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Gold Deposits in Metamorphic Belts: Overview of Current Understanding, Outstanding Problems, Future Research, and Exploration Significance

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Abstract

Metamorphic belts are complex regions where accretion or collision has added to, or thickened, continental crust. Gold-rich deposits can be formed at all stages of orogen evolution, so that evolving metamorphic belts contain diverse gold deposit types that may be juxtaposed or overprint each other. This partly explains the high level of controversy on the origin of some deposit types, particularly those formed or overprinted/remobilized during the major compressional orogeny that shaped the final geometry of the hosting metamorphic belts. These include gold-dominated orogenic and intrusion-related deposits, but also particularly controversial gold deposits with atypical metal associations.

Orogenic lode gold deposits of Middle Archean to Tertiary age are arguably the predominant gold deposit type in metamorphic belts, and include several giant (>250 t Au) and numerous world-class (>100 t Au) examples. Their defining characteristics and spatial and temporal distributions are now relatively well documented, such that other gold deposit types can be compared and contrasted against them. They form as an integral part of the evolution of subduction-related accretionary or collisional terranes in which the host-rock sequences were formed in arcs, back arcs, or accretionary prisms. Current unknowns for orogenic gold deposits include the following: (1) the precise tectonic setting and age of mineralization in many provinces, particularly in Paleozoic and older metamorphic belts; (2) the source of ore fluids and metals; (3) the precise architecture of the hydrothermal systems, particularly the relationship between first- and lower-order structures; and (4) the specific depositional mechanisms for gold, particularly for high-grade deposits.

Gold-dominant intrusion-related deposits are a less coherent group of deposits, which are mainly Phanerozoic in age, and include a few world-class, but no unequivocal giant, examples. They have many similarities to orogenic deposits in terms of metal associations, wall-rock alteration assemblages, ore fluids, and, to a lesser extent, structural controls, and hence, some deposits, particularly those with close spatial relationships to granitoid intrusions, have been placed in both orogenic and intrusion-related categories by different authors. Those that are clearly intrusion-related deposits appear to be best distinguished by their near-craton setting, in locations more distal from subduction zones than most orogenic gold deposits and in provinces that also commonly contain Sn and/or W deposits; relatively low gold grades (≤1–2 g/t Au); and district-scale zoning to Ag-Pb-Zn deposits in distal zones. Outstanding problems for intrusion-related deposits include the following: (1) lack of a clear definition of this apparently diverse group of deposits, (2) lack of a definitive link for ore fluids and metals between mineralization and magmatism, (3) the diverse nature of both petrogenetic association and redox state of the granitoids invoked as the source of mineralization, and (4) mechanisms for exsolution of the CO_2-rich ore fluids from the relatively shallow level granitoids implicated as ore-fluid sources.

Gold deposits with atypical metal associations are a particularly diverse and controversial group, are most abundant in Late Archean terranes, and include several world-class to giant examples. Most are probably modified Cu-Mo-Au porphyry, volcanic rock-hosted Zn-Pb-Ag-Au massive sulfide, or Zn-Pb-Ag-Au or Ba-Au-Mo-Hg submarine epithermal systems, overprinted or remobilized during the events in which orogenic gold deposits formed, but there is lack of consensus on genesis. Outstanding problems for these deposits include the following: (1) lack of a clear grouping of distinctive deposits, (2) lack of published, well integrated studies of their characteristics, (3) generally a poorly defined timing of mineralization events, and (4) lack of assessment of metal mass balances in each stage of the complex mineralization and overprinting events.

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Both orogenic gold deposits and gold deposits with atypical metal associations contain a few giant and numerous world-class examples, whereas the intrusion-related group contains very few world-class examples, and no giants, unless Muruntau is included in this group. Preliminary analysis suggests that the parameters of individual world-class to giant gold deposits of any type show considerable variation, and that it is impossible to define critical factors that control their size and grade at the deposit scale. However, there appears more promise at the terrane to province scale where there are greater indications of common factors such as anomalous subduction-related tectonic settings, reactivated crustal-scale deformation zones that focus porphyry-lamprophyre dike swarms in linear volcanosedimentary belts, complex regional-scale geometry of mixed lithostratigraphic packages, and evidence for multiple mineralization or remobilization events.

There are a number of outstanding problems for all types of gold deposits in metamorphic belts. These include the following: (1) definitive classifications, (2) unequivocal recognition of fluid and metal sources, (3) understanding of fluid migration and focusing at all scales, (4) resolution of the precise role of granitoid magmatism, (5) precise gold-depositional mechanisms, particularly those producing high gold grades, and (6) understanding of the release of CO_2-rich fluids from subducting slabs and subcreted oceanic crust and granitoid magmas at different crustal levels. Research needs to be better coordinated and more integrated, such that detailed fluid-inclusion, trace-element, and isotopic studies of both gold deposits and potential source rocks, using cutting-edge technology, are embedded in a firm geological framework at terrane to deposit scales. Ultimately, four-dimensional models need to be developed, involving high-quality, three-dimensional geological data combined with integrated chemical and fluid-flow modeling, to understand the total history of the hydrothermal systems involved. Such research, particularly that which can predict superior targets visible in data sets available to exploration companies before discovery, has obvious spin-offs for global- to deposit-scale targeting of deposits with superior size and grade in the covered terranes that will be the exploration focus of the twenty-first century.

Introduction

METAMORPHIC BELTS are exceptionally complex regions of the earth's crust where accretionary or collisional orogenies have added new continental crust and/or thickened existing continental crust. These tectonic processes are of lithospheric scale, and, as such, involve thermal and stress anomalies that progressively cause the following succession of events: (1) generate magmatic arcs and fore arcs with associated thick sedimentary prisms and back arcs with associated extensional basins; then (2) deform and metamorphose these, normally with continued extensive granitoid plutonism; and, finally, (3) uplift and erode these with the generation of new sedimentary basins. Gold-bearing deposits can be generated and/or modified in each evolutionary stage of orogen development. Therefore, it is not surprising that metamorphic belts within an orogen can contain diverse auriferous deposits that may be juxtaposed with, or even overprint, each other, leading to considerable controversy concerning their origin. The deposits may include shallowly formed ore systems preserved in less eroded parts of an orogen, and more deeply formed systems exposed within unroofed metamorphic belts.

Gold deposit types that formed during early volcanism and sedimentation in convergent margin settings, or were accreted to cratons in oceanic arcs or obducted oceanic crust in such settings, include epithermal Ag-Au, porphyry Cu-Au, and Au-rich volcanic-hosted massive sulfide deposits (Fig. l). Unless controversial, because of subsequent remobilization during metamorphism-deformation or overprinting by contrasting deposit styles, these well defined gold deposit types are not considered further in this paper. The gold-rich deposits discussed below are formed or overprinted/remobilized broadly synchronous with the deformation, metamorphism, and granitoid magmatism, normally in the fore-arc region of convergent margins, during the major orogeny that produced the major compressional rock fabrics and shaped the final geometry of the metamorphic terranes within the orogenic belts in which they reside.

Gold deposits that formed in this metamorphic environment are diverse in terms of their age (Middle Archean to Tertiary), geometry (single veins to vein arrays to stratabound replacement to disseminated deposits), structural controls (reverse to strike-slip, and, less commonly, normal faults), host rocks (mafic-ultramafic rock sequences, sedimentary rocks, or granitoid plutons), metamorphic grade of host rocks (subgreenschist to granulite facies, although mainly greenschist facies), temperature and pressure of formation (≈200°–650°C; 0.5–5 kbars), and consequent wall-rock alteration assemblages (carbonate to diopside, muscovite to biotite/phlogopite) and metal associations (Au with variable Ag, As, B, Bi, Cu, Pb, Sb, Te, W, and Zn).

As a result of this diversity, there have been various classification schemes developed for gold deposits in metamorphic belts, as reviewed, for example, by Groves et al. (1998), Hagemann and Cassidy (2000), and Bierlein and Crowe (2000). While it is generally accepted that there is diversity of gold deposit styles in metamorphic belts (e.g., Witt, 1997; Robert and Poulsen, 1997; Robert et al., 1997; Sillitoe and Thompson, 1998; Poulsen et al., 2000), global reviews (e.g., Hodgson, 1993; Kerrich and Cassidy, 1994; McCuaig and Kerrich, 1998; Goldfarb et al., 2001) indicate that the dominant style is represented by orogenic gold deposits, as defined by Groves et al. (1998). These are deposits that formed during the late stages of orogenesis, within the main phase of crustal shortening in compressional or transpressional regimes, in which the penetrative deformational and metamorphic fabrics were generated and/or reactivated. These criteria are important because this deposit type can be used as a basis for comparison with deposits assigned to other types by various authors, or for deposits where possible overprinting of more than one style of mineralization, or alteration, has led to controversy concerning their origin (e.g., Hemlo in Pan and Fleet, 1992, Michibayashi, 1995, and Robert and Poulsen, 1997; Boddington in Roth, 1992, Allibone et al., 1998, and McCuaig et al., 2001; and Bousquet in Valliant and Hutchinson, 1982, Marquis et al., 1990, Tourigny et al., 1993, and

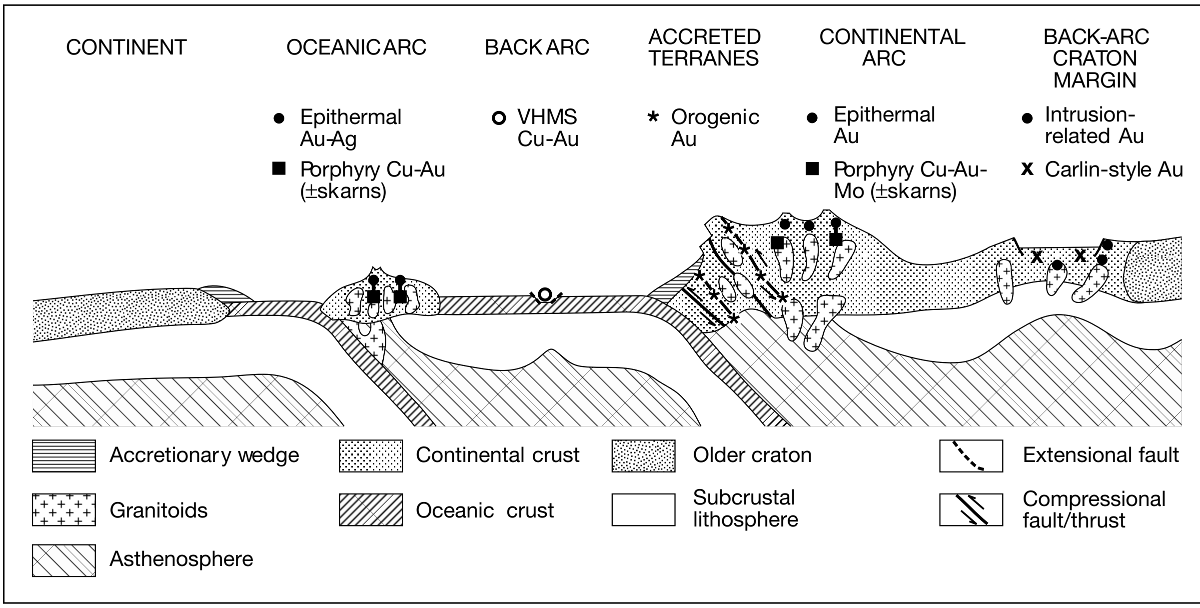

FIG. 1. Tectonic settings of gold-rich epigenetic mineral deposits. Vertical scale is exaggerated to allow schematic depths of formation of various deposit styles to be shown. Adapted from Groves et al. (1998). Abbreviations: VHMS = volcanic-hosted massive sulfide.

