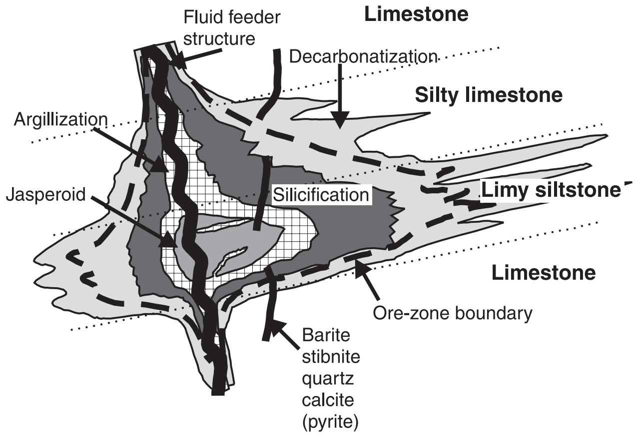


Figure 17. *Schematic diagram illustrating the main features of Carlin-type gold deposits (after Arehart, 1996).*

Non-carbonate stockwork-disseminated deposits (11)

This poorly defined group of deposits includes the Andacollo gold deposit in Chile, the ‘stage I’ mineralization at Porgera, Papua New Guinea, and perhaps the bulk of the ore at Muruntau, Uzbekistan. This deposit type consists of discordant to stratabound stockwork and disseminated sulphide zones along faults, permeable units, and lithological contacts (including intrusive contacts) in miogeoclinal siliciclastic and volcaniclastic sequences in volcano-plutonic arcs in oceanic and continental settings. The deposits are hosted mostly by supracrustal rocks, but in cases where felsic sills, dykes, and stocks are present, the ore may also occur within and along the contacts of intrusions (Sillitoe, 1991a).

Disseminated sulphide minerals (1–20 volume per cent) are mostly pyrite, with smaller amounts of chalcopyrite and arsenopyrite, accompanied by hematite, magnetite, tellurides, and anhydrite in some deposits. The ores have variable, but generally gold-rich, compositions (Au:Ag > 1) and contain elevated concentrations of copper, arsenic, bismuth, tellurium±tungsten, fluorine, and boron. Associated alteration involves potassium metasomatism (sericite, biotite, or K-feldspar) and/or sodium metasomatism (albite), typically accompanied by carbonatization and, in some deposits, silicification.

Copper-gold sulphide-rich vein deposits (12)

These deposits consist of groups of sulphide-rich veins (>20 volume per cent sulphide minerals), up to several hundred metres in strike length, in volcano-plutonic arcs and greenstone belts of all ages. As in the case of Rossland, British Columbia (Fyles, 1984), they occur in faults and fractures hosted by a wide variety of volcanic and intrusive rocks; individual veins commonly follow dykes or sills of dioritic, tonalitic, or lamprophyric composition. In many cases, there is a marked structural control by regional fault systems.

The veins consists of variable proportions of pyrite, pyrrhotite, chalcopyrite, and magnetite, with subordinate amounts of sphalerite and galena, in a gangue of quartz and carbonate with smaller amounts of chlorite and sericite. The veins typically contain more silver than gold (Au:Ag = 1:2 to 1:5) and 0.5–3% Cu. The associated hydrothermal alteration consists of chlorite and sericite, and is generally restricted to the immediate vicinity of the veins.

Batholith-associated quartz-vein deposits (13)

These deposits, including Chenoan, Korea, and Ling Long and Jiaojia, China, are commonly referred to as ‘Korean type’ (Shelton et al., 1988) and consist of quartz veins in brittle-ductile faults and adjacent crushed, altered wall rocks and veinlet zones in tectonic uplifts containing metamorphic basement and abundant granitoid rocks. Orebodies are hosted both by granitoid batholiths and adjacent medium- to high-grade schist and gneiss. Deposits are controlled by regional fault systems and form extensive districts (Fig. 19) that locally contain porphyry and epithermal styles of mineralization as well. Veins contain small amounts of pyrite and minor base-metal sulphide minerals, and stibnite in some cases, in a gangue of quartz and minor calcite (Fig. 20a, *see* colour section), and, in some cases, the vein materials have been cataclastically deformed to yield black, pyritic, crushed zones (Fig. 20b, *see* colour section). Ores of this deposit type contain nearly equal abundances of gold and silver (Au:Ag = 1:5 to 5:1), and locally high concentrations of copper, lead, and zinc. Hydrothermal alteration consists of sericitization and chloritization of wall rocks, generally within a few metres of the veins. These deposits share with the gold-copper vein deposits (*see* above) the characteristic of occurring in vein swarms which may be intrusion related, but which are not disposed in a clear pattern around an identifiable intrusive centre.

Greenstone-hosted quartz-carbonate-vein deposits (14)

Deposits of this group (Fig. 21), typified by the Late Jurassic to Early Cretaceous Mother Lode and Grass Valley areas of California, as well as numerous Precambrian examples (Hodgson, 1993), consist of quartz-carbonate veins in moderately to steeply dipping brittle-ductile shear zones and locally in related shallow-dipping extensional fractures (Fig. 22, *see* colour section). They are commonly distributed along major fault zones in deformed greenstone terranes of all ages. Veins have strike and dip lengths of 100 to 1000 m and occur singly or, more typically, constitute complex vein networks. The veins are hosted by a wide variety of host rock types, but there are district-specific lithological associations.

Veins of this type are dominated by quartz and carbonate, with lesser amounts of chlorite, scheelite, tourmaline, and native gold; pyrite, chalcopyrite, and pyrrhotite constitute less than 10 volume per cent of the veins. The ores are gold-rich (Au:Ag = 5:1 to 10:1) and have elevated concentrations of arsenic, tungsten, boron, and molybdenum, with very low base-metal concentrations. Despite their significant vertical extent (commonly >1 km), the deposits lack any clear vertical mineral zoning. Wall-rock alteration haloes are zoned and consist of carbonatization, sericitization, and pyritization.

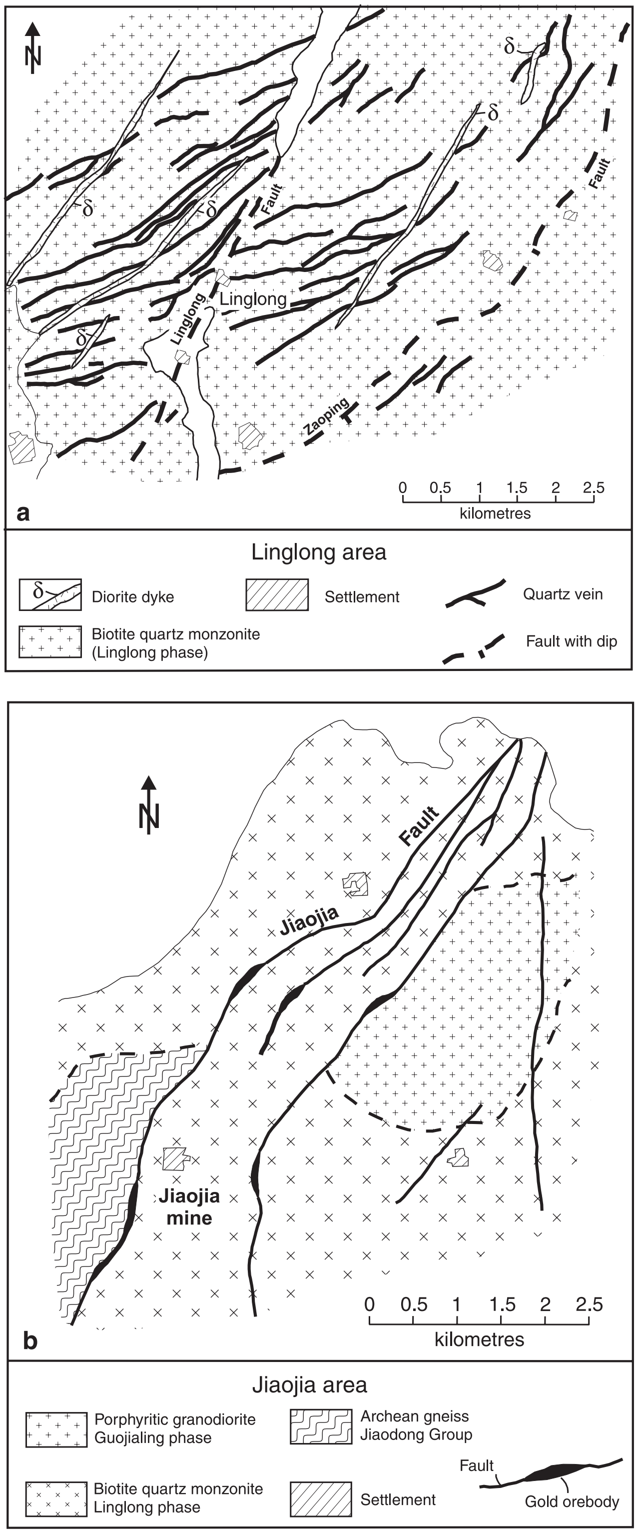


Figure 19. *Plans of Linglong and Jiaojia deposits, Shandong Province, China, as examples of Korean-type deposits (from Poulsen et al., 1990).* ***a****) Linglong quartz-vein swarm.* ***b****) Jiaojia veins and faults. The Jiaojia mine is at lat. 37°25′N, long. 120°04′E.*

Halo dimensions vary with the composition of the host rock types and may envelope entire deposits in mafic and ultramafic rocks.

Turbidite-hosted quartz-carbonate-vein deposits (15)

These deposits consist of veins (Fig. 23) and vein arrays in folds (saddle reefs), faults, and brittle-ductile shear zones in turbidite sequences of all ages, deformed and metamorphosed to lower to upper greenschist facies (Boyle, 1986). Graphitic schists in such sequences are particularly favourable hosts, and intrusive rocks are generally lacking within and immediately around the deposits. The deposits are commonly associated with anticlines and related limb-thrust faults as exemplified by Bendigo and Ballarat, Australia (Cox et al., 1991; Phillips and Hughes, 1996). The veins consist of quartz and carbonate, with smaller amounts of chlorite and sericite; arsenopyrite and pyrite typically constitute less than 10 volume per cent of the veins. The ores are gold rich (Au:Ag > 5) and contain elevated concentrations of arsenic and tungsten. Wall-rock alteration, in the form of sericitization and some silicification, is generally restricted to the immediate vicinity of veins.

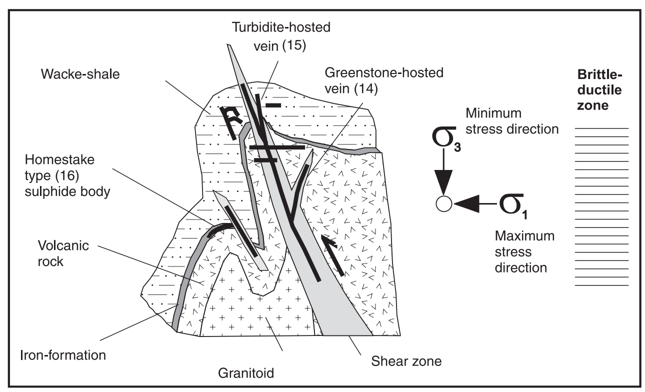


Figure 21*. Schematic model of Mother Lode– (14), Homestake- (16), and Bendigo-type veins (15).*

Figure 23. *Bedding-parallel laminated quartz vein; Bendigo, Australia (photograph by F. Robert). GSC 1999-015G*

Iron-formation-hosted vein and disseminated deposits (16)

This class of deposits consists of stratabound, disseminated to massive-sulphide lenses and discordant quartz veins in folded iron-formation (Kerswill, 1993). Also commonly termed 'Homestake-type' deposits (Caddey et al., 1991), they occur in mixed volcanic, volcaniclastic, and sedimentary sequences in greenstone belts of all ages, typically metamorphosed to greenschist to lower amphibolite facies. Host rocks are oxide-, carbonate-, and sulphide-facies iron-formation, commonly at or near a volcanic-sedimentary contact. The deposits occur in regionally extensive banded iron-formation at local sites of structural complexity such as fold hinges and discordant shear zones. Stratabound sulphide lenses consist of pyrite, pyrrhotite, arsenopyrite, and native gold. Gold is more abundant in the ore than silver (Au:Ag = 5:1 to 10:1) and typically correlates positively with arsenic. Sulphidation of pre-existing iron-formation facies is most common adjacent to quartz veins (Fig. 24, *see* colour section), and chloritic and carbonate alteration form distal envelopes at some deposits.

Conclusions

The 16 well established types of lode gold deposits identified above are distinguishable mostly by differences in the nature and the geological setting of mineralization. These differences are further reflected by corresponding differences in less-diagnostic attributes of the deposits, including the composition of the ore and the nature of associated hydrothermal alteration, attesting to the coherent nature of the classification.

Despite the large number of geological types of deposits, it is clear that many of them correspond to different components of large, district-scale, hydrothermal systems and are in fact genetically related. This is the case for porphyry, skarn, breccia-pipe, carbonate-replacement, and high-sulphidation types of deposits, which are generally regarded as components of large, intrusion-centred hydrothermal systems (Sillitoe, 1991a). Other deposit types may also be related to similar magmatic-hydrothermal systems, but their exact links are less well understood; this is the case for sediment-hosted micron gold, gold-copper, sulphide-rich vein, low-sulphidation, and submarine gold-rich massive-sulphide deposits.

CANADIAN GOLD DEPOSIT TYPES

Introduction

Gold deposits are distributed throughout the major orogenic belts of Canada (Fig. 2). The most important ones occur in the Archean cratons of the Canadian Shield with fewer, and in some cases smaller, deposits in Proterozoic and Phanerozoic terranes. Differences in ages of rocks in the host terranes, the known secular variations in some geological processes (e.g. was there subduction in the Archean?) that have operated in them, differences in state of preservation, and their wide geographic separation lead to difficulty in applying deposit models with uniformity across the country. Cooke (1946) divided Canadian deposits into two fundamental types, 'vein' and 'disseminated', and noted that both were present in terranes of all ages. Nonetheless, it is still common to find subdivision of Canadian deposits by their age and their host terranes (e.g. Appalachian or Cordilleran gold deposits vs. Archean deposits). In the following pages, selected gold deposits representing the major metallogenic epochs and major gold-bearing terranes in Canada are treated equally and are compared against the standard global gold deposit types identified in the previous section, 'Gold Deposit Types'.

Archean deposits in the Canadian Shield

Archean terranes account for a major proportion of the world's gold resources (Woodall, 1988), and those in Canada contain an estimated 8125 t of gold, accounting for approximately 80% of the country's production and reserves. The Superior Province stands second among gold-producing Archean terranes of the world, next to South Africa's Kaapvaal Craton with its giant Witwatersrand paleoplacer gold deposits.

Despite the presence of significant volumes of Archean rocks in the Churchill and Grenville provinces in Canada, Archean gold deposits are largely restricted to the Superior and Slave provinces (Fig. 2). These two geological provinces host in excess of 220 gold deposits each containing more than 1 t Au; the largest concentration of deposits occurs in the southern Superior Province (Fig. 25a). In both provinces, gold deposits are hosted mainly by supracrustal sequences and coeval intrusions. The majority of them occur within, or immediately adjacent to, greenstone belts, commonly in spatial association with crustal-scale fault zones marking major lithological boundaries (Card et al., 1989; Poulsen et al., 1992). Only a few deposits, such as those in central Slave Province, are hosted by sedimentary sequences (Padgham, 1992). The majority of deposits contain between 400 000 and 10 000 000 t of ore at grades between 4 and 12 g/t Au, corresponding to 3 to 100 t of contained gold, but 14 of the deposits described below contain more than 100 t of gold and are regarded as 'world class'.

The Archean deposits and their host districts share a number of recurring geological characteristics (Table 4), similar to those in other Archean cratons around the world. With the exception of Lupin in Nunavut, hosted by a turbidite sedimentary sequence, the deposits typically occur at, or near, lithospheric fault zones marking boundaries between lithologically contrasting domains within greenstone belts or along their margins (Fig. 25a). Most districts hosting these deposits have also experienced a similar deformation history recorded in three generations of structures and related fabrics. These structures can be interpreted in terms of at least three main increments of deformation (*see* Card, 1990): D_1, characterized by local thrusts, open folds, and axial planar cleavages, and responsible for tilting of supracrustal units; D_2, defined by upright, regional, penetrative foliation and isoclinal folds and by steep reverse shear zones; and D_3, characterized by crenulation cleavages and asymmetric, steeply plunging folds, mostly developed along domain-bounding fault zones, as well as local strike-slip shear zones. The structural history of most districts can be interpreted in terms of D_1 'thin-skin' and D_2 'thick-skin' shortening, evolving into D_3 transcurrent deformation. There is ample evidence to indicate that deposition of unconformable fluvial-alluvial sediments, present in and around several world-class deposits described above, took place between D_1 and D_2 deformation increments (Card, 1990; Bleeker, 1995). The turbidite sedimentary sequence hosting the Lupin deposit has also undergone a complex structural evolution, mainly resulting from crustal shortening. Rocks around all of the deposits described below have undergone greenschist- to lower-amphibolite-grade metamorphism. The greenschist-amphibolite transition occurs within or in close proximity to several of the deposits (Table 4).

The following descriptions summarize key geological elements of several significant Canadian Archean gold deposits (Table 4). They emphasize the timing relationships of mineralization to other geological events (deformation, metamorphism, etc.) and current genetic models are discussed, based both on the work of others, on the authors' own observations, and, where appropriate, on comparisons with the globally recognized deposit types described in the previous section, 'Gold Deposit Types'. The deposits are described in an order that reflects similarities among deposits and a range of ore styles from quartz vein, to disseminated sulphide, to massive sulphide. Quartz-vein-type deposits are further grouped according to their lithological settings, i.e. volcanic-hosted, sediment-hosted, and intrusion-centred

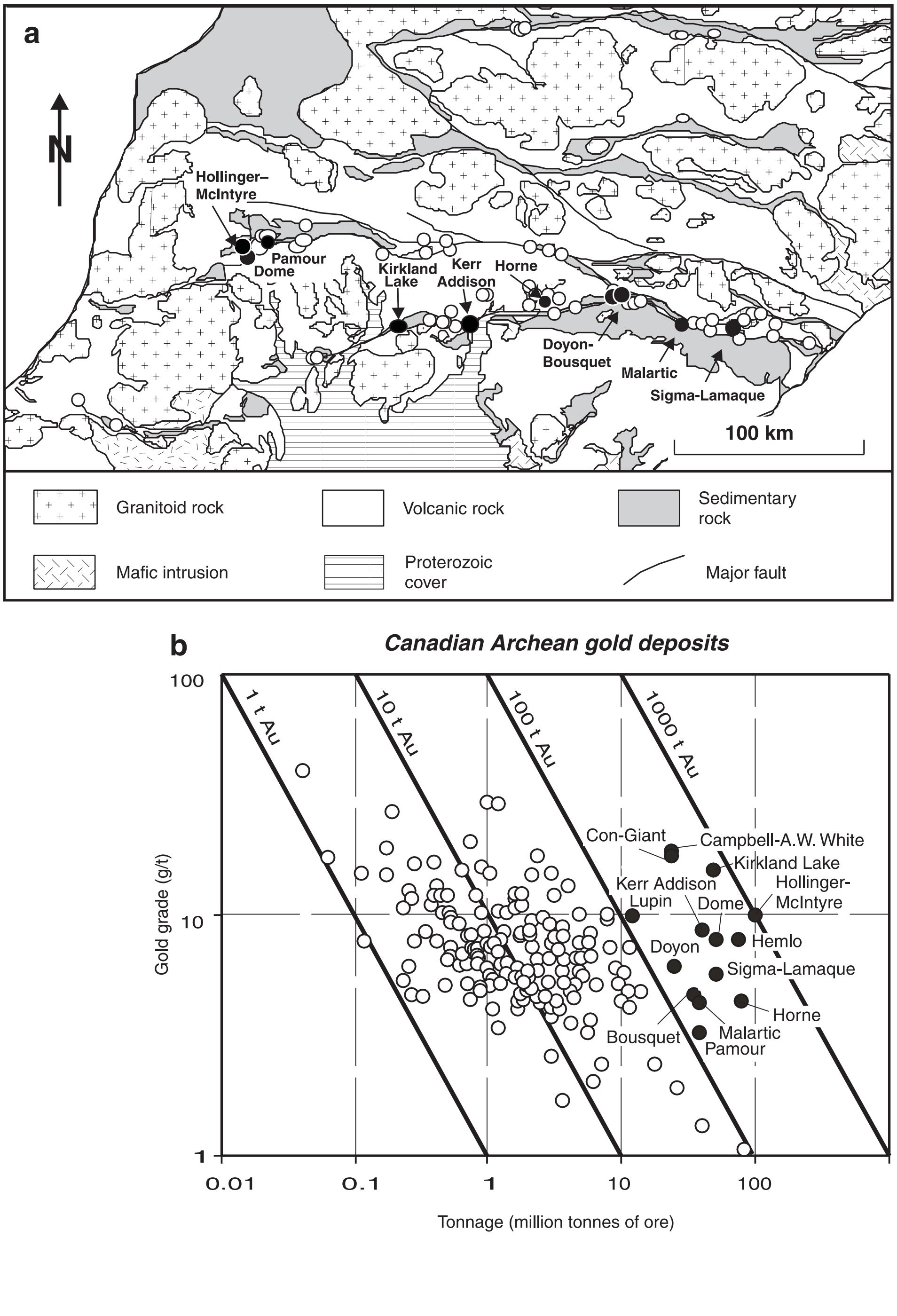


Figure 25.

***a**) Simplified geological map of parts of the Abitibi greenstone belt showing the distribution of major fault zones and of world-class (solid circles) and other gold deposits (open circles denote gold deposits containing less than 100 t of gold). **b**) Grade-tonnage diagram representing 220 gold deposits in the Superior and Slave provinces. Open circles denote gold deposits containing less than 100 t of gold, solid circles denote world-class deposits.*

Table 4. Summary of geological characteristics of Canadian Archean world-class gold deposits.

Deposit (mines)	**Kerr Addison (Kerr Addison, Chesterville)**	**Con–Giant**	**Lupin**	**Pamour**	**Dome**	**Hollinger–McIntyre**	**Sigma–Lamaque**
Size (tonnes of gold)	340	412.7	117.3	123.8	393.2	978.1	291.0
Summary description	Volcanic-hosted quartz vein stockworks and disseminated pyrite zones	Volcanic-hosted quartz veins and stockworks	Iron-formation-associated quartz veins and massive sulphide minerals	Sediment-hosted quartz veins and stockworks	Intrusion-centered quartz-vein arrays	Intrusion-centered quartz-vein arrays	Intrusion-centered quartz-vein arrays
Host rocks	Mafic and ultramafic volcanics flows adjacent to their structural contact with unconformably overlying sequence of fluvial-alluvial conglomerate and arkose. Volcanic rocks intruded by a swarm of pre- and post-ore diorite dykes.	Tholeiitic basalts overlain by intermediate to felsic volcanic and clastic sedimentary rocks, unconformably overlain by fluviatile sandstone and conglomerate, and intruded in the west by granodiorite batholith.	Turbidites interlayered with amphibolitic iron-formation consisting of garnet-amphibole-chlorite and sulphide-amphibole-chlorite end-member varieties. Felsic intrusive rocks are absent.	Tholeiitic basalt and komatiite flows unconformably overlain by polymictic conglomerate, greywacke and slate. Felsic intrusive rocks are absent.	Tholeiitic basalt flows and interflow sediments intruded by quartz-feldspar porphyry stocks and unconformably overlain by conglomerate and slate.	Tholeiitic basalt flows intruded by pre-ore quartz-feldspar porphyry stocks coalescing at depth, and by pre-ore albitite dykes.	Andesitic volcanic flows and pyroclastic rocks, intruded by an irregular mass of subvolcanic porphyritic diorite, and by pre-ore feldspar-porphyry dykes and subvertical tonalite stocks.
Structure	Volcanic and sedimentary units affected by upright, E- to NE-trending regional folds, overprinted by anastomosing schist zones of the NE-striking Larder Lake–Cadillac fault zone. Post-ore brittle faults also present.	NE-striking upright volcanic units facing to the SE, transected by a complex array of NNE-trending auriferous reverse shear zones, and by Proterozoic NNW-striking transcurrent faults.	Doubly folded iron-formation; upright, northerly-plunging F_2 isoclinal folds, with associated penetrative S_2 foliation, cut by late NE-striking subvertical quartz veins.	Steeply N-dipping but S-facing volcanic and sedimentary units on the north limb of an overturned syncline with its south limb truncated by the Porcupine–Destor Fault zone.	Steeply north-dipping volcanic units truncated by a folded unconformity defining an east-plunging syncline, itself truncated by the subvertical Dome fault.	Doubly-plunging anticline, overprinted by penetrative ENE, subvertical foliation and steeply E-plunging elongation lineation. Younger brittle faults parallel penetrative foliation.	Upright, tightly folded volcanics and porphyritic diorite, overprinted by E-W, vertical foliation and by conjugate sets of auriferous E-W steep reverse shear zones and few barren vertical ones.
Metamorphic grade	Greenschist	From middle amphibolite in the west to greenschist in the east.	From upper greenschist near surface to lower amphibolite at depth.	Greenschist	Greenschist	Greenschist	Greenschist; ~horizontal biotite isograd at depth of ~1km
Nature of ore	Quartz *stockwork zones* in carbonatized ultramafic flows (green carbonate ore) and zones of *disseminated pyrite* in carbonatized tholeiitic basalts (flow ore) and in albitized mafic dykes.	Quartz-ankerite *veins and stringer zones*, and sulphide-bearing *silicified zones* within the central portions of reverse shear zone. Veins also contain pyrite, arsenopyrite, pyrrhotite, stibnite and scheelite.	Spatially coincident gold-bearing pyrrhotite *banded iron-formation* and abundant *discordant quartz veins*, with local gold and scheelite, fringed by arsenopyrite-loellingite haloes.	Extensive *laminated quartz±ankerite veins* and zones of *sheeted quartz veinets and disseminated sulphides*. Veins contain minor pyrite, pyrrhotite, arsenopyrite, sphalerite, galena and tourmaline.	Laminated concordant ankerite and discordant quartz *veins* and zones of *disseminated sulphides* with or without extensional quartz *vein arrays and stockworks*. Veins may contain ankerite, pyrite, tourmaline, and pyrrhotite.	*Quartz-ankerite veins* and pyritized wall rocks. Tabular branching veins, sheeted vein zones and sigmoidal vein arrays, with small amounts of pyrite, albite, scheelite and tourmaline.	*Quartz-tourmaline-carbonate veins* and their pyritized wallrocks. Array of shear-zone-hosted laminated veins, fringing flat extensional veins. Veins also contain pyrite, scheelite, and pyrrhotite.
Alteration	Regional carbonate alteration zone, grading to orebody-scale fuchsite-iron carbonate alteration, and to vein-scale inner selvages of carbonate-albite-pyrite alteration.	Orebody-scale progressive carbonate, sericite and pyrite/arsenopyrite alteration, generally coincident with shear zones.	Possible hornblende alteration of background grunerite in and around ore zones; arsenide minerals and calc-silicate rocks (with scheelite) form alteration zones around late quartz veins.	Zoned, orebody-scale carbonate (calcite-chlorite) and proximal sericite (ankerite-sericite-sulphide) alteration. Pyrrhotite and arsenopyrite common in altered sedimentary rocks.	Regional carbonatization (calcite-chlorite) and orebody scale sericitization (ankerite-sericite-sulphides), with abundant fuchsite in altered komatiites.	Regional carbonate alteration zone (chlorite-calcite) accompanied by deposit-scale sericitization (ankerite-sericite) and vein- to orebody-scale albitization (albite-ankerite-sericite-pyrite).	Vein-scale carbonate, sericite and pyrite alteration, with variable additions of albite and tourmaline.
Composition of ore	*Metals*: Au, Ag, W *Au:Ag* = 20 *Zoning*: none documented except for slight decrease in Au/Ag with depth	*Metals:* Au, Ag, As, W, Sb, Zn, Cu. *Au:Ag* = 5 *Zoning*: poorly documented along-strike and depth variations in Sb, Zn and Ag content of ore.	*Metals*: Au, Ag, As, W. *Au:Ag* = 6 *Zoning*: none documented	*Metals*: Au, Ag, Zn, As, Pb *Au:Ag* = 8.2 *Zoning*: none documented	*Metals*: Au, Ag, Zn, B *Au:Ag* = 5.7 *Zoning*: none at the deposit scale; lateral zoning in ankerite veins.	*Metals*: Au, Ag, W (B, Zn, Te, Bi) *Au:Ag* = 5 *Zoning*: none documented over the entire vein array.	*Metals*: Au, Ag, B, W (Te) *Au:Ag* = 9 *Zoning*: tourmaline-pyrite giving way to pyrrhotite-chlorite-biotite in some deep veins.
Selected references	Thomson (1941b); Baker (1957); Kishida and Kerrich (1987); Smith et al. (1990)	Boyle (1961); Brown (1992); McDonald et al. (1993)	Lothka and Nesbitt (1989); Kerswill (1993); Bullis et al. (1994)	Price and Bray (1948); Duff (1986); Walsh et al. (1988)	Rogers (1982); Proudlove et al. (1989)	Mason and Melnik (1986); Burrows and Spooner (1986); Marmont and Corfu (1989)	Wilson (1948); Daigneault et al. (1983); Robert and Brown (1986a, b)

Table 4 (cont.)

Deposit (mines)	Kirkland Lake	Campbell–A.W. White	Hemlo (Page Williams, Golden Giant, and David Bell)	Malartic (East Canadian, Barnat, Sladen, Canadian Malartic)	Doyon	Bousquet (Bousquet #1, #2, Donald LaRonde)	Horne
Size (tonnes of gold)	758.2	434.7	596.6	162.4	162.7	120.3	345.1
Summary description	Intrusion-centred quartz-vein arrays	Carbonate-quartz veins and silica-sulphide replacement zones	Disseminated sulphide and stockwork zones	Intrusion-associated disseminated sulphide and stockwork zones	Intrusion-associated sulphide veins and veinlet zones	Sulphide veinlet zones and massive-sulphide lenses	Discordant massive-sulphide bodies
Host rocks	Composite syenite stock intruding a sequence of fluvial-alluvial conglomerate, wacke, and trachytic tuffs, which unconformably overlies mafic volcanic rocks.	Fe-tholeiite, mafic-ultramafic sills, interflow sediments and minor felsic volcanic rocks, near their folded contact with chemical and clastic sedimentary rocks, and cut by post-ore porphyry and lamprophyre dykes.	Greywacke-mudstone sequence with fragmental (in part conglomerate) and quartz-eye porphyry units, intruded by post-ore aplite, diorite, and feldspar porphyry dykes, near a fault contact with mafic volcanic rocks.	Porphyritic to equigranular stocks, dykes, and sills of monzodiorite and younger dykes of diorite intruding greywacke-mudstone and mafic-ultramafic volcanic rocks, juxtaposed along the Cadillac tectonic zone.	Mafic volcanic and felsic volcaniclastic rocks and their derived quartz-sericite schists, cut by the multiphase Mooshla tonalitic subvolcanic intrusion in the west.	Mafic and felsic volcanic and volcaniclastic rocks and derived chlorite-carbonate and quartz-sericite schists, near their structural contact with greywacke, mudstone and minor conglomerate in the south.	Rhyolite flows, pyroclastic breccia and tuffs, in contact with andesite flows to the east. Intruded successively by post-ore gabbro sills and dykes, syenite porphyry stocks and dykes, and late diabase dykes.
Structure	Fluvial-alluvial sequence and basal unconformity affected by NE-trending folds and a weak NE-striking, subvertical foliation. Sequence cut by NE-striking steep reverse-fault system controlling the distribution of ore.	Steeply dipping lithological units overprinted and transposed by SW-dipping penetrative foliation. Main ore-bearing structures parallel to and overprinted by foliation. Numerous late faults.	Steeply dipping lithological units overprinted by a penetrative ESE-striking, steeply N-dipping foliation, and related isoclinal folds, parallel to a regional shear zone. Small Z-shaped folds overprint the penetrative foliation.	In sedimentary rocks: SE-trending F_2 folds, upright penetrative foliation and parallel faults, overprinted by ESE-cleavage and brittle faults. In volcanic rocks: anastomosing ESE-striking schist zones in ultramafic volcanics.	South-facing volcanic succession overprinted by a penetrative E-striking subvertical foliation, grading into zones of schist and of intense transposition in and near the deposit. Local younger Z-shaped folds.	South-facing volcanic succession overprinted by a penetrative E-striking subvertical foliation, grading into zones of schist and of intense transposition in and near the deposit. Local younger Z-shaped folds.	Upright volcanic units strike ESE to N, facing to the NNE, overprinted by a weak E-W foliation and bounded to the N and S by ~E-W subvertical faults. Possible ESE-trending anticlinal fold within the fault-bounded block.
Metamorphic grade	Lower greenschist	Greenschist-amphibolite isograd cut obliquely across the deposit.	Prograde amphibolite and retrograde greenschist.	Upper greenschist to lower amphibolite.	Prograde lower amphibolite and retrograde greenschist	Prograde lower amphibolite and retrograde greenschist	Greenschist
Nature Of ore	Quartz-carbonate veins, breccia veins and sheeted veinlet to stockwork zones. Veins contain <2% pyrite, with traces of gold and tellurides.	*Fissure filling veins* of Fe-dolomite-chert and quartz-arsenopyrite-native gold; *replacement bodies* of silica-sulphide (pyrite-arsenopyrite grading into pyrrhotite-arsenopyrite-pyrite at depth to the SE); *sheeted veinlet zones.*	Tabular zones of 5–10% *disseminated and fracture-controled* pyrite and molybdenite, with varied amounts of barite and quartz±stibnite±cinnabar veinlets. Gold-rich zones of remobilized barite and sulphides are common.	Irregular zones of 5–20% *disseminated pyrite* and variable *stockwork* of quartz-albite-K-feldspar veinlets in altered and fractured rocks. Contain minor amounts of tellurides, scheelite, tourmaline, chalcopyrite.	Zones of *disseminated pyrite* and arrays of *sulphide-rich quartz veins and veinlets* in sericite schist and tonalite. Vein sulphides are pyrite, chalcopyrite± sphalerite, galena, tellurides.	Zones of *sulphide-rich veinlets* and disseminated pyrite and *massive sulphide lenses* of pyrite, chalcopyrite, bornite, chalcocite ±sphalerite, tennantite, galena, tellurides.	*Massive-sulphide lenses* of pyrite, pyrrhotite, chalcopyrite, magnetite± sphalerite; low-grade *disseminated to massive-sulphide lenses* of pyrite-sphalerite±chalcopyrite; local zones of *auriferous sulphide veinlets.*
Alteration	Deposit occurs within large Fe-carbonate alteration zones; vein-scale sericitization and silicication, with minor pyritization.	*Deposit -scale* feldspar-destructive silicification and carbonatization with anomalous As, Sb and Au. *Orebody-scale* biotite-chlorite alteration, grading into actinolite, garnet, chloritoid, andalusite at depth to the SE.	Orebody-scale K-feldspar±roscoelite alteration in ore, grading outward to muscovite alteration in quartz-eye porphyry and fragmental unit. Al-silicate alteration in neighbouring greywacke-mudstone.	Orebody- to vein-scale K-feldspar±biotite alteration and carbonatization, best developed in intrusions, and silicification along fault zones and intrusive contacts, best developed in greywacke.	Orebody-scale aluminous alteration in schists (quartz-sericite to quartz-kyanite-andalusite-pyrophillite)with 1-10% pyrite; vein-scale sericite-carbonate±chloritoid alteration in tonalite.	Orebody-scale aluminous alteration, grading outward from quartz-andalusite to quartz-sericite to locally garnet-chlorite schists, all containing 1–10% disseminated pyrite.	Extensive sericitization± silicification of rhyolites within fault-bounded block; only localized chloritization in immediate footwall and sidewalls of massive-sulphide bodies.
Composition of ore	*Metals*: Au, Ag, Te (W, Mo) *Au:Ag* = 5 *Zoning*: none documented over the entire deposit.	*Metals*: Au, Ag, As+ W, Sb, Zn, Cu, Mo (Hg) *Au:Ag* = 11 *Zoning*: ore and alteration minerals vary according to metamorphic grade	*Metals*: Au, Mo+Ag, As, Sb, Hg, Te *Au:Ag* = 20 *Zoning*: Hg and Sb more abundant in SE half of deposit and Te in NW.	*Metals*: Au, Ag+Te, Cu, W. *Au:Ag* = 3.4 *Zoning:* none documented.	*Metals*: Au, Ag, Cu+ Zn, Pb, Te, As. *Au:Ag* = 10 *Zoning*: none documented.	*Metals*: Au, Ag, Cu, Zn+ Pb, Te, Sb, Sn, As. *Au:Ag* = from 11 in west to <0.02 in east *Zoning*: more Ag-rich and Zn-rich towards the east	*Metals*: Au, Ag, Cu, Zn+ Pb, Te, Se, As. *Au:Ag* = 0.46 *Zoning*: H orebodies Cu-Au-rich; Zone 5 orebody Zn-rich
Selected references	Thomson et al. (1950); Kerrich and Watson (1984)	MacGeehan and Hodgson (1982); Mathieson and Hodgson (1984); Andrews et al. (1986); Rogers (1992)	Corfu and Muir (1989a, b); Kuhns et al. (1994); Mishibayashi (1995); Pan and Fleet (1995); Muir (1997)	Gunning and Ambrose (1940); Eakins (1962); Sansfaçon and Hubert (1990); Trudel and Sauvé (1992)	Savoie et al. (1990, 1991); Trudel et al. (1992)	Tourigny et al. (1988, 1989); Marquis et al. (1990a, b, c, d); Trudel et al. (1992); Tourigny et al. (1993)	Price (1949); Kerr and Mason (1990); Barrett et al. (1991); Cattalani et al. (1993)

quartz-vein arrays. It should be noted that all supracrustal and most intrusive rocks hosting the deposits considered here are strictly metamorphic rocks but the prefix 'meta' has been omitted for clarity.

Kerr Addison, Ontario

The Kerr Addison deposit is hosted within the Larder Lake–Cadillac fault zone in the Larder Lake district of south-central Abitibi greenstone belt (Fig. 25a). It occurs where the contact between Fe-tholeiites of the Kinojevis Group to the northwest and Fe-tholeiite, komatiite, and turbidite units of the Larder Lake Group to the southeast is unconformably overlain by conglomerate, arkose and trachytic volcanic rocks of the Timiskaming Group (Fig. 26). The contact is further overprinted by the Larder Lake–Cadillac fault zone, characterized by chlorite-carbonate and talc-chlorite-carbonate schist, derived from Fe-tholeiite and komatiite, respectively (Kishida and Kerrich, 1987). The Larder Lake–Cadillac fault zone also truncates east- to northeast-trending folds in both Timiskaming and Larder Lake groups (Fig. 26). Rocks of the Kinojevis and Larder Lake groups have ages of 2701 ± 3 Ma and 2705 ± 2 Ma, respectively, and trachytic volcanic rocks of the Timiskaming Group have been dated at 2677 ± 2 Ma (Corfu, 1993). (All ages quoted in this paper are U-Pb zircon ages determined by conventional techniques unless otherwise indicated.)

Mineralization occurs within a 150 m wide, laterally extensive zone of carbonate alteration of komatiite- and tholeiite-derived schist units of the Larder Lake–Cadillac fault zone (Fig. 26), and extends to a depth of at least 1.4 km. Intense carbonate alteration around ore zones overprints and partly obliterates the foliation in the Larder Lake–Cadillac fault-zone schist (Thomson, 1941a). Two main ore types occur in the deposit: 1) intense stockworks of quartz-carbonate veins with minor pyrite in zones of fuchsite-carbonate alteration of komatiite flows (Fig. 27), and 2) zones of disseminated pyrite (<10–15% pyrite) and weak stockworks of quartz-carbonate veinlets in carbonatized and silicified tholeiitic volcanic rocks and in albitized diorite-syenite dykes and stocks (Thomson, 1941a; Baker, 1957; Smith et al., 1990). Both pre- and post-ore diorite-syenite dykes have been documented, suggesting broadly coeval emplacement of mineralization and the mafic dyke swarm (Smith et al., 1990; Spooner and Barrie, 1993).

The overprinting of schist units by ore-related alteration and the synkinematic nature of the mineralized veins (Thomson, 1941a; Smith et al., 1990) indicate that mineralization occurred during the late stages of deformation within the Larder Lake–Cadillac fault zone, after fold development within the Timiskaming Group (Fig. 26). Thus, the Kerr Addison quartz-vein array formed during late-stage deformation of the Abitibi greenstone belt and is considered to be the product of deeply generated magmas and fluids during final collisional stages of orogenic processes (Hodgson and Hamilton, 1989). The green-carbonate ore at Kerr Addison is one of the rare Canadian examples of significant gold mineralization in an ultramafic host, but is a good example of a Mother Lode–type deposit. By global comparison, the green-carbonate ores are 'listwaenites' and lithologically comparable

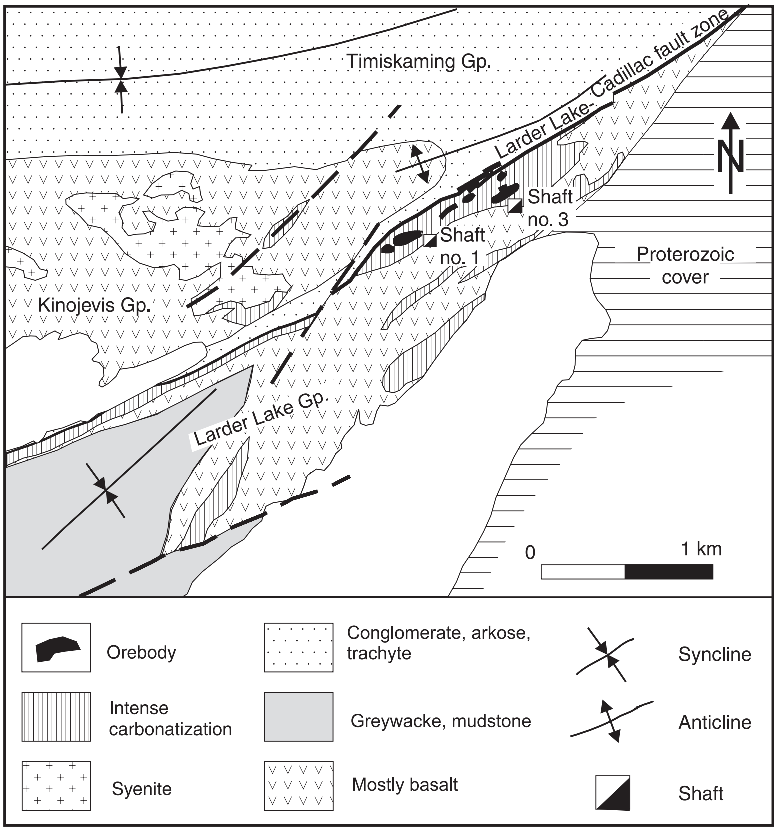


Figure 26.

Simplified map of the geology around the Kerr Addison deposit, Larder Lake district, Ontario (modified from Thomson and Griffis, 1941). Shaft no. 3 is at lat. 48°08′13″N, long. 79°34′46″W.

Figure 27. *Green carbonate ore consisting of a stockwork of quartz veins and pyrite disseminations in altered ultramafic rock; Kerr Addison mine, Ontario (photograph by K.H. Poulsen). GSC 1999-015J*

to ophiolite-hosted mineralization in younger orogenic belts. The disseminated pyrite ores remain enigmatic, however, and have been regarded as having the same origin as the quartz-vein arrays (Kishida and Kerrich, 1987; Hodgson and Hamilton, 1989) or as having a pretectonic, exhalative origin (Ridler, 1970; Hutchinson, 1993).

Con–Giant, Northwest Territories

The Con–Giant gold deposit occurs in the Yellowknife greenstone belt in southwestern Slave Province (Fig. 2). It is hosted by the Kam Group basaltic sequence, dated between 2716 ± 9 Ma and 2683 ± 5 Ma (Isachsen et al., 1991), overlain in the east by intermediate to felsic volcanic rocks and clastic sedimentary rocks of the Banting Group, both of which are unconformably overlain by fluviatile sandstone and polymictic conglomerate of the Jackson Lake Formation. The volcanic sequence has been tilted to an upright, northeast-striking position prior to intrusion of large granodiorite bodies in the west (Fig. 28), one of which has been dated at 2620 ± 8 Ma (Henderson, 1987). This was followed by the development of as anastomosing array of north-northeast-striking reverse shear zones, later dissected by Proterozoic faults. The auriferous Con and Giant shear-zone systems are generally regarded as segments of a more continuous shear-zone system that has been offset along the West Bay Fault (Fig. 28).

Gold mineralization consists of laminated quartz-ankerite veins and veinlet zones (Fig. 29a, *see* colour section), as well as sulphide-bearing zones of silicification (Fig. 29b), extending to depths of nearly 2 km (Boyle, 1961; McDonald et al., 1993). Orebodies occur in central portions of shear zones within zoned alteration haloes confined to the shear zones. Alteration mineral assemblages vary from ankerite-sericite to calcite-chlorite away from the orebodies, and they retrograde the regional epidote-amphibolite metamorphic assemblage characteristic of lithologies outside shear zones (Boyle, 1961). Mineralized veins within the shear zones are variably folded and boudinaged, and have been overprinted by at least some of the shear-zone deformation (Fig. 29, *see* colour section). However, because of their restriction to shear zones and locally preserved vein geometries compatible with shear-zone kinematics, they are interpreted as having formed during the early stages of shear-zone development (Boyle, 1961; Kerrich and Allison, 1978; Brown, 1992). The shear zones locally overprint the large granodiorite intrusion and cut related quartz-feldspar-porphyry dykes intruding the volcanic pile. Given the young age of this plutonic event, the Con–Giant deposit is interpreted to have formed during the late stages of deformation of the Yellowknife greenstone belt and is generally comparable to a Mother Lode–type deposit. Models proposed for the origin of mineralizing fluids include regional metamorphic dehydration (Kerrich, 1989) and the lateral secretion theory of Boyle (1961) involving metamorphic/magmatic fluids related to crystallizing granitic plutons.

Lupin, Nunavut

Lupin is a banded-iron-formation-hosted deposit in central Slave Province (Fig. 2). It occurs in a sequence of greenschist- to amphibolite-grade turbidite and oxide- to

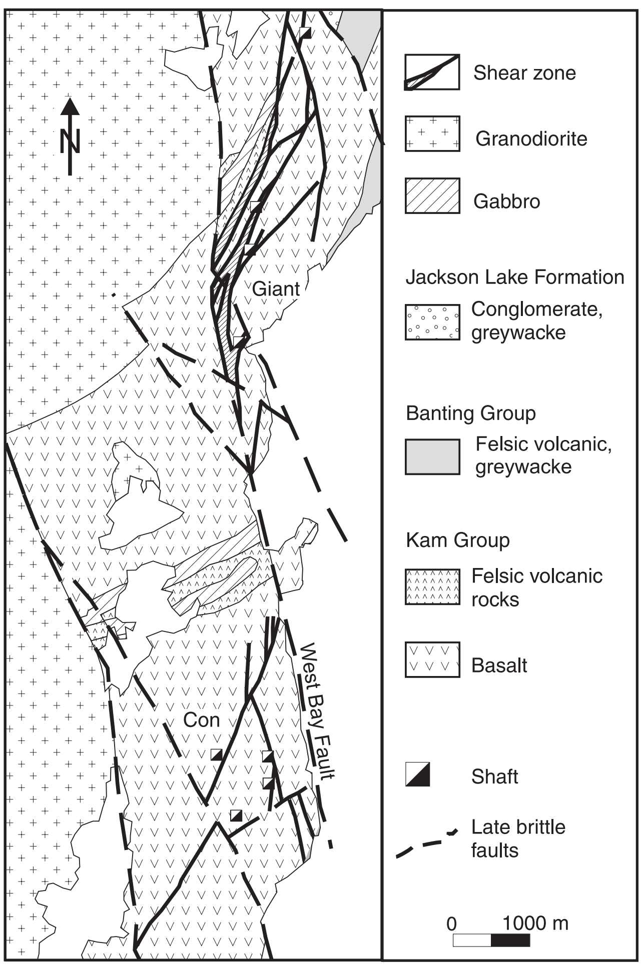


Figure 28. *Simplified map of the geology around the Con–Giant deposit, Yellowknife, Northwest Territories (modified from Boyle 1961). The Con mine is at lat. 62°26′10″N, long. 114°21′00″W; the Giant mine is at lat. 62°30′10″N, long. 114°21′25″W.*

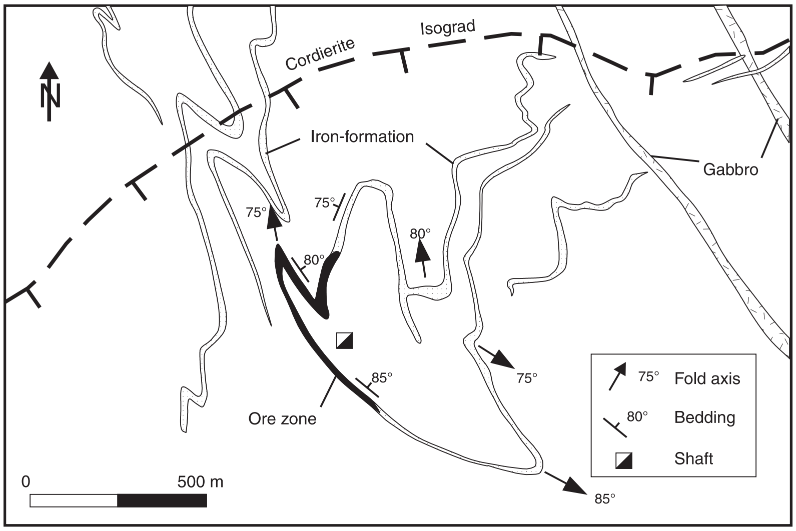


Figure 30.

Simplified map of the geology around the Lupin deposit, Contwoyto Lake area, Nunavut (modified from Lhotka and Nesbitt, 1989; Bullis et al., 1994). The Lupin mine is at lat. 64°45′54″N, long. 111°13′30″W.

sulphide-facies banded iron-formation of the Contwoyto Formation of the Yellowknife Supergroup. Sedimentary rocks have been multiply folded about northeast-trending F_1 folds and steeply plunging, north-trending F_2 folds; they display a penetrative S_2 foliation (Fig. 30; Bullis et al., 1994). A cordierite isograd, dipping moderately to the south, transects F_2 folds north of the deposit (Fig. 30) and intersects it at a depth of 550 m (Bullis et al., 1994).

Gold mineralization at Lupin is confined to the amphibolitic iron-formation and is centred on a anticline-syncline pair (Fig. 30), along which it extends down-plunge to depths in excess of 1 km. Orebodies consist of pyrrhotite-banded iron-formation, with pyrrhotite contents between 20 and 80%, as well as of varying proportions of late discordant quartz veins fringed by arsenopyrite haloes replacing pyrrhotite up to 2 m away from the veins (Fig. 31, *see* colour section). Economic concentrations of gold occur both in pyrrhotite layers and arsenopyrite haloes, with only minor amounts of gold in the veins themselves (Bullis et al., 1994).

On the basis of the delicate banding in pyrrhotite iron-formation and the uniform distribution of ore-grade gold concentration within the orebodies, Kerswill (1993, 1996) proposed a syngenetic origin for both the gold and the pyrrhotite, with late quartz veins only introducing arsenic and tungsten. However, Lhotka and Nesbitt (1989) documented a lateral transition in the composition of iron-formation from unmineralized grunerite-rich, sulphide-poor to sulphide- and hornblende-rich, grunerite-poor iron-formation closer to and within ore. Furthermore, Bullis et al. (1994) showed that in areas of less intense mineralization on the fringes of orebodies, not only the distribution of arsenopyrite-loellingite, but also that of pyrrhotite and gold, are controlled by the late discordant veins with the pyrrhotite replacement of layers extending much farther from the veins than arsenopyrite. Both types of evidence strongly support an epigenetic origin for both the gold and at least some of the sulphide minerals as is the case for Homestake-type deposits (Fig. 24). According to this interpretation, uniformly mineralized, pyrrhotite-rich, banded iron-formation represents coalesced, gold-rich, pyrrhotite-replacement zones around late veins and, in many respects, resembles the ore of manto-type deposits.

Pamour and Dome, Ontario

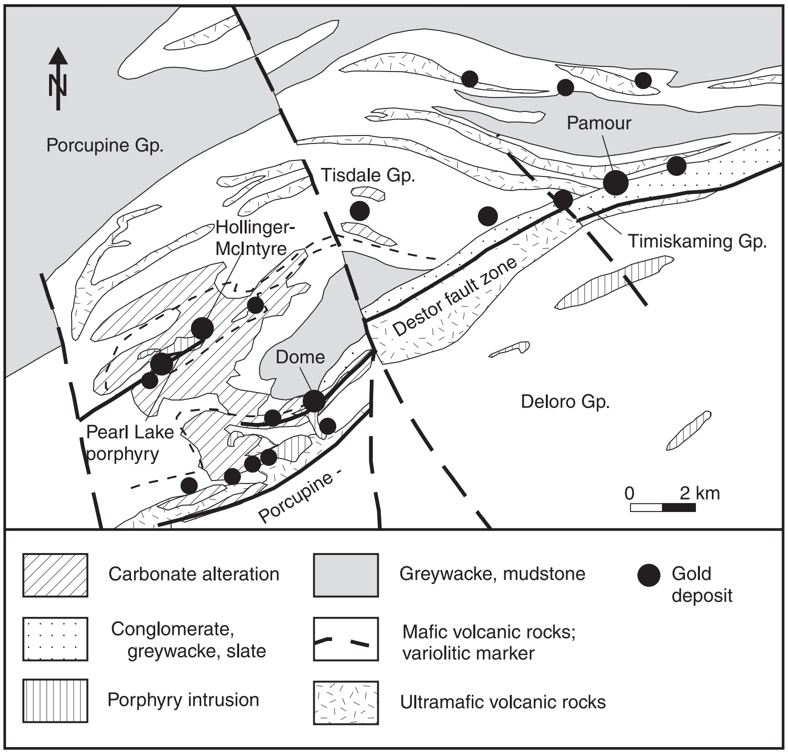
The Pamour and Dome deposits occur in the Timmins district of the Abitibi greenstone belt, approximately 1 km north of the Porcupine–Destor fault zone (Fig. 25a and 32). They occur in similar geological settings and have a number of other characteristics in common, so they are described together. Both deposits are spatially associated with a folded angular unconformity at the base of Timiskaming Group conglomerate, greywacke, and slate (younger than 2679 ± 2 Ma), overlying tholeiites and komatiites of the Tisdale and Deloro groups (older than 2698 ± 4 Ma) and turbidites of the Porcupine Group (Fig. 32; Corfu, 1993). Rocks in both deposits are overprinted by a weak to moderate, subvertical foliation, striking east-northeast (Pyke, 1982).

At Pamour, volcanic and sedimentary host rocks are overturned to the south and represent the north limb of a syncline truncated by the Porcupine–Destor fault zone. The deposit is part of a larger mineralized system extending along the unconformity over a strike length of 5 km (Fig. 32); mineralization at Pamour occurs on either side of the steeply north-dipping unconformity and extends down to depths in excess of 1.5 km. The bulk of the ore consists of zones of sheeted quartz stringers and disseminated sulphide minerals in surrounding altered, but low-strain, rocks; this type of ore is best developed in conglomerate and to a lesser extent in greywacke (Price and Bray, 1948; Duff, 1986). Gold also occurs in extensive, moderately to steeply dipping, laminated quartz veins hosted by reverse shear zones cutting both volcanic and sedimentary rocks, and locally fringed by flat extensional veins (Duff, 1986; Walsh et al., 1988).

At Dome, the unconformity and overlying Timiskaming Group sedimentary rocks define an asymmetric syncline, plunging shallowly to the east and overlying steeply north-dipping volcanic units. This syncline is truncated in the

Figure 32.

Simplified map of the geology of the Timmins district, Ontario, showing the location of Hollinger–McIntyre, Dome, Pamour, and other smaller deposits (modified from Pyke (1982); Ferguson (1968)). The Dome mine is at lat. 48°27′45″N, long. 81°14′33″W.



south by the Dome Fault, a zone of highly strained and altered rocks parallel to the Porcupine–Destor fault zone. Quartz-feldspar-porphyry stocks, dated at 2690 ± 2 Ma (Marmont and Corfu, 1989), intrude the volcanic rocks, but are truncated by the unconformity. Gold mineralization in the Dome deposit comprises several types of orebodies in volcanic and sedimentary rocks, spread over an area of 2.7 km by 1.2 km, and extending down to a depth of 1.6 km. Vein-type mineralization includes extensive laminated veins, either as concordant ankerite veins (Fig. 33, *see* colour section) along interflow sedimentary rocks, or as discordant quartz-tourmaline or quartz-fuchsite veins, and arrays and stockworks of extensional veins (Fig. 34), locally overprinting concordant veins. Disseminated sulphide mineralization consists of zones of 2–10% pyrite and pyrrhotite, and may occur with or without associated extensional vein arrays and stockworks (Rogers, 1982; Proudlove et al., 1989). Laminated veins are largely restricted to volcanic rocks, whereas disseminated sulphide mineralization and extensional vein arrays and stockworks occur in all rock types, including Timiskaming Group sedimentary rocks.

Gold orebodies at both deposits consists of vein-type and disseminated sulphide mineralization, fringed by similar carbonate-sericite alteration haloes. There has been some debate over the timing of concordant ankerite veins at the Dome deposit. Among others, Proudlove et al. (1989) argued for a syngenetic, pre-Timiskaming origin for these veins, based on their overprinting by extensional vein arrays, and based on the presence of auriferous pyrrhotite clasts in Timiskaming conglomerate. However, given the similarities in mineral assemblages between concordant ankerite and discordant quartz-tourmaline veins (e.g. tourmaline in both) the authors regard both the Dome and Pamour deposits as having formed relatively late in the evolution of the Timmins area, during or after folding of Timiskaming Group sedimentary rocks and therefore they are considered to be good examples of greenstone-hosted quartz-carbonate-vein deposits. The auriferous sulphide clasts in Timiskaming conglomerate at Dome and Pamour suggest the existence of an earlier gold-mineralizing event (Hutchinson, 1993), despite uncertainties regarding the timing of gold introduction within the clasts (pre- or postsedimentation?).

Hollinger–McIntyre, Ontario

The Hollinger–McIntyre deposit, located in the Timmins district of the Abitibi greenstone belt (Fig. 25a and 32), is the largest gold deposit in Canada (Fig. 25b). It occurs in tholeiitic basalts of the Tisdale Group in the core of a northeast-trending, doubly plunging anticline (Fig. 32). Mineralization is spatially associated with a group of steeply plunging quartz-feldspar-porphyry stocks emplaced after tilting of the volcanic units. The stocks coalesce into a single composite body at depth and their ages cluster at 2690 Ma (Marmont and Corfu, 1989). A younger, moderate to strong subvertical foliation, striking east-northeast and containing a steeply east-plunging lineation, overprints both the volcanic rocks and porphyry bodies (Mason and Melnik, 1986). Early, porphyry-style, disseminated and stockwork copper-molybdenum±gold mineralization also occurs in the Pearl Lake porphyry at depth, in association with pervasive albite, hematite-anhydrite, and sericite alteration (Davies and Lutha, 1978). Quartz-feldspar porphyry and sericite alteration related to porphyry-style copper-molybdenum±gold mineralization are cut by albitite dykes (Mason and Melnik, 1986), dated at 2673 +6/-2 Ma by Marmont and Corfu (1989).

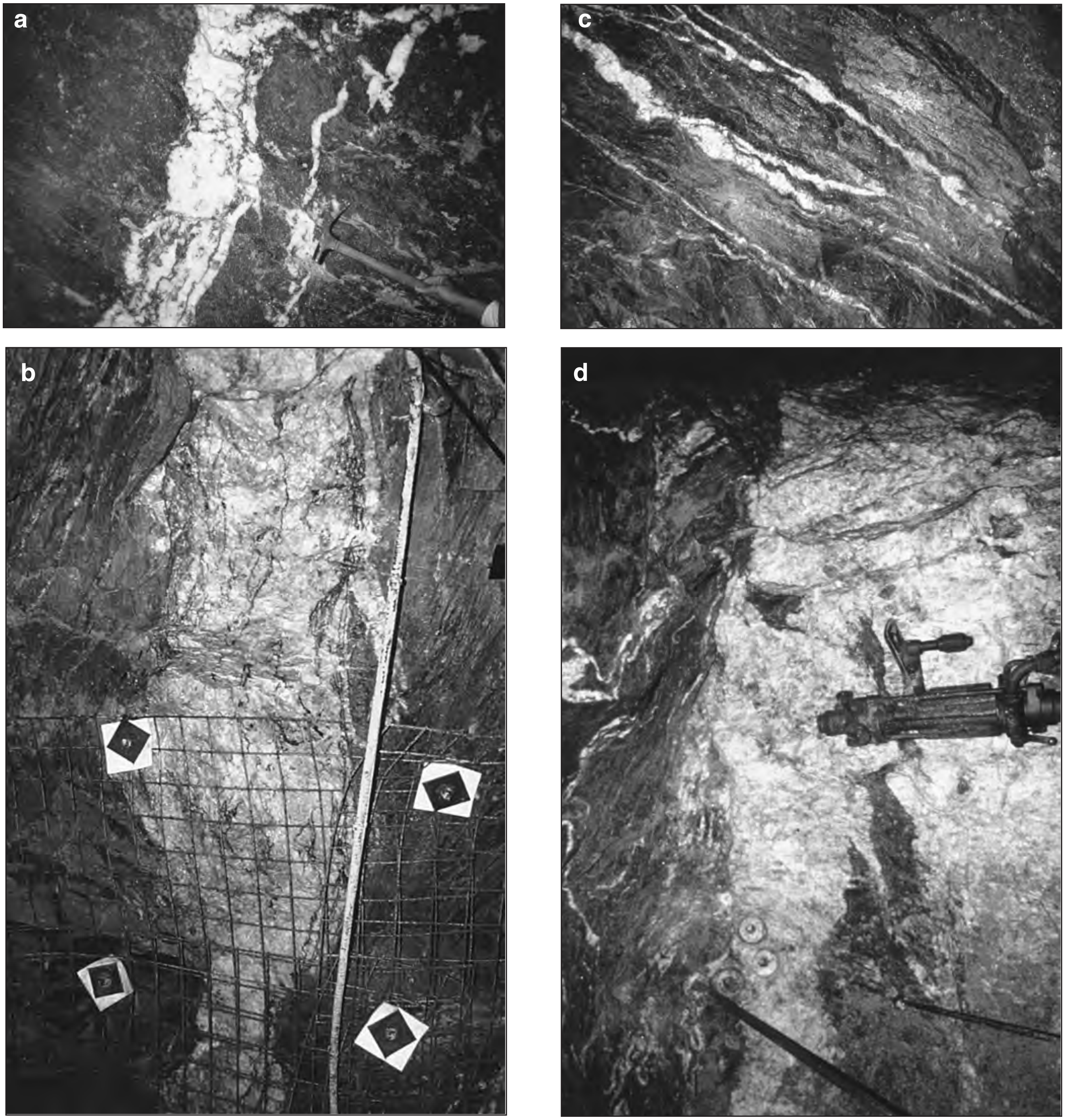


__Figure 34.__ Quartz veins; Dome mine, Timmins district, Ontario. ***a****) Extensional vein in conglomerate (photograph by K.H. Poulsen). GSC 1999-016D* ***b****) Boudinaged quartz vein (photograph by F. Robert). GSC 1999-015P* ***c****) Quartz stringers with gold in shear zone (photograph by F. Robert). GSC 1999-015Q* ***d****) Quartz vein oblique to foliation (photograph by F. Robert). GSC 1999-015R*

The bulk of the gold mineralization at Hollinger–McIntyre consists of quartz-ankerite veins, largely of extensional type, which define an extensive array developed mainly west of the Pearl Lake porphyry stock (Fig. 32). This array covers an area of 2 by 1 km on surface and plunges steeply to the east to a depth of 2.4 km, although most mineralization occurs above a depth of 1.4 km (Mason and Melnik, 1986). The veins dominantly strike northeast and dip steeply to the southeast, subparallel to the regional penetrative foliation. Gold mineralization is also centred on a regional carbonate alteration zone (Fig. 32) which is internally zoned (Table 4) around the core of the vein array (Smith and Kesler, 1985). Quartz-ankerite veins cut across albitite dykes and are therefore significantly younger than the porphyry bodies with which they are associated, ruling out any possible genetic connection between the two, as proposed by Mason and Melnik (1986). Given the age of the albitite dykes, quartz-ankerite veins of the Hollinger–McIntyre gold deposit postdate Timiskaming Group sedimentation in the Timmins district. The bulk of the greenstone-hosted, quartz-carbonate, vein-gold mineralization postdates porphyry-style copper-molybdenum±gold mineralization and is possibly of the same age as at the Dome and Pamour deposits described above. Although Wood et al. (1986) viewed the veins as having formed during the late stages of shear-zone-related foliation development, Mason and Melnik (1986) provided convincing arguments for the veins being overprinted by heterogeneous strain. It is not clear if they formed prior to, or during, late-stage shortening of the area.

San Antonio, Manitoba

A tholeiitic mafic body, less than 100 m thick, within epiclastic rocks of the Hare's Island Formation of the Bidou Lake Subgroup, hosts the San Antonio gold deposit at Bissett, Manitoba. This body, locally known as the San Antonio mine unit (Fig. 35) has been variously interpreted as a sill (Stockwell, 1935; Poulsen et al., 1986) or as a mafic flow (Theyer, 1983). The San Antonio mine unit has a melanocratic base and a leucrocratic upper part which hosts most of the ore in the mine (Ames et al., 1991).

Gold orebodies are preferentially located in the upper leucocratic part and include both stockworks and shear-zone-hosted quartz veins oblique to the plane of the San Antonio mine unit (Fig. 35b). The stockworks (Fig. 36) are complex, elongate, lens-shaped zones of intensely fractured and mineralized host rock confined to the sill in en échelon fashion, and several attain thicknesses of 10 m. The stockworks typically comprise three structural elements: an inner central quartz vein; a central breccia zone composed of angular, altered wall-rock fragments cemented by vein quartz; and a peripheral zone containing arrays of extensional, sigmoidally shaped 'ladder veins' that are oriented at a mean angle of 45° to the stockwork zones. The shear veins form arrays of northeasterly striking and northwesterly dipping quartz veins that typically occupy central fractures in sinistral, reverse, ductile shear zones containing intensely foliated and lineated schist derived from the host rock. The shear veins, although of similar composition and gold grade to those of the stockworks, rarely exceed a width of 1 m and tend to pinch and swell along strike and down dip.

Carbonatization of host rocks adjacent to both ore types has produced alteration-mineral assemblages which pseudomorphically replace metamorphic minerals and which define alteration isograds that record changes in mineral assemblages. In the leucogabbro, these isograds correspond to a zonation inward toward veins of actinolite-epidote to calcite-chlorite to paragonite-ankerite to albite-muscovite (Ames et al., 1991). Mass-balance calculations show that CO_2, sulphur, and potassium were added to the gabbroic rocks from the hydrothermal fluid with a change in the oxidation state of iron toward reducing conditions. Boron and sodium were also added at the contacts of veins in the form of metasomatic tourmaline and albite. Pyrite is most directly related to the occurrence of gold, and formed after muscovite and ankerite. Quartz-calcite-chlorite veins crosscut and replace earlier-formed alteration minerals.

The San Antonio deposit displays most of the geological attributes of a Mother Lode–type deposit, and in detail it most resembles the larger Mount Charlotte deposit in Western Australia, which is also hosted by the leucocratic members of a differentiated and layered tholeiitic sill. The only distinctive aspect of the San Antonio deposit is the observation that the shear veins appear to consistently overprint the stockworks, suggesting the superposition of the two mineralization styles.

Sigma–Lamaque, Quebec

Sigma–Lamaque is the largest of a group of shear-zone-related quartz-tourmaline-vein deposits occurring north of the Larder Lake–Cadillac fault zone in the Val d'Or district in southeastern Abitibi greenstone belt (Fig. 25a; Robert, 1994b). The deposit consists of a large vein network hosted by andesitic flows and volcaniclastic rocks, dated at 2705 ± 1 Ma, intruded by an irregular mass of subvolcanic porphyritic diorite of an identical age of 2704 ± 3 Ma (Table 4; Wong et al. 1991). A swarm of 2694 ± 2 Ma high-level feldspar-porphyry dykes, striking east-west and dipping steeply to the south, overprints both rock types, and is in turn locally cut by steeply plunging nonporphyritic diorite-tonalite stocks dated at 2685 ± 2 Ma (Fig. 37; Jemielita et al., 1989). Volcanic rock and porphyritic diorite contacts are generally subvertical and strike east-west, a result of tight to isoclinal F_2 folding, and parallel to a regional S_2 foliation, which also postdates the feldspar-porphyry dykes. A subhorizontal biotite isograd overprints all intrusive rock units at a depth of about 1 km (Robert and Brown, 1986a).

All intrusive rocks are overprinted by conjugate reverse-oblique shear zones, striking east-west and dipping moderately to steeply north or south, with which mineralized veins are associated (Fig. 37; Robert and Brown, 1986a). The auriferous vein network extends over an area of 2 by 1.5 km on surface (Fig. 37) and to a depth of 1.8 km. It consists of laminated veins within shear zones (Fig. 38a, b, *see* colour section), locally accompanied by jigsaw-puzzle breccia units; subhorizontal extensional veins extending laterally away from shear zones into less strained rocks (Fig. 38c, d, *see* colour section); and stacked extensional veins within competent intrusive rocks, locally grading into stockwork zones (Robert and Brown, 1986a). Zoned alteration haloes (Fig. 38c, d) generally extend up to several metres away from the veins. They consist of progressive carbonatization, sericitization, pyritization, and local albitization; pyritized wall rocks commonly carry ore-grade gold concentrations (Robert and Brown, 1986b). A property-scale gold anomaly documented by Perrault et al. (1984) around the deposit suggests that broader alteration zones may also be present.

The close spatial association of mineralized veins with intrusive rocks at Sigma–Lamaque led to proposals that gold mineralization could be related to late diorite-tonalite plugs

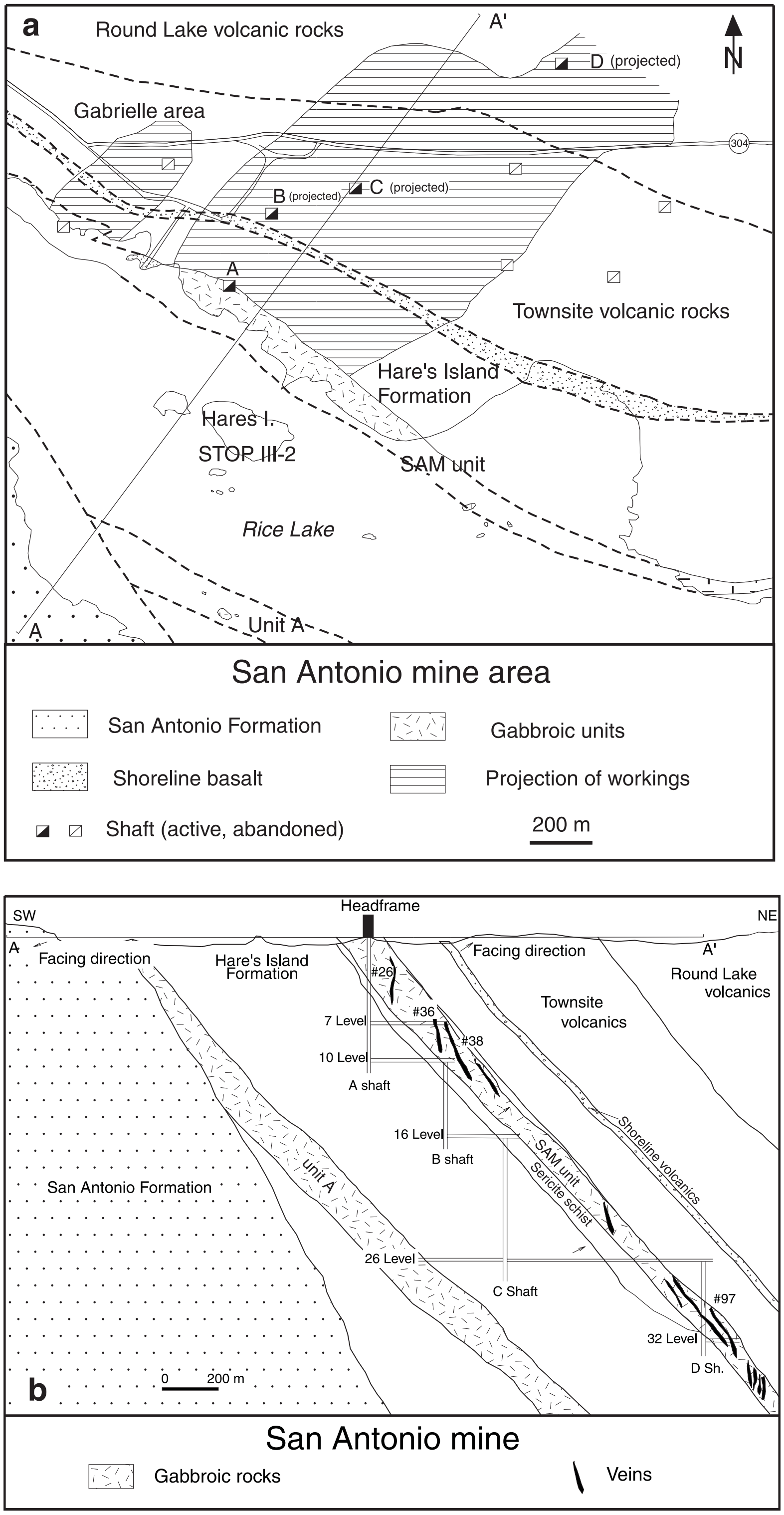


Figure 35.

*Geology around the San Antonio deposit, Rice Lake Belt, southeast Manitoba (modified from Poulsen et. al., 1996). **a**) Plan view. **b**) Cross-section. The San Antonio mine is at lat. 51°01′24″N, long. 95°40′42″W.*

and, by inference, is magmatic-hydrothermal in origin (Burrows and Spooner, 1989; Morasse et al., 1995). Taner and Trudel (1991) suggested a two-stage process in which gold, preconcentrated during early geothermal activity, was remobilized during deformation, whereas others have argued for syndeformation emplacement of mineralization, from deep-seated fluids of unspecified origin (Daigneault et al., 1983; Robert and Brown, 1986a). The facts that mineralized quartz-tourmaline veins and their host structures cut across all intrusive types, and that wall-rock alteration minerals around veins replace metamorphic minerals above and below the biotite isograd (Robert and Brown, 1986b) clearly attest to the late, post-peak metamorphic emplacement of the veins and these deposits are varieties of Mother Lode–type deposits. The coherence of vein geometries and structures with the kinematics of their host shear zone indicates that they formed in late, active shear zones, with only minor degree of overprinting by late transcurrent deformation (Robert, 1990).

Kirkland Lake, Ontario

The Kirkland Lake deposit, exploited by seven different mines, is located approximately 2 km north of the Larder Lake–Cadillac break in south-central Abitibi greenstone belt (Fig. 25a). The deposit is largely hosted by a steeply plunging composite stock of syenite, augite syenite, and syenite porphyry

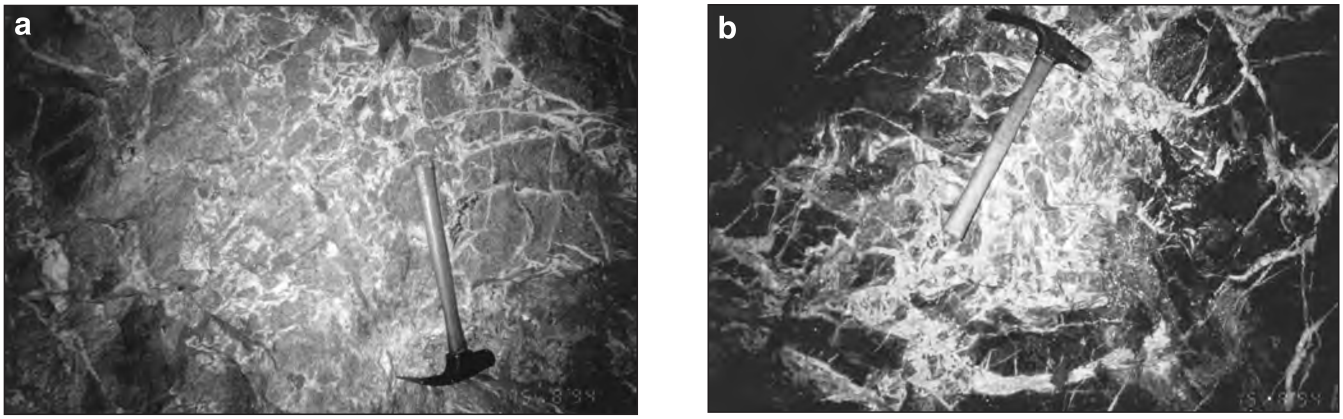


***Figure 36. a**), **b**) Stockwork mineralization; San Antonio mine, Manitoba (photograph by K.H. Poulsen).*
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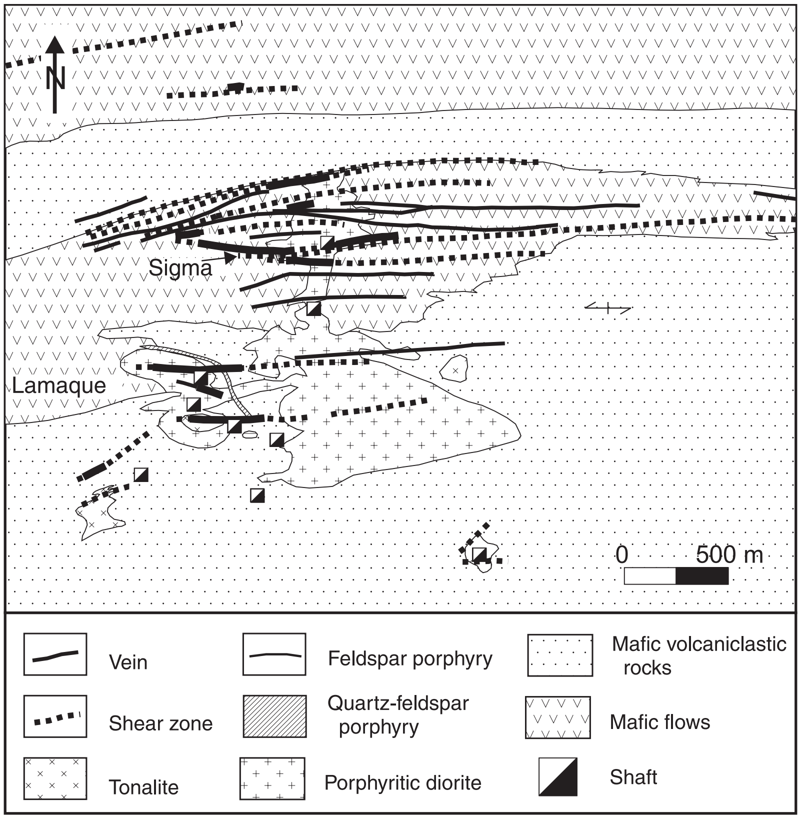


Figure 37.