Poulsen and Hannington, 1996). In turn, this classification can be important in attempting to define the parameters that control whether these are world-class to giant deposits, and whether there are specific end-member types that are more likely to provide world-class to giant deposits, as these are the current focus of major exploration companies. For example, the overprinting or remobilizing process may be particularly important with increasing deposit size, as several of the larger deposits and districts show multiple episodes of gold mineralization (e.g., Kalgoorlie and Boddington, Western Australia; Timmins and Hemlo, Canada).

The major objectives of this paper are to define the areas of uncertainty in the current understanding of gold deposits in metamorphic rocks within orogenic belts, and to define those future research areas that can potentially resolve these uncertainties and lead to better genetic and exploration models. In order to achieve this, the major characteristics of the important deposit styles in metamorphic belts are defined, with orogenic gold deposits used as a reference against which other deposit types are compared. From these considerations, equivocal parameters and/or genetic aspects and future research needs are defined. An Appendix provides the location and classification of the deposits discussed in the text, together with a recent reference for each.

Potential Diversity of Gold Deposit Types in Metamorphic Belts

Groves et al. (1998) reviewed the problems of nomenclature for gold deposits in metamorphic belts. They emphasized the overall similarities in tectonic setting, structural controls, geochemistry of alteration, ore-element association, and fluid and isotopic composition of the most abundant Au-dominant (Au > Ag, low Cu-Pb-Zn) deposits in metavolcanic rock (greenstone) and turbidite/slate (accretionary prism) terranes. Groves et al. (1998) used "orogenic gold deposit," following Bohlke (1982), as a unifying term to describe this group of deposits, widely interpreted to form late in an orogenic cycle from mid- to lower-crustal metamorphic fluids, although deeply sourced magmatic fluids are also possible. The term orogenic gold deposit is not universally accepted, but because no better all-embracing term has been proposed, it is retained here.

Other authors have suggested that some gold deposits in metamorphic belts that have broadly similar characteristics to orogenic deposits, but which show a close spatial and temporal association with granitoid intrusions, should be termed intrusion-related deposits (e.g., Sillitoe, 1991; Sillitoe and Thompson, 1998; Thompson and Newberry, 2000; Lang et al., 2000). Some syenite-associated deposits in the Abitibi belt (e.g., Robert, 2001) may be a definable subgroup within the intrusion-related group. Other workers (Mueller, 1991; Mueller et al., 1996; Mueller and McNaughton, 2000) have suggested that certain calc-silicate–bearing gold deposits in amphibolite facies settings of well documented orogenic gold provinces, particularly in the Yilgarn craton of Western Australia, are gold skarns. In summary, these intrusion-related gold deposits are suggested by some workers to be representative of a distinct group of deposits, because they all formed as a proximal part of a magmatic-hydrothermal system, rather than from a fluid of more regional extent, favored by many authors to be of a metamorphic origin, which circulated throughout much of an orogen.

Orogenic gold deposits are typically developed in terranes that have experienced moderate- to high-T–low- to moderate-P metamorphism (Powell et al., 1991), with consequent generation of large volumes of granitic melts. Hence, a distal spatial relationship with certain intrusions is also expected for these deposits, and there is a possibility of a genetic connection.

In addition, there are gold-bearing deposits in metamorphic belts with element associations unlike those of typical orogenic deposits (e.g., Cu ± Pb ± Zn ± Au ± Ag ± Ba; Cu ± Au ± Mo; W ± Sn ± Au), which include some cited as intrusion-related deposits, gold-rich volcanic-hosted massive sulfide or gold-overprinted volcanic-hosted massive sulfide, and deformed Cu ± Au ± Mo porphyry deposits or their overprinted equivalents. A recurrent theme in many in this group of anomalous and controversial deposits is the possibility of overprinting of one ore system on preexisting alteration or on a different type of ore system, and local remobilization of preexisting mineralization during deformation and metamorphism. Possible examples include an orogenic gold overprint on volcanic-hosted massive sulfide deposits (Mount Gibson, Western Australia) or on sea-floor–related alteration (Campbell-Red Lake, Canada); an orogenic or intrusion-related gold overprint on porphyry-style systems (Boddington, Western Australia; Hollinger-McIntyre at Timmins, Canada); and metamorphic remobilization of porphyry or submarine epithermal-style systems (Hemlo, Canada).

Such diversity is not unexpected, given the complex and lengthy (~100–200 m.y.) evolution of composite metamorphic belts along active continental margins. The orogenic gold deposits are likely to be preserved in these belts unless the orogens are eroded down to their high-grade metamorphic roots (Goldfarb et al., 2001). Porphyry Cu-Au ± Mo and epithermal Ag-Au deposits, generated at relatively shallow levels in the volcanoplutonic arcs and back arcs, are typically less likely to be preserved in metamorphosed sequences. These types of deposits form prior to the major phase(s) of orogenesis, involving compressional to transpressional deformation, regional metamorphism, and postvolcanic granitoid magmatism, during which the orogenic gold deposits form. During the main phases of orogenesis, the porphyry, epithermal, and volcanic-hosted massive sulfide deposits commonly will be deformed and weakly metamorphosed, but would then typically be eroded during uplift of the orogens following crustal thickening, leading to their rarity in preserved orogens older than Mesozoic (Kerrich et al., 2000), although volcanic-hosted massive sulfide deposits that were formed in other settings may be preserved. However, the rare occurrence of undoubted, little-deformed Precambrian porphyry deposits (e.g., Clark Lake porphyry Cu-Mo-Au and related Au-Cu veins at Chibougamau; Pilote et al., 1995), and even rarer possible epithermal deposits (Groves and Barley, 1994), shows that preservation and, hence, overprinting by younger hydrothermal systems, are possible, given an appropriate P-T-t path.

The potential diversity of deposit types, and the controversial nature of some of them, mean that the research strategies required to resolve problems related to each group and each genetic controversy are not necessarily the same in all cases.

Orogenic Gold Deposits: The Most Common Type?

Groves et al. (1998) defined the unifying term "orogenic gold deposit" to include those deposits widely referred to as mesothermal (Nesbitt et al., 1986) in the past 20 yr, but also classified in terms of their ore associations (e.g., gold-only), their host sequences (e.g., greenstone-hosted, slate-belt style, turbidite-hosted), their form (e.g., lode, quartz-carbonate vein, or disseminated deposits), or even their specific location (e.g., Mother lode-style deposits). Following Gebre-Mariam et al. (1995), Groves et al. (1998, p. 22) further suggested the use of the terms "epizonal," "mesozonal," and "hypozonal" to describe specific depth segments of the vertically extensive orogenic-gold systems, with epizonal deposits <6 km, mesozonal deposits from 6 to 12 km, and hypozonal deposits >12 km in depth (Fig. 2A)

Giant deposits (>250 t or >8 Moz Au) or districts, in the sense of Laznicka (1999), which have been universally ascribed to orogenic gold systems, include the following, from oldest (Archean) to youngest (Mesozoic): Hollinger-McIntyre, Timmins, Canada; Golden Mile, Kalgoorlie, Western Australia; Kolar, India; Ashanti, Ghana; Homestake, South Dakota; Bendigo and Ballarat, Victoria, Australia; Berezovsk, Russia; Kumtor, Kyrgyzstan; and Mother lode, California. Muruntau in Uzbekistan, Vasil'kovsk in Kazakhstan, and Morro Velho in Brazil are also giant deposits that probably belong to this group, but there are conflicting data in the literature on classification of these deposits. The poorly described giant Russian deposits at Olympiada and Sukhoi Log have been assigned to this group in some descriptions (Safonov, 1997; Goldfarb et al., 2001; Yakubchuk et al., 2001), but field observations by one of us (F.R.) suggest that such a classification is far from certain. In addition, there are numerous world-class deposits (>100 t or 3 Moz Au) in more than 20 of the 75 metallogenic provinces that contain orogenic gold deposits worldwide (Goldfarb et al., 2001).

Definition and distinction from other gold deposit styles

The features common to orogenic gold deposits have been extensively reviewed by Kerrich and Cassidy (1994), Groves et al. (1998), McCuaig and Kerrich (1998), and Goldfarb et al. (2001), and several papers in Hagemann and Brown (2000), and are only briefly summarized below and in Table 1.

These deposits form along convergent margins during terrane accretion, translation, or collision, which were related to plate subduction and/or lithospheric delamination. They formed typically in the latter part of the deformational-metamorphic-magmatic history of the evolving orogen (Groves et al., 2000). Country rocks are most commonly regionally metamorphosed into belts with extensive greenschist through lower-amphibolite facies rocks. Importantly, ores developed synkinematically, with at least one stage of the main penetrative deformation of the country rocks, and they inevitably have a strong structural control involving faults or shear zones, folds, and/or zones of competency contrast (Hodgson, 1989). They show vertical dimensions of as much as 1 to 2 km, with only subtle metal zoning, and distinctive, strong, lateral zonation of wall-rock alteration, which normally involves addition of K, As, Sb, LILE, CO_2, and S, with variable additions of Na or Ca in specific cases, particularly in deposits sited in amphibolite-facies rocks (Ridley et al., 2000). Due to considerable variation in the temperature of the hydrothermal systems, proximal wall-rock alteration assemblages typically vary from sericite-carbonate-pyrite at high crustal levels, through biotite-carbonate-pyrite, to biotite-amphibole-pyrrhotite and biotite/phlogopite-diopside-pyrrhotite at deeper crustal levels (Ridley et al., 2000). Quartz ± carbonate veins are ubiquitous and are commonly gold bearing, although in many systems it