Simplified map of geology around the Sigma–Lamaque deposit, Val d'Or district, Quebec. The Sigma mine shaft is at lat. 48°05′56″N, long. 77°45′35″W.

intruding Timiskaming Group conglomerate, wacke, and Tracadie tuff. This sedimentary sequence, dated between 2680 ± 3 Ma and 2677 ± 3 Ma (Corfu et al., 1991) unconformably overlies mafic volcanic rocks of the Kinojevis Group which predate 2700 Ma. In the south, the deposit is separated from ultramafic and mafic flows of the Larder Lake Group, dated at 2705 ± 2 Ma (Corfu, 1993), by the Larder Lake–Cadillac fault zone (Fig. 39). Timiskaming Group rocks define a broad asymmetric syncline, truncated in the south by the Larder Lake–Cadillac fault zone. The composite syenitic stock is interpreted to postdate folding of sedimentary strata (Thomson et al., 1950); it is cut by the Kirkland Lake main break, a system of narrow reverse faults, striking east-northeast and dipping steeply south, with which mineralization is associated (Fig. 39).

Gold mineralization consists of quartz-carbonate-sulphide veins (Fig. 40, *see* colour section) occurring as single continuous veins, sheeted veinlet to stockwork zones, and vein breccias (Thomson et al., 1950). It is distributed along the Kirkland Lake main break and subsidiary structures over a strike length of 5 km (Fig. 39) and down to a depth of 2 km. Orebodies occupy segments of these structures, or they extend into their walls over distances of up to 10 m in the case of sheeted veinlet and stockwork zones. Large zones of Fe-carbonate alteration of syenitic and sedimentary rocks are associated with the deposit, although they may not be related to ore (Thomson et al., 1950). Sericitization (±local K-feldspar) and silicification occur immediately adjacent to quartz-carbonate veins (Kerrich and Watson, 1984). Post-ore quartz-calcite veins contain barite, gypsum, and small amounts of magnetite and hematite. Late movements along the Kirkland Lake main break also disrupt the veins.

On the basis of sulphur-isotopic composition of pyrite and the presence of (largely post-ore) hematite and sulphate minerals, Cameron and Hattori (1987) proposed a magmatic-hydrothermal origin for the fluids, and a genetic connection between mineralization and syenitic plutonism. In contrast, based on oxygen-isotopic composition of silicates and the CO_2-rich nature of the ore fluids, Kerrich and Watson (1984) suggested that the gold-bearing fluids were of possible metamorphic origin and were produced during a period of late ductile deformation and batholithic granitoid emplacement. This interpretation is consistent with formation of the Kirkland Lake vein array in a late reverse-fault system, overprinting folded rocks of Timiskaming age, similar in many respects to the setting of the Kerr Addison, Dome, and Pamour deposits described above.

Campbell–A.W. White, Ontario

The Campbell–A.W. White deposit is located in the north-eastern part of the Red Lake greenstone belt within the Uchi Subprovince (Fig. 2). It is hosted by a sequence of Fe-tholeiites, dated at 2989 ± 3 Ma (Corfu and Andrews, 1987), near their folded contact with younger chemical and clastic sedimentary rocks to the east (Fig. 41). Both sequences are overprinted by a strong penetrative foliation, striking to the northwest, dipping 65° to the southwest, and containing an elongation lineation raking steeply to the northwest (Andrews et al., 1986). The penetrative foliation defines a regional northwest-trending deformation zone which is, in part, coincident with a zone of regional silicification and carbonatization, enriched in arsenic, antimony, and gold, and on which the deposit is centred (Pirie, 1981; MacGeehan et al., 1982). Isograds defining a greenschist- to amphibolite-grade transition strike approximately north-south and dip moderately to the west, cutting obliquely across the deposit (Fig. 41; Andrews and Hugon, 1985).

Mineralization occurs largely along two major foliation-parallel structures, over 2 km of strike length (Fig. 41). Four main types of ore (Table 4) commonly occur together and display consistent temporal relationships: early, and most abundant, carbonate-chert veins are overprinted by quartz-arsenopyrite–native gold veins and replacement zones, silica-sulphide replacement bodies, and sheeted veinlet zones. The

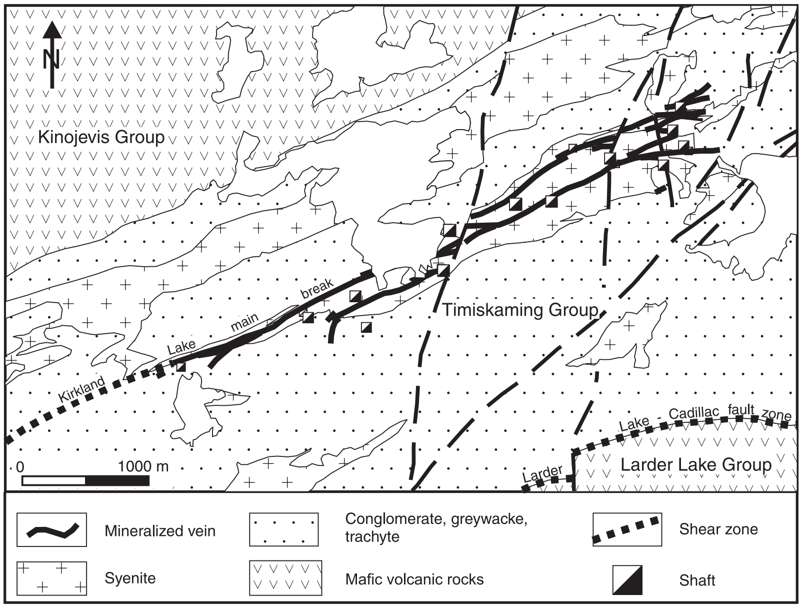


Figure 39.

Simplified map of the geology around the Kirkland Lake deposit, Ontario (modified from Thomson, 1945). The Macassa shaft no. 1 is at lat. 48°08′28″N, long. 80°04′10″W.

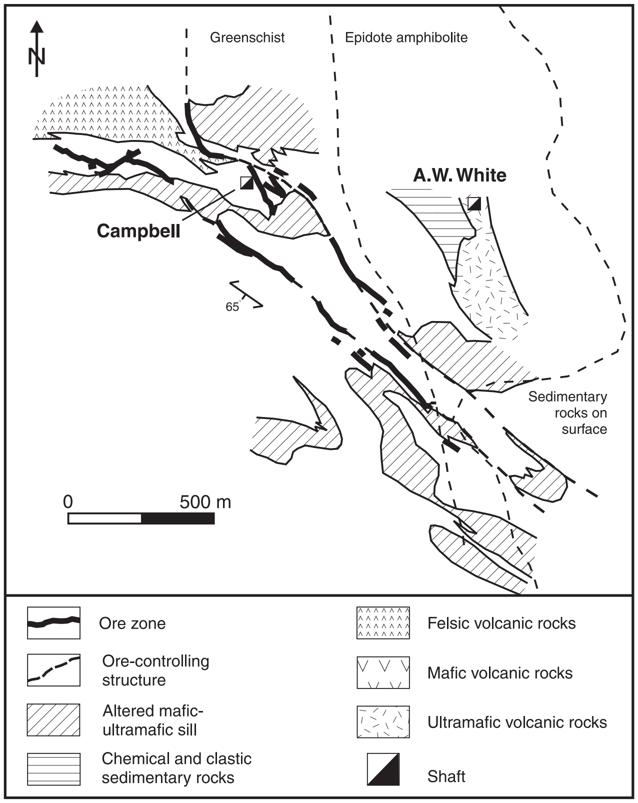


Figure 41. *Simplified map of underground geology of the Campbell–A.W. White deposit, Red Lake, Ontario: level 14 at Campbell, level 15 at A.W. White. The trace of the western contact of chemical and clastic sedimentary rocks on surface is also shown (modified from Rigg and Helmsteadt, 1981). The Campbell mine is at lat. 51°03′45″N, long. 93°44′30″W.*

distribution of ore types defines a deposit-scale zoning: vein-type ores are more abundant in the northwest and upper parts of the deposit, whereas replacement-type ores prevail in the southeast and deeper parts (Rogers, 1992). A similar zoning pattern is defined by mineral assemblages in alteration zones around replacement orebodies (Table 4; Rogers, 1992), although such mineral zoning can be explained in part by the greenschist- to amphibolite-grade transition within the deposit. Carbonate-chert veins have unique internal textures that are highly reminiscent of those in Cenozoic low-sulphidation epithermal veins (*see* descriptions *in* MacGeehan and Hodgson, 1982; Penczak and Mason, 1997) .

Orebodies are clearly overprinted by the penetrative foliation and many show evidence of crenulation and folding (Fig. 42; Andrews and Hugon, 1985). The two main mineralized structures (Fig. 41) have been interpreted as early, ore-related strike-slip faults by a number of authors (MacGeehan and Hodgson, 1982; Mathieson and Hodgson, 1984; Penczak and Mason, 1997), which is consistent with the evidence of deformation and metamorphic overprinting of the bulk of the deposit.

Figure 42. *Complexly folded quartz-carbonate veins in ore zone; Campbell mine, Red Lake, Ontario. Width of photograph is 1.7 m (photograph by F. Robert). GSC 1999-015W*

Multiple origins and timings of ore formation have been proposed for the Campbell–A.W. White deposit. Models range from syngenetic (for the ESC ore zone; Kerrich et al., 1981), to syntectonic (Zhang et al., 1997), to metamorphogenic related to emplacement of late external granitoid batholiths (Andrews et al., 1986), to predeformation, premetamorphic epithermal (Penczak and Mason, 1997). A multistage origin has also been considered by MacGeehan and Hodgson (1982) whereby carbonate-chert veins formed in response to early deep-crustal metamorphic-deformation processes, and were overprinted by quartz-arsenopyrite veins and silica-sulphide replacement bodies related to a younger, relatively near-surface geothermal system.

Based on the ample evidence for overprinting of mineralization by penetrative strain and metamorphism, the abundance of carbonate-chert veins and their peculiar internal textures, the abundance of siliceous replacement zones, and the metallic associations of the ore, the authors consider the early low-sulphidation epithermal origin proposed by Penczak and Mason (1997) to be the most appropriate. However, the possibility remains that the quartz-arsenopyrite veins and replacement bodies are a younger syntectonic overprint (Zhang et al., 1997), and that a simple classification may not be appropriate for this deposit.

Hemlo, Ontario

The Hemlo deposit is currently Canada’s largest gold producer, with more than 29 t of gold produced in 1998. It is located in the Hemlo–Heron Bay greenstone belt of the Wawa Subprovince (Fig. 2), near a regional transition between intermediate to felsic volcanic rocks and related sedimentary rocks, and clastic sedimentary rocks (Muir, 1997). The deposit is hosted by a domain of tightly folded clastic sedimentary rocks, a few hundred metres north of the regional-scale Hemlo shear zone that separates it from a southern domain of mafic volcanic and clastic sedimentary rocks (Fig. 43). The host sequence of the deposit consists of greywacke, mudstone, and minor conglomerate (along with other fragmental units). It also contains a quartz-eye porphyry unit of uncertain extrusive or intrusive origin with which gold mineralization is closely spatially associated. This porphyry unit, variously referred to as the Golden Sceptre (Kuhns et al., 1994) or the Moose Lake (Kusins et al., 1995) porphyry, has been dated at 2772 ± 2 Ma to the west of the deposit (Corfu and Muir, 1989a). All rock units are subparallel to a strong penetrative S_2 foliation, striking south-southeast and dipping steeply to the north, and intensifying toward the Hemlo reverse shear zone. Map-scale F_2 folds are also defined by the distribution of fragmental units (Fig. 43). Numerous, weakly to nonfoliated, post-ore dykes of feldspar porphyry and diorite, parallel to the foliation, intrude the orebodies and the quartz-eye porphyry. A post-ore diorite dyke has been dated between 2690 and 2680 Ma, and retrograde greenschist metamorphism at 2672 ± 3 Ma (Corfu and Muir, 1989a, b).

Mineralization is hosted by both the porphyry and a fragmental rock unit widely distributed along its margins (Fig. 43). The main ore zone forms a tabular body along the northern margin of the porphyry, traced over 2 km along strike and over 1 km at depth. The lower ore zone occurs at depth along the southern margin of the porphyry, whereas other mineralized zones to the west are hosted entirely by the porphyry or by adjacent sedimentary rocks (Fig. 43). Mineralization consists of fracture-controlled and disseminated pyrite and molybdenite. Ore zones commonly contain barite, roscoelite, telluride minerals, and quartz-stibnite-cinnabar-realgar veinlets, all of which tend to have a specific distribution within the deposit and define deposit-scale zoning (Harris, 1989). Mineralization is associated with intense K-feldspar alteration, grading away into muscovite alteration in the porphyry unit, and to alumino-silicate alteration in the sedimentary rocks (Fig. 43; Kuhns et al., 1994).

In parts of the main and lower orebodies, sulphide-bearing fractures and veinlets are almost completely transposed into the foliation planes (Fig. 44, *see* colour section), with local fold hinges (hooks) preserved. In areas of lower strain, the fracture-controlled and stockwork nature of mineralization is more apparent. At the North zone, for example, molybdenite, roscoelite, and gold occur along stockwork fractures fringed by inner K-feldspar and outer biotite alteration selvages (*see* Fig. 3.13 *in* Kusins et al., 1995). These relationships suggest that gold mineralization predates the development of the penetrative S_2 foliation. This is also supported by the occurrence of a post-ore aplite dyke that cuts across ore-grade mineralization, but is itself transposed and folded by the S_2 foliation, as illustrated in Figure 45. Furthermore, there is abundant evidence of remobilization of barite, sulphide minerals, and gold into late faults, fractures, and breccia units (Michibayashi, 1995).

The Hemlo deposit and its host rocks have undergone a complex geological history (Muir, 1997) which has resulted in different interpretations of the timing and origin of mineralization, as reviewed by Pan and Fleet (1995). Proposed

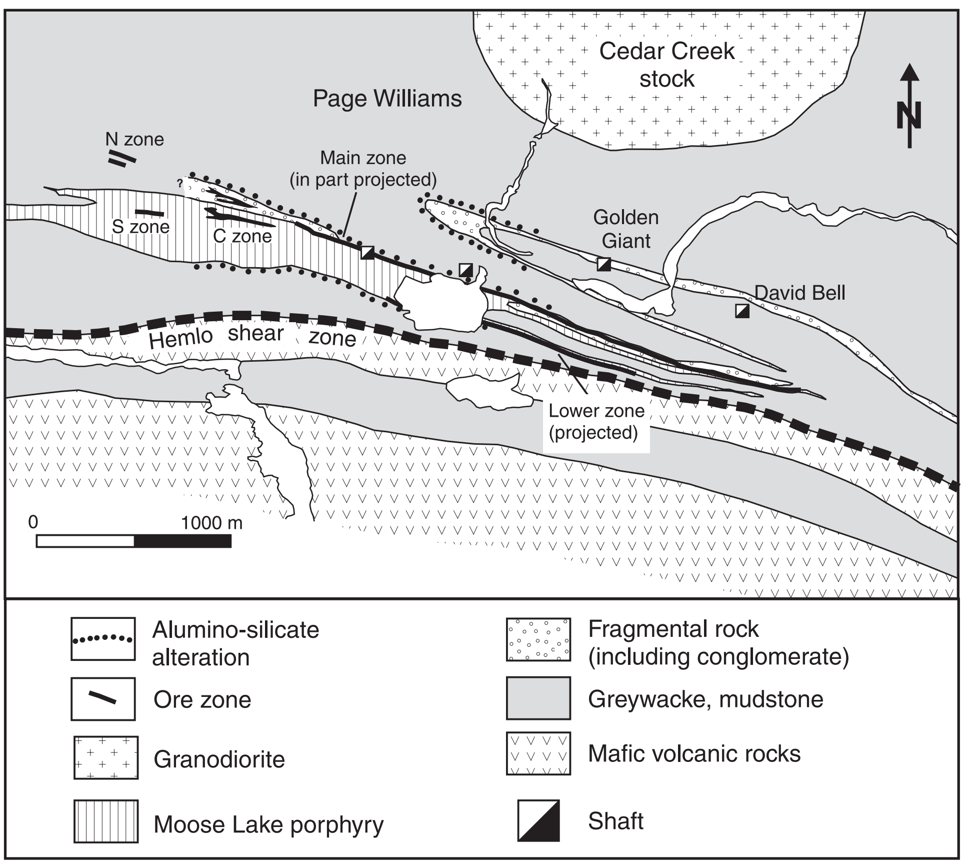


Figure 43.

Simplified map of the geology around the Hemlo deposit, Marathon district, Ontario (modified from Kusins et al., 1995). The Golden Giant mine is at lat. 48°42′N, long. 85°54′W.

models include predeformation, premetamorphic, syngenetic (Valliant and Bradbrook, 1986); geothermal-epithermal (Goldie, 1985); porphyry-type (Walford et al, 1986; Kuhns et al., 1994) models, as well as syn- to late-deformation, single to multistage replacement models (Hugon, 1986; Pan and Fleet, 1992; Michibayashi, 1995).

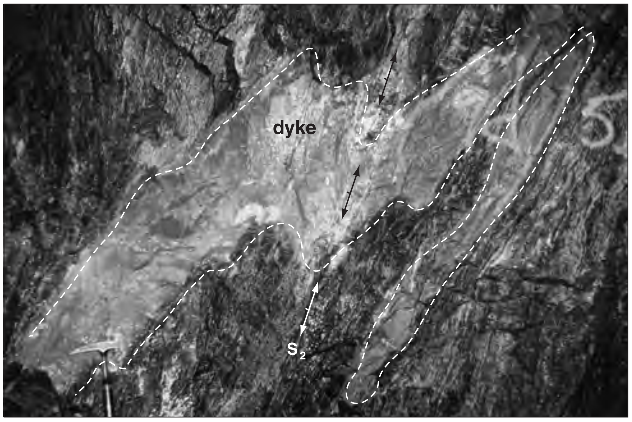


__Figure 45.__ Looking east at a post-ore aplite dyke (light grey), cutting across a foliated high-grade ore zone containing 10% pyrite. The dyke is clearly folded and transposed by the penetrative S_2 foliation; David Bell mine, Hemlo, Ontario (photograph by B. Dubé). GSC 1999-015X

The transposition of sulphide veinlets and of a post-ore aplite dyke by penetrative S_2 foliation clearly indicates that gold mineralization at Hemlo formed early in the geological history. This is consistent with the textural observations (Powell and Pattison, 1997) which show that the mineralization predates, or is synchronous with, the earliest stages of peak metamorphism. The gold-molybdenum-arsenic-mercury-antimony (and possibly barite) metallic association supports a magmatic-hydrothermal connection, and the intense K-feldspar and muscovite alteration, together with the fracture-controlled stockwork nature of mineralization, supports a porphyry-type model, as argued by Kuhns et al. (1994), but the overall characteristics of the deposit correspond best with the noncarbonate stockwork-disseminated deposit. However, proper interpretation of mineralization will require reconstruction of the initial configuration of the deposit, and of the quartz-eye porphyry, by removing the effects of superimposed multiple folding and shearing events.

Malartic district, Quebec

The Malartic district is located along the Larder Lake–Cadillac fault zone in southeastern Abitibi greenstone belt (Fig. 25a), and it straddles the contact between mafic-ultramafic volcanic rocks of the Piché Group and greywacke-mudstone sequence of the Pontiac Group to the south (Fig. 46). Although some mineralization is hosted by volcanic rocks, most of it occurs within the sedimentary domain, where gold

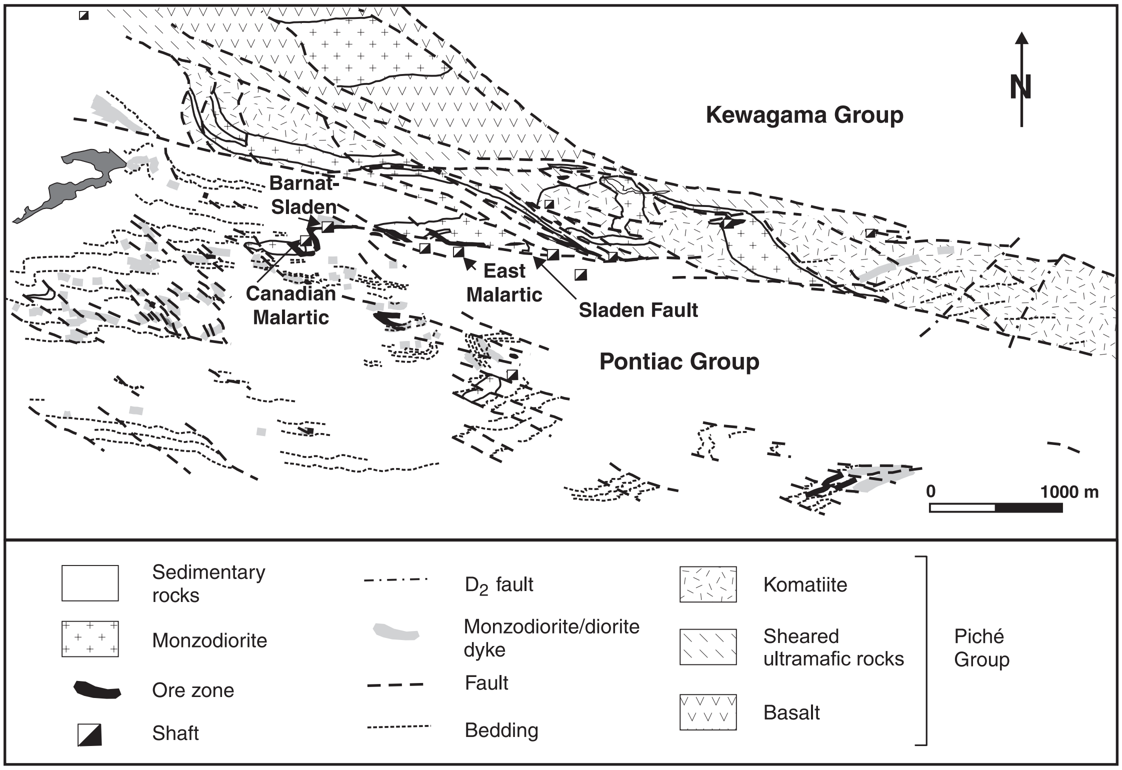


__Figure 46.__ Simplified map of the geology around the Malartic deposit, Quebec (modified from Trudel and Sauvé, 1992). The Canadian Malartic main shaft is at lat. 48°07′49″N, long. 78°07′53″W.

ore is spatially associated with small porphyritic monzodiorite bodies, younger diorite intrusions, as well as crosscutting silicified brittle faults (Fig. 46).

The host rocks of the deposits have experienced a complex structural history. Present-day distribution of sedimentary beds is largely controlled by early, northeast-trending F_1 folds, by overprinting asymmetric F_2 folds related to a southeast-striking penetrative S_2 cleavage, and by brittle faults parallel to S_2 (Fig. 46; Sansfaçon and Hubert, 1990). Monzodiorite dykes and sills are overprinted by F_2 folds. The volcanic domain is characterized by anastomosed schist zones derived from ultramafic and mafic volcanic rocks. A number of significant east-southeast- to east-striking brittle faults are present near the boundary between volcanic and sedimentary domains (Fig. 46). One such fault, the Sladen Fault, represents an important control on the distribution of orebodies within the deposits. East-southeast-striking faults are considered by Sansfaçon and Hubert (1990) to be broadly synchronous with S_2-parallel faults on the basis of mutually crosscutting relationships.

There are two main styles of gold ore in the Malartic deposits (Eakins, 1962; Trudel and Sauvé, 1992). The first occurs as elongate zones of disseminated auriferous pyrite in fractured and altered (‘silicified’) greywacke (Fig. 47a, *see* colour section) and adjacent porphyritic monzodiorite along east-southeast-striking faults, such as the Sladen Fault, but also along S_2-parallel faults (Fig. 46). The second style of ore consists of stockwork zones of quartz-albite–K-feldspar veinlets and intervening disseminated pyrite in intensely fractured and altered monzodiorite porphyry (Fig. 47b, *see* colour section) and diorite, adjacent to the same faults. The alteration consists mainly of K- and Na-feldspar additions, accompanied by carbonatization, silicification in greywackes, and by variable biotite development, mainly in intrusive rocks. The total pyrite content of mineralized rocks ranges from generally less than 5% to 10% in altered greywacke and porphyritic monzodiorite, and between 5 and 20% in altered diorite, which may also contain abundant magnetite. Hematite is commonly associated with K-feldspar alteration. At the Barnat no. 6 orebody, disseminated pyrite and gold are controlled by a small, fine-grained, monzonitic dyke cutting a larger monzonite porphyry intrusion (Issigonis, 1980).

Few genetic models have been proposed for the origin of Malartic deposits. On the basis of disseminated-stockwork style of ore, associated K-feldspar–biotite alteration, and association with a late dyke at the Barnat no. 6 orebody, Issigonis (1980) argued for a porphyry-type model. Kerrich (1983) argued for a syngenetic origin for the silicified greywacke ore at the East Malartic mine, which he considered to be a tuffaceous chert. Although the porphyry model of Issigonis (1980) is very attractive, temporal relations of ore to faults (such as the Sladen Fault) and to porphyry intrusions, remain ambiguous. For example, it is not clear whether ore along the Sladen Fault predates the faulting, in which case a temporal link with intrusions is possible, or is synchronous with or later than the faulting, in which case mineralization represents a younger event, unrelated to presently exposed porphyries. On the other hand, Sansfaçon and Hubert (1990) considered the various orebodies of the Malartic deposits to be parts of a large deposit that has been segmented and dispersed by post-ore faulting.

Harker–Holloway district, Ontario

The Harker–Holloway district is centred on the Porcupine–Destor fault zone, marked by the presence of narrow bands and slivers of turbidites and of Timiskaming-type sedimentary rocks, and separating two contrasting domains of well-preserved volcanic rocks, which dip moderately to steeply to the south (Fig. 48a, b). Rocks have been metamorphosed to the greenschist facies and display variably developed subvertical penetrative foliation and down-dip elongation lineations. The Holloway deposit, north of the fault zone, occurs in a sequence of mafic and ultramafic flows of the Stoughton–Roquemaure Group (2717–2713 Ma), whereas orebodies of the Holt–McDermott deposit, south of the fault zone, occur in Fe-tholeiites of the Kinojevis Group (2701 Ma). Volcanic rocks on both sides of the fault zone are cut by a number of steeply south-dipping, brittle and/or ductile faults which may represent splays of the main Porcupine–Destor fault zone (Fig. 48a). Several small, irregular, syenitic dykes are present south of the fault zone, within and around orebodies in the Holt–McDermott deposit.

Orebodies typically consist of tabular zones of disseminated pyrite (generally <5 volume per cent) and gold in intensely altered tholeiitic basalt, with variably developed microveinlet stockworks. The ore is gold rich (Au:Ag>5) and contains elevated concentrations of arsenic. The orebodies occur in a variety of geological settings (Fig. 48b), reflecting a variety of controls on the localization of the ore: along low-strain lithological contacts (Lightning zone at the Holloway deposit), along brittle and/or ductile faults (McDermott, Worvest, and Mattawasaga orebodies), and as shallowly dipping discordant zones (Tousignan and South), one of which is spatially coincident with an array of shallowly dipping syenitic dykes (South zone). Economic gold concentrations are coincident with zones of intense albite-ankerite alteration of the host basalt (Fig. 49a, *see* colour section), which, in turn, are partly fringed by sericite alteration haloes at Holloway and fringed by broader zones of calcite alteration. Syenitic dykes within orebodies at Holt–McDermott are nearly completely albitized (Fig. 49b, *see* colour section). Disseminated specular hematite is also commonly present in mineralized albite-ankerite alteration zones. Subhorizontal extensional veinlets of quartz-calcite±pyrite and scheelite are present in several orebodies (Fig. 49c, *see* colour section); because they are perpendicular to the penetrative elongation lineations, they are interpreted as syntectonic veinlets developed in pre-existing competent albitized rocks.

The age of ore in the Harker–Holloway district is uncertain, but the overprinting of orebodies by syntectonic extensional veinlets suggests that mineralization predates the development of subvertical penetrative foliation and its contained down-dip elongation lineation. Similarly, the origin of the gold ore remains enigmatic; Robert (1997) has suggested that the Holt–McDermott and Holloway deposits represent distal components of hydrothermal systems centred on monzonite-syenite stocks of Timiskaming age (~2675–2680 Ma), with which mineralization may be temporally related. The disseminated to microstockwork nature of ore, as well as the spatial association with syenitic dykes at Holt–McDermott, bears similarity with younger deposits such as Golden Reward, South Dakota (Emanuel et al., 1990), and stage I mineralization at Porgera, Papua New Guinea (Richards and Kerrich, 1993), which are interpreted as magmatic-hydrothermal deposits.

Doyon and Bousquet, Quebec

The Doyon, Bousquet No. 1, and Bousquet No. 2–LaRonde deposits occur in the same succession of volcanic rocks, share a number of geological characteristics, and are discussed together. (The LaRonde portion of the Bousquet No. 2–LaRonde deposit was previously known as the Dumagami mine. The LaRonde property contains three shafts. Shaft no. 1 exploited the Agnico-Eagle portion of the

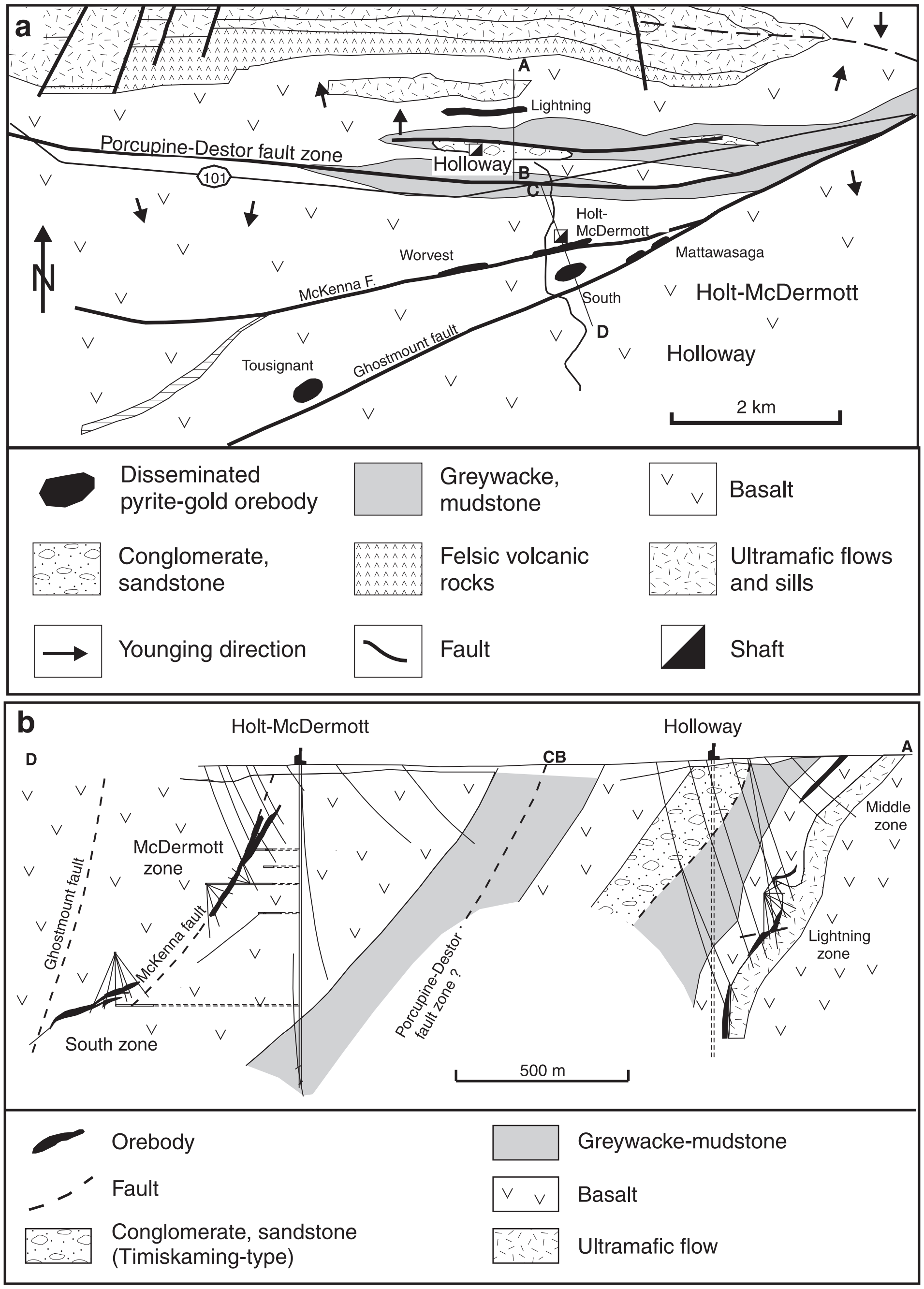


Figure 48. ***a****) Simplified map of the geology of the Harker–Holloway District, Ontario.* ***b****) Simplified cross-section of the Harker–Holloway deposits. The Holt-McDermott shaft is at lat. 48°30′38″N, long. 79°44′39″W.*

Bousquet No. 2 orebody. Shafts no. 2 and 3 exploited adjacent orebodies. Shaft no. 3 mined large, zinc-gold±copper-rich, massive-sulphide lenses.)

These three deposits (Doyon, Bousquet No. 1, and Bousquet No. 2–LaRonde), as well as several smaller ones, occur north of the Larder Lake–Cadillac fault zone, in a narrow band of volcanic rocks representing the attenuated eastern extension of the Blake River Group, which hosts volcanic-associated massive-sulphide deposits of the Noranda district (Fig. 25a). These volcanic rocks are in fault contact with clastic sedimentary rocks of the Kewagama and Cadillac groups to the north and south, respectively (Fig. 50). The deposits occur in the southern portion of the volcanic belt, which contain subequal proportions of felsic volcaniclastic rocks, and mafic flows and volcaniclastic rocks, striking east and dipping steeply to the south. These rocks were intruded in the east by the Mooshla intrusive complex, consisting of gabbro, quartz diorite, porphyritic tonalite, and trondhjemite phases (Savoie et al., 1991).

Volcanic and intrusive rocks in the southern part of the volcanic belt have been overprinted by the Dumagami high-strain zone (Trudel et al., 1992), characterized by an intense penetrative S_2 foliation, which dips steeply to the south, with a steeply west-plunging elongation lineation. Intensity of deformation increases toward laterally continuous zones of quartz-sericite and chlorite-carbonate schist, derived from felsic and mafic protoliths, respectively.

Mineralization is sulphidic and constitutes three main types of orebodies: 1) massive-sulphide lenses (Fig. 51a, b, c, *see* colour section), 2) zones of sulphide-rich (>25% sulphide minerals) veins, typically less than 20 cm thick, with intervening disseminated pyrite (Fig. 51d, e, *see* colour section), and 3) zones of 5–20% disseminated pyrite without significant veins (51f, *see* colour section). Most orebodies, irrespective of their type, occur within a laterally extensive zone of schists derived mostly from altered felsic volcanic rocks (Fig. 50), which grade from quartz-andalusite±kyanite to quartz-sericite assemblages away from the orebodies. The sulphide-rich veins of the West zone at Doyon are hosted by low-strain porphyritic tonalite; they are fringed by vein-scale alteration with only an incipient aluminous character (Table 4). The diverse alteration assemblages are interpreted to result from metamorphism of various degrees of argillic and advanced argillic alteration of volcanic and intrusive rocks (Marquis et al., 1990c).

Genetic interpretations of the Doyon, Bousquet No. 1, and Bousquet No. 2–LaRonde deposits hinge heavily on the timing of emplacement of sulphide minerals and gold. At Doyon, pressure shadows are well developed on pyrite in disseminated sulphide zones in schist, and north-south sulphide-rich veins are crenulated by S_2 in low-strain tonalite and are transposed parallel to S_2 in schist zones, where they are folded and boudinaged. In the West zone, a barren diorite dyke crosscuts auriferous sulphide-rich veins and is itself folded by F_2 folds and foliated by S_2 (Gosselin et al.,1994). These relations indicate that sulphide minerals and gold predate at least D_2 deformation.

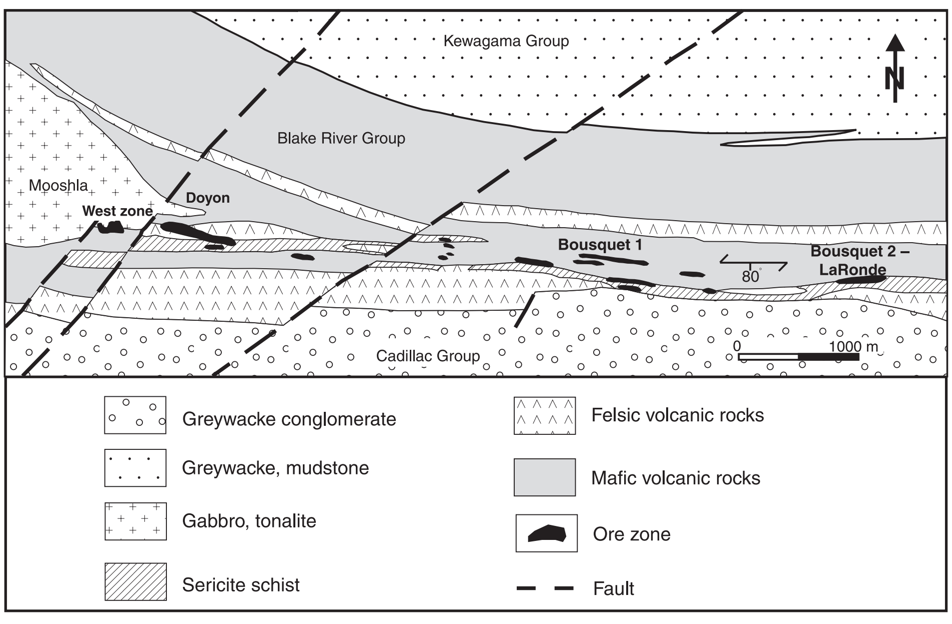


Figure 50. *Simplified map of the geology of the Bousquet district, Quebec, showing the location of the Doyon and Bousquet No. 1 and Bousquet No. 2–LaRonde deposits (modified from Marquis et al., 1990b). The Doyon mine is at lat. 48°15′21″N, long. 78°31′13″W; the Bousquet No. 2–LaRonde mine is at lat. 48°15′02″N, long. 78°27′07″W.*

At Bousquet No. 2–LaRonde, massive-sulphide orebodies display evidence of overprinting by D_2 deformation, including boudinage, piercement structures, and transposition of sulphide-lens contacts (Marquis et al., 1990b). However, within the massive-sulphide bodies, gold commonly occupies late sites such as late north-south fractures cutting across S_2 (Tourigny et al., 1993). Vein-type orebodies contain transposed early sulphide veinlets as well as syntectonic sulphide veins, both of which are auriferous (Tourigny et al., 1989). At Bousquet, there are clearly several generations of gold-bearing structures, ranging in age from predating ductile deformation to forming synchronous with late brittle deformation.

A variety of genetic models have been proposed for the Doyon, Bousquet No. 1, and Bousquet No. 2–LaRonde deposits. Synvolcanic models propose that gold was introduced together with the sulphide minerals during felsic volcanism and associated plutonism either by subseafloor, or possibly shallow-marine exhalative, hydrothermal processes (Valliant and Hutchinson, 1982; Stone, 1990; Tourigny et al., 1993). In these models, sulphide minerals and gold have been remobilized into various structural sites during subsequent deformation and metamorphism. According to multistage models, aluminous alteration and massive-sulphide lenses were formed during volcanism, as in the previous case, but gold and most sulphide-rich veins were introduced during deformation by fluids of metamorphic origin (Marquis et al., 1990a). Others have considered that both the aluminous alteration and gold and sulphide-mineral introduction were synchronous with deformation and metamorphism (Savoie et al., 1990).

Given the presence of folded and foliated post-ore dykes, there is very little doubt that aluminous alteration, sulphide minerals, and gold at Doyon predate D_2 deformation and metamorphism. The very close correlation between gold and copper values in the Bousquet No. 2–LaRonde orebody argues strongly in favour of coprecipitation of both metals, and hence for early introduction of gold, as pointed out by Tourigny et al. (1993). A model of early, synvolcanic origin for the Bousquet No. 2–LaRonde massive-sulphide deposit is therefore favoured. The distinct aluminous nature of the alteration and metal associations (e.g. tellurium, antimony, tin, arsenic) at Bousquet No. 2–LaRonde supports the possibility raised by Poulsen and Hannington (1996) that these deposits formed as shallow-marine, high-sulphidation, epithermal systems, as recently defined by Sillitoe et al. (1996). The Doyon deposit shares most characteristics of gold-copper, sulphide-rich, vein-type deposits.

Horne, Quebec

The Horne deposit is a giant volcanic-associated massive-sulphide deposit, but, due to its overall production grade of 5.8 g/t Au and 2.2% Cu, it is generally regarded as a gold deposit. It is hosted by Blake River Group volcanic rocks in the Noranda district of the Abitibi greenstone belt (Fig. 52).

The deposit is contained within a fault-bounded block of rhyolite flows of tholeiitic affinity, pyroclastic breccia, and tuff, in contact with andesite flows to the east (Fig. 52). It is juxtaposed against andesite flows and a diorite intrusion to the south, and calc-alkaline rhyolite units to the north, containing

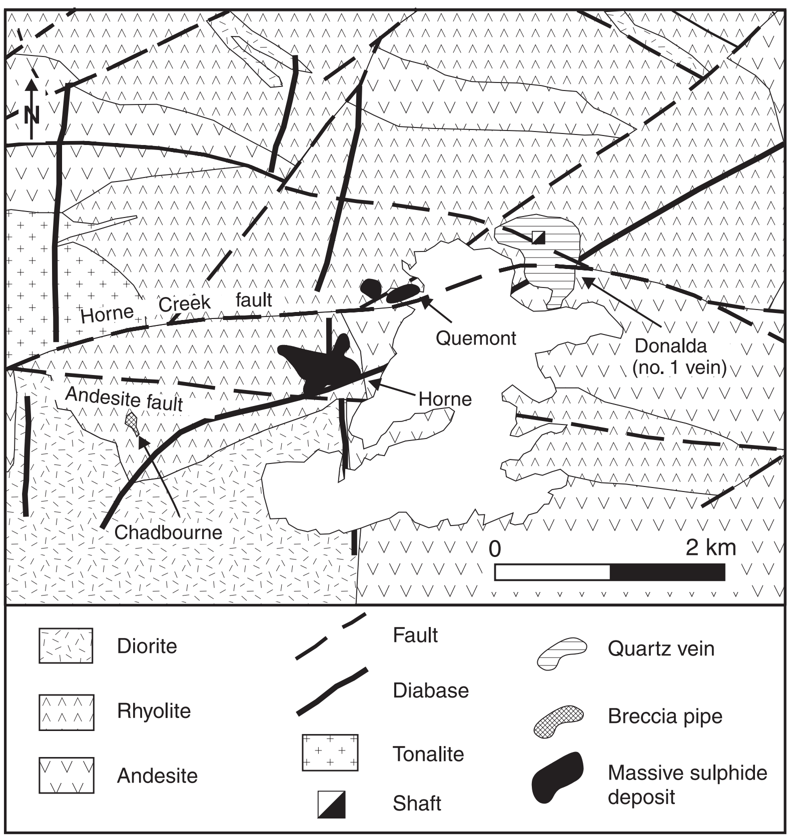


Figure 52.

Simplified map of the geology around the Horne deposit, Rouyn–Noranda district, Quebec (modified from Cattalani et al., 1993). Quartz veins and massive-sulphide deposits are projected to surface. The shaft is at lat. 48°17′38″N, long. 79°00′36″W.

the Quemont deposit, another auriferous massive-sulphide deposit. Two younger gold deposits also occur in the vicinity of the Horne deposit (Fig. 52): the shallow-dipping quartz vein of the Donalda deposit (Riverin et al., 1990), and the Chadbourne breccia pipe (Walker and Cregheur, 1982).

Within the fault block, steeply dipping felsic volcanic units strike approximately east-southeast and face to the northeast, but their contacts with overlying andesite flows strike north-south immediately east of the deposit (Fig. 52). Although stratigraphic relations are obscured by the presence of a post-ore, quartz-diorite, sill-dyke complex, volcanic units are likely folded about an east-southeast-trending, steeply east-plunging anticline, as suggested by Wilson (1962), truncated on both limbs by the Horne Creek and Andesite faults (Fig. 52). With the exception of rocks in the vicinity of the faults, and of a few local shear zones, rocks around the deposit are only weakly strained and display a weak, east-west, subvertical S_2 foliation.

Exploited copper-gold orebodies comprise subconcordant lenses of massive pyrite, pyrrhotite, chalcopyrite, and magnetite±sphalerite, interpreted to have formed by subseafloor replacement (Kerr and Mason, 1990). These orebodies contain elevated gold concentrations (e.g. >3 g/t Au) over intervals in excess of several tens of metres (Barrett et al., 1991). The deposit also contains a very large subeconomic zone of disseminated to massive pyrite-sphalerite, with significantly lower copper and gold grades. Zones of auriferous sulphide veinlets with Fe-chlorite selvages are also present (Kerr and Mason, 1990), but the deposit lacks a well defined stringer zone and alteration pipe. Most rhyolitic rocks within the fault block have been affected by weak sericitization and silicification, which become more intense near the orebodies to produce a quartz-sericite±pyrite assemblage. Chlorite alteration is largely restricted to immediate footwall and sidewalls of the deposit, except for local discordant zones in the footwall, and locally contains elevated amounts of copper and gold (Barrett et al. 1991).

It is now well accepted that the Horne deposit is a conventional volcanic-associated massive-sulphide deposit. However, early workers (e.g. Price, 1949) considered sulphide mineralization to postdate late diabase dykes and to be related to them, largely on the basis of the presence of sulphide-replacement minerals and veins within such dykes. Today, these features would be regarded as resulting from sulphide remobilization during intrusion of the dykes. The timing of gold introduction within the deposit is also an important issue (*see* Kerr and Mason, 1990). Price (1949) saw no evidence for a temporal connection between gold and sulphide minerals in light of higher gold concentrations along discordant chloritic zones and in late faults. However, the presence of gold-rich sulphide clasts in otherwise barren pyroclastic rocks above the deposit (Kerr and Mason, 1990), and the elevated gold concentrations over major intervals of massive-sulphide ore (Barrett et al., 1991) argue strongly in favour of a synvolcanic origin for the gold.

Chibougamau–Chapais district, Quebec

The Chibougamau–Chapais district possesses a wide diversity of deposit types (Guha et al., 1990), but is mostly characterized by several copper-gold vein-type deposits clearly distinct from the typical greenstone-hosted quartz-carbonate veins present elsewhere in the Superior Province. The copper-gold deposits of the Chibougamau camp (Copper Rand, Henderson, Portage, Main Mine, Merrill) occur within the gabbroic Dore Lake Complex, whereas the Cooke mine in the Chapais area is hosted by a gabbroic sill of the Cummings Complex (Dubé and Guha, 1992) (Fig. 53a, b, *see* colour section). The geology of the area has been described in detail by Graham (1956), Allard (1976), and Daigneault and Allard (1990). Most copper-gold deposits in the Chibougamau camp occur in southeasttrending ductile shear zones, and, less commonly, in northeast-trending ductile shear zones. These mineralized shear zones have steep dips to the southwest and have been interpreted as reverse-oblique structures (Guha et al., 1983; Daigneault and Allard, 1990). Most mineralized shear zones occur within meta-anorthosite and gabbroic phases of the Dore Lake Complex. Mineralization consists of lenses and veins of semimassive- to massive-sulphide minerals with variable proportions of quartz and carbonates (Allard, 1976; Guha et al., 1988). The sulphide minerals are mainly chalcopyrite, pyrite, and pyrrhotite with minor amounts of sphalerite, galena, and magnetite, and the silver-to-gold ratio is 2:1. The sheared meta-anorthosite hosting the veins is hydrothermally altered and mainly consists of sericite-carbonate and chlorite (± chloritoid) schist. The mineralized shear zones of the Chibougamau camp contains numerous subparallel to oblique quartz diorite to porphyritic tonalite dykes with which the orebodies are commonly spatially associated (Allard, 1976; Daigneault and Allard, 1990).

Several conflicting interpretations have been proposed for the origin and the timing of emplacement of the copper-gold orebodies. Some authors have proposed sulphide-mineral emplacement during active development of the shear zones (e.g. Guha et al., 1983, 1988), whereas others consider the sulphide ores to be genetically related to the Chibougamau pluton and have subsequently been deformed (e.g. Duquette, 1970; Allard, 1976). Guha and Koo (1975) further presented textural evidence for metamorphism and deformation overprinting sulphide mineralization. Recent work by Robert (1994a) and Pilote et al. (1995 a, b) based on 1) the crosscutting and overprinting relationships between mineralization-alteration and deformation and 2) the presence of dykes both pre- and postdating mineralization indicate a genetic links between mineralization and plutonism as originally proposed by Allard (1976). The deposits share analogies with porphyry copper-gold deposits such as the Ann Mason deposit, Nevada (Dilles and Einaudi, 1992) in the Cordillera (Pilote et al., 1995a, b). Uranium-lead dating of pre- and intermineralization dykes (Pilote et al., 1997, 1998) indicates an age of 2715 Ma for the Cu-Au mineralization in Chibougamau, an age similar to the early porphyritic tonalitic phases of the Chibougamau pluton (2716–2718 Ma).

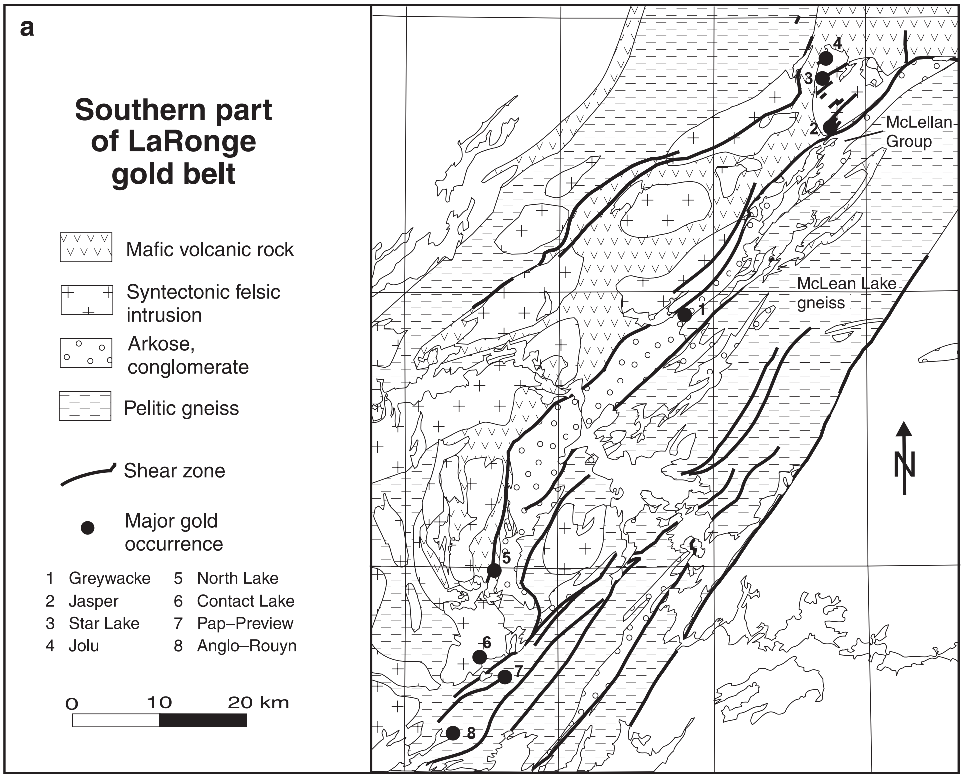
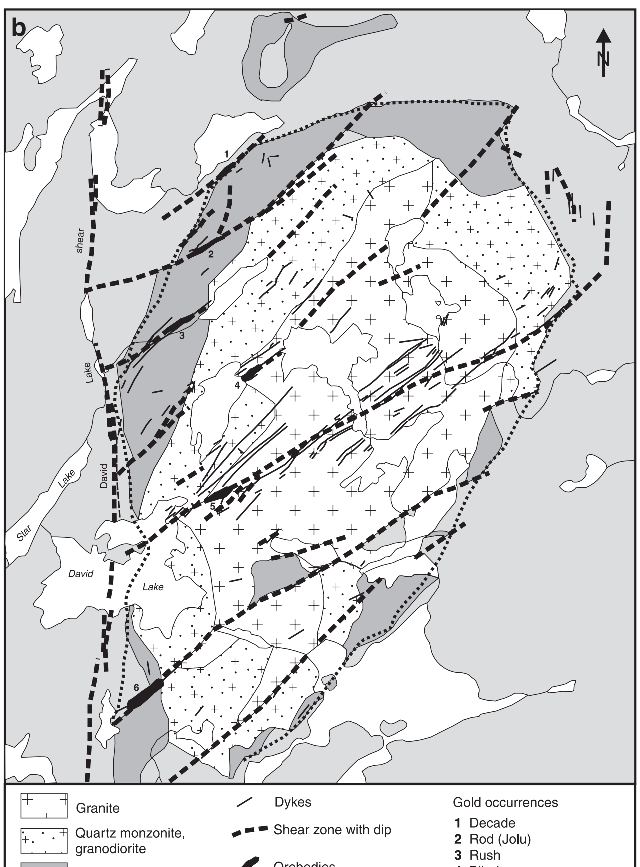


Figure 54.

*Geology and gold deposits of the LaRonge Belt, Saskatchewan. **a**) General geological setting. **b**) Simplified geology of the Star Lake Pluton, LaRonge Belt, Saskatchewan (after Poulsen, 1989).*



Despite their controversial origin, mainly due to the complex structural and hydrothermal history that these deposits have undergone, they represent some of the best Canadian examples of the copper-gold sulphide-rich vein-type deposit.

Proterozoic deposits in the Canadian Shield

Although Archean gold deposits are dominant in the Canadian Shield, significant examples of Early Proterozoic deposits are present in the Churchill and Grenville provinces (Fig. 2). Most of these deposits occur in the 1850–1800 Ma Trans-Hudson Orogen, but there are preliminary indications that deposits such as the Box mine in the in the western Churchill Province maybe related to an older, *circa* 2000 Ma orogenic event. In this respect they may be analogues to western and central Africa, where gold occurs in both Eburnean (*circa* 2000 Ma) and Ubendian (*circa* 1800 Ma) orogenic belts. The settings and types of Canadian Proterozoic gold deposits are generally similar to those of their Archean counterparts, with the exception that the Proterozoic examples are found commonly in rocks of the amphibolite facies rather than in the greenschist facies that so predominates the Archean gold belts.

La Ronge district, Saskatchewan

The gold deposits of the La Ronge area occur in the southern part of the La Ronge–Lynn Lake Domain of the juvenile Reindeer Zone of the Early Proterozoic Trans-Hudson Orogen in the Churchill Province of the Canadian Shield (Fig. 54). The La Ronge–Lynn Lake Domain is bounded to the west by the Paull River fault, part of the Birch Rapids

Straight Belt, in the migmatitic Rottenstone Domain, and to the east by the Stanley Fault. It comprises five belts, including the Central Magmatic Belt, that have been interpreted to be the surface expressions of westerly dipping, easterly directed thrust sheets (Lewry et al., 1990). The Central Magmatic Belt is a granite-greenstone terrane composed of the La Ronge volcanic rocks and numerous discrete oval plutons, and, in the north, the plutonic-dominated Numabin complex. The structural history of the La Ronge–Lynn Lake Domain has been interpreted by Lewry (Lewry et al., 1990; Coombe et al., 1986) to involve four deformational increments. The D_1 and D_2 structures are presumably coincident with near-peak metamorphic conditions and account for most mesoscopic fabrics, whereas D_3 and D_4 mainly involve large-scale open folding and redistribution of early structures. The numerous shear zones and faults that are present in this area have only been tentatively correlated with specific deformational increments.

The most productive deposits that have been discovered to date occur within the Central Magmatic Belt. They all are quartz-vein deposits hosted by shear zones that transect granitoid rocks (Fig. 54a). Deposits of this type are concentrated in the Star Lake–Island Lake (Jolu, Star, Jasper Pond) and the Contact Lake–Preview Lake (Bakos, Pap SW) areas. In the Star Lake area, host plutonic rocks range from quartz monzonite to diorite (and locally gabbro) and all deposits of this type occur in steeply dipping mylonitic shear zones that strike east-northeast to northeast (Fig. 54b). Deposits consist of one or more discrete quartz veins, laminated in the case of Jolu (Fig. 55), and a breccia vein in the case of Star Lake. These deposits are analogous in many respects to the batholith-hosted Korean or Grass Valley (Mother Lode) types of deposits in that, although intrusion-hosted, they occur in parallel arrays of faults which transect both intrusions and country rocks. Only at the Contact Lake deposit is there evidence for multiple stages of mineralization indicative of an earlier preshear, intrusion-related stockwork style of gold emplacement.

Figure 55. *Laminated quartz vein; Jolu mine, LaRonge Belt, Saskatchewan (photograph by K.H. Poulsen). GSC 1999-016I*

Montauban, Quebec

Gold-rich, pyritic, sulphide minerals occur along-strike from the Montauban zinc-lead orebody in Middle Proterozoic gneisses of the Grenville Supergroup in Quebec. The North and South zones of the Montauban deposit produced subequal amounts of gold (0.7 tonnes Au) and silver (0.9 tonnes Ag) from a zone of disseminated pyrite-sphalerite-chalcopyrite associated with cordierite-anthophyllite and quartz-biotite-garnet assemblages within quartz-biotite and quartz-sillimanite gneiss (Morin, 1987). The gold zones contained up to 30% disseminated sulphide minerals, but high gold values appear to have been independent of base metal values. Although of high metamorphic grade, the quartz-plagioclase-biotite gneiss adjacent to the Montauban deposit has been interpreted to be derived mainly from felsic volcaniclastic rocks with local sedimentary intercalations (Morin, 1987; Nadeau et al., 1999). A unit of sillimanite gneiss envelopes the deposit, with locally abundant cordierite, anthophyllite, and manganiferous garnets (Morin, 1987; Jourdain et al., 1987). Because of deformation and metamorphism there is considerable uncertainty about the correct classification of the deposit. Evidence for the late, structurally controlled siting of gold at the Montauban deposit (Jourdain et al., 1987) is similar to that at Bousquet, but the strong stratigraphic control shared by the gold and zinc-lead orebodies makes a high-sulphidation, volcanogenic massive-sulphide model attractive, at least for pretectonic introduction of gold into the environment.

Meliadine River, Nunavut

The Meliadine district (Fig. 2), where gold was first discovered in 1989, is located in the northeastern part of the Late Archean (2.7–2.6 Ga.) Rankin–Ennadai greenstone belt (Armitage et al., 1993), approximately 15 km north-northeast of Rankin Inlet in Nunavut. The district occurs along a regional boundary between clastic sedimentary and volcanic rocks within the Archean Rankin Inlet Group (Fig. 56). A homoclinal succession of greywacke to the northeast is in contact with mafic and minor felsic volcanic rocks to the southwest, on the north limb of a regional synform (Tella, 1994). Two closely spaced and laterally extensive units of oxide-facies banded iron-formation (not distinguished in Fig. 56),

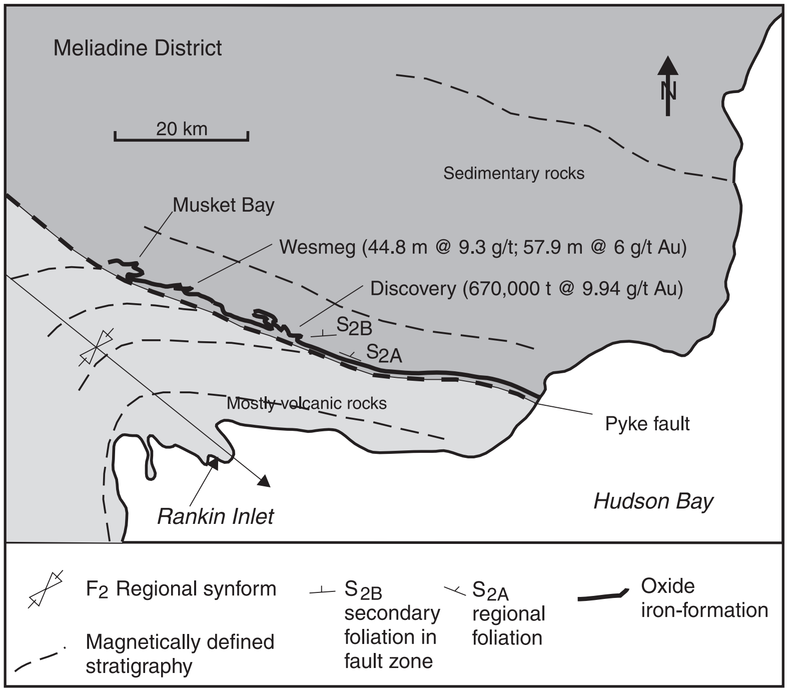


Figure 56.

Sketch map of the setting of gold deposits in the Meliadine River area, Nunavut. The Meliadine Discovery location is at lat. 62°58′N, long. 91°57′W.

one in greywacke and one in volcanic rocks, also mark the contact. This regional lithological boundary is also coincident with a regional shear zone, the Pyke Fault Zone, which overprints local remnants of Early Proterozoic Hurwitz Group orthoquartzite scattered throughout the area. The Pyke Fault Zone is a Proterozoic reverse ductile shear zone that has been subsequently reactivated as a dextral shear zone, producing a series of mesoscopic to map-scale Z-shaped folds of the banded iron-formation and surrounding schist.

Two settings of mineralization are known within the zone of influence of the Pyke Fault Zone. At the Discovery and F-Grid zones, gold occurs in oxide-facies banded iron-formation, in association with zones of quartz-carbonate-arsenopyrite veinlets and their haloes of sulphidized banded iron-formation, along the hinges of Z-shaped folds and along the intersections with east-west shear zones. At the Tiriruniak zone, however, gold occurs in quartz-carbonate veins in sheared mafic volcanic rocks. The main alteration minerals associated with banded-iron-formation-hosted mineralization are hornblende, biotite, and grunerite (Miller et al., 1995), whereas mineralization in mafic volcanic rocks is accompanied by sericite-carbonate alteration. Although hosted in rocks of Archean age, gold mineralization is interpreted to be Proterozoic because of its control by structures related to the Proterozoic Pyke Fault Zone; this is consistent with a $^{40}Ar/^{39}Ar$ plateau age on metasomatic hornblende obtained at the Discovery zone by Miller et al. (1995).

The Meliadine district has many similarities with the Quadrilatero Ferrifero district in Brazil, including the association of mixed Archean volcano-sedimentary succession with oxide-facies banded iron-formation, thrust-related Proterozoic deformation, epigenetic mineralization in banded iron-formation units and neighbouring shear zones, and the lack of felsic porphyry intrusions.

Late Proterozoic to Paleozoic deposits of the Appalachian Orogen

Although there has been production of historic interest, the Appalachian Orogen accounts for a small percentage of Canadian gold endowment. Most significant are Hope Brook in the Avalon Terrane, Newfoundland; a cluster of deposits associated with an ophiolitic suture at Baie Verte, Newfoundland; and the turbidite-hosted veins of the Meguma Terrane, Nova Scotia. The gold deposits at each of these localities are of different geological types and ages, and related to different tectonic events in the Orogen, ranging from Late Proterozoic arc development in the Avalon to Devonian granitic magmatism in the Meguma Terrane.

Hope Brook, Newfoundland

Hope Brook is the largest gold deposit ever mined in the Canadian Appalachians and constitutes the best Canadian example of an epithermal, high-sulphidation gold deposit. It is located in southwestern Newfoundland within the Late Proterozoic (760–540 Ma) Avalon Terrane, close to its tectonic contact with the Ordovician–Silurian Central Mobile Belt of the Appalachian Orogen (Williams et al., 1988, O'Brien et al., 1991). The deposit is located within the volcaniclastic Whittle Hill Sandstone (>583 Ma) intruded by a Late Proterozoic, quartz-feldspar-porphyry, sill-dyke complex of the Roti Intrusive Suite. The mineralization is confined within the hanging wall of the Late Silurian Cinq Cerf fault zone (Fig. 57) and has been strongly deformed and metamorphosed (Stewart, 1992; Dubé et al., 1998). The post-tectonic Chetwynd Granite (390 ± 3 Ma) cuts across the fault zone and its contact-metamorphic aureole overprints the deposit (McKenzie, 1986; Yule et al., 1990; O'Brien et al., 1991; Stewart, 1992; Dubé et al., 1998).

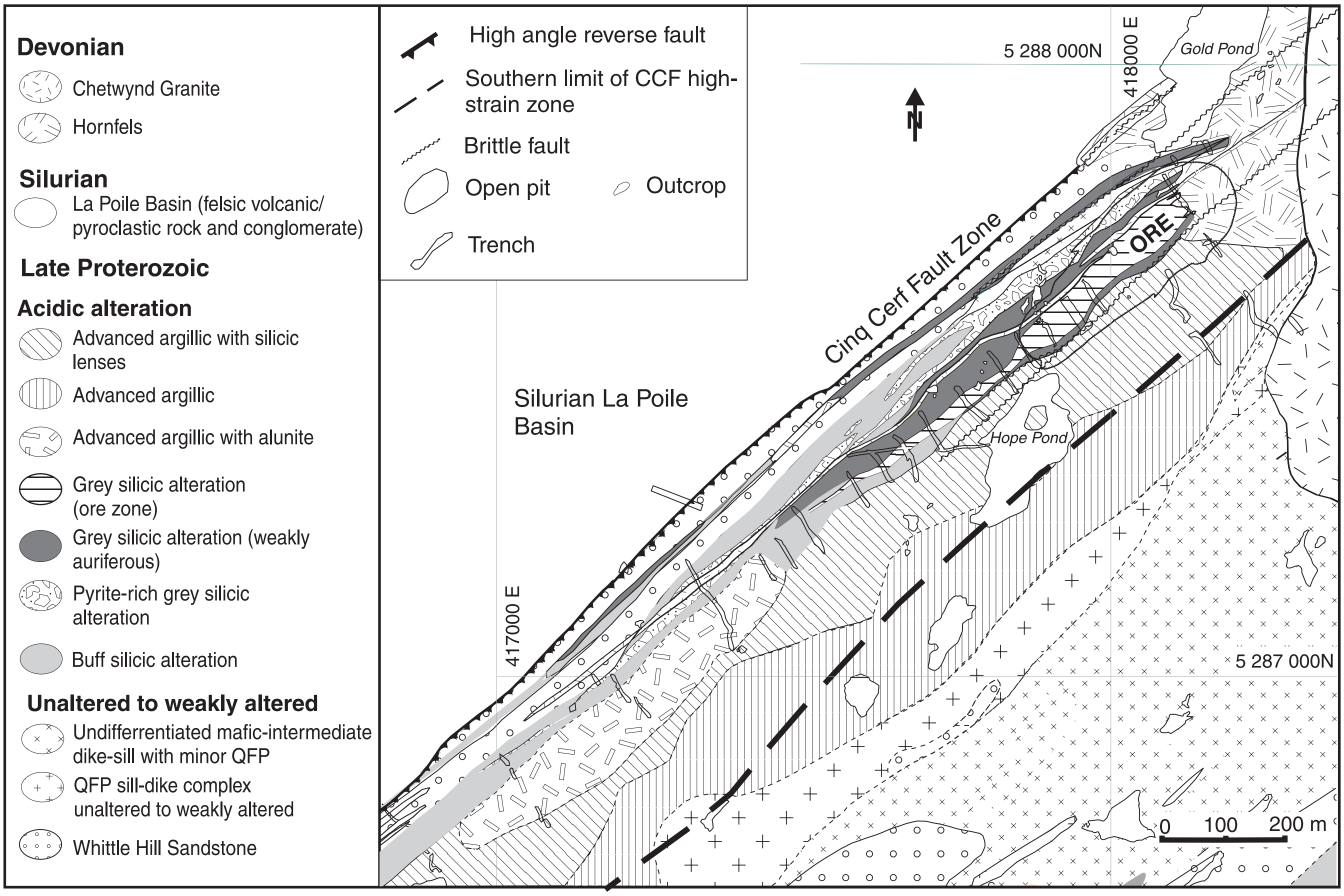


Figure 57. *Simplified geological map of the Hope Brook gold deposit, Newfoundland (after Dubé et al., 1998). Hope Brook is at lat. 47°43′42″N, long. 58°04′54″W.*

The deposit is a steep, south-easterly dipping, tabular zone of disseminated sulphide minerals (750 x 500 x 70 m) enclosed within a wide, acidic, hydrothermal alteration zone (Fig. 57) which is more than 3 km long, up to 400 m wide, and which narrows to the southwest (McKenzie, 1986; Stewart, 1992; Dubé et al., 1998). This zone of alteration is characterized by 1) extensive, advanced argillic alteration with pyrophyllite, kaolinite, andalusite, sericite, alunite, rutile, and pyrite which is mostly developed in the structural hanging wall of the ore zone; and, 2) two stages of massive silicic alteration (Dubé et al., 1994; Dubé et al., 1998). A buff-coloured, massive, first silicic stage (>98% SiO_2) extends for 3 km laterally away from the deposit, constitutes a barren to weakly auriferous zone, and likely results from the pervasive acid leaching of the original host rocks. The gold mineralization is hosted by rocks displaying a second stage of silicic alteration characterized by grey to dark grey colour and vuggy silica (Fig. 58, *see* colour section). The mineralization is characterized by several per cent pyrite and smaller amounts of chalcopyrite and bornite either as disseminations, impregnations, or veinlets, and some tennantite with local traces of enargite. Other than gold and copper, there are negligible quantities of other metals, but overall the hydrothermal system shows, at least locally, anomalously high concentrations of arsenic, antimony, bismuth, and lead, and the silver-to-gold ratio is low.

Hope Brook has been the subject of conflicting interpretations and genetic controversies over the years mainly due to the difficulty of defining primary geological and hydrothermal features in the face of overprinting deformation and metamorphism. Swinden (1984), Kilbourne (1985), and McKenzie (1986) proposed an Ordovician epithermal model for the deposit, whereas Dubé (1990) classified Hope Brook as a deformed, pre-Late Silurian, disseminated, stratabound, sulphide-gold deposit. Yule et al. (1990) proposed that it represents a premetamorphic and preshearing, modified, mesothermal, (sub)volcanic-hosted deposit of probable Cambrian age that also shares analogies with the acid-sulfate epithermal style, but Stewart (1992) interpreted Hope Brook to be a syntectonic multistage (Late Precambrian to Early Devonian) shear-hosted, acid-sulphate-type gold deposit. Stewart (1992) further proposed that the emplacement of the Late Devonian Chetwynd Granite had played an important role in the formation of the economic ore zones by concentrating earlier shear-zone-hosted, low-grade mineralization. Based on the ages of altered (pre-ore and late-ore) quartz-feldspar porphyry units and of an unaltered (post-ore) intermediate

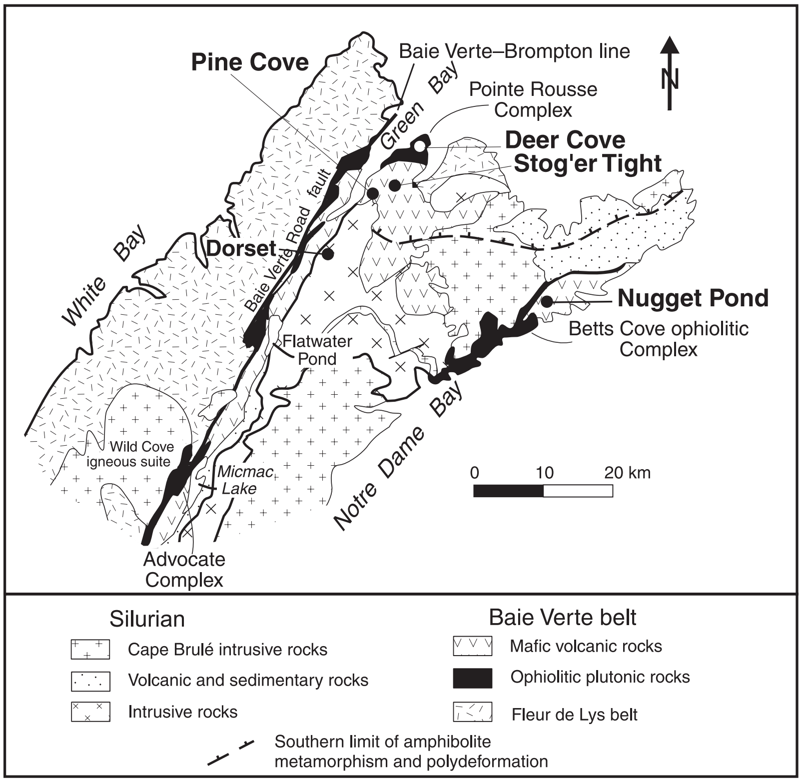


Figure 59.

Geology of the Baie Verte Peninsula, Newfoundland, and location of the principal gold deposits (modified from Hibbard, 1983). Nugget Pond is at lat. 49°50′31″N, long. 55°46′30″W.

dyke cutting altered rocks, the age of mineralization and alteration is constrained to a relatively short time interval between 574 and 578 Ma (Dubé et al., 1998). This temporally and genetically links mineralization and alteration to plutonism of the Roti Intrusive Suite. This chronological relationship, and the present distribution of the alteration zones, suggests that the surface exposure likely represents a section through a now tilted deposit (Dubé et al., 1998). The alteration and mineralization predate the D_2 phase of ductile shearing. Despite a strong spatial relationship between gold mineralization and the major Late Silurian Cinq Cerf fault zone, the deposit bears no genetic relationship with such ductile deformation. This high-sulphidation epithermal deposit was formed in Late Proterozoic time, 150 Ma prior to development of the fault zone.

Baie Verte, Newfoundland

Numerous gold deposits, showings, and prospects occur within the Baie Verte Peninsula in Newfoundland (Fig. 59). The geology of the peninsula is dominated by the Baie Verte–Brompton Line, a northeast-trending major suture between the Cambro-Ordovician continental margin (Humber Zone) on the west, and the Ordovician–Silurian Iapetus Ocean domain (Dunnage Zone) on the east (Williams and St-Julien, 1982). On the Baie Verte Peninsula, the Humber Zone is represented by the Fleur de Lys belt, whereas the Dunnage Zone is represented by the Baie Verte belt (Hibbard, 1983). Most of the gold mineralization is located in the Dunnage Zone in the vicinity of the Baie Verte–Brompton Line, the only exception being the Nugget Pond mine located 30 km east of it (Fig. 59).

Nugget Pond is a small, but high-grade, deposit hosted by a 50 m thick, iron-rich red turbidite horizon within Ordovician basalt of the Betts Cove Ophiolite (Swinden et al., 1990; Lavigne et al., unpub. rept; Sangster et al., 1997). Orebodies are disseminated, pyrite-rich, tabular alteration zones adjacent to extensional arrays of pyrite-feldspar-carbonate veins (Fig. 60). The associated alteration is characterized by stilpnomelane, carbonate, biotite, and chlorite with local silicification. Sulphur-isotopic compositions suggest that the auriferous pyrite is magmatic in origin (Sangster et al., 1997).

Figure 60. *Gold-bearing pyrite-rich haloes concentrated along margins of extensional quartz–pink albite–calcite veinlets cutting iron-rich sedimentary rocks; Nugget Pond mine, Newfoundland (photograph by B. Dubé). Width of photograph is 1 m. GSC 1999-014V*

Other important deposits and prospects in the district are Pine Cove, Stog'er Tight, Deer Cove, and Dorset. Dorset is adjacent to the Baie Verte–Brompton Line and is hosted by the Ordovician Advocate Complex and Silurian Flat Water Pond Group (MacDougall and MacInnis, 1990). The other deposits and prospects, which are adjacent to secondary faults such as the Scrape Thrust (Pine Cove and Stog'er Tight) and the Deer Cove Sole Thrust (Deer Cove), are hosted by the Lower Ordovician Point Rousse Complex (Fig. 61). All of these deposits are structurally controlled. The ore at Dorset occurs as northeast-striking, shear-hosted, sulphide-rich, fault-fill quartz veins (Bélanger et al., 1996), whereas at Deer Cove, the mineralization is mainly in a north-south-trending breccia-quartz vein (Fig. 62) oriented at a high angle to the Deer Cove Sole Thrust. High-grade ore is located in a dragged portion of the breccia adjacent to the thrust and may be associated with later reactivation of the fault (Dubé et al., 1993). At Pine Cove, gold is present both in pyrite-rich veins and as disseminations within sheared mafic volcanic rocks and gabbro units adjacent to the veins. At Stog'er Tight, gold and pyrite are disseminated in iron-rich differentiated gabbroic sills and are thought to be genetically related to a northeast-striking D_1 ductile fault zone (Kirkwood and Dubé, 1992).

All of these mineralized zones are located within areas of greenschist-facies metamorphism. Alteration is variable in intensity and composition, but is commonly characterized by Fe-carbonate, sericite, and chlorite with pink albite, directly related to the ore zone at Stog'er Tight (Kirkwood and Dubé 1992; Ramezani, 1992). Pyrite is common at all the deposits, base metals are especially abundant at Dorset (Bélanger et al., 1996), and the gold-to-silver ratio is approximately 10:1. Intense Fe-carbonate and green-mica alteration (listwaenite) hosted by ultramafic rocks is present along major second-order structures in the vicinity of most deposits, but commonly contains only anomalous amounts of gold.

The age of the mineralization at Stog'er Tight has been determined to be 420 ± 5 Ma by U-Pb analysis of hydrothermal zircon (Ramezani, 1992). This Silurian age is also compatible with the interpreted age at Dorset (Bélanger et al., 1996) and at Deer Cove (Patey and Wilton, 1993). Uranium-lead analyses of xenotime from quartz-feldspar-carbonate-pyrite veins at Nugget Pond yielded a Devonian age (375 ± 8 Ma; Sangster et al., 1997), suggesting at least two separate gold events in the peninsula.

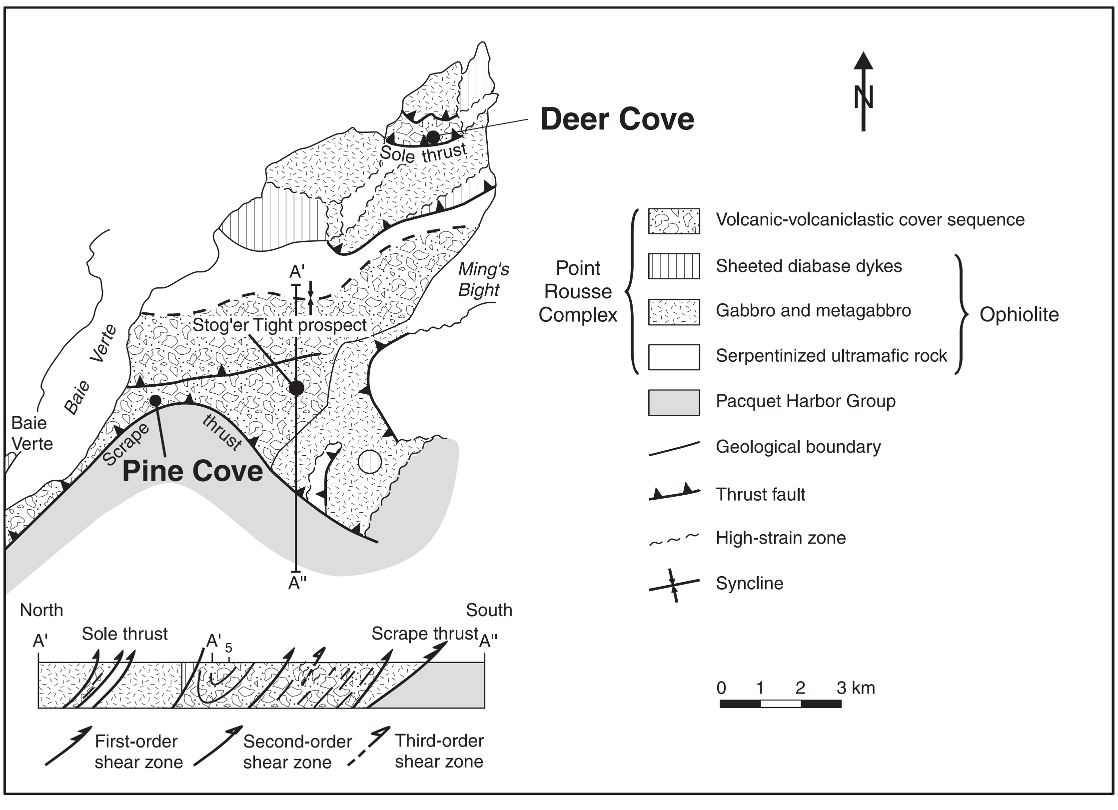


Figure 61. *Geology of the Point Rousse Complex area, Newfoundland, and location of the gold deposits. Regional north-south cross-section of the Point Rousse Complex showing the structural setting of the Stog'er Tight and Pine Cove deposits (modified from Hibbard, 1983; Kirkwood and Dubé, 1992). Deer Cove is at lat. 50°01′03″N, long. 56°02′44″W.*

Most of the lode gold deposits present in the Baie Verte Peninsula share strong analogies with Mother Lode–type deposits. They are structurally controlled, and the primary iron content and competent nature of the host rocks also played key roles in the formation of several deposits. As typically found in the Superior Province, gold is associated with second- or third-order structures rather than with the first-order Baie Verte–Brompton Line (Tuach et al., 1988; Dubé, 1990). The complex and protracted structural history of the Baie Verte–Brompton fault system and associated subsidiary structures is probably responsible for the younger post-ore deformation of several mineralized zones.