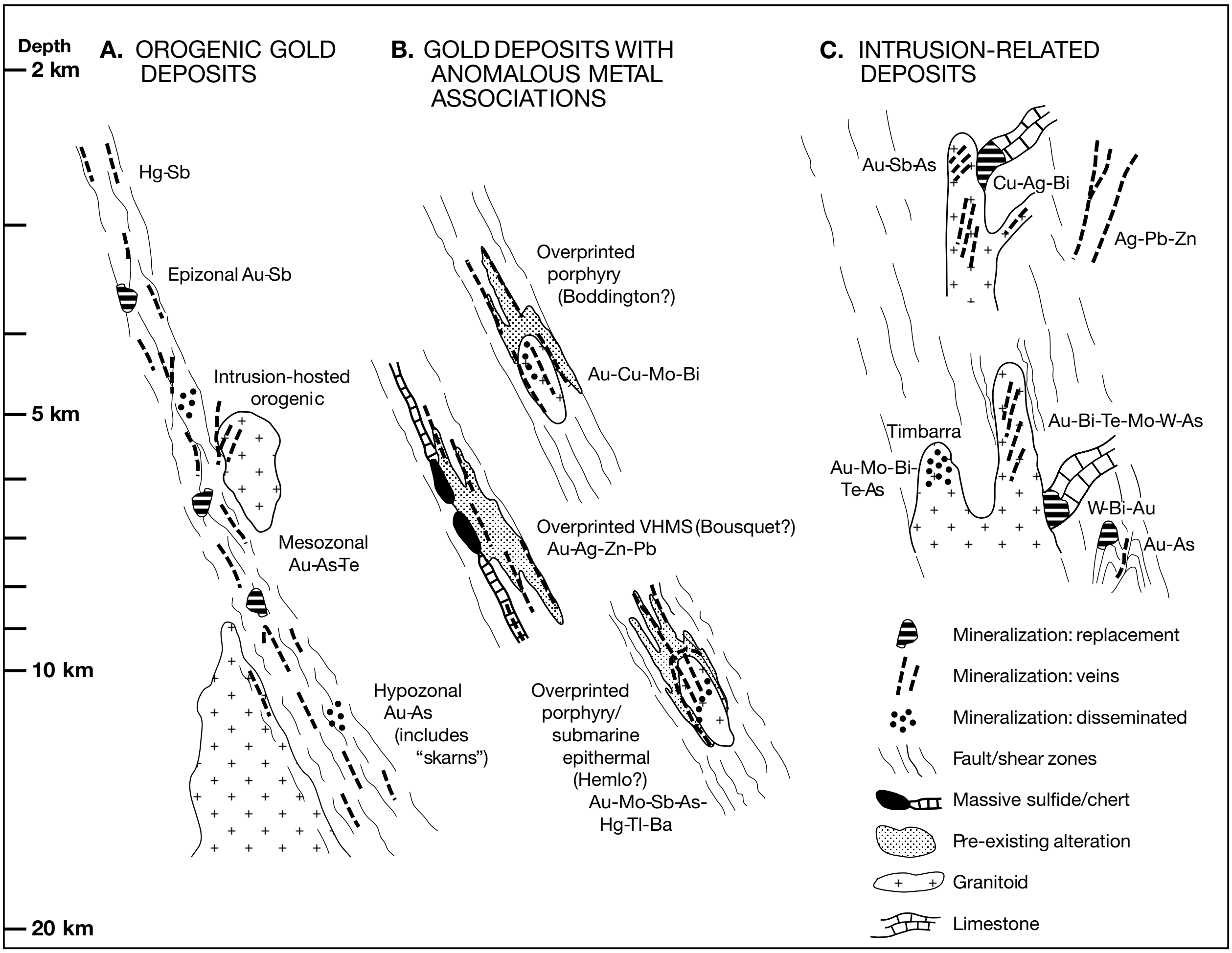

FIG. 2. Schematic representation of crustal environments of orogenic gold deposits, gold deposits with anomalous metal associations, and intrusion-related gold deposits, in terms of depth of formation and structural setting. The figure is, by necessity, stylized. Adapted partly from Groves et al. (1998) and Lang et al. (2000). Abbreviations: VHMS = volcanic-hosted massive sulfide.

is the sulfidized, high Fe/Fe + Mg + Ca wall rocks adjacent to the veins that contain most ore (e.g., Bohlke, 1988).

A distinctive metal enrichment association (Au-Ag ± As ± B ± Bi ± Sb ± Te ± W) is characteristic of the deposits, with Ag, Sb (e.g., Wiluna, Western Australia; Hillgrove, New South Wales, Australia; Sarylakh, Russia), and As (e.g., Salsigne, France) present in high-enough concentrations in some places to be mined as byproducts. The ores typically have background values to only slight enrichments in Cu, Mo, Pb, Sn, and Zn, and have high gold fineness (generally >900) and high bulk Au/Ag ratios (generally ≥5/1). They were deposited from low-salinity, near-neutral, H_2O-CO_2 ± CH_4 ± N_2 fluids, which transported gold as a reduced sulfur complex. The CO_2 concentrations are, everywhere, >5 mole percent, with variable $H_2O/CO_2/CH_4$ ratios commonly caused by phase separation during extreme pressure fluctuations (Sibson et al., 1988). Typical $\delta^{18}O$ values for hydrothermal fluids are about 5 to 8 per mil in Archean greenstone belts, and about 2 per mil heavier in Phanerozoic gold lodes. Sulfur and C isotope ratios vary because the fluids had a variable redox state, between the H_2S/SO_4 and CO_2/CH_4 buffers, at the depositional sites (Mikucki, 1998), and there were inherent differences in the isotopic composition of these species in fluid source regions.

A few gold deposits in well defined orogenic gold provinces are characterized, however, by atypical metal associations and ratios, alteration assemblages, or fluid salinities (final two columns of Table 1). These are differentiated from orogenic gold deposits in recent overview papers (Robert et al., 1997; Groves et al., 1998; Kerrich et al., 2000; Goldfarb et al., 2001), although these may result from preferential overprinting by orogenic gold systems. As noted above, there are also other deposits that have the geologic characteristics of orogenic gold systems and that have been grouped with the orogenic deposit types by Groves et al. (1998) and Goldfarb et al. (2001), but have been alternatively classified as intrusion-related (Sillitoe 1991; Matthai et al., 1995; McCoy et al., 1997; Sillitoe and Thompson, 1998; Brisbin, 2000; Thompson and Newberry, 2000; Lang et al., 2000; Lang and Baker, 2001) or syenite-associated (Robert, 2001) deposit types (Fig. 2C; Table 1). These latter two classifications are partly on the basis of the close spatial and temporal association of gold

TABLE 1. Comparison of Orogenic Gold Deposits, Intrusion-Related Gold Deposits (Excluding Associated Skarns), and Gold Deposits with Atypical Metal Associations in Terms of Their Critical Regional- to Deposit-Scale Characteristics

Critical characteristics	Orogenic gold deposits	Intrusion-related gold deposits	Gold deposits with anomalous metal associations
Age range	Middle Archean to Tertiary; peaks in Late Archean, Paleoproterozoic, Phanerozoic	Mainly Phanerozoic; some Proterozoic; rare Late Archean	Mostly Late Archean; some Phanerozoic
Tectonic setting	Deformed continental margin mainly of allochthonous terranes	Pericratonic terranes of the miogeocline margin	Back-arc to arc early?; accretionary to collisional terranes late
Structural setting	Commonly structural highs during later stages of compression and transtension	Compressional to extensional transition in fold and thrust belts	Late evolution similar to that of orogenic deposits
Host rocks	Variable; mainly mafic volcanic or intrusive rocks or greywacke-slate sequences	Major examples in grantioid intrusions; some in sedimentary rocks	Variable; commonly felsic intrusive or volcanic rocks
Metamorphic grade of host rocks	Mainly greenschist facies but subgreenschist to lower granulite facies	Mainly subgreenschist to greenschist facies	Greenschist to amphibolite facies
Association with intrusions	Commonly felsic to lamprophyre dikes or continental margin batholiths	Strong association with granitoid stocks; lamprophyre dikes	Strong association with granitoid stocks and/or felsic to lamprophyre dikes
Mineralization style	Variable; large veins, vein arrays, saddle reefs, replacement of Fe-rich rocks	Commonly sheeted veins, lesser breccias, veins, and disseminations	High variable; disseminated to vein styles
Timing of mineralization	Late-tectonic; post-(greenschist) to syn-(amphibolite) metamorphic peak	Very late tectonic; postregional metamorphic peak	Synvolcanic and premetamorphic?; late- evolution syn- to postmetamorphic.
Structural complexity of ore bodies	Complexity common, particularly in brittle-ductile regimes	Mainly simple vein arrays in relatively brittle regimes	Complexity normal, causing extreme controversy for this deposit style
Evidence of overprinting	Strong overprinting in larger deposits; multiple veining events	Minor evidence of overprinting by late structures	Strong evidence of overprinting in most deposits
Metal association	Au-Ag ± As ± B ± Bi ± Sb ± Te ± W	Au-Ag ± As ± B ± Bi ± Sb ± Sn ± Te ± W (Pb-Zn distal)	Au-Ag ± Ba ± Cu ± Hg ± Mo ± Pb ± Zn
Metal zoning	Cryptic lateral and vertical zoning	Strong district-scale zoning; Au-W/Sn-Ag/Pb/Zn	Variable, but strong in some deposits
Proximal alteration	Varies with metamorphic grade; normally mica-carbonate-Fe sulfide	Mica-K feldspar-carbonate-chlorite-Fe sulfide	Extremely variable due to different deposit styles and metamorphic overprint (?)
P-T conditions	0.5–4.5 kbars, 220°–600°C Normally 1.5 ± 0.5 kbars, 350° ± 50°C	0.5–1.5 kbars, 200°–400°C for Au-rich systems	Variable; now largely reflect metamorphic conditions of host rocks
Ore fluids	Low-salinity H_2O-CO_2 ± CH_4 ± N_2	Variable-salinity H_2O-CO_2, very minor CH_4 ± N_2	Variable; high-salinity H_2O to low-/moderate-salinity H_2O-CO_2
Proposed heat sources	Varied; asthenosphere upwelling to midcrustal granitoids	High-level granitoids in gold district	Early igneous heat source?; later deep crustal/lithosphere heat source
Proposed metal sources	Subducted/subcreted crust and/or supracrustal rocks and/or deep granitoids	High-level granitoids and/or supracrustal rocks	Variable; magmatic, metamorphic, or deep crustal sources proposed

Note: Examples are discussed in text and shown in Table A1 and Figure A1 in Appendix

deposits with granitoid intrusions. These deposits, with many features of both orogenic and intrusion-related gold deposits, are particularly problematic and diverse, perhaps because of inconsistent model descriptions between the various studies. Hence, they are singled out for discussion later in this paper.