Figure 62. *Quartz-breccia vein; Deer Cove deposit, Newfoundland (photograph by B. Dubé). GSC 1999-014W*

Meguma, Nova Scotia

The Meguma is an historically important gold district in spite of the fact that individual deposits are small, and, compared to the major Precambrian districts, production has been limited. The deposits occur in a Cambro-Ordovician turbidite sequence consisting of quartz-rich greywacke of the Goldenville Formation overlain by thinly laminated slate of the Halifax Formation (Graves and Zentilli, 1982). These rocks are folded into upright northeast- to east-northeast-trending anticlines and synclines with attendant low-grade metamorphic steep cleavage, cut by younger northwest-trending faults and intruded by Devonian granitoid bodies (Fig. 63) that impart a contact-metamorphic overprint on regional metamorphic fabrics. Most deposits, composed of quartz-carbonate-pyrite-arsenopyrite veins, are located at the crests of the shallow-plunging anticlines. Common bedding-parallel veins (Fig. 64) mimic the regional folds. All evidence points to most bedding-parallel veins having formed

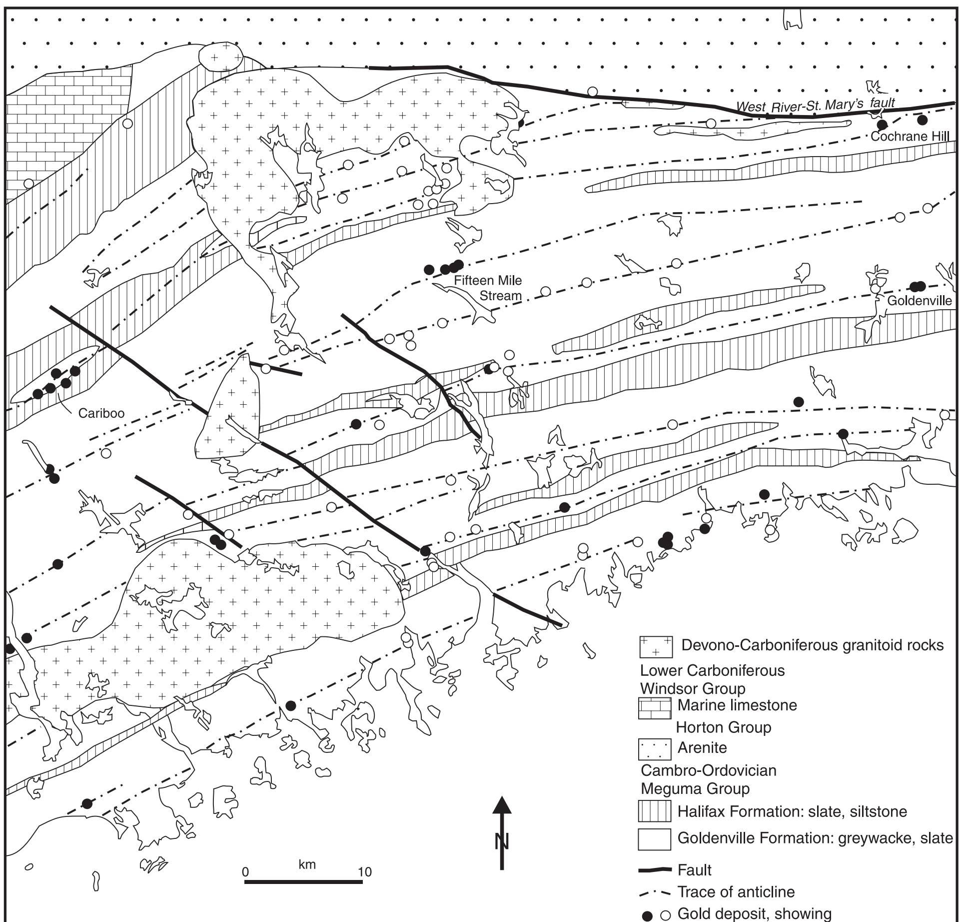


Figure 63.

General geology of the Meguma gold district, Nova Scotia (modified from Boyle, 1979). The Goldenville mine is at lat. 45°07′30″N, long. 62°02′00″W.

syntectonically during the development of regional folds and cleavage. They show convincing evidence of having filled by incremental crack-seal growth as initially flat-lying 'water sills' (Henderson and Henderson, 1990), as well as evidence of their subsequent shortening by buckle folds in regional fold hinges and extension by 'pinch and swell' along fold limbs.

Figure 64. *Bedding-parallel quartz vein; Harrigan Cove, Meguma district, Nova Scotia (photograph by K.H. Poulsen). GSC 1999-016J*

Many models have been proposed to account for the setting and form of the Meguma veins, but they tend to group around two apparently conflicting aspects of the deposits. The first is the clear evidence of an early paragenesis of bedding-parallel veins coincident with the onset of metamorphism. This has led to the interpretation of a relatively early age of mineralization with respect to regional magmatism and tectonism. On the other hand, direct dating of hydrothermal muscovite at approximately 370 Ma (Kontak et al., 1993) places at least some mineralization in a postmetamorphic stage of regional development more closely related to the emplacement of late-tectonic granitic intrusions, as suggested by Kontak et al. (1990). These contradictory lines of evidence are resolvable only if one accepts that the early bedding-parallel veins were not inherently gold bearing, but that they were mineralized during shear-zone development after their initial formation (Williams and Hy, 1990) or that hydrothermal effects overprinted and enhanced pre-existing auriferous quartz veins.

Despite some differences of scale, the Meguma district is Canada's foremost analogue of the Victorian gold province of southeastern Australia (Phillips and Hughes, 1996; Cox et al., 1991) and the deposits are clear examples of the turbidite-hosted quartz-carbonate vein type.

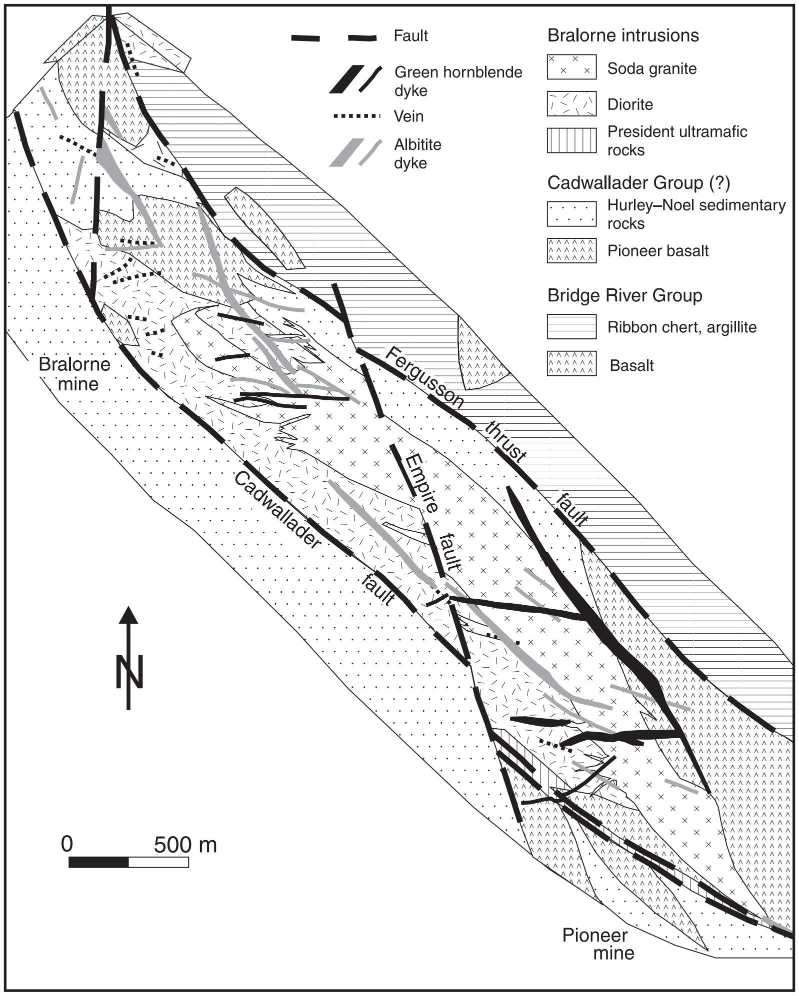


Figure 65.

General geology of the Bralorne area, British Columbia. The Bralorne mine is at lat. 50°46′50″N, long. 122°48′45″W.

Mesozoic to Cenozoic deposits of the Cordilleran Orogen

Although small compared to the two main Archean cratons, gold production from the Cordilleran Orogen is third among major geological domains in Canada. Because the geological terranes of the Canadian Cordillera are natural extensions of adjacent geological units in the United States, it is not surprising that gold deposits within them are most comparable to many well known deposit types that characterize the western United States. As in the American segment of the Cordillera, Mesozoic gold deposits in Canada occur both in the miogeoclinal rocks and in accreted volcanic-arc and oceanic terranes, whereas Tertiary deposits are superimposed on both continental and accreted crust. A significant difference between the American and Canadian segments of the Cordillera is that Tertiary gold deposits predominate in the former and Mesozoic ones in the latter.

Bralorne–Pioneer, British Columbia

The Bralorne–Pioneer is the largest gold producer to date in the Canadian Cordillera. This vein-type deposit is located near the regional tectonic contact between the Permian to Early Jurassic Cadwallader Terrane of island-arc affinity and the Early Permian to Early Cretaceous Bridge River Terrane of oceanic affinity, about 10 km east of the Late Cretaceous to Paleocene Coast Plutonic Complex. The deposit occurs within a fault-bounded block of steeply dipping turbidites, argillites, and basaltic andesites of the Cadwallader Terrane, intruded by hornblendite, diorite, and sodic granite of the Bralorne intrusions (Fig. 65), dated at 270 Ma (Leitch et al., 1991). This block is bounded to the southwest by the Cadwallader fault, marked by the presence of slivers of serpentinized ultramafic rocks, and is separated from ribbon chert, argillite, and basalt of the Bridge River Terrane to the northeast by the Fergusson fault (Fig. 65). All these rocks have been affected by sub- to lower greenschist metamorphism (Leitch, 1990).

The deposit comprises an array of quartz-carbonate veins, extending vertically for at least 2 km, without significant mineralogical zoning. The array consists of three main vein sets: 1) dominant and most extensive ribboned shear veins in narrow brittle-ductile, reverse to reverse-oblique shear zones (Fig. 66), striking 290° and dipping 70°N; 2) extensional veins forming links between shear veins, striking at 250° and dipping 75°NW; and, least important, 3) 'cross' veins, striking north-south and dipping moderately to steeply to the west (Fig. 65). The vein system is interpreted to have formed during compressional reactivation of a pre-existing fault array formed in a sinistral strike-slip regime (Leitch, 1990). The quartz-carbonate veins contain gold and small amounts of pyrite, arsenopyrite, tetrahedrite, and trace amounts of scheelite and tourmaline. The veins are fringed by zoned carbonate-sericite alteration haloes consisting of inner quartz-ankerite-sericite–sulphide-mineral assemblages and outer calcite-chlorite-albite assemblages (Leitch, 1990). The age of mineralization is constrained by pre-ore albitite dykes dated at 91.4 Ma, and by intra- to postmineralization hornblende-porphyry dykes dated at 85.7 Ma (Leitch et al., 1991). The Bralorne–Pioneer deposit shares most attributes of Archean greenstone-hosted quartz-carbonate-vein deposits, and it represents the clearest Mesozoic example of this gold deposit type in Canada.

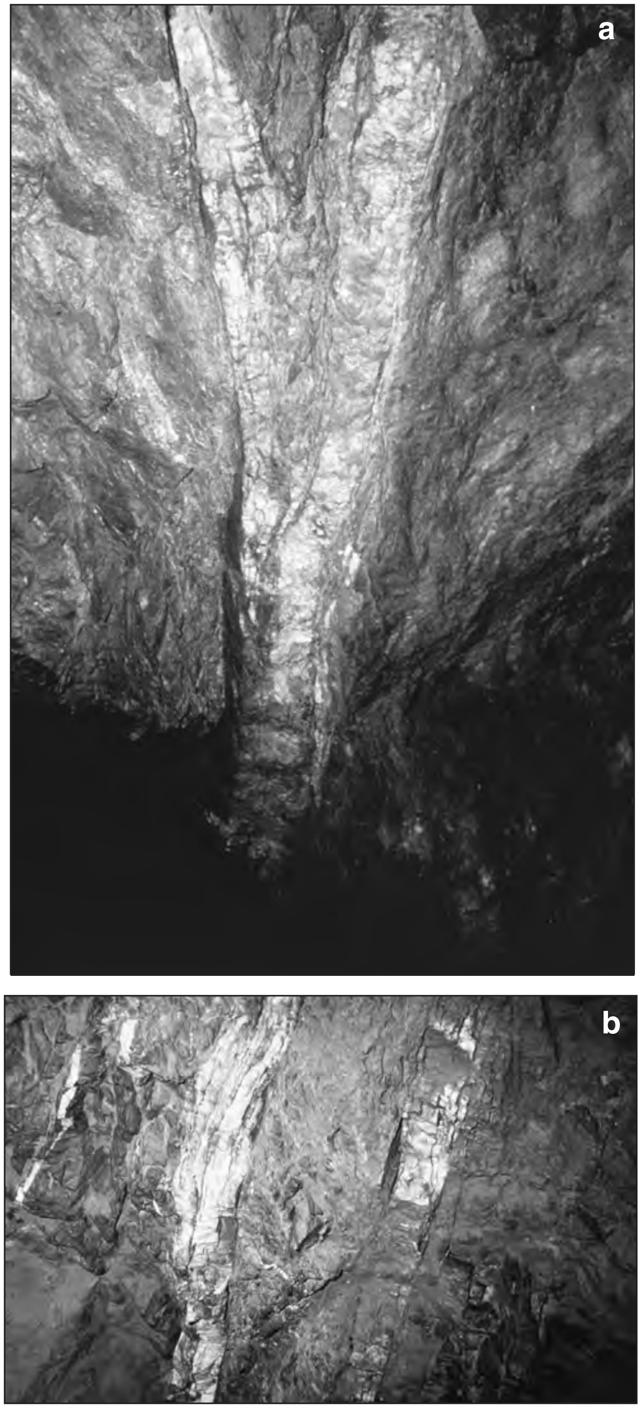
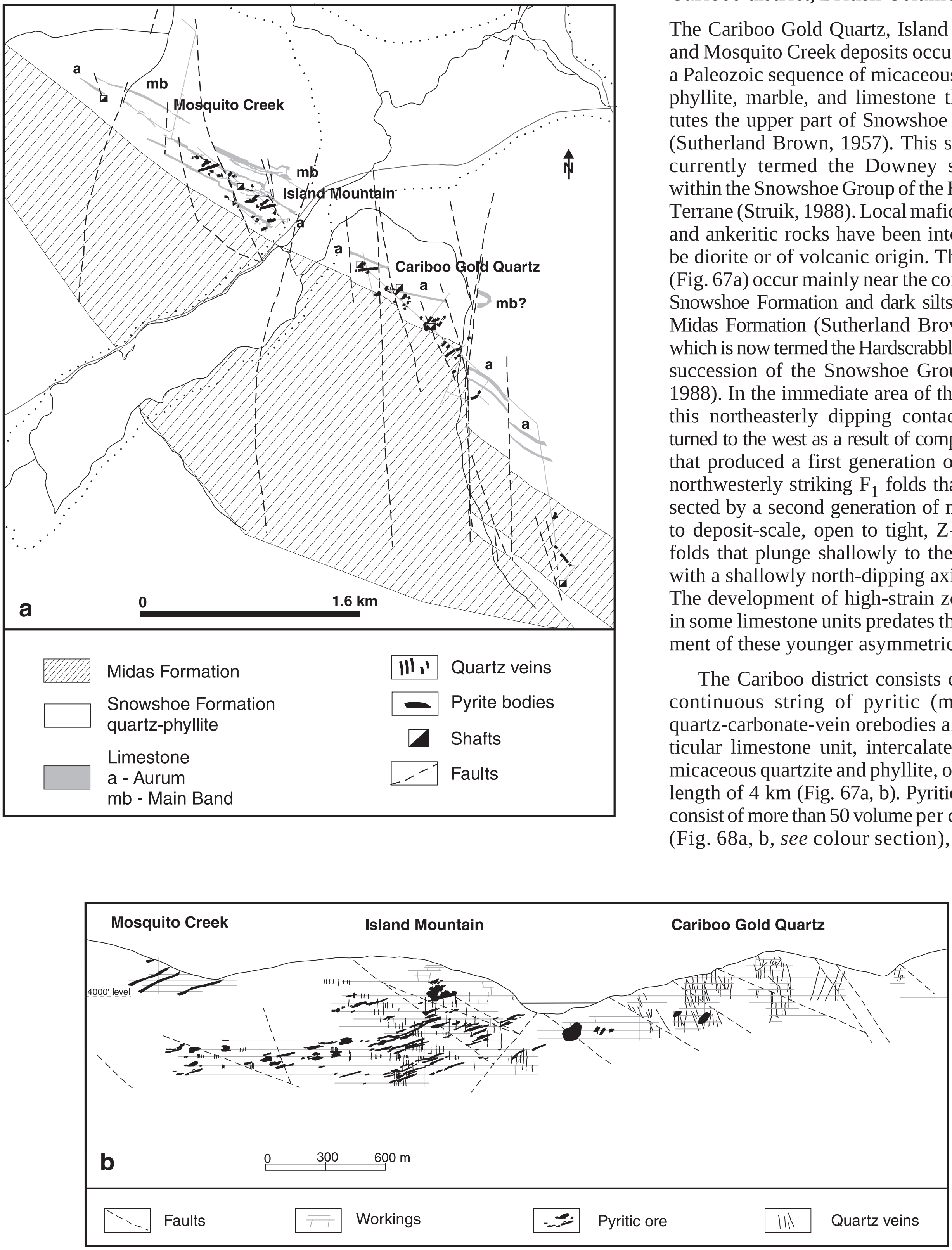


***Figure 66.** **a**), **b**) Ribboned quartz-carbonate vein in foliated diorite, 812 vein, Bralorne mine, British Columbia. Width of photograph a) is 1 m, and b) is 1.5 m. (Both photographs by F. Robert.) GSC 1999-015GG, GSC 1999-015HH*



Cariboo district, British Columbia

The Cariboo Gold Quartz, Island Mountain, and Mosquito Creek deposits occur mainly in a Paleozoic sequence of micaceous quartzite, phyllite, marble, and limestone that constitutes the upper part of Snowshoe Formation (Sutherland Brown, 1957). This sequence is currently termed the Downey succession within the Snowshoe Group of the Barkerville Terrane (Struik, 1988). Local mafic, chloritic, and ankeritic rocks have been interpreted to be diorite or of volcanic origin. The deposits (Fig. 67a) occur mainly near the contact of the Snowshoe Formation and dark siltstone of the Midas Formation (Sutherland Brown, 1957), which is now termed the Hardscrabble Mountain succession of the Snowshoe Group (Struik, 1988). In the immediate area of the deposits, this northeasterly dipping contact is overturned to the west as a result of complex folding that produced a first generation of regional, northwesterly striking F_1 folds that are transected by a second generation of mesoscopic to deposit-scale, open to tight, Z-shaped F_2 folds that plunge shallowly to the northwest with a shallowly north-dipping axial surface. The development of high-strain zones (D_1?) in some limestone units predates the development of these younger asymmetric folds.

The Cariboo district consists of a nearly continuous string of pyritic (manto) and quartz-carbonate-vein orebodies along a particular limestone unit, intercalated between micaceous quartzite and phyllite, over a strike length of 4 km (Fig. 67a, b). Pyritic orebodies consist of more than 50 volume per cent pyrite (Fig. 68a, b, *see* colour section), occurring

Figure 67. *General geology of the Cariboo–Mosquito Creek area, British Columbia.* ***a****) level plan, 4000 level.* ***b****) Longitudinal section. The Cariboo mine is at lat. 53°06′06″N, long. 121°34′57″W.*

either as granoblastic aggregate of millimetre-sized grains or as centimetre-sized porphyroblasts, accompanied by small amounts of arsenopyrite; these bodies are commonly fringed by narrow haloes of silicification of the thin limestone units within the Snowshoe Formation. They are particularly common in the Aurum (also known as the Baker or 339) Limestone member, a marker that was locally used to divide the Snowshoe Formation into Rainbow (west) and Baker (east) members. The pyritic orebodies also occur in the main band limestone (Fig. 67a). In both stratigraphic settings, the pyritic orebodies are located most commonly in the hinge areas of F_2 folds, forming pencil-like orebodies plunging shallowly to the northwest (Fig. 67b), although they also occur on their long limbs; in F_2 fold hinges, the pyrite bodies show evidence of intense transposition by the S_2 cleavage. This type of ore, which dominates in the northwestern half of the district (Fig. 67b), averages 20 g/t Au and accounts for one third of the total gold production of the district. Several sets of mineralized quartz-carbonate veins occur in the immediate structural footwall of the mineralized limestone units, where they reach several tens of metres along strike, and are particularly abundant in the southeastern part of the district (Fig. 67a, b). The two main sets are oblique and orthogonal subvertical veins, oriented at moderate to high angles to the axes of F_2 folds, respectively. Both vein sets are extensional in nature (Fig. 68a, c, *see* colour section) and cut the S_2 cleavage and F_2 folds; orthogonal veins occupy AC fractures related to F_2 folds (Robert and Taylor, 1989). The veins contain minor amounts of pyrite and white mica, mostly as alteration products of wall-rock slivers within in the veins, and they are surrounded by sericite-carbonate alteration haloes; some of the orthogonal veins may contain significant quantities of pyrite, chalcopyrite, sphalerite, and galena.

Samples of white mica from quartz-carbonate veins have been dated by the K-Ar method at ~ 140 Ma (Alldrick, 1983). The quartz-vein and pyritic ores have been historically regarded to be coeval and genetically related (e.g. Alldrick, 1983), but they clearly represent two distinct stages of mineralization: pyritic orebodies are transposed by S_2 cleavage and predate the development of F_2 folds, whereas the oblique and orthogonal veins have formed late in the development of these folds. The quartz-carbonate veins are typical of 'mesothermal' vein deposits (Nesbitt et al., 1986), but the pyrite bodies represent examples of deformed limestone-replacement-type (manto) mineralization that is independent of the veins. Such mantos are generally regarded to be intrusion related but, in the Cariboo district, suitable progenitor intrusions are lacking, perhaps apart from the possible rare diorite bodies and the local felsic 'Prosperine' dykes of Sutherland Brown (1957).

Blackdome, British Columbia

The Blackdome deposit in the Clinton district, British Columbia is hosted by 52 Ma andesite-dacite volcanic rocks unconformably overlying a basement of Cretaceous metavolcanic rocks and overlain disconformably by post-ore 24 Ma (Oligocene–Miocene) basalt (Fig. 69). Ore is confined to vuggy quartz veins up to 1.5 m thick in northeast-striking normal faults that contain fault gouge and breccia. Veins are banded,

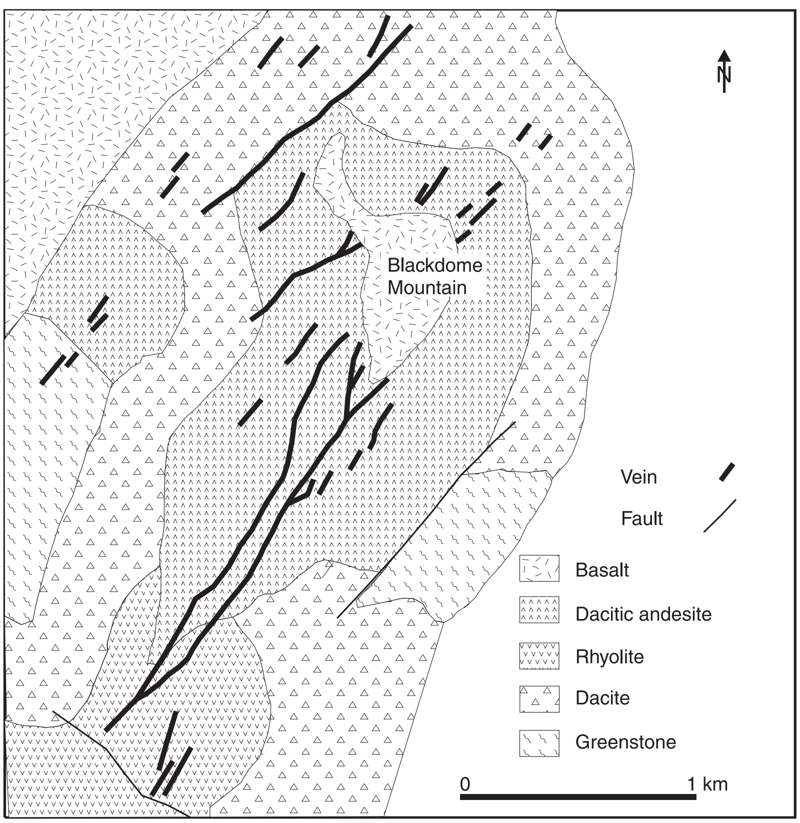


Figure 69.

Geology of the epithermal vein system at Blackdome Mountain, British Columbia (after Faulkner, 1986). The Blackdome mine is at lat. 51°19′40″N, long. 122°29′05″W.

many are vuggy, and comb-textured quartz is common (Fig. 70). Visible gold and sulphide minerals are rare, but native gold, silver, electrum, acanthite, argentite, along with minor pyrite, pyrrhotite, chalcopyrite, sphalerite, and galena have been reported (Faulkner, 1986). Silicification and adularia-bearing argillic alteration are developed near the veins, whereas propylitic alteration occupies a more distal position.

Although a relatively small deposit, Blackdome is one of Canada's clearest examples of a Tertiary low-sulphidation epithermal deposit. Its association with an andesite-dacite-rhyolite sequence, with normal faults and adularia-bearing alteration assemblages, and the open-space-filling textures of the ore are all directly comparable to features in similar deposits worldwide.

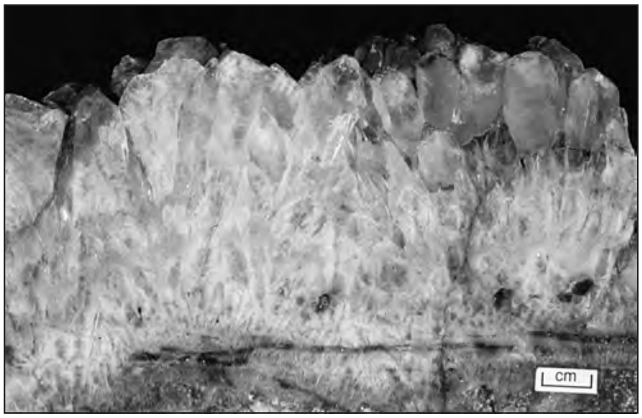


Figure 70. *Comb quartz with gold; Blackdome mine, British Columbia (photograph by F. Robert). GSC 1999-015LL*

Wheaton River district, Yukon Territory

The Mount Skukum and Skukum Creek deposits in the Wheaton River district are related to a subcircular Early Eocene (56 Ma) volcanic complex composed of andesite, dacite, and rhyolite flows as well as pyroclastic and epiclastic rocks (Fig. 71). The volcanic rocks are interpreted to occupy a caldera (McDonald, 1990) that overlies the basement composed of Paleozoic to Late Proterozoic Nisling Terrane, the Jura-Cretaceous chert-pebble conglomerate of the Tantalus Formation, and voluminous mid-Cretaceous granitic rocks of the Coast Plutonic Complex (Hart, 1992). Intrusions related to the volcanic complex include basaltic andesite dykes and porphyritic rhyolite stocks and dykes (McDonald, 1990; Hart,1992). The low-sulphidation, epithermal Mount Skukum deposit consists of quartz-carbonate-adularia-rhodochrosite veins in steeply dipping, northerly striking, normal faults cutting shallow strata within the volcanic complex (Love et al., 1998). Electrum and native silver occur in the sulphide-poor crustiform, chalcedonic, and breccia quartz veins (Fig. 72) which also contain minor pyrite, and rare sphalerite and galena. Local bladed and skeletal lattice calcite in the veins has been interpreted to indicate boiling during vein formation (McDonald, 1990). Proximal silicification adjacent to veins gives way outward to adularia-sericite, and

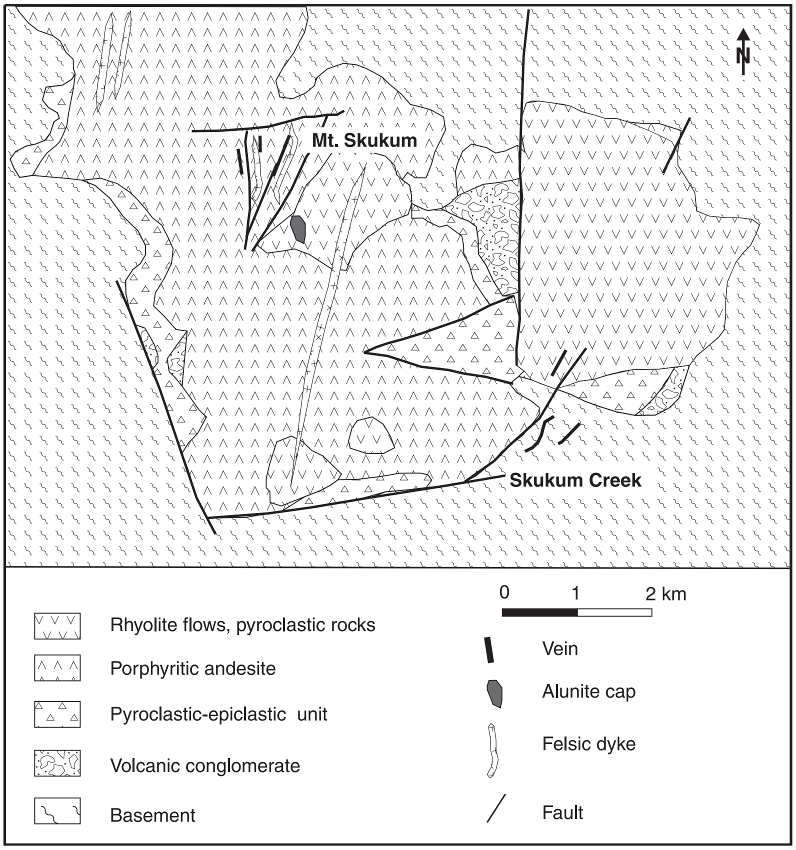


Figure 71.

Geology of the Wheaton River area, Yukon Territory (after McDonald, 1990; Hart, 1992). The Mount Skukum deposit is at lat. 60°13′00″N, long. 135°27′30″W.

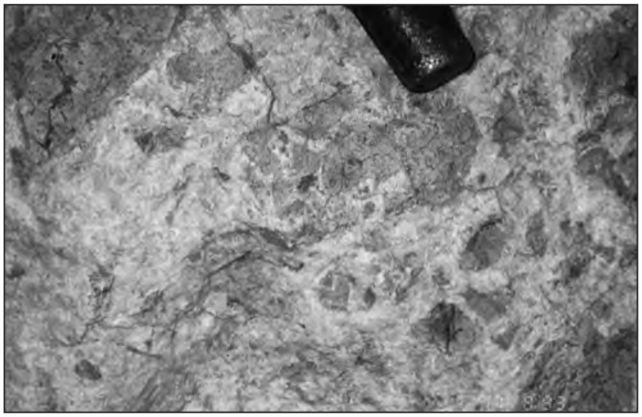


Figure 72. Quartz breccia vein; Mount Skukum deposit, Yukon Territory. Scale object is the blunt end of a geological hammer (photograph by K.H. Poulsen). GSC 1999-016K

propylitic alteration. A separate zone of advanced argillic alteration, the ‘Alunite cap’ represents an earlier stage of barren alunite-kaolinite-type alteration centred on a small rhyolitic stock (Love et al., 1998). The alunite cap alteration has been dated at 55.69 ± 0.24 Ma, whereas the age of the low-sulphidation gold mineralization of the Cirque and Lake zones of the Mount Skukum deposit is 54.05 ± 0.31 Ma (Love et al., 1998).

The Skukum Creek deposit (Fig. 71) occurs within medium-grained Cretaceous hornblende granodiorite cut by Eocene andesite and rhyolite dykes that are thought to be related to the adjacent and overlying Mount Skukum volcanic complex (Hart, 1992). Quartz-sulphide veins at Skukum Creek occur in curved northeast-trending splays off the east-west-striking Berney Creek fault. Veins and fault-related stockworks occur mainly within felsic dykes and contain moderate quantities of pyrite, arsenopyrite, galena, and sphalerite, as well as minor chalcopyrite, pyrargerite, pyrrhotite, and stibnite. Vein-scale alteration is mainly sericitic and silicic.

Although relatively small, the Mount Skukum and Skukum Creek deposits, like Blackdome, are good examples of low-sulphidation epithermal deposits. Both lateral and vertical metal zoning are indicated in this area (Hart, 1992) and stibnite veins in the basement rocks may be part of the same hydrothermal system. An additional significant feature of the Wheaton River district is the presence of zones of advanced argillic alteration such as the gossanous ‘Alunite cap’ which is thought to result from near-surface hypogene acid leaching related to an early magmatic hydrothermal stage within the volcanic complex (Love et al., 1998). Elsewhere in the world, such leaching is thought to result from the dissolution of low-salinity magmatic vapour into groundwater aquifers in zones of steam-heated upflow and outflow. Many such zones, like the Alunite cap, are not strongly mineralized with gold; those that are mineralized have commonly been overprinted by a second stage of ore-forming alteration, including silicicification. At Mount Skukum, Love et al. (1998) proposed a succession from a barren alunite-kaolinite-type (high sulphidation) to an auriferous adularia-sericite-type system (low sulphidation), both formed during ongoing magmatism in the Mount Skukum Volcanic Complex.

Nickel Plate, Hedley district, British Columbia

The Nickel Plate deposit at Hedley in the Similkameen District, British Columbia is hosted by Late Triassic limestone and calcareous siltstone of the Hedley Formation of the Nicola Group (Ray et al., 1996), which also includes an overlying tuff and lapilli tuff package of the Whistle Creek Formation (Fig. 73). The host rocks are cut by Late Triassic to Early Jurassic quartz diorite, diorite, and gabbro of the Hedley Intrusive Suite, which take the form of dikes, sills, and stocks. A mid-Jurassic suite of granodiorite to quartz monzonite intrusions is represented by the Cahill Creek pluton. The deposit consists of shallow, west-dipping, tabular to irregular, stratabound sulphide lenses (Fig. 74, *see* colour section) at the edge of an extensive zone of calcic exoskarn and endoskarn surrounding the Toronto stock, one of the larger Hedley intrusions that is accompanied by numerous peripheral dikes and sills. Ore is composed of arsenopyrite, pyrrhotite, lesser pyrite, gold, hedleyite, native bismuth, and minor chalcopyrite, sphalerite, and galena (Ettlinger et al., 1992). Gold concentration correlates strongly with that of bismuth and copper (Ray et al., 1988), although large quantities of sulphide minerals do not ensure the presence of comparable gold concentration. The mineralization occurs mainly near the base of a 200–300 m thick prograde biotite–K-feldspar–Fe-pyroxene–garnet-quartz skarn which has locally been overprinted by the ore-stage sulphide minerals, scapolite, axinite, and epidote, as well as retrograde chlorite, epidote, sericite, and prehnite (Ray and Webster, 1991; Ettlinger et al., 1992).

Nickel Plate is Canada’s foremost skarn gold deposit and is also generally regarded as one of the world’s best examples of this deposit type (e.g. Meinert, 1989; Ray and Webster, 1991). The high ratios of pyrrhotite to pyrite and of pyroxene to garnet, as well as the occurrence of iron-rich hedenbergitic pyroxene are evidence that Nickel Plate, like Fortitude, Nevada, is a reduced calcic skarn deposit. It formed in association with relatively mafic magmas that are interpreted to be subduction related, yet emplaced in a back-arc rift environment (Ray and Webster, 1994).

Golden Bear, British Columbia

The Golden Bear (Muddy Lake) deposits occur within Permian limestone and dolomitic limestone of the Paleozoic Stikine Assemblage within the Stikine accreted terrane. The limestone units are overlain by Carboniferous (*circa* 320 Ma) mafic volcanic flows and local felsic tuff units that were intruded by 220 Ma granodiorite and diorite, as well as gabbro of probable Jurassic age (Oliver and Gabites, 1993). A D_1 thrust fault separates the carbonate rocks from overlying volcanic rocks, and together the rocks have been deformed into an antiformal structure (Fig. 75) by the interference of F_2 northerly to northwesterly trending folds and F_3 northeast-southwest-trending folds (Oliver, 1995). The steep, east-dipping Ophir break, one of three subparallel north-northwesterly striking faults

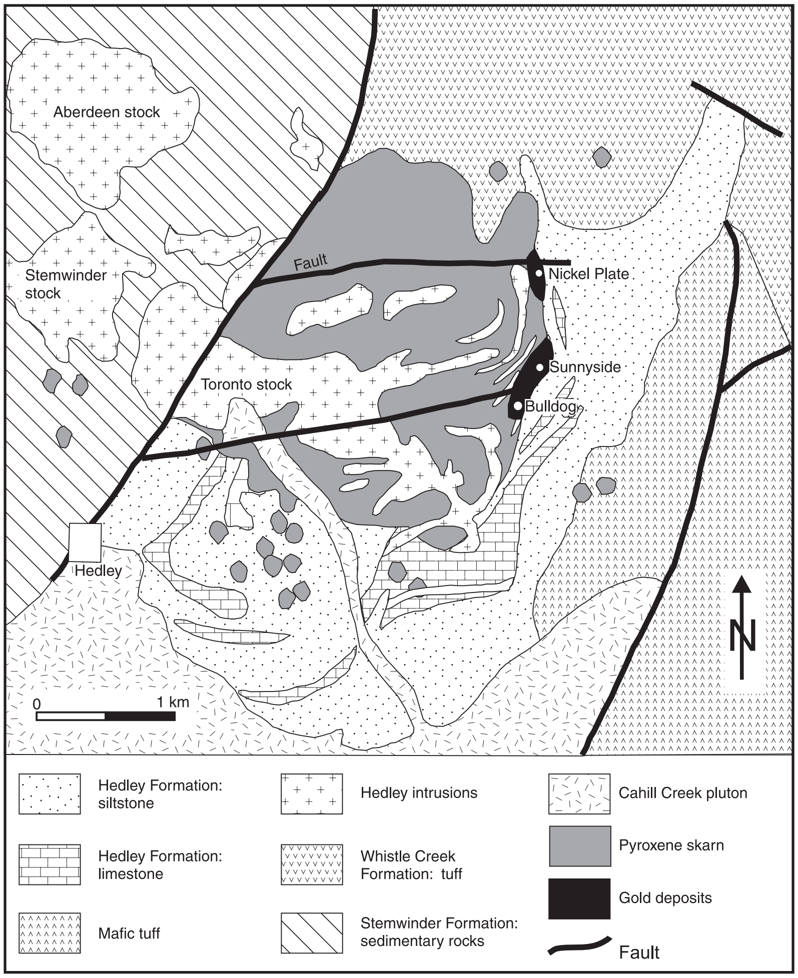


Figure 73.