Current knowledge

With increasingly sophisticated geochronology, using robust isotopic systems, the temporal distribution of orogenic gold deposits is now broadly known (Fig. 3). There is a heterogeneous temporal distribution of formation ages marked by two Precambrian peaks (2800–2550 and 2100–1800 Ma), a singular lack of deposits for 1,200 m.y. (1800–600 Ma), and a continuous genesis since 600 Ma. Combined with the general agreement that orogenic gold deposits formed in areas of continental growth throughout geological time, Goldfarb et al. (2001) described how the temporal distribution was related to evolution of plate-tectonic processes as the earth progressively cooled. They interpreted the two earlier Precambrian formation episodes to major, plume-influenced mantle overturn (e.g., Davies, 1995) in the hotter early earth (ca. >1800 Ma), with major orogenic gold-forming events correlated to major periods of crustal growth (Condie, 1998). These gold deposits have been preserved in roughly equidimensional, large masses of buoyant continental crust (e.g., cratons). Evolution to a less episodic, more continuous, modern-style

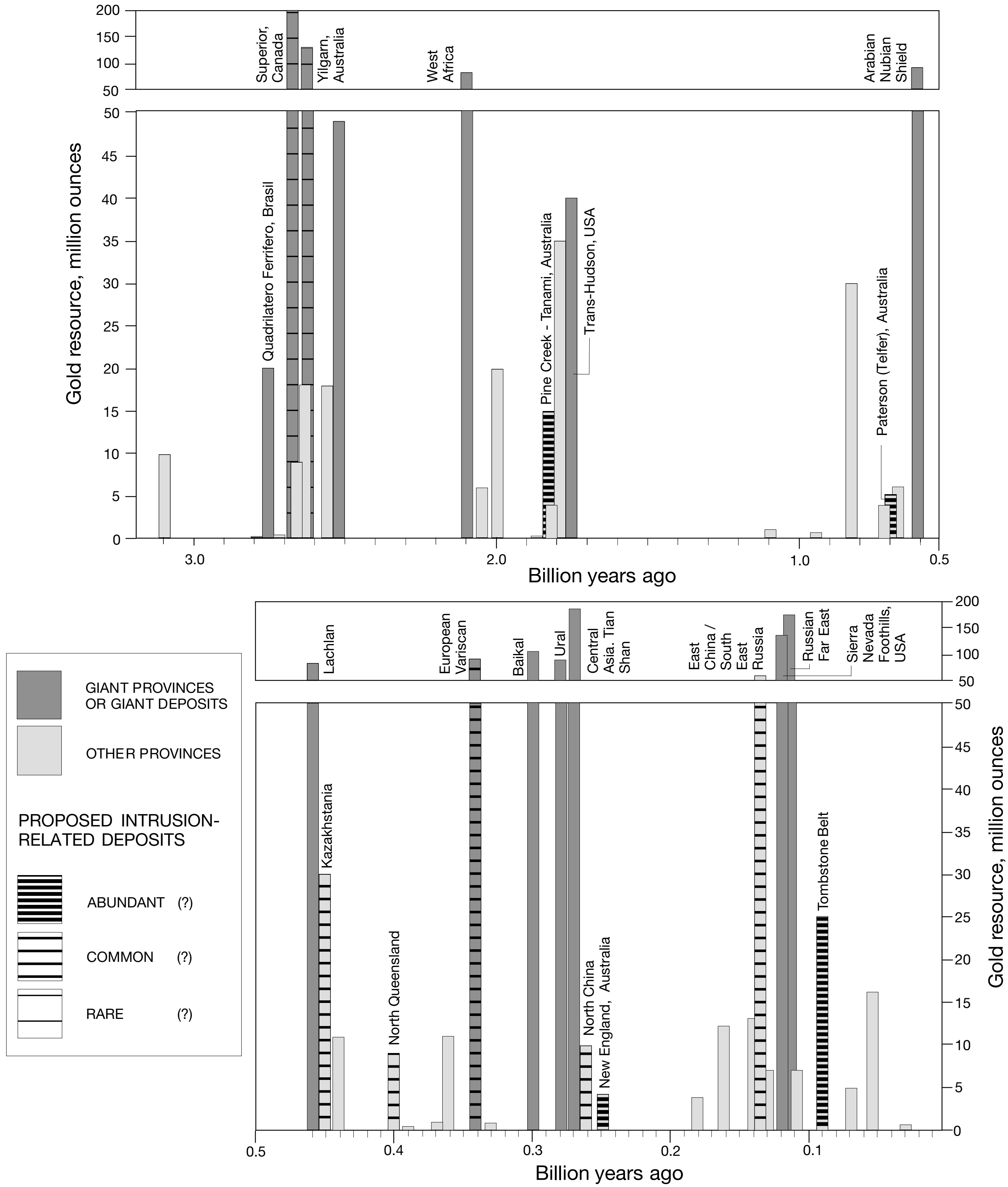

FIG. 3. Distribution of gold production from orogenic gold deposits with geological time. Provinces in which intrusion-related gold deposits are considered by some authors to be a major contributor to production are shown. Adapted from Goldfarb et al. (2001).

plate-tectonic regime, beginning near the start of the Mesoproterozoic, is interpreted to have led to the more common accretion of volcanosedimentary arcs and oceanic terranes as linear orogenic belts surrounding the margins of the more-buoyant Archean to Paleoproterozoic cratons. Uplift and erosion of these linear belts, and any contained orogenic gold deposits, to expose their high-grade metamorphic cores, can explain the noticeable lack of preserved deposits at 1800 to 600 Ma, their preferred exposure in 600 to 50 Ma orogens, the importance of placers associated with Phanerozoic lodes older than ca. 100 Ma, and the general absence of orogenic deposits in the still-shallow levels of orogenic belts that are younger than ca. 50 Ma (Fig. 3).

The district-scale controls on orogenic gold deposits are relatively well defined. Crustal-scale deformation zones, particularly those hosting swarms of felsic porphyry intrusions, serpentinized ophiolite fragments, and/or lamprophyre dikes, play an important role in localizing deposits in many of the better endowed gold provinces (e.g., Abitibi belt, Canada; Norseman-Wiluna belt, Australia; Ashanti belt, Ghana; Juneau and Mother lode belts, USA). On this scale, bends or jogs in these regional, deep-crustal structural zones, their interaction with lower-order shear zones, major competency contrasts in lithostratigraphic sequences, anticlinal or uplifted zones, and irregularities along granitoid contacts may all play a role in creating low minimum or mean stress zones into which ore fluid could be focused at the district or camp scale (Groves et al., 2000). In general, there is no consistent spatial association between the orogenic gold deposits and specific granitoid composition either within or between provinces, although abundant granitoid intrusions are a feature of most orogenic gold provinces (e.g., Kerrich and Cassidy, 1994; Bierlein et al., 2001b; Goldfarb et al., 2001) because they are a logical consequence of the collisional-accretionary processes at convergent margins.

At the deposit scale, all orogenic-gold ore bodies show strong structural control. Although the nature of that control varies within and between provinces, faults with a reverse component of shear are more commonly mineralized than those with a normal or dominant strike-slip shear component (Sibson et al., 1988). Host rocks are extremely variable, although there is an overall trend from volcanic rock- or intrusion-hosted deposits in Archean provinces to sedimentary rock-hosted deposits in Paleoproterozoic to Tertiary provinces, and for the larger deposits to be hosted in a few of the physically and/or chemically more-favorable units within the lithostratigraphy in any province.

As noted above, orogenic gold deposits may be hosted in rocks that have been metamorphosed from subgreenschist to granulite facies. However, most giant and world-class deposits that are ascribed to orogenic gold systems, with the notable exceptions of Kolar and perhaps Muruntau, are hosted in greenschist facies rocks.

The relative timing of orogenic gold deposit formation worldwide has recently been summarized by Groves et al. (2000), with emphasis on the Yilgarn craton of Western Australia. They concluded that orogenic gold deposits most commonly form during progressive D_2 to D_4 deformation events in a D_1 to D_4 deformational sequence, normally 20 to 100 m.y. after the deposition of volcanosedimentary host rocks, although there may be a greater hiatus in some provinces. There are very few Precambrian or early Paleozoic cases where synchronicity between gold deposition and emplacement of adjacent granitoid intrusions has been demonstrated unequivocally; adjacent or hosting intrusions may both predate gold mineralization, as in most examples from the Yilgarn block (Groves et al., 2000), or postdate them by as much as 80 m.y. in the central Victorian gold fields of Australia (Bierlein et al., 2001b), and actually contact metamorphose preexisting gold deposits in the Stawell and Maldon gold camps (Foster et al., 1998; Bierlein et al., 2001a). Importantly, Wilde et al. (2001) demonstrated that gold mineralization at Muruntau postdates subjacent granitoids by about 30 m.y., making its classification as an intrusion-related deposit dubious. In some younger terranes, such synchronicity is better documented. For example, Eocene orogenic gold deposits of the Juneau gold belt in southeastern Alaska formed simultaneously with shallower emplacement of some plutons of the massive Coast batholith, which crops out about 10 km landward of the ores (Miller et al., 1994). In the Chugach accretionary prism of southern Alaska, Tertiary gold deposits and crustal-melt granitoids are coeval in a belt extending for more than 2,000 km along the Gulf of Alaska margin (Haeussler et al., 1995).

Depositional mechanisms for gold in orogenic deposits are summarized by Mikucki (1998). For replacement deposits or deposits dominated by gold disseminated in altered wall rock, desulfidation of reduced aqueous sulfur complexes of gold by reaction with rocks with high Fe/Fe + Mg ratios is the most viable precipitation mechanism (Phillips and Groves, 1983; Bohlke, 1988), although pH changes may be important in ultramafic rocks (Kishida and Kerrich, 1987). For free-gold deposition in quartz-carbonate veins, large pressure fluctuations during hydrofracturing, accompanied by phase separation, are the most likely mechanisms for destabilizing aqueous sulfur complexes of gold, although there are competing physicochemical changes, some of which increase, whereas others decrease, gold solubility (Mikucki, 1998). Mixing of externally derived fluid (e.g., meteoric water) with the main ore fluid has been suggested for some epizonal deposits (Nesbitt et al., 1986; Craw and Koons, 1989; Hagemann et al., 1994), but, on the basis of existing H and O isotope data, cannot be a widespread depositional mechanism. Fluid reduction and destabilization of gold complexes by back-mixing of fluid, which has reacted with local wall rocks, is also a possibility (Cox et al., 1995), particularly in sedimentary rock sequences containing carbonaceous matter, where fluid-rock reaction could contribute CH_4, or other hydrocarbons, and/or N_2. This may explain why, in a single gold province, fluid inclusions from gold-bearing veins hosted in metasedimentary country rocks are typically enriched in these reduced volatiles, whereas CO_2 comprises almost the entire nonaqueous fluid phase where similar veins cut intrusions emplaced into the same metasedimentary sequence (e.g., Goldfarb et al., 1989).

The fluid chemistry and source of ore fluids for orogenic gold deposits is reviewed extensively by Ridley and Diamond (2000). They point out that careful scrutiny of fluid inclusion data from deposits of this style leads to the unequivocal conclusion that the deposits were formed from low-salinity, mixed aqueous-carbonic fluids, which are different from those depositing all other major groups of gold deposits (e.g., epithermal, porphyry Cu-Au, volcanic-hosted massive sulfide), although individual deposits may provide exceptions. The fact that broadly synmetamorphic deposits occur in amphibolite-facies domains (Ridley et al., 2000) indicates that the ore fluid must be derived from at least the depth represented by peak metamorphism, and, hence, a deep source for the fluid is generally accepted. However, despite the extensive stable and radiogenic isotope database available on both ore-related minerals and fluid inclusions, there is no consensus on the source of this fluid. Ridley and Diamond (2000) demonstrated that this is not surprising, given the long fluid pathways and the siting and availability in different wall rocks with variable elemental (e.g., K/Rb) or isotopic ratios. Ridley and Diamond (2000) pointed out that certain elements that dominate the ore fluids, such as N, Br, Cl, C, and H, have isotopic charactistics that may be useful in constraining the fluid source. However, they also emphasized that H isotopes appear prone to resetting, the deeper crustal chemistry of N, Br, and Cl is poorly known, and earlier-formed reservoirs of C in the form of graphite or carbonate alteration along fluid conduits may alter isotopic ratios.

Available fluid inclusion, geochemical, and isotopic data cannot unequivocally distinguish between a metamorphic and deep-magmatic source for the ore fluids in orogenic gold systems. A deep magmatic source is feasible, given the modeling by Cline and Bodnar (1991), which demonstrates that salinity of magmatic fluids is strongly dependent on pressure, with the existence of mixed aqueous-carbonic magmatic fluids possible above about 3 kbars. However, the mechanism of release of such fluids, given the high degree of magma crystallization prior to water saturation at these pressures (e.g., Burnham, 1979), is unresolved. In addition, unless the considered source is specifically a broad zone of deep-crustal melting, the recognized intrusion bodies are too limited in extent in many gold provinces to be the source of the required voluminous fluid flow and high gold tonnage.