Geology of the Hedley area, British Columbia (after Ray and Webster, 1991). The Nickel Plate mine is at lat. 49°22′18″N, long. 120°01′43″W.

that offset F_2 and F_3 folds, is a 20 km long structure that controls the locations of the gold deposits, which typically are steep, tabular, commonly brecciated, siliceous zones within and adjacent to fault strands (Fig. 75). Visible sulphide minerals and gold are rare within the orebodies, but pyrite, minor arsenopyrite, and traces of stibnite, tetrahedrite, chalcopyrite, and pyrrhotite have been reported (Schroeter, 1986; Oliver and Hodgson, 1989). Micron-sized gold particles are associated with zoned arsenian pyrite. The trace elements arsenic, antimony, and mercury are geochemical indicators of the presence of gold at the property scale. Although ankeritic and sericitic alteration is characteristic of the overlying volcanic rocks (Oliver and Hodgson,1989; Schroeter,1986), the most remarkable form of hydrothermal alteration is silicification of the host limestone bodies (Fig. 76) both at the deposit and district scale. Orebodies occur in original carbonate rocks that now range from being decarbonated (Ursa and Grizzly) to moderately silicified (Main Bear) to intensely silicified (Kodiak deposits). In addition, the Totem silica zone (Fig. 75) is an extensive mass of silicified, but weakly mineralized, limestone adjacent to the Ophir break. Traces of relict bedding within the silicified rock (close to 100% silica) attest to its origin occurring largely through metasomatic replacement. Brecciated (and re-silicified?) zones are also common (Fig. 76).

Their combined geological features make the Golden Bear deposits the most convincing Canadian examples of ‘Carlin-type’ mineralization known to date. They are truly “siliceous, limestone replacement deposits” in the sense of Lindgren (1933), and share the following attributes with Nevada’s Carlin-type deposits: carbonate host rocks in a domal structure involving an overthrust of non-carbonate rocks, distinctive arsenic-antimony-mercury geochemical signature, low sulphide content with micron-sized gold particles, and an association with extensive zones of silicification and brecciation. The extensive silicification, represented mainly by the Totem silica zone, corresponds to ‘jasperoid’ in Great Basin terminology, and the siliceous breccia ores in the Kodiak deposits are analogous to the ‘jasperoid breccia’ ores of Nevada. A significant difference, however, is the fact that the overall tectonic setting of the Golden Bear deposits is within an island-arc terrane with flanking and interdigitated carbonate sequences (Gabrielse and Yorath, 1991), whereas the Carlin-type deposits of the Great Basin are hosted by continental miogeoclinal carbonate sequences. In this respect, the setting of Golden Bear is perhaps more analogous to those Carlin-type deposits like Mesel, Indonesia, and Bau, Malaysia, which formed in island-arc terranes (e.g. Garwin, et al., 1995).

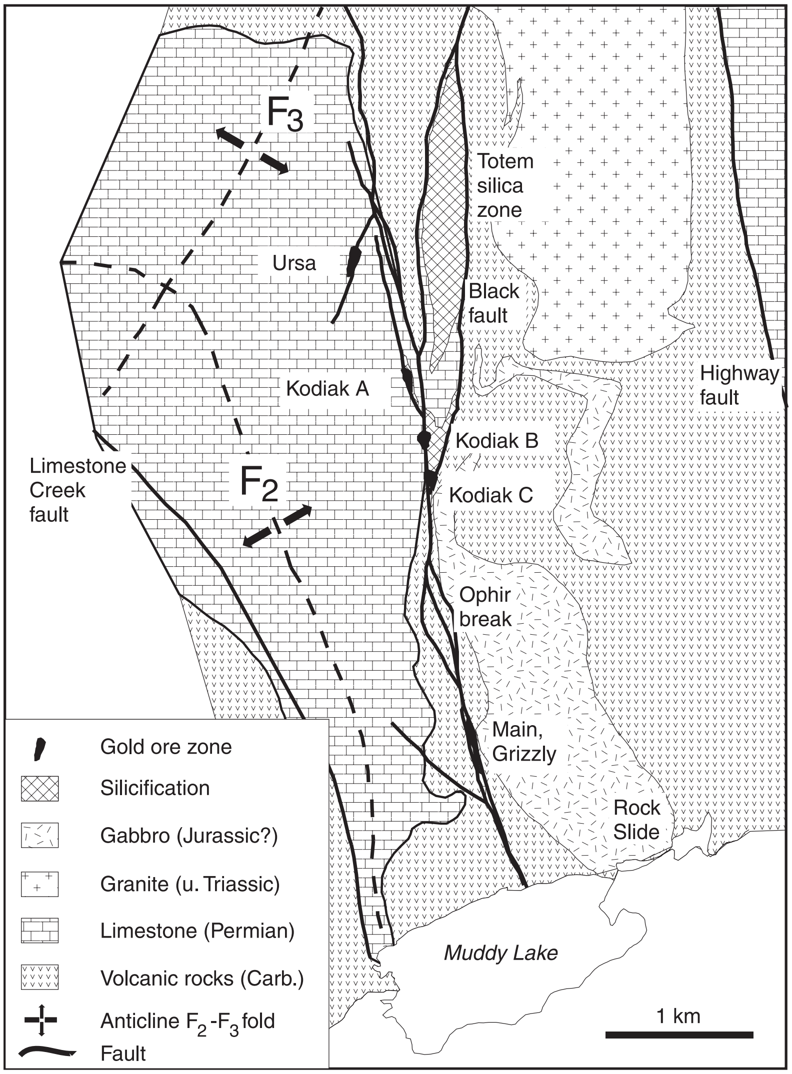


Figure 75.

Geology of the Muddy Lake area, British Columbia (after Oliver, 1995; Schroeter, 1986). Muddy Lake is at lat. 58°13′N, long. 132°10′W.

Figure 76. *Jasperoid breccia; Kodiak A deposit, Golden Bear mine, British Columbia (photograph by K.H. Poulsen). GSC 1999-016M*

Ketza River, Yukon Territory

The Ketza River deposits occur within the northern Cassiar Platform, which is generally regarded to be a segment of the Cordilleran miogeocline that has been transported 450 km northward along the dextral transcurrent Tintina Fault. The deposits are mainly hosted by limestone on the southern flank of the Ketza uplift within the west-northwesterly striking Ketza–Seagull Arch, a major regional structure within the Cassiar Platform (Abbott, 1986). The core of the Ketza uplift is composed of Neoproterozoic sandstone, siltstone, and argillite of the Hyland Group that are overlain in turn by lower Cambrian limestone and phyllite of the Atan Group, and shale, mudstone, and minor limestone of the Kechika Group. The rocks within this domal structure have been deformed by easterly striking thrusts (e.g. the Peel fault) and folds with steep axial surfaces overprinted by shallow crenulation cleavage and subsequently by north-northwest-striking normal faults (e.g. the NW fault, Fig. 77). Orebodies such as the Ridge and

Fork zones are mainly auriferous zones of limonite-goethite-hisingerite supergene oxide minerals that have developed on stratabound massive-sulphide lenses in the folded and faulted limestone (Stroshein, 1995). The hypogene sulphide bodies, such as the Peel zone, are replacements, mainly in Atan limestone, consisting of pyrrhotite-arsenopyrite-pyrite with minor sphalerite, galena, and siderite (Cathro, 1988). Gold content correlates positively with arsenopyrite and total sulphide-mineral content, and occurs as 0.5 to 25 micron grains associated with native bismuth and chalcopyrite in microfractures in other sulphide phases (Cathro, 1988). Quartz-calcite veinlets and stockworks in the limestone are cut by the sulphide minerals, and dolomitization has locally affected the adjacent limestone. Local magnetite-actinolite-epidote skarns are present near the orebodies (Fork zone), quartz-arsenopyrite veins (the Shamrock zone approximately 1.5 km northeast of the Ridge zone) are present in Hyland rocks, and several silver-lead-zinc veins and mantos occur peripheral to the gold zones (Cathro, 1988).

The hypogene mineralization at Ketza River is the clearest Canadian example of a carbonate-replacement manto-type gold deposit (Fig. 78, *see* colour section). The mineralization is thought to be mid-Cretaceous and related to as yet unidentified

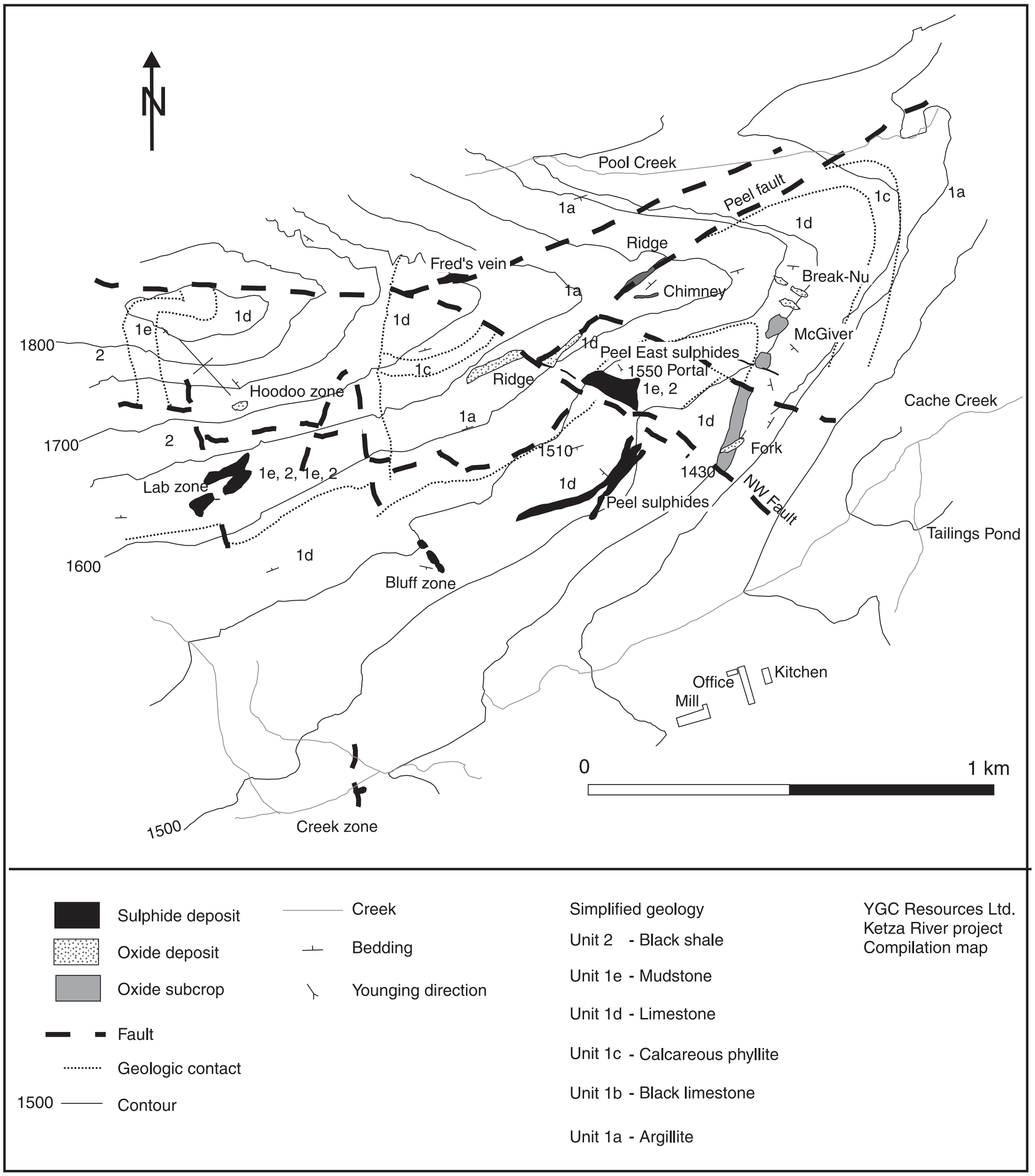


Figure 77. *Geology of the Ketza River gold deposits, Yukon Territory (after Stroshein, 1995; Cathro, 1988).*

buried intrusions underlying an area of hornfels and calc-silicate development in the vicinity of the Fork zone. The relative timing of mineralization with respect to deformation is nonetheless in some doubt. The stratabound gold ore is concordant with a well defined fold in the limestone (Stroshein, 1995) suggesting either that the mantos have been folded or that they have formed at the expense of previously folded limestone beds adjacent to transverse normal faults. The style of mineralization and geological setting of the Ketza River deposits compare favourably with the Ruby Hill district, Nevada (Fig. 16) where Carlin-type mineralization (the Archimedes deposit) has recently been discovered adjacent to the mantos at higher stratigraphic levels (Dilles et al., 1996).

Brewery Creek, Yukon Territory

The Brewery Creek deposits occur within the Paleozoic miogeoclinal sequence of the Selwyn Basin. Stratigraphically, they occur at the unconformable contact between argillite, turbiditic sandstone, and conglomerate of the Devono-Mississippian Earn Group and underlying siltstone and dolomitic siltstone of the Ordovician to Silurian Road River Group (Fig. 79). Also present are Road River argillite and chert, as well as calcareous phyllite and mafic volcanic rocks of the Cambro-Ordovician Kechika Group. The host sequence is folded into steep attitudes and is intruded by biotite monzonite and syenite stocks with distinct contact aureoles containing hornfels and local calc-silicate rocks, and by somewhat younger porphyritic quartz monzonite (quartz-feldspar porphyry) dykes and sills which do not produce significant contact metamorphic effects. Both stocks and sills yield 91 Ma U-Pb zircon ages (Mortensen et al., 1996). Shallow faults are marked by disrupted zones of graphitic argillite, particularly along margins of sills, and locally by fault breccia: steep normal and listric normal faults cut all rocks types.

Gold ore occurs in three settings. Most common (Canadian, Fosters, Kokanee, Bohemian, and Moosehead deposits) are irregular zones of steep millimetre- to centimetre-thick subvertical quartz veinlets within the porphyry sills, but restricted to the hanging walls of normal faults. The Blue and Pacific deposits are composed of auriferous disseminated sulphide minerals, steep breccia (Fig. 80a, *see* colour section), and fault zones within Earn Group argillite and sandstone. The third style of ore, represented by the North Slope deposit, is hosted by dolomitic mudstone of the Steel Formation of the Road River Group. This zone consists of a shallow-dipping body of brecciated mudstone (Fig. 80b, *see* colour section) in a fault zone that is concordant with strata in its hanging wall, but discordant to beds in its footwall. All settings contain mineralization of essentially the same composition: micron-sized gold particles, particularly in arsenian rims on minor pyrite; local arsenopyrite and common stibnite in veins and breccia; and local realgar-orpiment (Diment, 1996). Sericitic alteration of the porphyry is common and mineralized sedimentary units are weakly silicified. Oxidation of the deposit typically extends 60–70 m below surface, allowing bulk mining of the supergene ore.

The age of the mineralization at Brewery Creek is uncertain, but a sericitic alteration selvage from a veinlet in the Bohemian deposit has yielded a 89 Ma K-Ar age (J.K. Mortensen, pers. comm.) suggesting a temporal overlap with the age of the quartz monzonite dykes and sills. Diment (1996) has interpreted the deposits to be epithermal, but the lack of coeval volcanic rocks, metal zoning, and associated

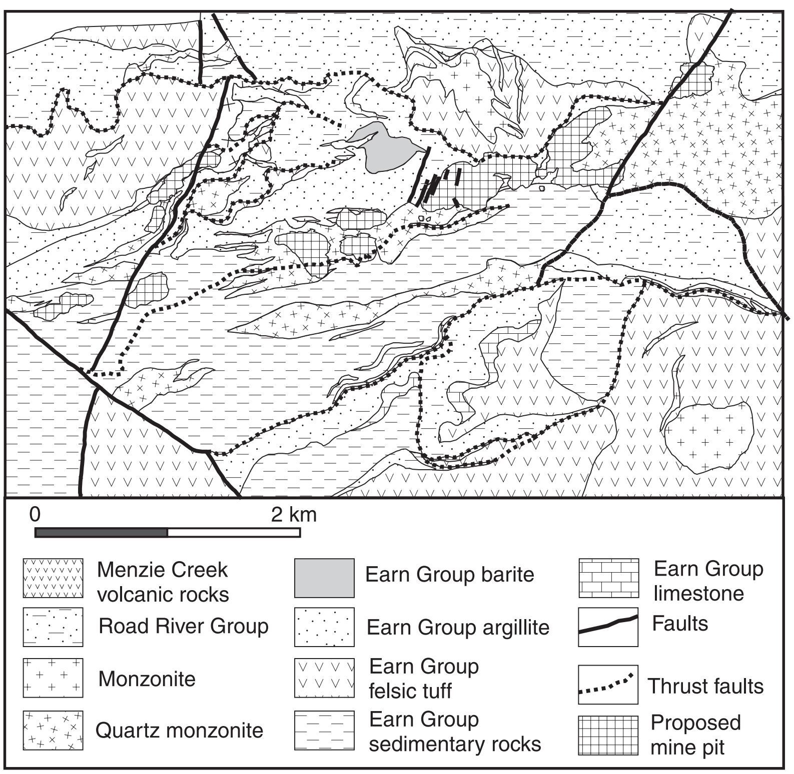


Figure 79.

Geology of the Brewery Creek area, Yukon Territory. (modified from Diment, 1996). The centre of the map is lat. 64°03′23″N, long. 138°16′44″W.

base metals and silver makes for unsatisfactory comparisons with most conventional epithermal systems. Poulsen (1996) and Poulsen et al. (1997) have suggested that the setting of the deposits within a miogeoclinal setting is comparable to that of the Great Basin (Turner et al., 1989). The presence of micron-sized gold, the arsenic-antimony-mercury geochemical signature, and the existence of disseminated carbonate-hosted mineralization in the North Slope deposit puts Brewery Creek within the realm of Carlin-type deposits. This interpretation is also unsatisfactory, however, if one considers that the bulk of mineralization at Brewery Creek is hosted either by intrusions or by siliciclastic rocks, and that there is neither extensive silicification of the impure carbonate rocks, nor evidence of truly stratabound mineralization. In many respects, the Brewery Creek deposits resemble the Tertiary deposits in the Black Hills of South Dakota (e.g. Golden Reward). The latter has been linked with Carlin-type deposits in the past (Lindgren, 1933) but Berger and Bagby (1991) suggested that they are sufficiently different from most other Carlin-type deposits to regard them merely as 'Carlin-like'. This is also a reasonable designation for the Brewery Creek deposits.

Dublin Gulch, Yukon Territory

The Dublin Gulch (Eagle zone) deposit occurs within rocks of the Cordilleran Miogeocline within Selwyn Basin. Hornfelsed, Neoproterozoic, Hyland Group phyllite, quartzite, and marble are intruded by the Cretaceous (92 Ma) Potato Hills granodiorite stock of the Tombstone plutonic suite (Mortensen et al., 1996). The Potato Hills stock (Fig. 81) has a well developed biotite hornfels and calc-silicate envelope which contains the gold- and sulphide-poor Ray Gulch scheelite-bearing skarn deposit hosted by Hyland Group limestone members (Lennan, 1986).

The Eagle zone gold deposit (Fig. 81) consists of a kilometre-square zone of centimetre-thick sheeted quartz veins (Fig. 82) that dip steeply south within the moderately north-dipping granodiorite and locally within adjacent southwest-dipping metasedimentary rocks. Rare stockwork zones are restricted to the core of the deposit. The quartz veinlets contain local disseminated arsenopyrite, bismuthinite, pyrite, pyrrhotite, molybdenite, scheelite, and native bismuth (Hitchins and Orssich, 1995). Potassium feldspar and biotite occur locally in the veins, and sericite occurs in narrow adjacent alteration selvedges. Ankeritic carbonate is present in some of the wider (up to 10 cm) and paragenetically younger veins of identical orientation. A younger, overprinting, chloritic alteration pervasively overprints parts of the deposits and the depth of supergene oxidation varies from 0–100 m. Through-going gold-bearing quartz veins are also present in and adjacent to the Potato Hills stock, and gold-lead-zinc veins occur beyond the hornfels front to the southeast and southwest (Fig. 81).

The Dublin Gulch deposit is generally regarded to be of the identical age and type as the larger Fort Knox deposit near Fairbanks, Alaska. This deposit has, in turn, been interpreted to be a variety of 'porphyry' gold deposit (Hollister, 1991) or a plutonic-related deposit (McCoy et al., 1997). Both deposits have attributes such as potassic alteration, bismuth mineralogy, and district-scale metal zoning that extends outward from the intrusions, all of which make porphyry analogues compelling, but they also possess anomalous characteristics in comparison to most alkalic and calc-alkaline gold-bearing porphyry systems (Sillitoe, 1991a). The dominance of sheeted veins over a stockwork style of mineralization may reflect a deeper level of formation, where regional stresses control fracturing to a greater degree than at shallower levels where more random, intrusion-driven, fracturing is the norm. The metal association of gold-arsenic-tungsten±molybdenum also contrasts with the more familiar copper-dominated alkalic

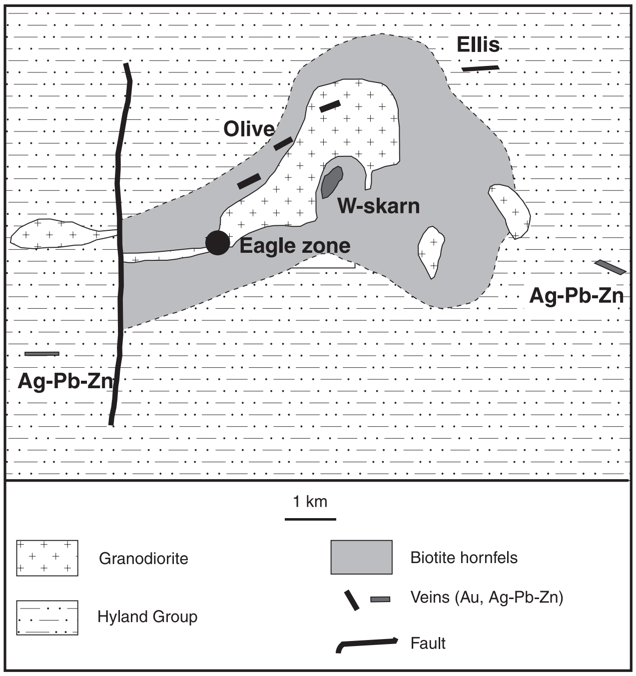


Figure 81. Geology of the Dublin Gulch area, Yukon Territory (after Lennan, 1986; Hitchens and Orssich, 1995). The Eagle zone is at lat. 64°01′57″N, long. 135°47′44″W.

Figure 82. Sheeted quartz veins in granodiorite; Eagle zone, Dublin Gulch deposit, Yukon Territory (photograph by K.H. Poulsen). GSC 1999-016O

and calc-alkaline porphyry deposits of the accreted-arc terranes elsewhere in the Canadian Cordillera, none of which, strictly speaking, are gold deposits.

Eskay Creek, British Columbia

The Eskay Creek deposit occurs in the Iskut River area of the Cordillera. It is hosted by Lower Jurassic rocks of the Hazelton Group in the Stikine Terrane in a stratigraphic sequence consisting of felsic flow-banded volcanic rocks and breccia units of a flow dome complex overlain by marine argillite and pillow basalt (Macdonald et al., 1996). The deposit consists of stratabound to stratiform lenses of semimassive to massive stibnite and realgar (21A zone) and a stratiform sulphide-sulphosalt zinc-lead-gold-silver zone composed of stibnite, arsenopyrite, pyrite, sphalerite, galena, and tetrahedrite (21B zone). The sedimentary textures of the stratiform ore in the 21B zone (Fig. 83, *see* colour section) are consistent with its detrital origin, whereas the 21A zone, with its underlying stockwork and disseminated zones, resembles epithermal mineralization. Alteration in underlying volcanic rocks includes choritization, silicification, and sericitization, and is comparable to that of volcanogenic massive-sulphide deposits. Most workers regard Eskay Creek to have composite characteristics of both deposit types (Sillitoe et al., 1996; Macdonald et al., 1996).

Conclusions

Examination of the geological characteristics of Canadian hydrothermal gold deposits reveals a significant diversity in style of mineralization and timing of emplacement that requires consideration of multiple models. The different styles of mineralization represented by Archean and Proterozoic deposits in Canada include, in approximate order of decreasing importance (number of deposits) the following: quartz-carbonate veins related to shear zones and folds (Dome, Pamour, Hollinger–McIntyre, San Antonio, Kerr Addison, Kirkland Lake, Sigma–Lamaque, Con–Giant, parts of Lupin, Meliadine); zones of disseminated sulphide minerals±stockworks around porphyry bodies (Hemlo, Malartic, Harker–Holloway); massive-sulphide lenses (Horne, Bousquet No. 2–LaRonde, parts of Lupin, Montauban); sulphide-rich veins, stockworks, and disseminated sulphide minerals (Doyon, Bousquet No. 1); carbonate±quartz veins (Campbell–A.W. White); and disseminated sulphide minerals in vuggy silica (Hope Brook). The first of these styles typifies what most authors consider to be ‘mesothermal’ vein deposits (*see* Hodgson, 1993); the rest, however, have little in common with such vein deposits and rather, are compatible with totally different origins. Some deposits combine more than one style of mineralization of a single or different ages: quartz-carbonate veins overprinting copper-molybdenum±gold stockwork sulphide minerals at Hollinger–McIntyre, and quartz veins and massive-sulphide layers at Lupin. The presence of auriferous sulphide clasts in Timiskaming Group conglomerate at Dome and Pamour provides further evidence for multiple stages of gold mineralization in some deposits.

The diversity of styles of mineralization among deposits also correlates with differences in composition of ore (Au:Ag ratios and metal associations), in associated hydrothermal alteration, and lithological or structural associations. Differences in hydrothermal alteration are particularly important: the spectrum of such highly contrasted types of alteration as carbonatization-sericitization at many quartz-carbonate vein deposits, K-feldspar alteration at Hemlo, aluminous alteration (advanced argillic) at Bousquet, and massive silicic alteration at Hope Brook, require that different types of hydrothermal fluids be involved in the formation of these deposits. This conclusion is also consistent with significant differences in composition of the ores.

Furthermore, deposits corresponding to the different styles of mineralization have formed at different stages in the evolution of their host terranes. For example, massive-sulphide lenses at Horne, sulphide-rich veins at Doyon, carbonate-chert veins at Campbell–A.W. White, and disseminated sulphide minerals at Hemlo all predate the main stage(s) of deformation. They likely formed during stages of *construction* of volcano-plutonic edifices, at relatively shallow crustal depths. In contrast, shear-zone-related quartz-carbonate veins have formed later in the tectonic evolution, either during D_2 at Sigma–Lamaque and San Antonio, or after post-D_2 folding of fluvial-alluvial sedimentary rocks at Dome, Pamour, Kirkland Lake, and Kerr Addison. Such quartz-carbonate vein deposits have formed during stages of *deformation* of volcano-plutonic edifices, in deeper crustal environments (Hodgson, 1993).

In summary, the geological attributes of many Archean and Proterozoic gold deposits in Canada point to a significant diversity among these deposits and several models have been proposed for Precambrian gold deposits in general. A number of authors emphasize deep sources of gold and fluids, and deposition of gold in a continuum of crustal levels (Colvine, 1989; Cameron, 1993; Groves et al., 1995), although there is considerable debate as to whether the ore fluids are ultimately of magmatic (Spooner, 1991) or metamorphic (Kerrich and Cassidy, 1994) origin. On the other hand, other authors have suggested that most, if not all, Archean gold deposits have a shallow-crustal magmatic origin and have merely been buried to be deformed at different crustal levels (Mason, 1992; Mason and Helmstaedt, 1992). Multistage models have also been proposed, with the common concept that gold is recycled either from early formed, perhaps subecononmic gold deposits (Hutchinson, 1993) or from gold-rich district-scale reservoirs that resulted from earlier increments of gold enrichment (Hodgson, 1993). Each of those models has merit and is certainly applicable to specific deposits, or groups of deposits. In many cases, however, the models have been portrayed as accounting for most, if not all, Archean and Proterozoic gold deposits, reflecting a unifying approach deemed too restrictive given the diversity of deposit types documented here.

As in the older terranes, Canadian Phanerozoic deposits display considerable diversity in setting and style of mineralization. There has been a tendency to divide these deposits into ‘epithermal’ and ‘mesothermal’ groups (Nesbitt et al., 1986), and further to recognize that there are transitional types between these two extremes (Panteleyev, 1991). There is also a natural tendency to compare the gold metallogeny of the Canadian segment of the Cordillera and Appalachians with those of the United States to the south (e.g. Poulsen, 1996). The geological history of the Cordillera records accretion of arc terranes in the Late Paleozoic and Mesozoic to the western miogeoclinal margin of North America, and that of the Appalachians records accretion of Late Proterozoic and Early Paleozoic terranes to the eastern miogeocline. In both cases, the high-level epithermal groups of deposits are either pre- or postcollisional whereas the mesothermal deposits tend to be related more closely with compressional deformation.

APPLICATION OF GOLD DEPOSIT MODELS

Introduction

The foregoing sections of this bulletin have discussed selected Canadian gold deposits against the standards of widely recognized, geologically defined deposit types. This has illustrated that, although many are adequately 'classifiable' in this way, others deviate in their characteristics from the standard types to a degree that their classification is ambiguous. In some extreme cases, one might better ask whether a deposit is sufficiently unique to warrant creation of a new deposit type (e.g. Hemlo).

The reasons for the difficulty in classification of some deposits may include extreme deformational overprinting or superposition of more than one hydrothermal system, but it is also likely that some problems stem from the method of classification. Two fundamental questions can be posed in this regard: Does the presentation of a list of deposit types with their characteristics really constitute a classification scheme in itself? Are there logical steps that one can follow in assessing a deposit to be of one type to the exclusion of another? The answer to both questions is that subdivision into the deposit 'types' described herein has developed historically from several sources and has not necessarily resulted from a systematic attempt at classification. Nonetheless, there are recurring parameters that geologists have used for decades in attempts to apply their particular classification schemes. These include geological environment, host rocks, ore types, and hydrothermal signatures as expressed by ore, alteration mineralogy, and chemistry. The use of these parameters to construct a classification scheme is also warranted by the fact their various combinations are distinctive for nearly all gold deposit types as illustrated in the'Gold Deposit Types' section. These parameters have therefore been used to construct a logical 'decision tree' or classification chart (Fig. 84) to explain how the globally recognized deposit types can be distinguished from one another. This is only one way of rationalizing the various deposit types identified in'Gold Deposit Types', but it does illustrate the point that the historical classification of gold deposits is much less of a random matter than it might first appear.

Classification parameters

The scheme illustrated in Figure 84 relies on four of the time-honoured parameters which geologists instinctively take into consideration when studying gold deposits (Tables 1, 2):

1. *Are the supracrustal rocks in and around the deposit mainly volcanic or sedimentary, and to what major tectonic environment can they be assigned?* For supracrustal sequences that are dominantly sedimentary, the decision is whether the rocks are composed mainly of basinal wacke and shale, of mature arenite and quartz-pebble conglomerate, or of shallow-water carbonate, sandstone, and shale. These correspond in a broad way to marginal basins, intracratonic basins, and continental miogeoclines, respectively. For supracrustal sequences that are dominantly volcanic, the two main possibilities are subaerial, commonly andesitic to dacitic volcaniclastic rocks and related sedimentary units; or mainly submarine, commonly basaltic to rhyolitic volcanic rocks and derived sedimentary rocks. These two environments can normally be distinguished from one another by the volcanic and sedimentary facies that predominate. In younger terranes, these two alternatives correspond broadly to continental volcanic arcs and oceanic-island arcs, respectively, whereas ancient 'greenstone' terranes are thought to be mainly of the second type.
2. *What is the main host for ore?* Intrusions in one form or another are ubiquitous features in and around gold deposits. Is the gold deposit in question hosted mainly by an intrusion or by supracrustal rocks? In most cases this is a relatively easy decision, but, in some cases, both the intrusion and the country rock host mineralization, and either a choice must be made in favour of the dominant host, or two alternate paths must be followed simultaneously to allow other parameters to assist in the decision-making process.
3. *What is the form of the ore?* This is one of the most accepted criteria used by economic geologists and typically involves a decision whether orebodies are discordant, stratabound, or stratiform, and whether, at the mesoscopic scale, ore can be classified as being of vein, stockwork, breccia, disseminated-sulphide, or massive-sulphide type. This is a decision that is relatively easy in undeformed deposits, but post-ore deformation may substantially modify the form or style of mineralization, in which case an understanding of chronological relationships between ore and deformation is commonly essential to correctly classify a deposit.
4. *What is the hydrothermal signature of the deposit as expressed by chemical composition and mineralogy of both ore and hydrothermal alteration products?* Ideally, this should be one of the most diagnostic parameters available and in some cases it is: for example, the combination of 'high-sulphidation' mineral assemblages involving enargite and 'massive silicic' alteration directly point to high-sulphidation-type epithermal gold deposits. Classical

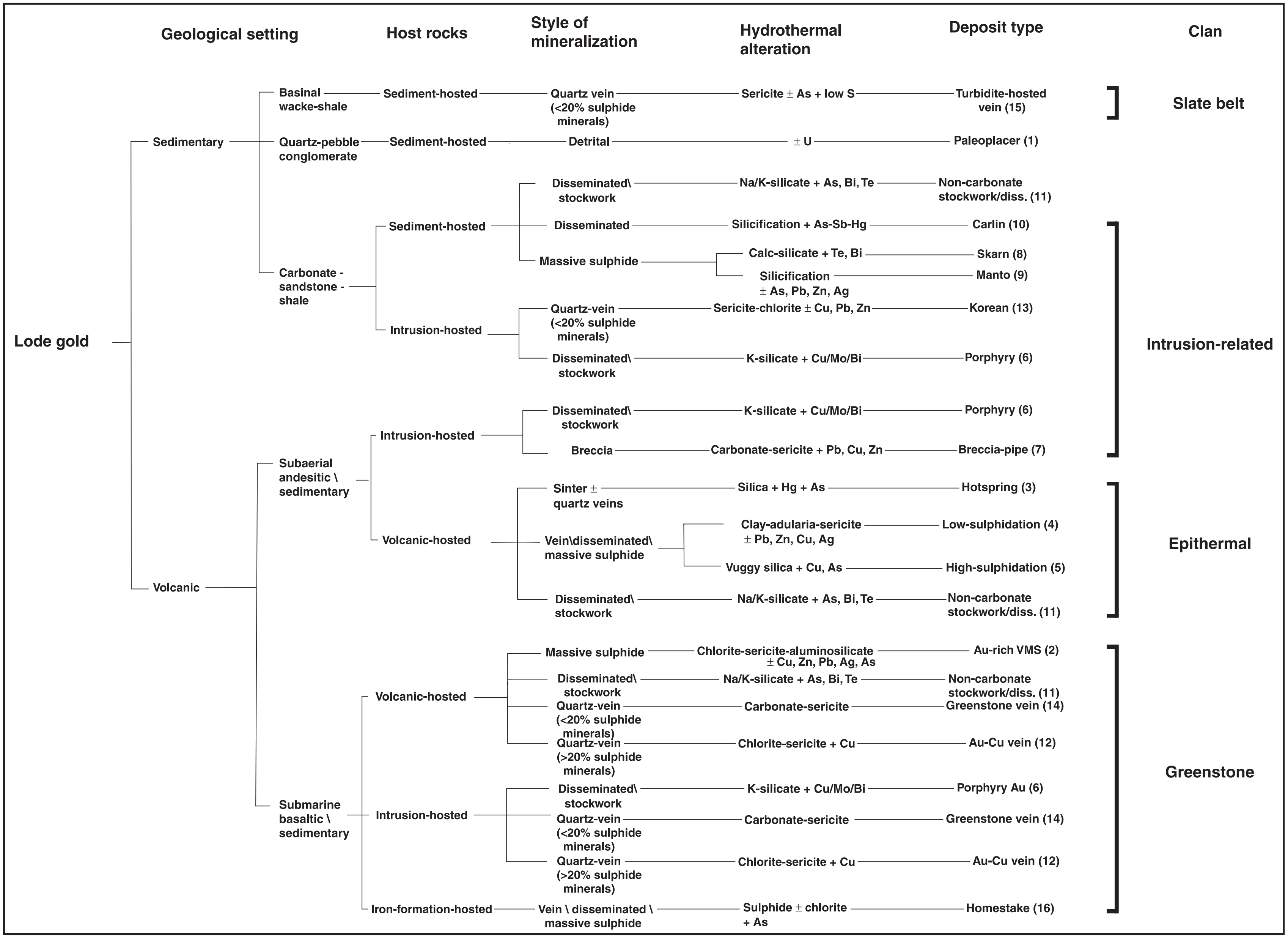


Figure 84. *Classification chart for lode gold deposits.*

treatments of gold deposits (e.g. Emmons, 1937) emphasized that variations in ore and gangue-mineral species in gold deposits were a reflection of lateral and depth zonation and hence, to some degree, of deposit type: for example, minerals such as arsenopyrite and pyrrhotite distinguished 'mesothermal' and 'hypothermal' deposits from 'epithermal' ones, and minerals such as tourmaline and scheelite were used to further distinguish the 'hypothermal' deposits from the 'mesothermal' ones. The use of such mineralogical distinctions is hampered, however, by the fact that ore-mineral assemblages are commonly thought to not only be a reflection of fluid composition and intensive constraints, but also a reflection of buffering by host rocks so that minerals such as arsenopyrite can occur in several deposit types in sedimentary environments, and minerals such scheelite sometimes indicate intrusive host rocks. In a similar fashion, most hydrothermal alteration assemblages result from a combination of original fluid composition and rock buffering: in some cases (e.g. advanced argillic) alteration is so fluid dominated as to be diagnostic, whereas in others (e.g. carbonatization), rock composition dictates alteration mineralogy and chemistry to a greater degree. Other difficulties in relying strictly on alteration as a diagnostic criterion are encountered in metamorphic terranes where hydrothermal alteration assemblages are indistinguishable from regional ones (e.g. propylitic assemblages in the greenschist facies) or are reconstituted into new assemblages (e.g. amphibolite facies).

Classification of commonly recognized gold deposit types

Despite the limitations of each of the above parameters, they can be combined in such a way (Fig. 84) as to illustrate how the commonly recognized types of gold deposits can be distinguished from one another even though they were defined at different times using different principles. It must be stressed that this is but one particular graphical arrangement of deposit types into a logical tree (*see* for example Fig. 5). Nonetheless, it is useful in that it serves to reveal several important aspects of gold deposit classification:

1. All deposit types are not classified at the same level in the chart. For example, for most workers, 'Homestake-type' deposits are distinguished simply by their iron-formation host whereas a 'porphyry-type' deposit can be identified not only by the nature of the host, but also by its form and by the type of hydrothermal alteration.

2. In the chart, deposits have been naturally arranged into 'clans', mainly on the basis of the broadly defined tectonic environments represented by the host rocks. Thus, terms like 'intrusion-related', 'epithermal', 'greenstone gold' all retain a meaning in that they refer to a group of deposit types, possibly genetically related, that reflect a particular environment. This point has been made previously by Cox and Singer (1986) to show the correlation of tectonic-geological environments and deposit models (Fig. 5). This has value in resource assessment where one tries to predict the likelihood of occurrence of a deposit type using a knowledge of geological environments, but conversely, certain clans of deposits may be used as indicators of particular geological environments.