Outstanding problems

For orogenic gold deposits, a major outstanding problem relates to the timing of mineralization, as this also affects other components of genetic models, including the potential source(s) of ore fluid and the architecture of crustal-scale flow systems at the time of gold mineralization. The unequivocal absolute age of deposits remains poorly established in many cases, due, at least in part, to the common absence of readily datable and robust ore-related minerals with sufficiently elevated closure temperatures (e.g., Kerrich and Cassidy, 1994). The structural timing (age of mineralization relative to host structures) of some deposits, especially those hosted in rocks of amphibolite and higher metamorphic grades, remains equivocal, owing to the difficulty in distinguishing those formed during shear-zone movements from those overprinted by shear zones (e.g., Robert and Poulsen, 2001). The question of the age of mineralization is further complicated by the existence of several generations of gold deposits with orogenic characteristics in a number of districts, including Val d'Or, Canada (Couture et al., 1994), Kalgoorlie, Australia (Clout et al., 1990), and Muruntau, Uzbekistan (Kempe et al., 2001; Yakubchuk et al., 2002).

No single model for the fluid and metal sources explains all observations from the orogenic gold deposits. Metamorphic Au-transporting fluids derived from deeper levels of the ore-hosting volcanosedimentary or sedimentary rock-dominant terranes are favored by some authors (e.g., Powell et al., 1991; Stüwe, 1998), whereas others favor an even deeper metamorphic source such as subducted oceanic crust or the residue of its previous melting (e.g., Fyfe and Kerrich, 1985). The alternative of a deep (distal) magmatic source also remains open (Ridley and Diamond, 2000). The lack of any known granitoid intrusions in the Otago orogenic gold province of South Island, New Zealand (Henley et al., 1976; Craw et al., 1995), provides an argument for a metamorphic source in deeply underthrusted rocks, if a single source is invoked for these deposits. The occurrence of several gold mineralization episodes in the same region (e.g., Val d'Or, Kalgoorlie) also suggests that simple metamorphism of hosting belts or basins is an unlikely source for the fluids in all episodes. However, the exact mechanisms, if any, for fluid release from subducted or subcreted oceanic crust are unknown, and this remains a major barrier to acceptance of these as an ore fluid source. Similarly, the source of gold remains controversial, with some workers suggesting a required crustal preconcentration (Bierlein et al., 1998), and others discounting the need for such in lieu of an effective regime for extraction of gold from common crustal lithologies (e.g., Fyfe and Kerrich, 1984). In the latter case, pyrite in marine sedimentary rocks and in greenstones is a likely leachable source mineral with high background concentrations of gold. Similarly, radiogenic isotope studies at Muruntau suggest that elements in scheelite and, by association, the gold itself, were derived from the Paleozoic metasedimentary host-rock sequences (Kempe et al., 2001).

A somewhat related problem concerns the distinction between hypozonal orogenic gold deposits, in the sense of Groves et al. (1998), and magmatic-related skarns, in the sense of Mueller (1991), in the amphibolite-facies terranes of Western Australia. Although described as intrusion-related gold deposits developed in a continental margin setting (Mueller and McNaughton, 2000), these controversial gold deposits are different from the intrusion-related deposits that are discussed below. Skarns, in the sense of Mueller (1991), represent deposits formed at deep crustal levels (>10 km), whereas most intrusion-related deposits, as defined by Lang et al. (2000), are interpreted to form at relatively shallow crustal levels (<7 km).

A major unknown in the architecture of the fluid plumbing systems is the role that the crustal-scale deformation zones play in fluid advection to middle and upper crustal levels. Gold deposits are commonly, although not exclusively, in second- or third-order structures that were probably connected to the first-order structures at the time of gold mineralization. However, the precise fluid-flow paths in the systems are not well understood, nor is how the fluid evolved as it passed from one part of the system to another, although some progress is being made (e.g., Cox, 1999; Lonergan et al., 1999; Neumayr et al., 2000, Neumayr and Hagemann, 2002). The inclination of permeable faults and shear zones relative to the regional hydraulic head gradient appears to be an extremely critical control on the focusing of gold-bearing fluids (Cox et al., 2001).

The dominance of one specific depositional mechanism for gold (e.g., desulfidation, pH change, phase separation, or back mixing) over all other mechanisms, particularly in high-grade vein deposits and at different crustal levels, is also not always clear. The role of As-, Sb-, and Te-bearing ligands in gold transport requires more investigation (Wood and Samson, 1998), particularly because initial research on Bi-Au systems shows liquid bismuth to be a viable complexing agent in relatively S poor systems and during Au-undersaturated conditions (Douglas et al., 2000). Whereas it has long been suggested that carbonaceous material within metamorphic belts may be important for destabilizing gold complexes, Bierlein et al. (2001b) suggested that such material may not be important in depositing gold locally, as indicated by the poor correlation between high gold grades and carbonaceous rocks at the deposit scale in the Victorian gold fields.

On a larger scale, the precise tectonic settings in which orogenic gold provinces formed, particularly those containing giant deposits, require better resolution. Evidence suggests that orogenic gold deposits may form at times of change in plate motion (e.g., Goldfarb et al., 1991), in environments where there were anomalous plate configurations, such as, for example, subduction reversals (e.g., Wyman et al., 1999), and/or where there were anomalous thermal conditions related to upwelling asthenosphere (e.g., Kerrich et al., 2000; Goldfarb et al., 2001).

Intrusion-Related Gold Deposits: A Coherent Group?

Hypothesized connections between hydrothermal ore deposits and granitoid intrusions have always been widely argued. There is now almost universal acceptance that porphyry Cu-Mo or Cu-Au deposits (e.g., Sillitoe, 1997), associated high-sulfidation Ag-Au epithermal deposits (e.g., Hedenquist and Lowenstern, 1994), and Au-bearing skarns (e.g., Meinert, 1993) are genetically related to adjacent porphyry intrusions. Other gold-bearing hydrothermal deposits are more controversial. The orogenic gold deposits are classic examples in which there is a broad spatial and, in places, temporal connection to regional granitoid magmatism (Groves et al., 1998; Goldfarb et al., 2001), but rarely a specific and proximal relationship to a given intrusion or intrusive suite.

During the past decade, there has been renewed emphasis on diversity in deposit styles within provinces containing orogenic gold deposits (e.g., Robert and Poulsen, 1997), with emphasis on intrusion-related gold deposits and their potential misclassification as orogenic gold deposits (e.g., Sillitoe and Thompson, 1998). Sillitoe (1991) described intrusion-related gold deposits as being mainly restricted to accreted terranes in Phanerozoic convergent plate margins, spatially associated with porphyry Mo or Cu-Mo mineralization, related to magnetite-series I-type intrusions, characterized by an As-Bi-Te geochemical signature, and having formed from magmatic and/or meteoric fluids. Sillitoe (1991) grouped these deposits into five distinct classes: (1) stockworks and disseminated ores in porphyritic (e.g., Lepanto, OK Tedi, Boddington) and nonporphyritic (e.g., Zortman-Landusky, Salave, Gilt Edge, Kori Kollo) intrusions; (2) skarns (e.g., Fortitude, McCoy, Nickel Plate, Red Dome) and replacement ores (e.g., Barney's Canyon, Ketza River, Yanicocha) in carbonate rocks; (3) stockworks, disseminated ores, and replacement bodies in country rocks to intrusions (e.g., Porgera, Muruntau, Mount Morgan, Quesnel River); (4) breccia pipes in country rocks (e.g., Montana Tunnels-Golden Sunlight, Kidston, Chadbourne); and (5) mesothermal and low-sulfidation epithermal veins in intrusions and country rocks (e.g., Charters Towers, Jiaodong Peninsula, Majara; see Sillitoe, 1991, for references to deposits). The classes obviously reflect many different types of gold deposits that are suggested to show a relatively local, spatial zonation within and surrounding a causative pluton. With some exceptions (e.g., Muruntau, Charters Towers, Jiaodong), there is little debate that most of these gold deposits are genetically associated with a well defined igneous body and are, thus, well classified as intrusion-related deposits.

Sillitoe and Thompson (1998) noted it is Sillitoe's (1991) class 5 of intrusion-related gold vein deposits that may have many characteristics identical to orogenic gold deposits. Of five geochemical associations that they identify within this class of vein-type deposits, only the deposits with the Au-Te-Pb-Zn-Cu (e.g., Charters Towers, Linglong, Dongping) and Au-As-Bi-Sb (e.g., Ryan lode) associations have features resembling, and potentially confused with, orogenic gold deposits. Subsequent overview descriptions of the intrusion-related gold deposit group (e.g., Thompson et al., 1999; Thompson and Newberry, 2000; Lang et al., 2000; Lang and Baker, 2001) concentrate on the Au-As-Bi-Sb group of Sillitoe and Thompson (1998), although deposits that would never be classed as orogenic gold deposits based on the definition of Groves et al. (1998; e.g., Salave, Spain; Kidston, Queensland, Australia; and those of the Bolivian polymetallic belt) are also discussed in the overviews.

Most descriptions of intrusion-related gold deposits, as viewed here, are not representative of a single, well defined group, but rather of a number of different deposit styles with different tectonic settings, metal associations, and ore fluids placed under a single umbrella term. For example, Wall (2000) suggested that the environment above large plutons (roof zone) is prospective for gold mineralization, due to the presence of thermal, fluid, and geochemical gradients and fluxes, as well as preexisting structures related to pluton emplacement. However, this concept, which has been argued to accommodate a diverse group of Archean, Proterozoic, and Phanerozoic gold deposits (including Fort Knox, Sukhoi Log, Pogo, Calie (Tanami), Muruntau, Telfer, and Kumtor), is genetically unconstrained. Deposits can form from circulating meteoric or connate fluids, fluids produced by thermal devolatilization within the aureole, or from those exsolved from a magma. As such, the pluton serves as the heat engine, but fluids, metals, ligands, etc., may be derived from the pluton, the aureole, or more distal environments.

Those deposits that occur in broadly similar tectonometamorphic settings to orogenic gold deposits, and have features that make distinction between the two deposit types equivocal, are discussed below. Into this category could also be added the potentially intrusion related gold deposits of the Pine Creek district, Northern Territory, Australia, including Cosmo Howley (e.g., Matthai et al., 1995), the syenite-associated gold deposits of the Abitibi belt, Canada (e.g., Robert, 2001), and possibly the Telfer gold deposits of Western Australia (e.g., Goellnicht et al., 1989; Rowins et al., 1997). However, recent $^{40}Ar/^{39}Ar$ geochronology in the Tanami region of

Northern Territory indicates an approximately 100 m.y. difference between magmatism and mineralization (Wygralak and Mernagh, 2001), such that lode gold deposits in this part of northern Australia no longer can be considered to best fit an intrusion-related model.