3. Although there is an ideal correlation between environments and deposit types, there are some types that can occur across environments. A good example is afforded by porphyry deposits (and possibly skarns) which are well known to occur in both (mainly submarine) island-arc and (mainly subaerial) continental-arc environments.

4. The chart illustrates an element of transition from clan to clan and deposit type to deposit type. Thus the 'intrusion-related' and 'epithermal' clans merge from one into another in that these are groups that are commonly discussed in the same context. Similarly, 'epithermal' deposits are placed in transition to gold-rich, volcanogenic, massive-sulphide deposits (e.g. Hannington, 1993). Note also that deposits on the lower part of the chart (the 'greenstone' clan) have well known similarities to those on the upper part (the 'slate belt' clan): in this case, it may be useful to view the chart in a cylindrical form with top and bottom edges joined.

5. There is no need to use the chart from left to right. As noted above, some deposits like those of the high-sulphidation type are identified mainly by one parameter, hydrothermal signature, and there is less need to establish all of the other parameters. Furthermore, all parameters relating to a deposit may not be understood at a point in time, yet the chart may still be used to narrow the choice of alternatives. In particular, the simple observable parameters such as host rock and form of ore can considerably narrow the possibilities and direct an observer to search for manifestations of those parameters that would allow further distinctions to be made.

6. There is no need to force a deposit into a particular class using the chart. The decision branches that are illustrated for each parameter are but a few of many possible alternatives: it is fully acceptable to add alternative branches that lead to potentially new deposit types or to individual atypical deposits.

Complicating Factors

Several problems may be encountered in applying this classification scheme as discussed in Robert et al. (1997). First, it is fully acceptable that some deposits can be classified as being of more than one type, in that the existence of transitional deposit types, such as those found between the epithermal and porphyry environments, has been proposed by several workers (Giggenbach, 1992; Panteleyev, 1996). Second, overprinting of different ore styles, either due to telescoping of distinct components of hydrothermal systems (Sillitoe, 1994), or due to superposition of two or more hydrothermal systems, is documented in a significant number of deposits and may have played a key role in the formation of world-class and giant gold deposits. This may lead to dual classification of the deposit, depending which parameters are emphasized. However, the main problem in deformed and metamorphosed terranes such as greenstone belts is that the primary characteristics of gold deposits may have been largely obscured by overprinting, deformation, and metamorphism to an extent that they are difficult to recognize. For example, a near-surface gold-rich VMS or epithermal deposit following a normal pressure-temperature-time path will progressively be buried and deformed. The deposit will move successively into the intrusion-related and into the deeper greenstone quartz-carbonate environment before returning along a similar path to its near-surface position following erosion and uplift. During such an evolution at different crustal levels, there is much scope for such a deposit to be modified or superimposed on by other style(s) of mineralization, ending in a complex ore deposit. However, the most fundamental elements to take into account to deal with such complicating factors are 1) basic chronological field relationships, combined with 2) accurate U-Pb geochronology in order to establish the definite chronological evolution between mineralizing event(s) and deformation/metamorphism phase(s).

Conclusion

The proposed decision tree (Fig. 84) provides a first-order way of assessing if a deposit can be ascribed to one of sixteen known types of lode gold deposit or not; i.e. being typical or atypical. If a deposit is identified as being atypical, possible explanations for its atypical character are

1. a hybrid deposit produced by overprinting styles of mineralization
2. a transitional deposit type with components of more than one type, such as those found between the epithermal and porphyry environments
3. a deformed and metamorphosed deposit to the extent that its primary characteristics have been obscured
4. a new geological type of gold deposit.

The task of developing an adequate classification of gold deposits is far from complete. There remains nonetheless an immediate need to categorize deposits for exploration and resource assessment. Despite imperfections in the method, such a decision chart can be used as a template for tackling the problem of identifying the main characteristics of a gold deposit at an early stage of development even if it is poorly exposed or incompletely documented. The chart can also be used to guide the generation of alternative targets in previously explored areas containing conventionally recognized deposits. It could also be used as a starting point for more rigorous analysis of gold deposits using modern digital technology.

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APPENDIX

CAPSULE SUMMARIES OF GOLD DEPOSIT TYPES

Paleoplacer gold (1)

Typical example

- Witwatersrand, South Africa

Other examples

- Global: Tarkwa Ghana, Jacobina, Brazil
- Canadian: rare — Huronian, Ontario; Sakami Lake, Quebec

Diagnostic features

- Pyrite-bearing quartz-pebble conglomerate and quartz arenite

Size and grade

- Many deposits in South Africa exceed 1000 t contained gold; commonly 1 to 100 million t grading 1 to 10 g/t Au

Orebodies

- Stratiform layers (blankets) of auriferous conglomerate; locally thin carbonaceous seams are enriched in gold

Geological setting

- In mature fluviatile- to deltaic-facies rocks in extensive cratonic sedimentary basins

Host rocks

- Quartz-pebble conglomerate, pebbly quartz arenite, and cross-bedded arenite

Ore and gangue minerals

- Native gold and pyrite which, in some cases is detrital in origin; heavy minerals include magnetite, uraninite, ilmenite, and locally hematite

Metal signature

- Au commonly much more abundant than Ag; Ag/Au typically 1:10
- Associated U is common

Hydrothermal alteration

- Sericitization and silicification overprints some placers and has a modifying influence
- Pyrite at some deposits is paragenetically late and may result from sulphidation of detrital oxide grains

Critical features

- Occur in mature portions of sedimentary basins
- Most significant deposits are Archean and Early Proterozoic, perhaps reflecting a control by an oxygen-poor atmosphere
- Primary sedimentary facies variations control detailed distribution of gold

Submarine gold-rich massive-sulphide (VMS type) (2)

Typical example

- Boliden, Sweden

Other examples

- Global: Mt. Lyell, Mt. Morgan, Australia
- Canadian: Horne, Bousquet No. 2–LaRonde, Quebec; Eskay Creek, J&L, British Columbia

Diagnostic features

- Stratabound volcanic-hosted massive-sulphide bodies
- Gold (in ppm) exceeds associated combined Cu, Pb, Zn (in per cent)
- Felsic volcanic rocks and subvolcanic intrusions common in district
- Aluminous alteration products common at the deposit scale

Size and grade

- 1 to 10 million t grading 3 to 10 g/t Au and 1 to 5% combined base metals

Orebodies

- Banded and stratiform massive-sulphide lenses and adjacent stockworks; syntectonic sulphide veins developed at deformed and metamorphosed deposits

Geological setting

- In mixed volcanic, volcaniclastic, and sedimentary sequences in greenstone belts of all ages, typically metamorphosed to greenschist and lower amphibolite facies

Host rocks

- Most felsic volcanic tuff and derived schists near interface with basalt or sedimentary strata

Ore and gangue minerals

- Pyrite and base-metal sulphide minerals in sericite schist, but commonly associated with a complex assemblage of minor phases including bornite, sulphosalts, arsenopyrite, and tellurides

Metal signature

- Ag commonly more abundant than Au; Ag/Au typically from 1:2 to 10:1
- Au and Cu typically correlate positively
- Locally high concentrations of As, Sb, Hg

Hydrothermal alteration

- Sericitization, silicification, and massive silicic alteration most commonly associated with ore, but may be enveloped by zones of advanced argillic alteration

Critical features

- Occur in districts along with gold-poor massive-sulphide deposits
- Thought to form from boiling of ore fluid and therefore more probable in shallow-water sequences that show a transition to subaerial conditions
- Aluminous-advanced argillic alteration either an artifact of boiling or of magmatic fluid or both

General references

- Sillitoe et al. (1996)
- Poulsen and Hannington (1996)

Hotspring Type (3)

Typical example

- McLaughlin, California

Other examples

- Canadian: Cinola, British Columbia

Modern examples

- Steamboat Springs, Nevada; Yellowstone, Wyoming; Champagne Pool, Waiotapu geothermal field, New Zealand

Diagnostic features

- Siliceous sinter caps (amorphous silica with columnar growth structures perpendicular to laminations) and geyserite (rounded balls of concretionary silica accumulate on rock fragments from the throat of the geyser interbedded with hydrothermal breccia)
- Downward transition into silicified hydrothermal breccia and vein stockwork of low-sulphidation epithermal type
- Mercury mineralization (cinnabar)
- Native sulphur present

Typical tonnage and grade

- Individual deposit typically less than 1 000 000 ounces, but could aggregate around an individual vent and produce world-class deposit such as McLaughlin (3 000 000 troy ounces (Gustafson, 1991) or 24.3 Mt at 4.49 g/t Au (Hedenquist et al., 1995))

Nature and form of orebodies

- breccia units, vein stockwork, and replacement of permeable units
- mushroom-shaped orebodies narrowing at depth into a structurally controlled vein stockwork (feeder) of low-sulphidation epithermal style

Geological environment

- subaerial volcanic centres/domes either felsic and/or mafic intermediate (McLaughlin, Buckhorn) (Steamboat Springs is within both mafic and felsic volcanic rocks), epiclastic sedimentary rocks (sandstone-siltstone (Verbena system)), subvolcanic porphyritic intrusion and associated shallow parts of geothermal systems
- Extensional tectonics
- Sinter terrace and hydrothermal vent form just underneath the paleosurface and are associated with high-temperature (>150°C) geothermal systems

Host rocks

- Silicified hydrothermal (cemented) vent breccia
- Crustiform banded quartz vein (with locally carbonate replacement textures) and quartz stockworks
- Locally siliceous sinter and silicified permeable lithologies

Ore and gangue minerals

- Micron-size native gold or electrum with microcrystalline silica (brown hydrocarbon-bearing opal and chalcedony) and/or quartz with several volume per cent pyrite±marcasite, cinnabar, stibnite, realgar, and tellurides
- Barite and carbonates (calcite, dolomite, siderite, and magnesite) occur as gangue

Metal signature

- Au, Ag, Hg, As, Sb, Tl, Ba, locally W
- Ag/Au: Highly variable due to steep zoning — from Ag/Au being less than 1:1 near surface, to more than 30:1 at depth (McLaughlin). Common enrichment in Hg, Sb, Tl, and As near surface. The strong vertical variations over tens of metres reflect shallow boiling level and steep thermal gradient.

Hydrothermal alteration

- From top to bottom: siliceous sinter, massive silicification passing into a stockwork of quartz-adularia veins at depth (part of the underneath low-sulphidation system)
- The core of mineralized silicification could be surrounded by a halo of steam-heated advanced argillic and argillic alteration (cristoballite, alunite, and kaolinite).

Critical features

- Thick deposit (5–50 m) of siliceous sinter (opal/chalcedony inverted from amorphous silica) around hydrothermal vent
- Co-exist with peripheral, lower grade stockwork mineralization
- Permeable units are favorable host rocks
- Best grade hosted by hydrothermal breccia capped by sinter
- Near-surface manifestation of low-sulphidation epithermal gold deposits

General references

- Berger (1985),
- Nelson (1988)
- Gustafson (1991)
- Hedenquist et al. (1995)

Low-sulphidation (adularia-sericite) type (4)

Typical example

- Creede, Colorado

Other examples

- Global: Hishikari, Japan; Round Moutain, Nevada; Cerro Vanguardia, Argentina
- Canadian: Blackdome, Toodoggone district, Lawyers, British Columbia

Diagnostic features

- Crustiform-colloform chalcedonic quartz veins with adularia-calcite and sericite in or near the veins. Silicified bladed calcite/barite. Hypogene alunite absent and enargite uncommon. Sulphide contents highly variable, but commonly low

Typical tonnage and grade

- Commonly less than 100 t Au, but there are also giant deposits with several hundred tonnes of gold, such as Round Moutain, Nevada; Ladolam, Western Pacific; Hishikari, Japan

Nature and form of orebodies

- Tabular and steep, banded, colloform, open-space-filling veins, irregular stockwork, and hydrothermal breccia, and, less commonly, disseminations and replacement bodies

Geological environment

- Subaerial intermediate to felsic volcanic vents and associated subvolcanic porphyritic intrusion within subduction-related volcano-plutonic arc. Frequently immediately above basement.
- Associated with, but not restricted to calderas
- Associated with extensional tectonics

Host rocks

- Diverse, although commonly intermediate to felsic calc-alkaline volcanic rocks (andesite). Also intrusive rocks and underlying basement rocks of any type (shale, sandstone, etc). Less commonly with alkalic intrusive and shoshonitic volcanic rocks.

Ore and gangue minerals

- Crustified chalcedonic quartz, adularia, manganoan carbonates, illite
- Pyrite, silver-sulphide minerals, electrum, sulphosalts, sphalerite, and galena

Metal signature

- Au-Ag, Pb, Zn, Cu, (As, Hg, Sb, Te)
- Precious metals diminish downward as Zn, Pb, and Cu contents increase

- Ag/Au ratio typically very high, but highly variable from 10:1 and base metal poor, to more than 25:1 and base metal rich
- Commonly zoned vertically
- One style is gold rich with Ag/Au of 1:10 to 10:1 and only traces of base metals, whereas the other is silver rich with Ag/Au of more than100:1 with economic quantities of Zn and Pb present (Hedenquist and Lowenstern, 1994)

Hydrothermal alteration

- Silicification, sericitic alteration (with illite/smectite) and disseminated fine-grained potassium feldspar (adularia) and calcite near the vein; grades outward into a propyllitic zone or less frequently into a potassic zone. Advanced argillic alteration may be present in upper part
- Silica pseudomorphs of bladed calcite/barite

Critical features

- Most significant deposits are Tertiary or younger
- Faults or fractures close to volcanic centres
- Genetically linked to magmatism generated at convergent plate boundaries
- Sometimes superimposed on high-sulphidation system or present in the vicinity
- High-grade vein gold at Hishikari (Japan) and Wapolu (Western Pacific) were precipitated beneath relatively impermeable lithologies

General references

- Heald et al. (1987)
- White and Hedenquist (1990)
- Hedenquist et al. (1995)
- Corbett and Leach (1998)

High-sulphidation (acid-sulphate, alunite-kaolinite) type (5)

Typical example

- Goldfield, Nevada; Summitville, Colorado

Other examples

- Global: El Indio, Chile; Pueblo Viejo, Dominican Republic; Nansatsu, Japan; Yanacocha, Peru
- Canadian: Hope Brook, Newfoundland; Mt. McIntosh/Hushamu, Lake, British Columbia

Modern examples

- White Island, New Zealand

Diagnostic features

- Ore as veins, breccia and/or more commonly as disseminations and replacement bodies characterized by pyrite and high-sulphur assemblages (enargite/ luzonite/covellite/tennantite) within vuggy silica-rich rock
- Associated advanced argillic alteration zones containing hypogene alunite
- Adularia absent

Typical tonnage and grade

- Up to 600 t Au; commonly 10–150 t Au
- The six largest contain more than 100 t Au

Nature and form of orebodies

- Irregular to mushroom-shaped disseminations/ replacement commonly confined within permeable aquifer lithologies. Also steeply dipping veins, stockwork, and irregular, discordant, hydrothermal breccia
- Commonly 500 m of vertical extent

Geological environment

- Subaerial intermediate to felsic calc-alkaline volcanic vents and domes and associated subvolcanic porphyritic intrusions within volcano-plutonic arcs at convergent plate margins. Maar-diatreme complexes less common.
- Typically associated with crustal extensional tectonics

Host rocks

- Typically porphyritic dacite-rhyodacite-andesite domes/vents (volcanic or intrusive); also volcanoclastic and sedimentary rocks (La Coipa, Chile; Yanacocha, Peru) or others underlying basement rocks. Also, less commonly in Maar sedimentary rocks and basaltic volcanic rocks (Pueblo Viejo, Dominican Republic)

Ore and gangue minerals

- vuggy and massive silicic-replacement bodies recrystallized in fine-grained quartz, with local alunite, barite, kaolinite, and pyrophyllite
- pyrite, enargite-luzonite, chalcopyrite, tennantite-tetrahedrite, covellite, and gold

Metal signature

- Au, Cu, As, Ag, Sb, Sn, locally Hg, Pb
- Ag/Au ratio highly variable from less than 2:1 to more than 10:1

Hydrothermal alteration

- Leached vuggy silica alteration associated with the ore, surrounded by or above advanced argillic alteration with alunite; grades outward into argillic, sericitic, and/or propyllitic zones
- Typically two stages of leached massive silicic alteration

Critical features

- Genetically associated with calc-alkaline magma of andesite to dacite composition
- Genetically and spatially associated with subvolcanic felsic intrusions and/or regional normal and diatreme ring faults
- Most deposits are Tertiary or younger with a few Mesozoic (Pueblo Viejo, Dominican Republic), Paleozoic, and Precambrian examples
- Potentially co-exist with copper or copper-gold porphyry system

General references

- Heald et al. (1987)
- White and Hedenquist (1990)
- Hedenquist et al. (1994, 1995)
- Arribas Jr. (1995)
- Corbett and Leach (1998)

Porphyry Type (6)

Typical example

Lepanto Far East, Philippines (gold-copper); Lobo, Chile (gold only)

Other examples

Global: Grasberg, Indonesia; Yu-Erya, China; Refugio, Chile; Fort Knox, Alaska

Canadian: Fish Lake, Kemess, British Columbia; Young-Davidson, Ontario, Douay, Troilus, Quebec

Diagnostic features

- Quartz-stockwork and potassium-silicate alteration zones in and immediately adjacent to small composite stocks of dioritic to syenitic composition
- The ppm gold exceeds %Cu, but marked Cu±Bi, Te association

Size and grade

- Deposits generally contain 50–100 t Au, with some in excess of 400 t
- Grades are typically in the range of 0.5–2 g/t Au, with typically less than 0.8% Cu

Geological setting

- Volcano-plutonic arcs (including greenstone belts) in continental or island-arc settings, developed over wide range of basement lithologies

Host rocks

- Composite stocks of diorite, granodiorite, quartz-monzonite (calc-alkalic) to monzonite, syenite (alkalic), with locally preserved remnants of coeval volcanic rocks
- Include inter- and late-mineral phases, as well as common hydrothermal and intrusive breccia

Orebodies

- Zones of quartz-pyrite stockwork (generally multidirectional) and associated pyrite disseminations; quartz stockworks poorly developed in alkalic systems
- Irregular pipe-like shapes and are largely confined to the host intrusions

Ore and gangue minerals

- Pyrite is the dominant sulphide mineral (typically 1–3% in ore, increasing to 5–10% outside)
- Generally more than 4% hydrothermal magnetite±hematite, disseminated or in stockwork

Metal signature

- Au:Ag ratio greater than 1, and other associated metals include Cu, Bi, ± Mo, Te

Hydrothermal alteration

- Potassium-silicate alteration (with albite and calc-silicate in alkalic deposits), coincident with ore, grades outward into propylitic alteration
- Argillic and advanced argillic alteration overprint parts or most of potassium-silicate alteration

Critical features/specific ore controls

- Host intrusion controlled by faults
- Level of erosion in case of upright deposits
- Intrusion-hosted quartz stockwork

General references

- Sillitoe (1991a, b)
- Corbett and Leach (1998)

Breccia-Pipe Type (7)

Typical example

- Montana Tunnels (gold-silver), Montana

Other examples

- Global: Kidston, Australia
- Canadian: Chadbourne, Noranda, Quebec

Diagnostic features

- Deposit confined within pipe-like (funnel-shaped) magmatic-hydrothermal, hydromagmatic, and collapse breccia
- Ore occurs as disseminations within the matrix of the breccia and in sheeted zones.

Typical tonnage and grade

- Highly variable from large tonnage and low grade (Kidston gold deposit contained 101 t Au) to small deposit (Chadbourne 6.8 t Au; 1 500 000 at 4.52 g/t)
- Typical tonnage 5 to more than 60 million t at 1–2 g/t Au

Nature and form of orebodies

- Nature: breccia discordant to lithologies
- Shape: pipe-like and funnel-shaped (cylindrical-conical) sheeted fractures, infill cavities, and disseminations in the matrix of the breccia

Geological environment

- Calc-alkaline volcano-plutonic (mafic-felsic) environment associated with cauldron subsidence underlain by ring complexes and granitic batholith, graben faults

Host rocks

- Magmatic-hydrothermal, phreatomagmatic (diatreme), hydraulic, and collapse breccia
- No particular host sequence

Ore and gangue minerals

- Ore: pyrite, chalcopyrite, sphalerite, galena, pyrrhotite, with minor molybdenite, bismuthite, and telluro-bismuthite, tetrahedrite
- Gangue: quartz, calcite-ankerite/siderite, manganocalcite (Montana Tunnels), specularite and tourmaline (Chadbourne)

Metal signature

- Au, Ag, Pb, Zn, Cu, (Mo, Mn, Bi, Te, W)
- Au-Ag, Pb, Zn core surrounded by Cu-Mo (Kidston)
- Ag/Au: 10:1 (Montana Tunnels)

Hydrothermal alteration

- Muscovite-quartz-carbonate-pyrite, weak to strong silicification (Chadbourne, Quebec; Golden Sunlight, Montana) and minor kaolinite. Grades outward beyond the ore zone to propylitic (Montana Tunnels, Montana)
- Early stage of potassic alteration (quartz, K-feldspar, biotite, epidote) locally documented (Kidston, Australia)

Critical features

- Magmatic-hydrothermal, hydromagmatic, hydraulic, and collapse funnel-shaped breccia
- Commonly associated with intrusion-related gold deposits and/or porphyry system

General references

- Baker and Tullemans (1990)
- Sillitoe (1991a, 1993)

Skarn gold (8)

Typical example

- Fortitude, Nevada

Other examples

- Global: Red Dome, Australia; Suan, Korea
- Canadian: Hedley, Tillicum, British Columbia; Marn, Yukon Territory; Akasaba, Quebec

Diagnostic features

- Aluminum-rich skarn assemblages
- Gold (in ppm) exceeds associated combined Cu, Pb, Zn (in per cent)
- Adjacent diorite to granodiorite
- As, Bi, Te association

Size and grade

- Rarely larger than 100 t contained gold; 1 to 10 million t grading 3 to 10 g/t Au and less than 1% combined base metals

Orebodies

- Disseminated to massive-sulphide lenses and veins cutting skarn

Geological setting

- Carbonate platform sequences overprinted by volcanic and/or plutonic arcs

Host rocks

- Limestone, calcareous siltstone and carbonatized volcanic rocks adjacent to diorite or granodiorite stocks, dykes, or sills; associated with aluminum-rich garnet-pyroxene skarn assemblages

Ore and gangue minerals

- Pyrite, pyrrhotite, and arsenopyrite and lesser tellurides

Metal signature

- Wide variations in Ag/Au ratios typically from 1:10 to 10:1
- Locally high concentrations of As, Bi, Te

Hydrothermal alteration

- Retrogression of prograde skarn assemblage is common

Critical features

- Occur in some districts along with porphyry copper-molybdenum mineralization
- Thought to form from retrogression of prograde skarn
- Associated with more mafic, hotter intrusions

General reference

- Ray and Webster (1991)

Carbonate-replacement (manto) type (9)

Typical example

- Cove, Nevada

Other examples

- Global: Mammoth, Utah; Foley Ridge, South Dakota
- Canada: Mosquito Creek–Island Mountain, British Columbia; Ketza River, Yukon Territory

Diagnostic features

- Semimassive to massive-sulphide bodies (mainly pyrite) in silicified limestone beds
- Represents an end-member of more typical gold-poor lead zinc mantos

Size and grade

- Deposits are of relatively small tonnage (few Mt) but high grades, commonly more than10 g/t Au

Geological setting

- In miogeoclinal carbonate sedimentary sequences overprinted by volcano-plutonic arcs

Host rocks

- Limestone and dolomite beds, within or outside a marble front, interlayered calcareous quartzite, quartzite and phyllite.
- Dykes or sills of dioritic composition may be present in the vicinity

Orebodies

- Typically form pipes, chimneys, and less commonly, tabular bodies in limestone beds
- Semimassive to massive-sulphide bodies (mostly pyrite) in limestone/dolomite

Ore and gangue minerals

- Pyrite, with which the gold is associated, and variable proportions of chalcopyrite, galena

Metal signature

Au:Ag highly variable, but typically Au<Ag, with various concentrations of Cu, Pb, Zn, As, Bi, Hg

Hydrothermal alteration

- Silicification of limestone and sericite alteration of adjacent clastic sedimentary rocks
- Generally restricted to immediate vicinity of ore

Critical features/specific ore controls

- Faults are important as feeders for hydrothermal solutions; fault intersections are sites of pipes

General reference

- Sillitoe (1991a)

Sediment-hosted micron gold (10)

Typical example

- Carlin, Nevada

Other examples

- Global: Mercur, Utah; Golden Reward, South Dakota; Guizhou, China
- Canadian: Golden Bear, British Columbia; Brewery Creek, Yukon Territory

Diagnostic features

- Stratabound low-sulphide replacement of carbonate rocks
- Micron-sized Au with negligible to low base metals
- Structurally and stratigraphically controlled zones of silicification and brecciation
- Strong geochemical correlation with As, Sb, Hg

Size and grade

- Up to 500 t Au; commonly 1 to 10 million t ore grading 1 to 10 g/t Au

Orebodies

- Irregular discordant breccia bodies and concordant stratabound disseminated zones confined to particular stratigraphic members

Geological setting

- In carbonate and impure carbonate-argillite facies of continental platforms and shelves that have been overprinted by regional thrusting, extension faulting, felsic plutonism, and zones of contact metamorphism

Host rocks

- Mostly in impure sedimentary carbonate rocks, but also rarely in granitoid rocks, clastic sedimentary rocks, and greenstones

Ore and gangue minerals

- Pyrite with overgrown arsenian pyrite rims containing gold inclusions; orpiment, realgar, cinnabar and stibnite common accessories at deposit scale

Metal signature

- Ag/Au highly variable, but typically less than 1
- Locally high concentrations of As, Sb, Hg

Hydrothermal alteration

- Decalcification and silicification (jasperoid) of carbonate rocks most commonly associated with ore, but may be enveloped by zones of argillic and sericitic alteration
- Nevada deposits deeply oxidized to produce supergene zones favourable for bulk mining and heap-leach processing

Critical features

- Occur in linear arrays along major structural features
- Commonly occur near hornfels, skarn, or calc-silicate rocks, but typically outward from the edge of contact-metamorphic aureoles
- Co-exist regionally with copper and/or molybdenum porphyry deposits, copper or tungsten-molybdenum skarns and silver-lead-zinc veins and mantos

General references

- Berger and Bagby (1991)
- Ichik and Barton (1997)

Non-carbonate disseminated-replacement type (11)

Typical example

- Andacollo, Chile

Other examples

- Global: Muruntau, Uzbekistan; Golden Reward, Black Hills, South Dakota; Salsigne (?), France; Kalgoorlie (?), Australia
- Canadian: Equity Silver; QR, British Columbia; Hemlo, Holt-McDermott, Ontario; Beattie, East Malartic, Quebec

Diagnostic features

- Stockwork, disseminated, or semimassive sulphide zones along faults, permeable units, and lithological contacts, in a variety of host rocks

Size and grade

- Most deposits 25–100 t Au, with giant deposits at greater than 500 t Au; typical grades in the 2–4 g/t Au range, with few deposits more than 6 g/t Au

Geological setting

- Volcano-plutonic arcs (oceanic or continental) and greenstone belts
- Miogeoclinal siliciclastic and carbonate sedimentary sequences

Host rocks

- Carbonate or siliciclastic sedimentary rocks, volcanic rocks
- Either a) proximal to, and locally overprinting, dioritic to syenitic stocks, sills, and dykes, or b) remote from any such intrusion

Orebodies

- Disseminated to semimassive sulphide zones with variably developed stockworks
- Stratabound to discordant (along faults or intrusive contacts), with tabular to irregular shapes

Ore and gangue minerals

- Disseminated (<1%–5%) to semimassive pyrite; with subordinate chalcopyrite, arsenopyrite±hematite, magnetite, with quartz-carbonate gangue. Tellurides, anhydrite, and hematite more abundant in syenite-associated deposits.

Metal signature

- Au:Ag ratios ranging from gold rich to slightly silver rich
- trace amounts Cu, As, Bi, Te±W, F, B

Hydrothermal alteration

- Potassium metasomatism (sericite, biotite, or K-feldspar); CO_2 metasomatism (ankerite), especially syenite-associated systems; Sodium metasomatism (albite), all with 1–10% pyrite
- Intense silicification present in some deposits

Critical features/specific ore controls

- Disseminated-replacement bodies controlled by permeable units, faults, and lithological (including intrusive) contacts

General reference

- Sillitoe (1991a)

Gold-copper sulphide-rich veins (12)

Typical example

- Rossland, British Columbia

Other examples

Global: Tennant Creek, Australia

Canada: Doyon (?), Sleeping Giant, Copper Rand, Portage, Cooke, Quebec; Snip, British Columbia

Diagnostic features

- Quartz-sulphide veins (>20% sulphide minerals) occurring in clusters
- Au generally < Ag

Size and grade

- Relatively small deposits (<5 Mt), but the veins are relatively high grades (>10 g/t Au)
- Some vein clusters yield significant amounts of gold (90 t at Rossland, British Columbia)

Geological setting

- Volcano-plutonic arcs and greenstone belts, intruded by younger tonalitic, monzonitic, and granitic plutons

Host rocks

- Variety of volcanic and plutonic rocks (including anorthosite at Chibougamau, Quebec) intruded by abundant dykes of diorite, tonalite, and lamprophyre

Orebodies

- Sulphide-rich veins (10 cm to >5 m thick, up to 1 km long) of multiple orientations, commonly following dykes

Ore and gangue minerals

- Pyrrhotite, pyrite, chalcopyrite, magnetite, with traces of sphalerite and galena
- Gangue typically quartz and carbonate, with lesser amounts of chlorite and sericite

Metal signature

- Au<Ag (ratio between 1:2 and 1:5)
- Typically contain 0.5–3% Cu, with traces of Zn and Pb

Hydrothermal alteration

- Generally restricted to proximity of veins
- Chloritization and sericitization

Critical features/specific ore controls

- Sulphide-rich veins controlled by faults and dykes

General reference

- Fyles (1984)

Batholith-associated quartz veins (13)

Typical example

- Cheonan, Korea

Other examples

- Global: Linglong, China; Charters Towers, Australia
- Canadian: Zeballos, Surf Inlet, British Columbia

Diagnostic features

- Quartz vein swarms in and adjacent granitoid batholiths
- Fault-controlled mineralization
- Minor base metals but general lack of metal zoning

Typical tonnage and grade

- Typically contain less than 50 t gold; commonly 1 to 5 million t grading 1 to 10 g/t Au

Orebodies

- Metre-wide quartz veins in brittle-ductile faults and crushed, hydrothermally altered veinlet zones adjacent to faults

Geological setting

- In tectonic uplifts containing metamorphic basement rock and abundant granitoid rocks

Host rocks

- Granitoid batholiths and adjacent medium to high-grade schist and gneiss

Ore and gangue minerals

- Gold, pyrite, and minor base-metal sulphide minerals in quartz veins; carbonate minerals are minor and typically in the form of calcite

Metal signature

- Ag and Au nearly equal in abundance; Ag/Au typically from 1:5 to 5:1
- Locally high concentrations of Cu, Pb, Zn

Hydrothermal alteration

- Sericitization and chloritization most commonly restricted to wall rocks a few metres from ore

Critical features

- Occur in extensive districts that only locally contain porphyry and epithermal deposits
- Thought to form at deeper levels than epithermal deposits, possibly transitional to the deeper 'mesothermal' environments
- Profound structural controls by regional fault systems

General reference

- Shelton et al. (1988)

Greenstone-hosted quartz-carbonate veins (14)

Typical example

- Mother Lode–Grass Valley, California

Other examples

Global: Mt-Charlotte, Norseman, Victory, Australia

Canada: Bralorne, British Columbia; Giant, Con, Northwest Territories; Contact Lake, Saskatchewan; San Antonio, Manitoba; Renabie, Dome, Kerr-Addison, Ontario; Silidor, Sigma-Lamaque, Norbeau Ferderber, Quebec; Deer Cove, Newfoundland

Diagnostic features

- Arrays and networks of fault- and shear-zone-related quartz-carbonate veins with associated carbonatization
- Significant vertical extent

Size and grade

- Deposits are typically 25–100 t Au, with many deposits greater than 250 t
- Grades in the range of 5–10 g/t Au

Geological setting

- Typically occur in deformed greenstone terranes
- Commonly distributed along major fault zones, but spatially associated with higher order shear zones

Host rocks

- Any lithology present in the local environment: mafic-ultramafic volcanic rocks, tholeiite sills, and granitoid intrusions
- District-specific lithological associations

Orebodies

- Moderately to steeply dipping shear-zone-hosted laminated veins, with or without fringing shallow-dipping extensional veins in brittle-ductile shear zones
- Veins are 10 cm to 5 m thick, 100–1000 m long

Ore and gangue minerals

- Quartz and carbonate dominate the gangue, with chlorite, scheelite, tourmaline
- Sulphide minerals typically less than 10% of the vein; pyrite>pyrrhotite>chalcopyrite
- Significant vertical extent, without significant zoning

Metal signature

- Gold-rich deposits (Au:Ag = 5–10); As, W, B, Mo; no or very low concentration of base metals

Hydrothermal alteration

- Carbonatization and sericitization and pyritization of wall rocks
- Zoned alteration haloes with significant dimensions in mafic-ultramafic rocks

Critical features/specific ore controls

- Shear-zone-related quartz-carbonate vein networks in vicinity

General reference

- Hodgson (1993)

Turbidite-hosted quartz-carbonate veins (15)

Typical example

- Victoria Goldfields, Australia

Other examples

Global: Ashanti, Ghana; Otago, New Zealand

Canada: Meguma, Nova Scotia; Cape Ray, Newfoundland; Little Long Lac, Ontario; Camlaren, Northwest Territories

Diagnostic features

- Fold- and fault-controlled quartz-carbonate veins in turbidite sequences
- Arsenopyrite is the dominant sulphide mineral

Geological setting

- Turbidite sequences deformed and metamorphosed to lower to upper greenschist facies

Host rocks

- Greywacke-mudstone sequence with or without associated intrusive rocks
- Graphitic schists are particularly favourable hosts

Orebodies

- Laminated quartz-carbonate veins in folds (saddle reefs), faults of shear zones

Ore and gangue minerals

- Quartz-carbonate gangue with smaller amounts of chlorite, sericite
- Sulphide minerals are less than 10% of the vein, typically arsenopyrite

Metal signature

- Veins are gold rich (Au>Ag); metal signature = As, W (?)

Hydrothermal alteration

- Generally limited to immediate vein proximity
- Sericitization and some silicification, with arsenopyrite±pyrite in wall rocks

Critical features/specific ore controls

- Associated with anticlinal structures and related limb-thrusts faults

General references

- Cox et al. (1991)
- Boyle (1986)

Iron-formation-hosted vein/disseminated gold (16)

Typical example

- Homestake, South Dakota

Other examples

- Global: Jardine, Montana; Cuiaba, Brazil; Hill 50, Australia
- Canadian: Lupin, Nunavut; Farley, Manitoba; Central Patricia, Cockshutt, Ontario; Nugget Pond, Newfoundland

Diagnostic features

- Stratabound sulphide minerals and discordant quartz veins
- Hosted by folded iron-formation

Typical tonnage and grade

- 1 to 10 million t grading 3 to 20 g/t Au

Orebodies

- Banded stratabound disseminated to massive-sulphide lenses;
- Syntectonic quartz veins developed at most deposits; gold is usually concentrated in vein selvedges rather than in the veins

Geological setting

- In iron-formation in mixed volcanic, volcaniclastic, and sedimentary sequences in greenstone belts of all ages, typically metamorphosed to greenschist and lower amphibolite facies

Host rocks

- Iron-formation of oxide, carbonate, and sulphide facies; most commonly at or near a volcanic-sedimentary rock contact

Ore and gangue minerals

- Pyrite, pyrrhotite, arsenopyrite, and native gold

Metal signature

- Ag much less abundant than Au; Ag/Au typically 1:5 to 1:10
- Au and As typically correlate positively

Hydrothermal alteration

- Sulphidation of pre-existing iron-formation facies is most common adjacent to quartz veins and orebodies
- Chloritic and carbonate alteration form distal envelopes at some deposits

Critical features

- Occur at local sites in districts along with regionally extensive banded iron-formation
- Occur at structurally complex sites such as fold hinges and in discordant shear zones
- Hydrothermal alteration results in oxide/carbonate consumption in iron-formation leading to anomalous geophysical response

General references

- Caddey et al. (1991)
- Kerswill (1993, 1996)

COLOUR SECTION

Figure 10a.

Figure 10b.

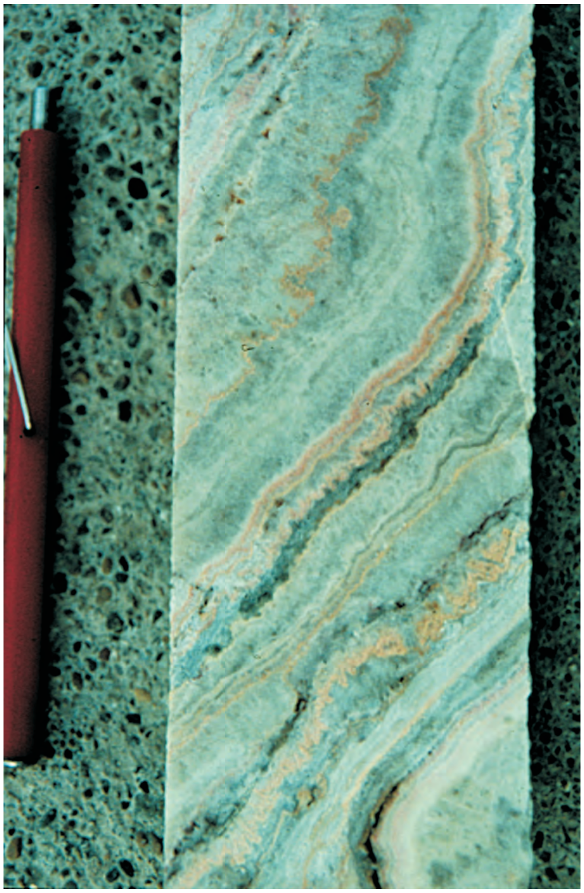

Figure 10c.

Figure 10. *Vein textures in low-sulphidation epithermal gold deposits.* ***a****),* ***b****) Colloform banded quartz-adularia vein; Gold Road orebody, Oatman district, Arizona (both photographs by F. Robert). GSC 1999-015A, GSC 1999-015B* ***c****) Crustiform-colloform banded quartz-adularia vein; Maria vein, Manantial Espejo, Argentina (photograph by B. Dubé). GSC 1999-014D*

Figure 10d.

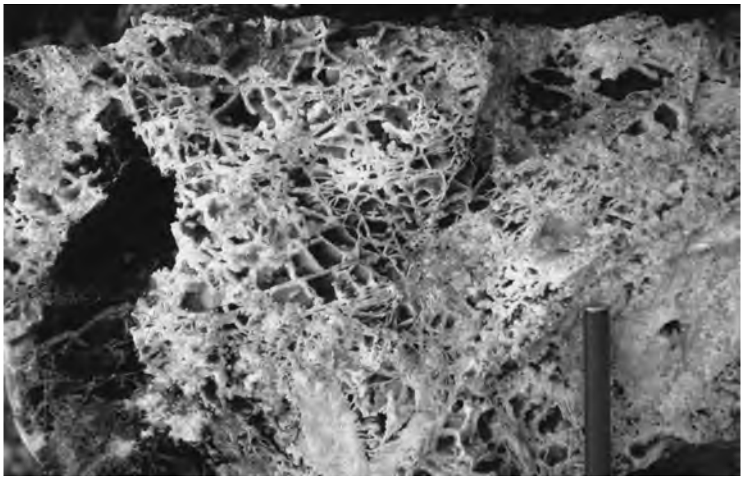

Figure 10e.

Figure 10f.