Distinction from orogenic gold deposits

In perhaps the clearest refinement of their defining characteristics, Lang et al. (2000), utilizing the studies of Sillitoe (1991), Newberry et al. (1995), McCoy et al. (1997), and Thompson et al. (1999), among others, summarized the major characteristics of intrusion-related gold deposits as an association of gold mineralization with the following: (1) metaluminous, subalkalic intrusions of intermediate to felsic composition, that span the boundary between ilmenite and magnetite series; (2) CO_2-bearing hydrothermal fluids; (3) a metal assemblage that variably includes Au with anomalous Bi, W, As, Mo, Te, and/or Sb, and typically has noneconomic base-metal concentrations; (4) comparatively restricted zones of hydrothermal alteration within granitoids; (5) a continental tectonic setting well inboard of inferred or recognized convergent plate boundaries; and (6) a location in magmatic provinces best or formerly known for W and/or Sn deposits. Lang et al. (2000) indicated that the most characteristic style of deposit is an intrusion- or hornfels-hosted, sheeted array of low-sulfide quartz veins with narrow alteration envelopes (Figs. 4A and 5A), but other styles occur and are commonly zoned surrounding the intrusions (Hart et al., 2000). Examples might include the base metal-bearing Keno Hill silver deposits and similar veins that are typically distal to many of the gold prospects in the Yukon part of the Tintina gold province. The deposits of the Pine Creek, Tanami, and Telfer districts of northern Australia broadly fit these criteria, although none are actually hosted in the associated granitoids. The syenite-associated group of deposits of Robert (2001) clearly does not fit the above category, but might represent a distinct, yet related, style of intrusion-related deposit in Archean greenstone belts.

In terms of the first four criteria above, there is clearly the potential for misclassifications between intrusion-related deposits and orogenic gold deposits that are sited in small granitic bodies due to their competency contrast with surrounding, less rigid, supracrustal rocks (e.g., Ojala et al., 1993; Groves et al., 2000). Perhaps the most useful distinctions are the last two criteria, which relate to the setting of the intrusion-related deposits distal to subduction zones, commonly in carbonate rock-bearing shelf environments, rather than in turbidite-dominated accreted terranes seaward of old cratonic margins. For example, the intrusion-related gold deposits of the Tintina gold province in Yukon occur in the Selwyn basin, part of the Neoproterozoic-early Paleozoic rifted margin of western North America, an area well recognized for its large, W-bearing skarn deposits. Many gold deposits and small tungsten skarns surround the same plutons that were emplaced in mid-Cretaceous times into the miogeoclinal strata (Hart et al., 2000, 2002). However, these two criteria are not easily established for many gold belts or districts, as the required knowledge of the overall tectonic setting of an area, particularly for Paleozoic and older environments, is typically complex and controversial.

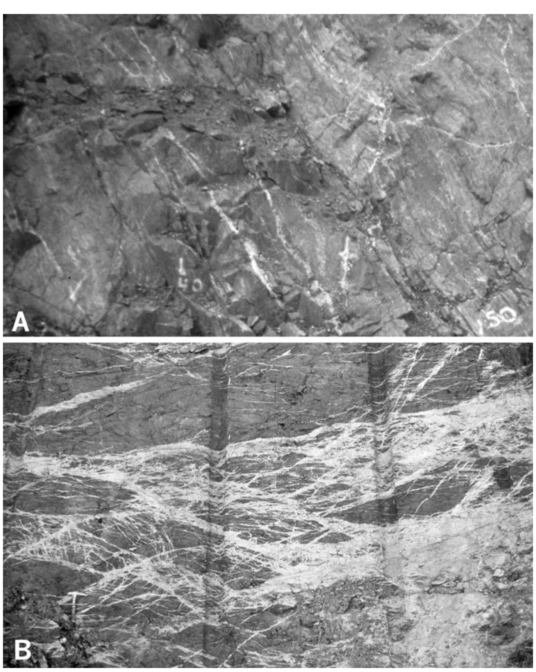

FIG. 4. Photographs showing difference in mineralization style between the following: A. the Fort Knox intrusion-related deposit, Alaska, comprising largely steeply dipping sheeted veins in granitoid with limited visible wall-rock alteration, and B. the Granny Smith orogenic gold deposit, Western Australia, comprising gently dipping conjugate-vein sets with intense bleaching of the host granitoid.

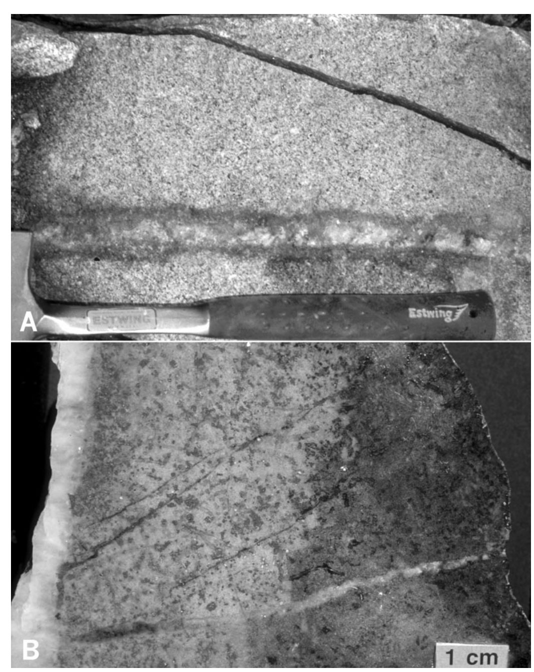

FIG. 5. Close-up of veins showing contrasts in alteration between the following: A. a sheeted vein in granitoid, with limited alteration, from the Fort Knox intrusion-related gold deposit, Alaska, and B. a sheeted vein in dolerite, with associated intensive alteration, from the Mount Charlotte deposit, Kalgoorlie, Western Australia.

An additional criterion for discriminating between orogenic and intrusion-related deposits is the timing of mineralization relative to penetrative deformation of the host rocks, even where both deposits are structurally controlled. In the case of orogenic gold deposits, as indicated above, mineralization is synchronous with, or postdates, the development of penetrative (ductile) structures such as shear zones and folds, and regional penetrative fabrics (typically during D_2 and/or D_3 of a D_1–D_4 district evolution). In the case of many intrusion-related deposits, certainly including those in Alaska and Yukon (e.g., Hart et al., 2002), the mineralization is younger than the penetrative, gneissic fabrics of the host rocks, as indicated by the fact that associated and mineralized intrusions cut penetratively deformed host rocks. Yet, in other cases, such as the syenite-associated gold deposits in the Abitibi greenstone belt, the deposits are overprinted by penetrative fabrics (Robert, 2001). This relatively early timing is clearly different from that of the syntectonic orogenic gold deposits in the area. Similar to the syenite-associated deposits of the Abitibi belt, the magmatism and Early to Middle Triassic mineralization at Timbarra are interpreted by Mustard (2001) to be overprinted by later deformation of the New England orogen.

Current knowledge

The defining characteristics of the intrusion-related gold deposit model are still being established because these systems have only been suggested as a distinct mineral deposit type within the last five years. If only those deposits that are Au dominant and base metal poor are considered, some generalizations can be made. The deposits placed in this group by Sillitoe and Thompson (1998), Thompson et al. (1999), Lang et al. (2000), and Thompson and Newberry (2000) are exclusively Phanerozoic. They are typically defined as situated near craton margins in magmatic provinces that are distal to active convergent plate margins, explaining their overlap with Sn-W provinces that tend to lie inboard of porphyry and epithermal provinces in arc and back-arc settings (Mitchell and Garson, 1981; Sawkins, 1984).

Whereas the intrusion-related gold deposits are certainly not recognized in accretionary prisms, some deposits assigned to this class are associated with subduction-related magmas emplaced after accretion within allochthonous terranes located only a few hundred kilometers inland from an active Phanerozoic continental margin. Deposits such as Timbarra in the New England fold belt of eastern Australia (Mustard, 2001) and those of the Tian Shan in central Asia (e.g., Muruntau: Sillitoe, 1991; Jilau: Cole et al., 2000) are such examples, according to some workers. These gold-hosting tectonic settings are clearly part of the deformed continental margin and not part of older cratons; gold ores are formed within rocks added during the same orogeny and not within rocks of the pre-accretionary continent. Similarly, two deposits, most commonly defined as intrusion-related within the Bohemian Massif (e.g., Mokrsko and Petrackhova hora; Zacharias et al., 2001), were also emplaced in an actively deforming collisional environment during the 360 to 320 Ma Variscan orogeny (e.g., Cliff and Moravek, 1995). All the above tectonic settings for the ores also characterize many undoubted orogenic gold deposits and, therefore, there is a clear spatial overlap that further hinders easy distinction between the deposit groups.

The tectonic settings of the older Pine Creek and Telfer gold provinces are equivocal, but there is overlap with Sn- or W-bearing deposits that suggests a setting inboard of the magmatic arc. The syenite-associated, and potentially other-intrusion related deposits in Archean metamorphic belts, would have formed in quite a different setting, such as, for example, during syndeformational sedimentation in a primitive back-arc setting, with no significant Sn or W mineralization.

The regional-scale structural controls on the proposed ore-related granitoids and associated deposits are not well understood. In the Tintina gold province (Alaska, United States, and Yukon, Canada), some of the deposits in the Yukon lie within 10 km of the crustal-scale Tintina fault, but at least part of the movement on this structure is postgold mineralization (Flanigan et al., 2000). Where the offset part of the magmatic belt continues into eastern Alaska, plutons and associated mineralization (e.g., Fort Knox) could be controlled by high-angle, northeast-trending, second-order faults between the Tintina and Denali regional faults (Newberry, 2000). In the Telfer province, the deposits align along what is interpreted to be a major basement structure (Rowins et al., 1997), and several of the larger deposits in the Pine Creek province lie along the crustal-scale Pine Creek shear zone (e.g., Partington and McNaughton, 1997). Although Robert (2001) documented an early timing for the syenite-associated deposits in the Abitibi belt, they are nevertheless closely associated with the crustal-scale deformation zones (breaks) that also controlled Timiskaming sedimentation and the gross distribution of later orogenic gold deposits.

The intrusions that are associated with these deposits, if considered on a global scale, show extreme variation, with most being I type, although some with more evolved phases have some S-type characteristics (e.g., Donlin Creek, Alaska; Goldfarb, unpub. data). McCoy et al. (1997) and Rombach and Newberry (2001) emphasized the reduced nature of intrusion-related gold deposits in Alaska, noting that, in more oxidized magmatic systems, magnetite tends to remove Au that would otherwise concentrate in the volatile phase from the melt. Lang et al. (2000) recorded that granodiorites to granites of metaluminous subalkalic intrusions, with oxidation states intermediate between magnetite- and ilmenite-series granitoids, are important in the Tintina gold province, but note that intrusions at Timbarra in New South Wales are more highly oxidized. The oxidized syenites from the Abitibi belt also contrast markedly with the host intrusions in the Tintina province, to a large degree reflecting a very different tectonic setting. In fact, Robert (2001) noted that magnetite is common within the gold ores. Similarly, many of the gold deposits along the northern margin of the North China craton, also interpreted by some authors as intrusion-related (e.g., Dongping: Sillitoe and Thompson, 1998; Niuxinshan: Yao et al., 1999), are associated with highly oxidized mineral assemblages. Granitoids in the Telfer region include both ilmenite and magnetite series, with the latter considered to be more closely related to gold mineralization (e.g., Goellnicht et al., 1989, 1991). In the Pine Creek region, granitoids belong to a peraluminous magnetite to ilmenite series (Klominsky et al., 1996). In both regions, the granitoids have high levels of heat-producing elements. The broad range in inferred melt f_{O_2} indicates that, if indeed all these deposits are taken as parts of a coherent gold deposit class, then oxidation state is not a critical factor in determining whether Au was present or absent within fluids exsolving from granitic melts.

At the deposit scale, there is variable structural control on intrusion-related gold mineralization (Fig. 2C). Within host intrusions, mineralization commonly occurs as sheeted veins (Figs. 4A and 5A), typically extensional, rather than shear veins. However, disseminated (e.g., Brewery Creek, Yukon: Hart et al., 2000; Timbarra, New South Wales: Mustard, 2001) and/or stockwork styles of mineralization (e.g., Donlin Creek, Alaska: Ebert et al., 2000; Shotgun: Rombach and Newberry, 2001) may be present at some deposits. Wall-rock alteration surrounding the sheeted vein systems of intrusion-related gold deposits is limited in intensity and distribution, relative to that associated with most orogenic gold deposits that are intrusion hosted (compare Figs. 4A and 5A with 4B and 5B). Rombach and Newberry (2001) suggested that porphyry-style stockworks systems are characteristic of the intrusion-related gold systems emplaced at shallow levels (<0.5 kbars). Country rocks, as well as dikes and sills related to the larger granitoid intrusions, may also contain both gently to steeply dipping sheeted veins or vein sets, as well as disseminated gold. In Proterozoic examples (Telfer and Pine Creek), saddle reefs and/or other bedding-parallel veins formed in sedimentary host rocks. In carbonate host rocks, skarns may be developed. Apart from the typical high-level skarns, many of these mineralization styles are similar to those ascribed to orogenic gold deposits. The Pogo deposit in eastern Alaska, defined as an intrusion-related gold deposit by Smith et al. (1999), in particular, contains quartz lodes with characteristics typical of a classic, shear zone-hosted, orogenic gold deposit.

In most cases, mineralization is approximately coeval with host or associated intrusions. At Clear Creek, Yukon, in the Tintina gold province, Ar-Ar ages of hydrothermal mica of 91 and 90 Ma are essentially identical to U-Pb ages of 92 to 91 Ma for the host stocks (Marsh et al., 2003). Similarly, Re-Os ages from hydrothermal molybdenite at the Fort Knox deposit in the Alaskan part of the belt overlap ages of granitoid crystallization (Hart et al., 2001; Selby et al., 2002). Overlapping ages also characterize ores and host rocks at the Petrackhova hora deposit in the Bohemian Massif, where Re-Os dating of molybdenite from a sheeted gold-bearing vein yields an age of 342 ± 1.5 Ma and the Rb-Sr whole-rock age on the host granodiorite is 348 ± 23 Ma (Zacharias et al., 2001).

Fluid inclusion data (McCoy et al, 1997; Cole et al., 2000; Baker and Lang, 2001; Zacharias et al., 2001) typically indicate that low-salinity H_2O-CO_2 ± CH_4 ± N_2 fluids formed the intrusion-related gold deposits, just as low-salinity fluids were responsible for most orogenic gold deposits (e.g., Ridley and Diamond, 2000). However, at least one fluid population of aqueous brines is reported from the intrusion-related gold deposits in the Yukon (e.g., Baker and Lang, 2001; Marsh et al., 2003), and at the Tennant Creek (Zaw et al., 1994), Shotgun (Rombach and Newberry, 2001), and Petrackhova hora (Zacharias et al., 2001) deposits. This may partly account for the high Cu concentrations in the latter three examples. Pressure and temperature estimates for intrusion-related gold deposits are similar to those of epizonal to hypozonal orogenic deposits, with ranges stated to be less than 0.5 kbars and 200°C to greater than 3 kbars and 600°C, as reviewed by Lang and Baker (2001).

Outstanding problems

A major problem with the recognition of the intrusion-related gold deposits, as defined by Sillitoe and Thompson (1998), is the diversity of tectonic settings, metal associations, wall-rock alteration, and fluid chemistry, among other parameters. Even within the gold-dominant, Au ± Bi ± W ± As ± Mo ± Te ± Sb association of Lang et al. (2000), there is a considerable diversity of deposit characteristics that are typically ascribed to variations in depth, host rocks, or distance from a causative pluton (Hart et al., 2002). If the intrusion-related deposits of the Pine Creek and Telfer districts are included, as well as the syenite-associated deposits of Robert (2001), the range of possible tectonic settings and associated intrusion types, alone, is very large.

Models for intrusion-related deposits typically stress their distinction from orogenic gold deposits based on a distribution of gold ores surrounding a causative pluton. However, in many cases, unequivocal supporting data to confirm the genetic link between mineralization and the host or spatially associated intrusion may not exist. Classifying a deposit as intrusion related based upon its geochemical signature may not be satisfactory, because all the elements in association with Au in such deposits may also be anomalous in orogenic gold deposits and, thus, none are specific to magmatic systems (Goldfarb et al., 2000). For example, the elements W, Bi, and Te are commonly regarded as critical pathfinders for the intrusion-related gold systems (e.g., Lang et al., 2000). Yet, within the class of orogenic gold deposits, the following are true: (1) W in the Otago gold fields (South Island, New Zealand) has been mined from many of the lodes (Paterson, 1977), where there are no granitoids (Henley et al., 1976); (2) Bi and Te are highly anomalous in the Ouro Preto ores of the Quadrilatero Ferrifero, Brazil, also without any spatially associated granitoids (Chauvet et al., 2001); (3) a Bi-Te-W signature, with as much as 470 ppm Bi, is recognized at the Beaver Dam turbidite-hosted gold deposit in the Meguma terrane (Nova Scotia, Canada; Smith and Kontak, 1988); (4) all three elements are highly anomalous at the Independence deposit (Willow Creek district, Alaska) within veins that cut a batholith emplaced 10 m.y. prior to hydrothermal activity (e.g., as much as 150 ppm Bi and 62 ppm Te; Madden-McGuire et al., 1989); and (5) Bi-bearing telluride minerals commonly occur in the giant Golden Mile deposit at Kalgoorlie (Western Australia). It is most likely that the common association of these elements, as well as Sb, As, and Au, simply results from their high degree of mobility within moderate-temperature, low-salinity, CO_2- and H_2S-bearing crustal fluids. This nonspecific association may also reflect some degree of crustal inheritance, which has led to repeated anomalous concentrations of specific elements in diverse types and ages of ore deposits in certain regions (e.g., Titley, 2001).

Similarly, the geochronological evidence presented for the synchronicity of intrusions and mineralization is not unique to intrusion-related gold deposits. As stated above, orogenic gold deposits and granitoids are spatially and temporally associated in the majority of the orogenic gold provinces. Well constrained geochronology from the southern Alaskan accretionary prism, for example, shows that spatially associated Eocene flysch-melt granitoids and orogenic gold deposits formed at the same time along the 2,000-km strike length of the belt (Haeussler et al., 1995). Therefore, the presence of gold and widespread granitoids of the same age in the same belt cannot be used as a criterion to identify intrusion-related gold systems. In fact, workers have even suggested such an association to indicate a granitoid-gold connection between the Otago gold fields and the major, roughly coeval Fiordland batholith that is exposed more than 200 km to the west (deRonde et al., 2000). However, it remains speculative as to whether this magmatic arc continues at depth to the east and, thus, could underlie the gold lodes. Deposits in the Pataz province in Peru were classified as intrusion related in recent models (e.g., Sillitoe and Thompson, 1998), but new geochronology has shown that the ores postdate the host batholith by about 15 m.y. and make such a genetic link unlikely (Moritz, 2000; Haeberlin, 2002).

One outstanding problem deserving particular study is the structural timing of intrusion-related deposits, which is to say their timing relative to the development of penetrative structures of the host rocks and the timing of mineralization relative to the tectonic evolution of the gold district. This aspect of intrusion-related deposits has yet to be studied adequately. As pointed out above, unequivocal orogenic deposits can be demonstrated to have formed in structures produced or reactivated during regional compressional or transpressional deformation. In contrast, it seems that many intrusion-related deposits have formed tens of millions of years after the penetrative fabrics of their host rocks and after the main compressional/transpressional stage in the evolution of the district (e.g., Yukon part of the Tintina province; Poulsen et al., 1997). However, other deposits that are considered to be intrusion related (e.g., Tower Hill of the Leonora area, Western Australia; Witt, 2001) are interpreted to predate much of the regional deformation and to have formed much earlier than orogenic gold deposits hosted in younger sequences within the same metallogenic province.

Paleodepth estimates for formation of the intrusion-related gold systems (see figure 6 in Lang et al., 2000) indicate pressures below those at which granitic magmas are likely to exsolve CO_2-rich fluids (i.e., >3 kbars; Eggler and Kadik, 1979; Cline and Bodnar, 1991). Lang et al. (2000) compared their data with those of Nabelek and Ternes (1996) from the Haney Peak Granite, but the fluids described by the latter exsolved at pressures of about 3.5 kbars, much greater than those expected at <7-km depths. In almost all cases, the intrusion-related gold ores cut the granitoids, suggesting that CO_2-bearing ore fluids escaped from deeper, still-uncrystallized parts of an evolving magmatic system, if indeed they are magmatic in origin.

A major problem in all provinces containing intrusion-related gold deposits, therefore, is a mechanism for the exsolution of carbonic fluids from the magmas at the depths depicted in the deposit models. Most models from the better studied intrusion-related gold systems show that ore deposition occurs late in the history of the local magmatic-hydrothermal system and at epizonal crustal levels. Yet, at such shallow crustal levels, volatile saturation typically should take place early in the crystallization history of the causative melts (Candela, 1997) and is likely to be characterized by $H_2O >> CO_2$ during emplacement of the more fractionated intrusions (Lowenstern, 2001). Baker (2002), using relationships shown in Lowenstern (see figure 5 of Lowenstern, 2001), argues, however, that significant amounts of CO_2 in many intrusion-related gold systems may have exsolved throughout the ascent of a magma from its source region.

An additional concern is that some proposed intrusion-related gold-system fluids evolve from low salinity to high salinity (e.g., Baker and Lang, 2001), whereas the opposite is recorded for other intrusion-related deposits (e.g., Zacharias et al., 2001). The controls on these changing fluid compositions, and what they mean for related gold tonnages, are poorly understood. A problem specific to the syenite-associated deposits is why they are restricted to provinces in which there are undoubted orogenic gold deposits, some of which are hosted by syenites (e.g., Duuring et al., 2000). If they are magmatic-hydrothermal deposits, then at least anomalous gold concentrations should be characteristic of syenites in other settings, such as, for example, intracratonic environments, where orogenic gold deposits are absent. Finally, it is important to determine the potential of intrusion-related gold deposits as high-grade exploration targets. Where hosted by granitoids, or immediately adjacent rocks, they are typically bulk-tonnage ores with grades below about 1 g/t Au (cf. other magmatic deposits such as porphyry-style systems with similar grades), with Pogo (eastern Alaska), if indeed it is correctly classified as intrusion related, being a possible exception. However, it is noteworthy that the Pogo deposit is located further seaward than the other intrusion-related gold lodes of the Tintina province and distal to any recognized Sn-W province.