Figure 10d*) Colloform banded quartz vein; Maria vein, Manantial Espejo, Argentina (photograph by B. Dubé). GSC 1999-014E* ***e****) Bladed barite and calcite replaced by silica; Manantial Espejo, Argentina (photograph by B. Dubé). GSC 1999-014F* ***f****) Bladed barite and calcite replaced by silica; Cerro Vanguardia, Argentina (photograph by B. Dubé). GSC 1999-014G*

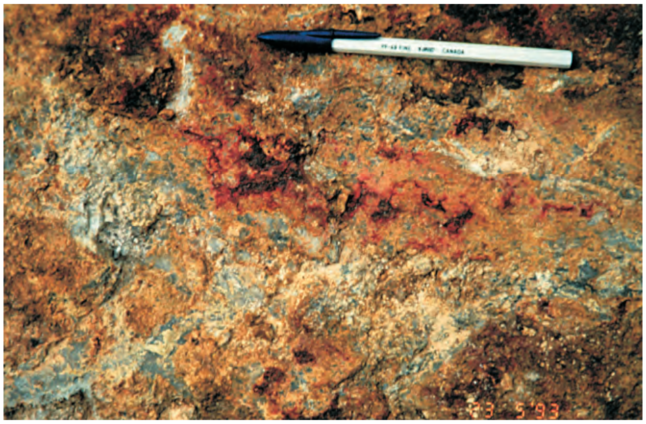

Figure 12a.

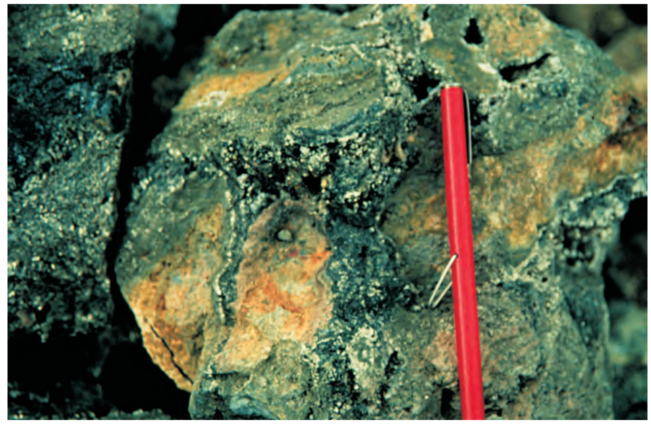

Figure 12d.

Figure 12b.

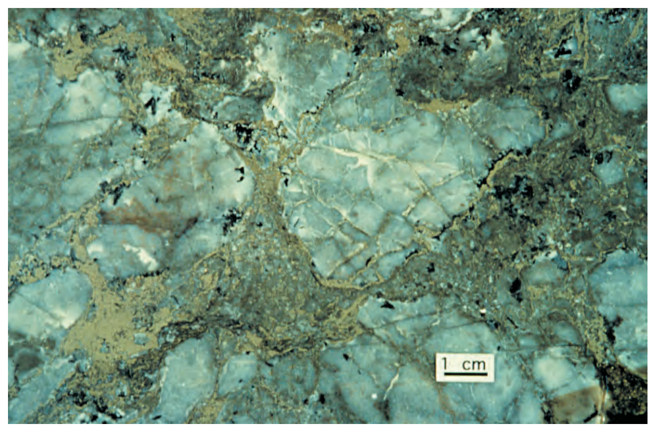

Figure 12e.

Figure 12c.

Figure 12. *High-sulphidation gold deposits.* ***a****) Siliceous gold- and pyrite-bearing veinlets (grey) in alunite-kaolinite altered volcanic rock (beige); Lahoca deposit, Hungary, (photograph by K.H. Poulsen). GSC 1999-016A* ***b****) Advanced argillic alteration with alunite in shale and sandstone containing approximately 1.5 g/t gold; ore zone, La Coipa deposit, Chile (photograph by B. Dubé). GSC 1999-014H* ***c****) Vuggy silica in silver-gold ore (0.5 g/t Au, 300 g/t Ag); Coipa Norte zone, La Coipa, Chile (photograph by B. Dubé). GSC 1999-014I* ***d****) Breccia ore composed of massive silicic clasts in a matrix of enargite and pyrite; Lauranie deposit, Bolivia (photograph by B. Dubé). GSC 1999-014J* ***e****) Breccia ore (3–4 g/t Au) composed of massive siliceous clasts in a silicic matrix containing pyrite and enargite (black grains); Brewer mine, South Carolina (photograph by B. Dubé). GSC 1999-014K*

Figure 14a.

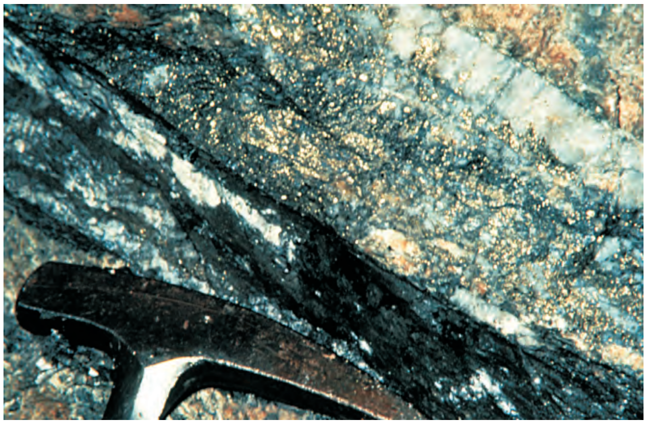

Figure 14c.

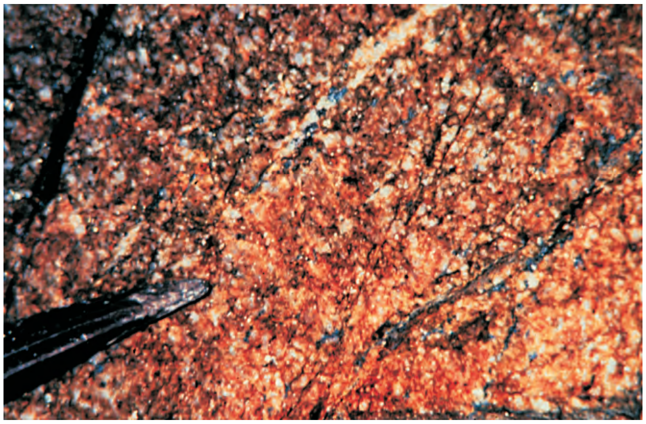

Figure 14b.

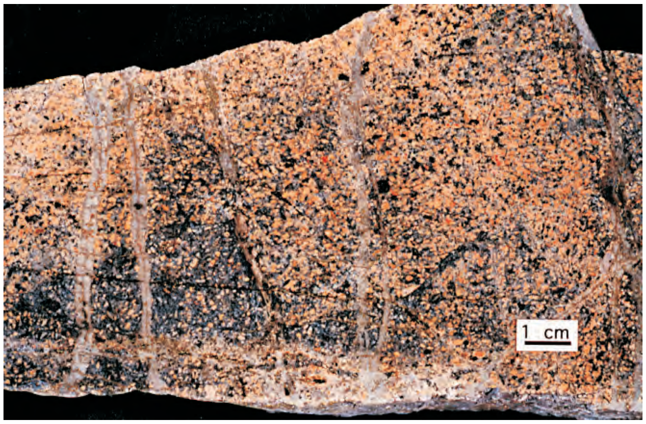

Figure 14d.

Figure 14. *Porphyry gold deposits.* ***a****) Sheeted veins within porphyry ore zone grading 2 to 3 g/t gold; Refugio deposit, Chile (photograph by B. Dubé). GSC 1999-014L* ***b****) Veinlet and disseminated sulphide minerals in porphyry; Yu Erya gold deposit, Eastern Hebei Province, China (photograph courtesy of J.K. Mortensen).* ***c****) Gold-quartz-sulphide veins in porphyry; Yu Erya deposit, Eastern Hebei Province, China (photograph courtesy of J.K. Mortensen).* ***d****) Quartz-sulphide stockwork with magnetite and secondary biotite in gold-copper porphyry; Grasberg deposit, Irian Jaya, Indonesia (sample to B. Dubé courtesy of R. Kyle, University of Texas, Austin). GSC 1999-014M* ***e)*** *Chalcopyrite-magnetite veinlets and disseminations in gold-copper porphyry; Grasberg deposit, Irian Jaya, Indonesia (sample to B. Dubé courtesy of R. Kyle, University of Texas, Austin). GSC 1999-014N*

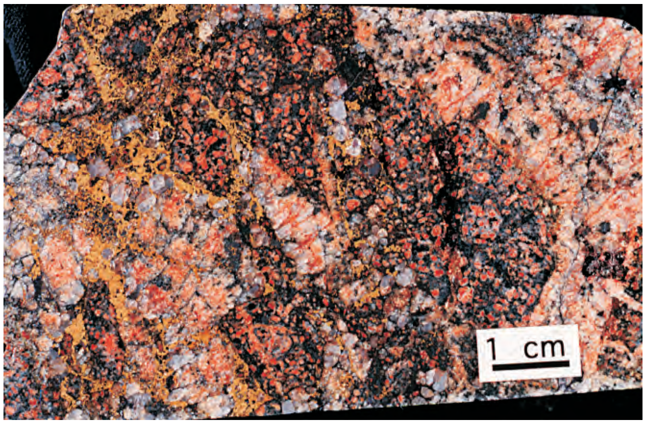

Figure 14e.

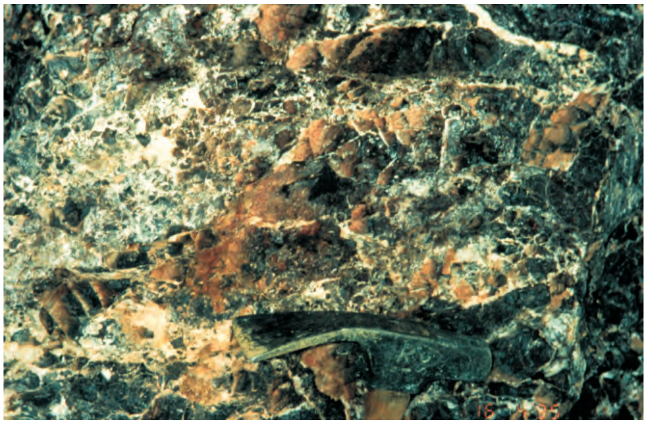

Figure 18a.

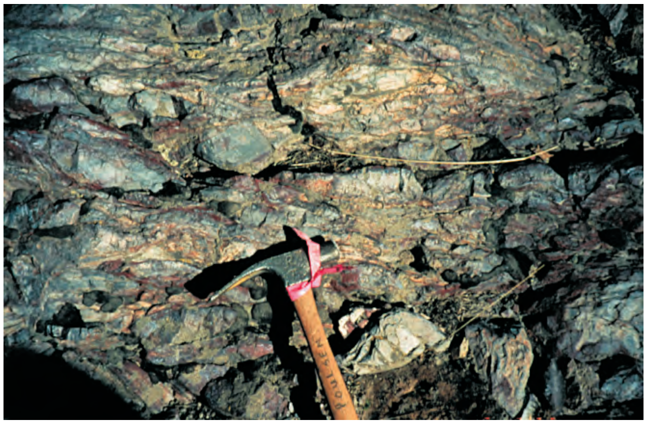

Figure 18b.

Figure 18. *Carlin-type mineralization.* ***a****) Jasperoid breccia; Gold Bar deposit, Nevada. GSC 1999-016B* ***b****) Bedded jasperoid; Griffin deposit, Nevada. (Both photographs by K.H. Poulsen.) GSC 1999-016C*

Figure 20a.

Figure 20b.

Figure 20. *Examples of ore from Korean-type deposits.* ***a****) Quartz-sulphide vein in fault zone parallel to lamprophyre dyke cutting Ling Long granite; Ling Long mine, Eastern Shandong, China. GSC 1999-015C* ***b****) Black cataclastic gold-pyrite ore in fault zone cutting feldspathically altered granite; Jiaojia mine, Eastern Shandong, China. (Both photographs by F. Robert.) GSC 1999-015D*

Figure 22a.

Figure 22b.

Figure 22. *Mother Lode–type quartz veins.* ***a****) Steep laminated quartz vein flanked by shallow extensional veins; Pine Tree mine, No. 6 crosscut, looking south: Mother Lode district, California. GSC 1999-015E* ***b****) Laminated quartz vein; Mother Lode district, California. Note the flanking ankeritic carbonate alteration (brown) adjacent to the main vein and the shallow extensional veins in the hanging wall. (Both photographs by F. Robert.) GSC 1999-015F*

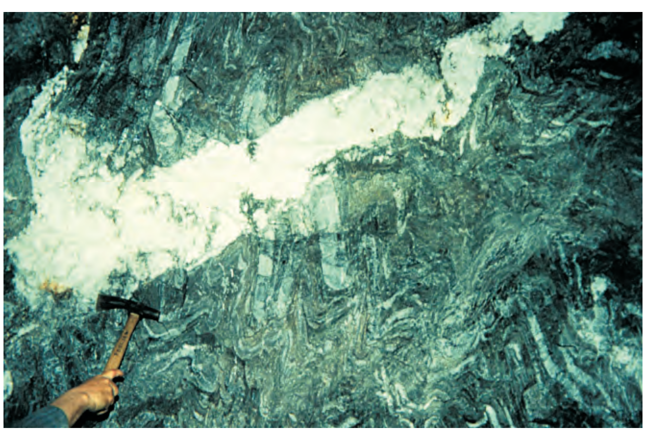

Figure 24a.

Figure 24b.

Figure 24. *Homestake-type mineralization.* ***a****),* ***b****) Arsenopyrite-pyrrhotite-gold are concentrated along the margins of extensional quartz veins cutting folded iron formation, Homestake mine, Lead, South Dakota. (Both photographs by F. Robert.) GSC 1999-015H, GSC 1999-015I*

Figure 29a.

Figure 29. *Mineralization at the Con–Giant deposit.* ***a****) Folded laminated quartz-carbonate vein with axial plane foliation in shear zone; 3196R stope, Con mine, Yellowknife, Northwest Territories. GSC 1999-015K* ***b****) Brecciated quartz-arsenopyrite vein in a halo of disseminated sulphide minerals; 3393F stope, Con mine, Yellowknife, Northwest Territories. (Both photographs by F. Robert.) GSC 1999-015L*

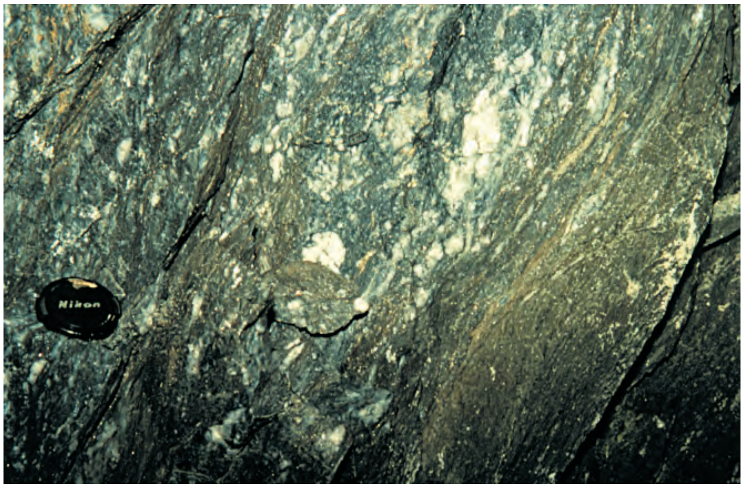

Figure 29b.

Figure 31a.

Figure 31b.

Figure 31. *Mineralization at the Lupin deposit, Contwoyto Lake area, Nunavut.* ***a****) Laminated pyrrhotite replacements of bedding and coarse arsenopyrite halo around an irregular quartz vein cutting iron-formation at the Lupin mine. GSC 1999-015M* ***b****) Coarse arsenopyrite halo around an irregular quartz vein cutting folded iron-formation at the Lupin mine. Width of photograph is 60 cm. (Both photographs by F. Robert.) GSC 1999-015N*

Figure 33.

Figure 33. *Boudinaged 'ankerite vein' cut by transverse quartz 'ladders'; Dome mine, Timmins (photograph by F. Robert). GSC 1999-015O*

Figure 38a.

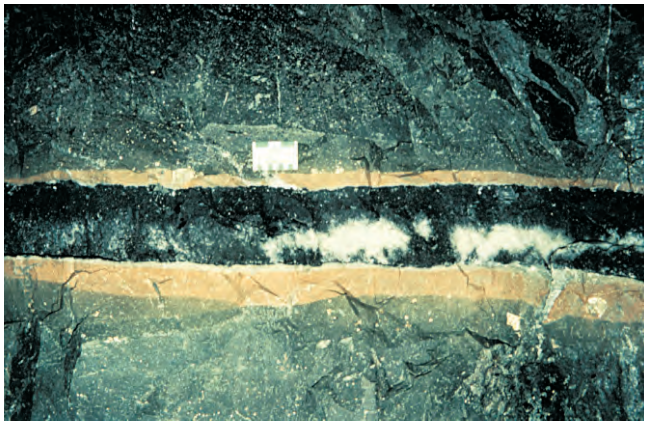

Figure 38c.

Figure 38b.

Figure 38d.

Figure 38. *Shear-zone-related quartz-tourmaline veins; Sigma–Lamaque deposit, Quebec.* ***a****) Vertical 'shear vein' in perspective view looking east, Sigma mine. Width of photograph is 1.7 m. GSC 1999-015S* ***b****) Vertical 'shear vein' in section, Sigma mine. GSC 1999-015T* ***c****) Quartz-tourmaline 'flat vein' cutting feldsparporphyry dike, Sigma mine. Note the bleached alteration halo which envelops the vein. GSC 1999-015U* ***d****) Extensional quartz-tourmaline 'flat vein' showing multiple stages of mineral growth perpendicular to vein walls, Sigma mine. (All photographs by F. Robert.) GSC 1999-015V*

Figure 40a.

Figure 40b.

Figure 40. *Quartz-carbonate-sulphide veins; Kirkland Lake deposit, Ontario.* ***a****) Quartz vein within the '05 break', 6600 level, Macassa mine, showing multiple stages of vein filling. Width of photograph is 0.5 m. GSC 1999-016G* ***b****) Quartz vein within the '04 break', 6600 level, Macassa mine. (Both photographs by K.H.Poulsen.) GSC 1999-016H*

Figure 44. *Hand sample of folded and transposed molybdenite-pyrite veinlets; 'A' ore zone, Williams mine, Hemlo, Ontario. GSC 1999-014O*

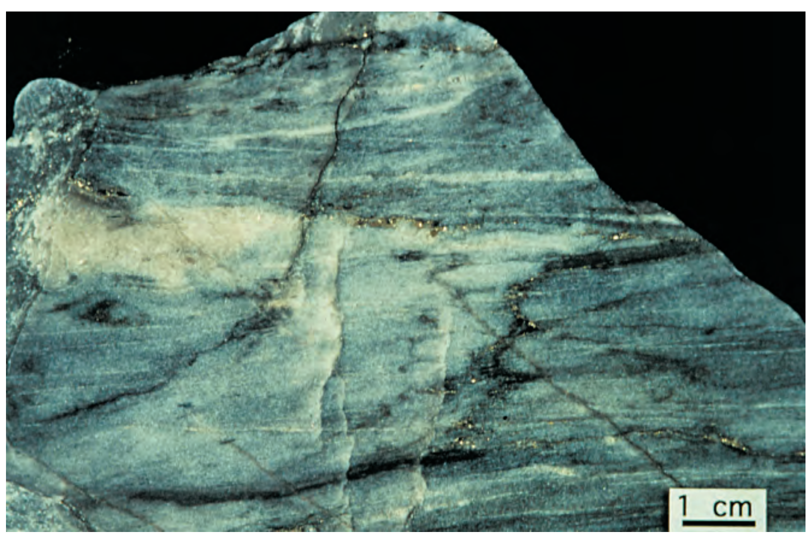

Figure 44.

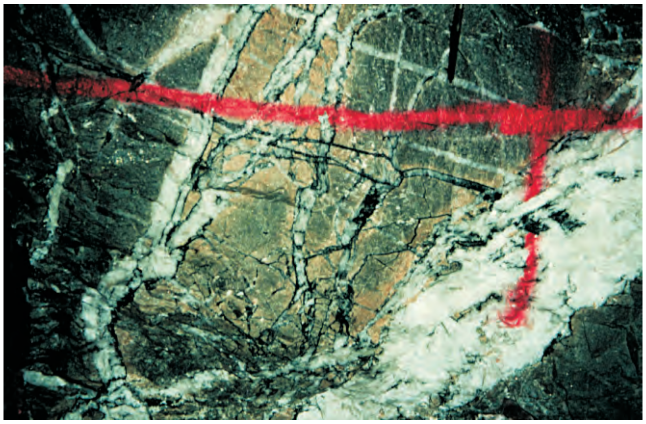

Figure 47a.

Figure 47b.

Figure 47. *Mineralized veins; Malartic deposit, Quebec.* ***a****) Sediment-hosted veins cutting bedding in Pontiac sedimentary rocks, Canadian Malartic deposit, Quebec. GSC 1999-015Y* ***b****) Quartz vein and stockwork in altered felsic dike, Rand Malartic mine, Quebec. (Both photographs by F. Robert.) GSC 1999-015Z*

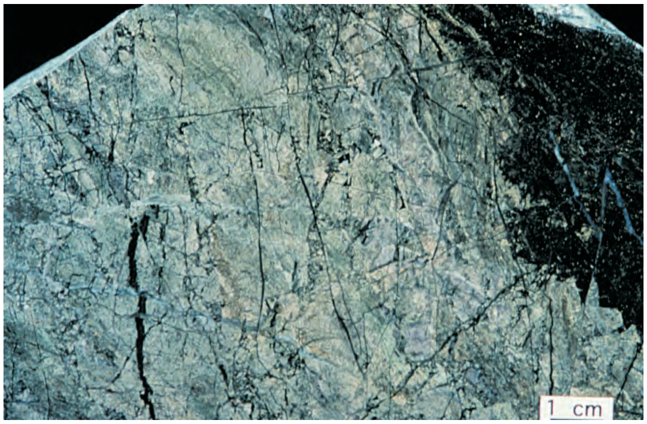

Figure 49a.

Figure 49c.

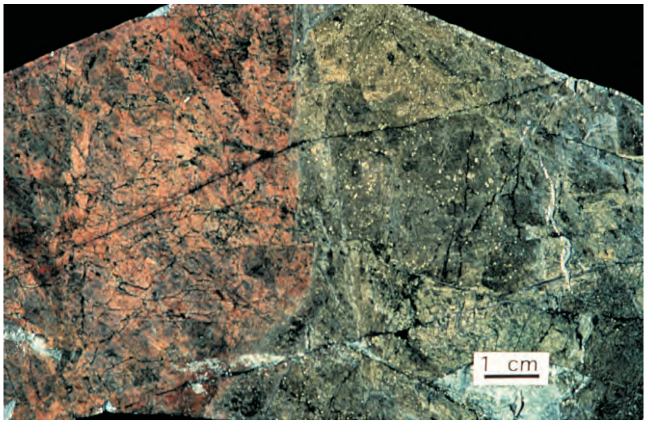

Figure 49b.

Figure 49. *Styles of alteration and mineralization; Harker–Holloway district, Ontario.* ***a****) Albitized basalt (left) in contact with carbonatized basalt, Holt McDermott mine.GSC 1999-015AA* ***b****) Albitized syenite dyke (left) in contact with albitized basalt, Holt McDermott mine. GSC 1999-015BB* ***c****) Albitic and pyritic gold ore overprinted by syntectonic extensional quartz veins, Lightning zone. (All photographs by F. Robert.) GSC 1999-015CC*

Figure 51a.

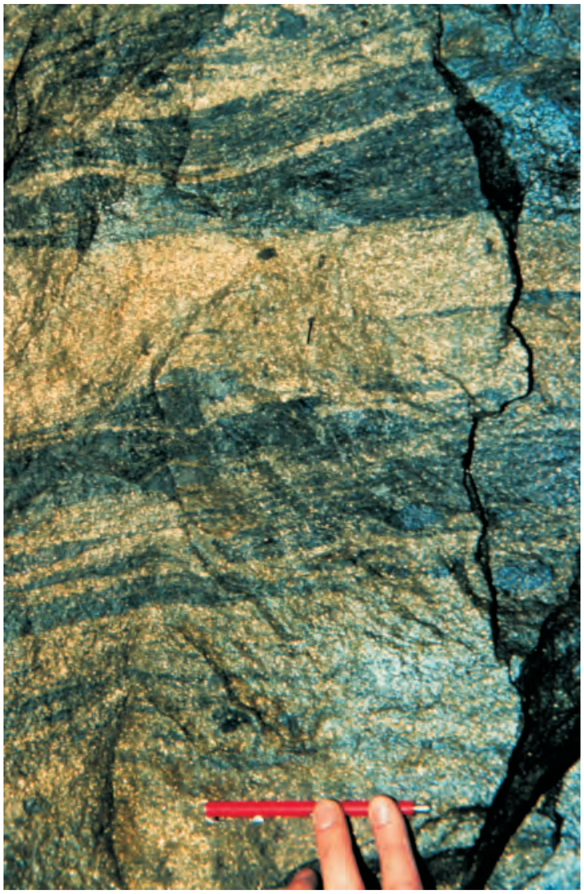

Figure 51b.

Figure 51c.

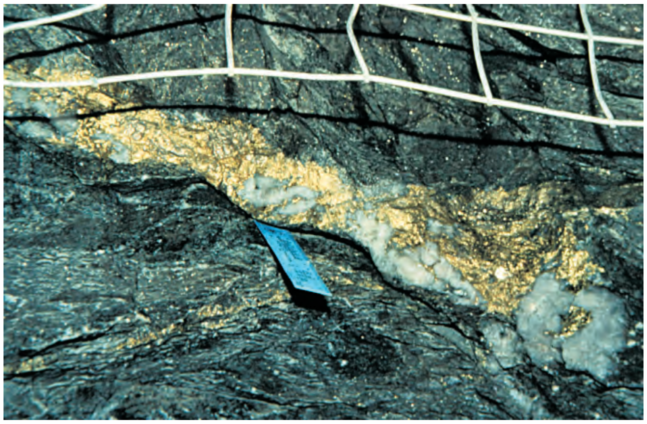

Figure 51d.

***Figure 51.** Ore styles; Bousquet district, Quebec. **a**) massive-sulphide 'vein' containing boudinaged wall-rock inclusions, West zone, 8th level, LaRonde mine. Width of photograph is 1.5 m (photograph by F. Robert). GSC 1999-015DD **b**) banded massive-sulphide ore, LaRonde mine (photograph by B. Dubé). GSC 1999-014P **c**) sulphide-matrix breccia with massive silicic clasts, LaRonde mine (photograph by B. Dubé). GSC 1999-014Q **d**) high-grade gold-copper-quartz vein, Doyon deposit (photograph by B. Dubé). GSC 1999-014R*

Figure 51e.

Figure 51f.

Figure 51e*) high-grade gold-copper-quartz vein, Doyon deposit. Width of photograph is 20 cm (photograph by F. Robert). GSC 1999-015EE* ***f****) sulphide-rich stockwork veins, Doyon deposit. Width of photograph is 60 cm (photograph by F. Robert). GSC 1999-015FF*

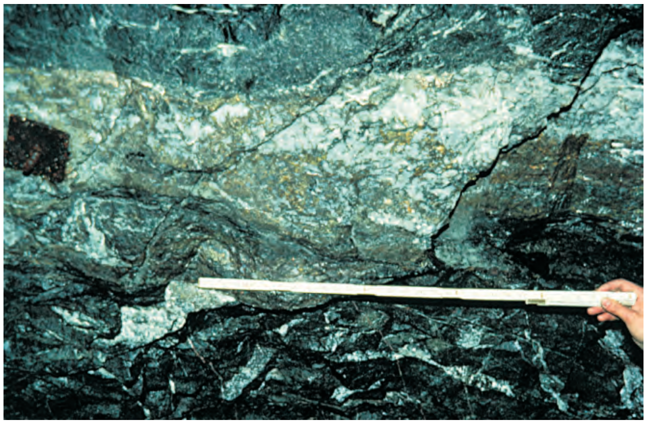

Figure 53a.

Figure 53b.

Figure 53. *Copper-gold veins; Chibougamau–Chapais district, Quebec.* ***a****),* ***b****) quartz-sulphide vein, Cooke mine, Chapais (both photographs by B. Dubé). GSC 1999-014S, GSC 1999-014T*

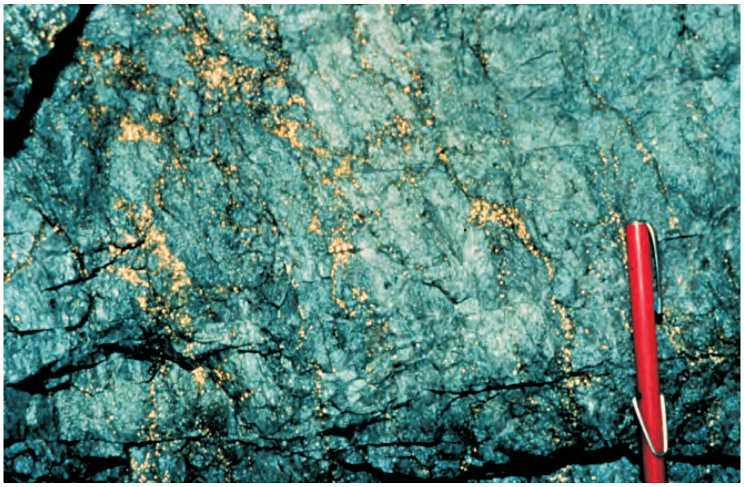

Figure 58. *Copper-bearing veinlets in zone of vuggy silica alteration characteristic of second-stage grey silicic alteration; Hope Brook deposit, Newfoundland (photograph by B. Dubé). GSC 1999-014U*

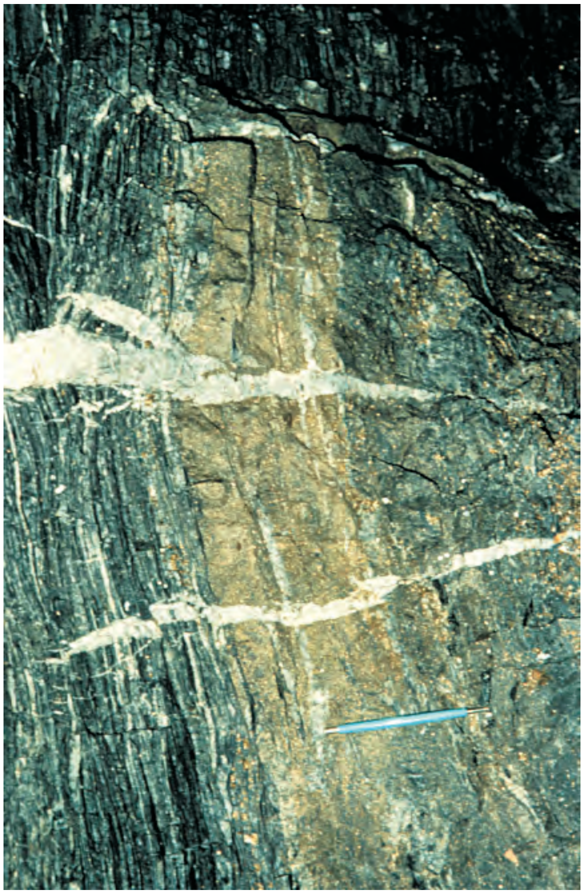

Figure 68a.

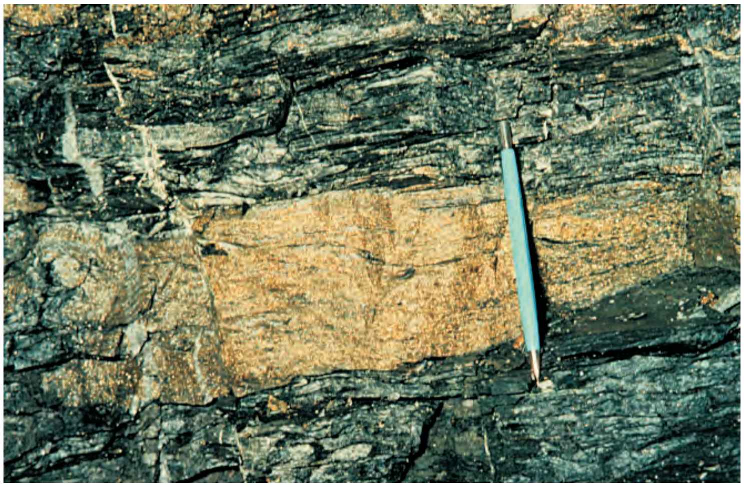

Figure 68b.

Figure 68. *Styles of sulphide and vein ores; Mosquito Creek gold mine, British Columbia.*
a*) stratabound massive-sulphide lens cut by transverse quartz veins. GSC 1999-015II*
b*) stratabound massive-sulphide lens, 2-184 stope. GSC 1999-015JJ*

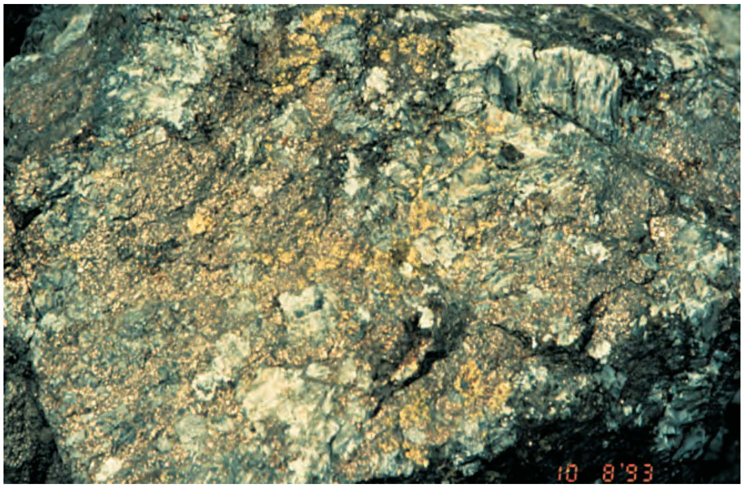

Figure 74.

Figure 74. *Pyrrhotite-chalcopyrite-arsenopyrite sulphide skarn ore; Hedley deposit, British Columbia. Width of photograph approximately 1 m (photograph by K.H. Poulsen). GSC 1999-016L*

Figure 78. *Stratabound massive-sulphide replacement ore in limestone; Ketza River, Yukon Territory (photograph by K.H. Poulsen). GSC 1999-016N*

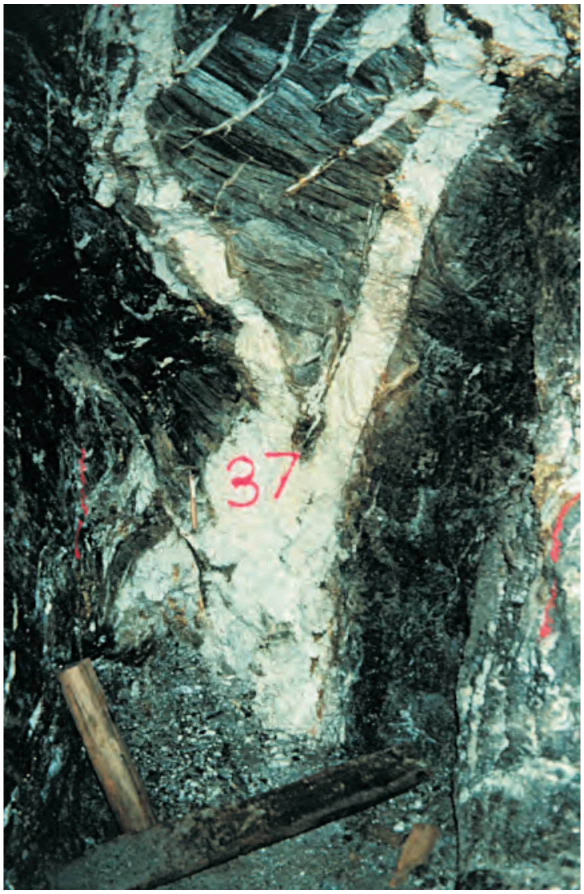

Figure 68c.

Figure 68c*). 'Oblique' quartz vein with extensional splays, 3rd level. Width of photograph is 1 m. (All photographs by F. Robert.) GSC 1999-015KK*

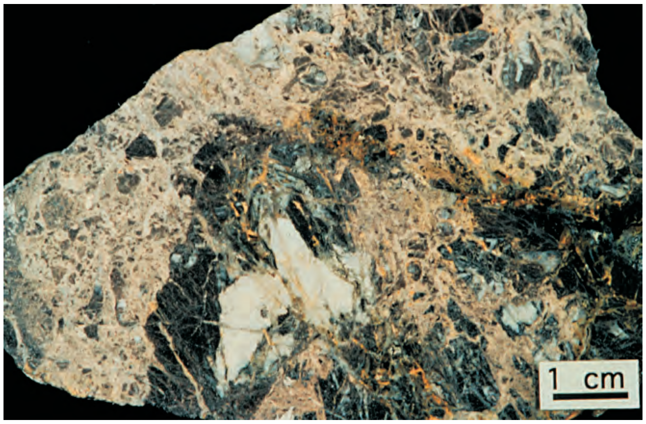

Figure 80a.

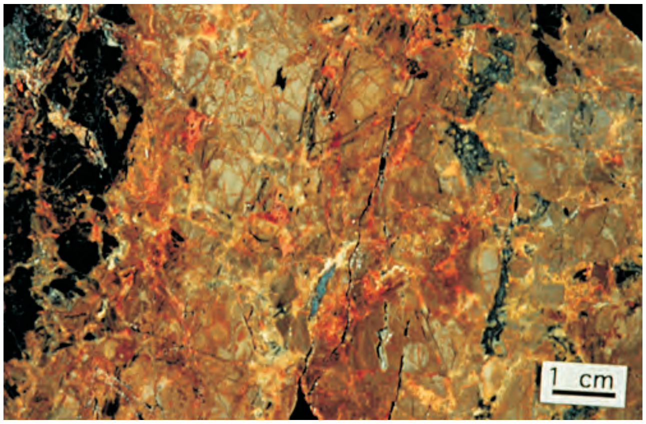

Figure 80b.

Figure 80. *Sediment-hosted breccia ores; Brewery Creek mine, Yukon Territory.* ***a****) In Devono-Mississippian Earn Group siliciclastic rocks, Blue deposit (17 g/t Au); grey mineral on right is stibnite. GSC 1999-014X* ***b****) In Silurian calcareous siltstone of the Steele Formation, North Slope deposit (27 g/t Au); grey mineral in fractures (centre right) is stibnite. GSC 1999-014Y*

Figure 83a.

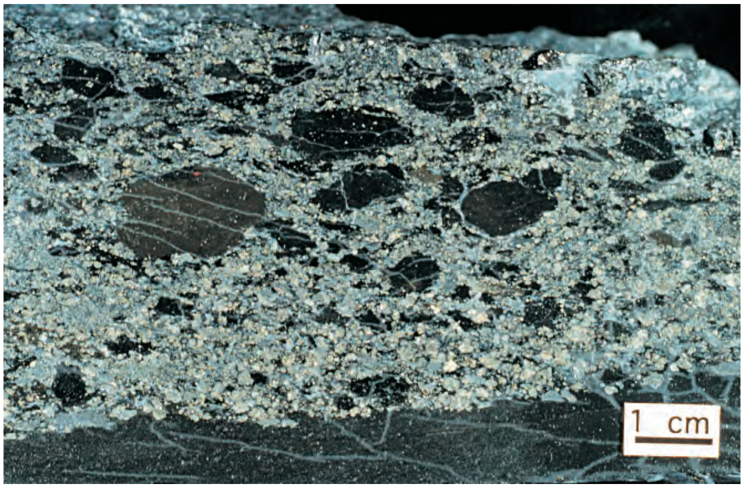

Figure 83b.

Figure 83. *Stratiform ores; Eskay Creek, British Columbia.* ***a****) Graded sulphide-silicate turbidite bed; 21B deposit (photograph courtesy of I. Jonasson).* ***b****) Tetrahedrite-rich (light grey) sedimentary debris flow containing siliceous argillite clasts (dark grey to black); 21B deposit (photograph courtesy of I. Jonasson).*