Gold Deposits with Atypical Metal Associations: Where Do They Fit?

Definition and contrasts with orogenic gold deposits

A number of enigmatic, gold-bearing deposits occur in provinces dominated by orogenic gold deposits. Broadly, these deposits fall into two groups, those enriched in Cu ± Mo (e.g., McIntyre-Timmins, Canada; Boddington, Australia) and those enriched in Cu-Zn ± Pb ± Ag and/or abundant pyrite (e.g., Bousquet, Canada; Mount Gibson, Australia; several deposits in Tanzania and Kenya, such as Bulyanhulu and Macalder, respectively; Carolina slate belt, USA; a few deposits of the Mount Read volcanic massive sulfide province, Australia), as well as those elements more normally associated with orogenic gold deposits (e.g., As, B, Bi, Sb, Te, W). The Hemlo deposit, Canada, with its anomalous enrichment in Ba, Mo, and Hg, among other elements, does not fall neatly into either group. Collectively, these deposits are the source of much controversy, with three main model types proposed for their genesis: (1) deformed and metamorphosed Au-rich porphyry to epithermal or volcanic-hosted massive sulfide deposits, (2) porphyry or volcanic-hosted massive sulfide deposits in which Au has been mobilized during deformation and metamorphism, or (3) porphyry or volcanic-hosted massive sulfide deposits that have been overprinted by orogenic gold systems later in the history of the orogen.

The superimposition of two contrasting ore-deposit styles may seem fortuitous, but is to be expected, given that structures controlling the location of early mineralization may be reactivated during subsequent events, and that wall-rock alteration (± massive sulfide minerals) changes the physical properties of rocks, generating new competency contrasts that can be exploited during later hydrothermal activity (e.g., Groves et al., 2000). An excellent example is provided by the coincidence of orogenic gold mineralization and massive Fe-Ni-Cu sulfide ores at the Hunt mine, Kambalda deposit, Western Australia (Phillips and Groves, 1984), and another is the overprint of volcanic-hosted massive sulfide-style mineralization by orogenic gold at the Mount Gibson deposit, Western Australia (Yeats et al., 1996).

It is difficult to generalize about such deposits because there is so much variation in detail between individual examples. For this reason, a few of the better documented systems are very briefly outlined below.

Probable modified porphyry/epithermal systems

The Hollinger-McIntyre deposit at Timmins is arguably the first of this type widely recognized as a potential modified porphyry deposit in studies spanning the last 25 yr. This deposit was the largest producer in Canada (>1,000 t Au), with the bulk of the ore derived from quartz-carbonate veins and a minor proportion from earlier, porphyry-style, disseminated and stockwork Cu-Ag-Au-Mo mineralization, mainly in the Pearl Lake porphyry (e.g., Smith and Kesler, 1985; Burrows et al., 1993). The latter averaged 0.67 percent Cu, 0.59 g/t Au, and 2.93 g/t Ag, with approximately 0.05 percent Mo (Burrows and Spooner, 1986), making it completely unlike orogenic gold deposits, with respect to Cu content and Au/Ag ratio (≈0.2). In addition to sulfide minerals, anhydrite and hematite are present (Burrows and Spooner, 1986). An early timing is suggested by crosscutting dikes that are about 15 m.y. younger than the host porphyry (e.g., Marmont and Corfu, 1989). Overprinting quartz-carbonate vein systems are localized by the Hollinger shear zone, which cuts the Pearl Lake porphyry, with the attitude of gold ore bodies partly controlled by anisotropies created by the rigid porphyry body (Burrows et al., 1993). Their mineralogy, metal associations, and wall-rock alteration are typical of orogenic gold deposits. The wealth of fluid inclusion and stable isotope data on the Hollinger-McIntyre deposit does little to resolve the precise genetic relationships between the quartz-carbonate veins and porphyry styles, but a reasonable interpretation is that a magmatic-hydrothermal Cu-Ag-Au-Mo system was overprinted by an orogenic gold system, in part localized by the rigid Pearl Lake porphyry. The other large deposit of the Timmins district, the Dome deposit, shows a similar overprinting on an early Cu-Au ± Mo system (Gray and Hutchinson, 2001).

The Boddington gold deposit is the second largest gold resource (>800 t Au) in the Yilgarn craton of Western Australia (e.g., Symons et al., 1990). Although mainly exploited to date for its supergene-enriched gold in lateritic regolith, it contains a large hypogene resource, albeit low grade (<1.1 g/t Au). The Cu-Au-Ag-Mo-Bi-W association, stockwork-style veins, and variably saline, low-CO_2 fluid inclusions (Roth, 1992), for at least part of the mineralization, clearly distinguish the deposit from Yilgarn orogenic gold deposits. Combined with the grade-tonnage characteristics, the occurrence of mineralization in and near dioritic intrusions, the dominant amphibole-biotite alteration and amphibole-rich veins, and the maximum mineralization temperatures being higher than peak temperatures of the regional upper-greenschist facies metamorphism, are strong evidence in favor of Boddington being a porphyry-style deposit, specifically of the diorite class, as interpreted by Roth (1992). The detailed structural studies of Allibone et al. (1998), however, cast doubt on the syndiorite formation of the mineralization, and instead place most of the mineralization late in a D_1 to D_4 deformation sequence, in which there were successive generations of veins with different mineralogical compositions. In this model, the timing of mineralization is broadly similar to that of the Yilgarn orogenic gold deposits, but the fluid compositions and temperatures still imply a local magmatic source. The lack of a recognized suitable magmatic source at the time of mineralization, as proposed by Allibone et al. (1998), is a problem, although their data imply that Boddington is another, albeit somewhat different, type of intrusion-related gold deposit. McCuaig et al. (2001) have recently presented a well constrained, two-stage ore genesis model for the Boddington deposit. They define intrusion-related, gold-forming events at ca. 2700 and 2612 Ma, with the latter post-tectonic magmatism responsible for the majority of the ore. It is stressed that, if this interpretation is correct, Boddington would represent the first example of a major Archean Au-Cu intrusion-related deposit that is associated with post-tectonic magmatism. The question remains whether the main mineralization at Boddington postdates the intrusion and it is simply coincidence that the deposit has most of the characteristics of a diorite porphyry Cu-Au-Mo deposit (e.g., Hollister, 1978); whether an original porphyry system has been reactivated, remobilized, and/or overprinted during subsequent orogenic events; or whether Boddington is an exotic example of the broadly defined, intrusion-related group of gold deposits, as suggested by McCuaig et al (2001).

The Hemlo deposit, in the Wawa subprovince of Canada, containing approximately 600 t Au at a grade of >7 g/t Au (Harris, 1989) in three main deposits (Williams, Golden Giant, and David Bell), is an even more contentious deposit, mainly because of the complex magmatic, structural, and metamorphic history of the district (e.g., Muir, 2002). Similar to more poorly understood gold deposits (e.g., Big Bell, Western Australia; Mueller et al., 1996), Hemlo is located in a high-grade metamorphic domain, in this case of mid-amphibolite facies (e.g., Corfu and Muir, 1989b). The metal association of Au-Mo-Sb-As-Hg-V-Tl-Ba, the high Hg and Ag contents of some native gold (e.g., Harris, 1989), and the unusual mineralogy, together with the moderate to high salinities of ore fluids (Pan and Fleet, 1992) and consistently negative $\delta^{34}S$ of ore minerals (Cameron and Hattori, 1985), clearly distinguish this deposit from most orogenic gold deposits. However, the high gold grades, high Au/Ag ratio, and metal association also make correlations with normal porphyry, epithermal, or volcanic-hosted massive sulfide systems equivocal. Potassic and calc-silicate alteration are common, but there is a complex array of alteration styles of both prograde and retrograde timing (Pan and Fleet, 1992). Mineralization is located in the Moose Lake porphyry and an adjacent fragmental unit within a host sequence of metasedimentary rocks, all of which are cut by later calc-alkaline granitoid bodies (Corfu and Muir, 1989a). Four stages of deformation are recognized in the sequence (Michibayashi, 1995; Lin, 2001).

Genetic models for Hemlo have ranged from those involving premetamorphic sea-floor or epithermal systems (Cameron and Hattori, 1985), to pre- to synmetamorphic hydrothermal events (Burk et al., 1986; Kuhns et al., 1986) that perhaps are magmatic in origin (Muir, 2002), to postpeak metamorphic events related to emplacement of granitoid intrusions (Pan and Fleet, 1992), or to mylonite development (Hugon, 1986; Corfu and Muir, 1989b). Recent structural studies (Michibayashi, 1995; Powell and Pattison, 1997; Lin, 2001) support a pre-D_2 and pre-amphibolite facies metamorphism timing for the main mineralization stage, or a pre- to early-D_2 timing, but a robust genetic model has still not been established. Perhaps an analogy in terms of metal association, if the Hemlo ores are premetamorphic, is the submarine epithermal-style mineralization at Conical Seamount, near Lihir Island, Papua New Guinea (Herzig et al., 1999). It is still possible that part of the complexity is due to overprinting of mineralization styles. For example, Michibayashi (1995) argued for second-stage remobilization of gold (plus barite and stibnite) in late shear zones, and Pan and Fleet (1992) suggested that some gold was deposited during late calc-silicate alteration.

Probable modified volcanic-hosted massive sulfide or submarine epithermal systems

The Bousquet group of gold deposits, with a total resource of about 280 t Au and a grade of about 5.35 g/t Au (Marquis, 1990), situated immediately north of the Larder Lake-Cadillac fault (a major break) in the Abitibi belt, Canada, is suggested here as an example of a modified sea-floor gold system. As described by Marquis et al. (1990), Tourigny et al. (1989, 1993), and Robert and Poulsen (1997), the deposits lie in a 500-m wide shear zone within felsic volcaniclastic rocks, and mafic volcanic and volcaniclastic rocks, which are locally intruded by a differentiated gabbro to trondhjemite complex and metamorphosed to greenschist facies. The overall morphology of ore bodies is strongly controlled by fabrics within the shear zone. Ore bodies comprise a variety of styles, including highly deformed massive pyrite (with lesser galena, sphalerite, or chalcopyrite) lenses, various generations of foliation-oblique to foliation-parallel quartz-carbonate-sulfide veins with >25 percent sulfide minerals, and disseminated (5–20% pyrite) mineralization in schistose host rocks. From the nature of the mineralization, particularly the high sulfide content, high Au-Cu correlation, and preshearing and premetamorphic timing for formation of the sulfide minerals, there has been general agreement that the pyrite-rich ore bodies formed during synvolcanic subsea-floor or exhalative processes (e.g., Marquis et al., 1990; Tourigny et al., 1993) with similarities to high-sulfidation epithermal systems (e.g., Poulsen and Hannington, 1996). The major area of controversy concerns whether most of the Au was synvolcanic and remobilized by subsequent events (e.g., Tourigny et al., 1993), or was introduced during the overprinting orogenic gold event that affected the surrounding district (e.g., Marquis et al., 1990). One of these processes must have operated, given the fact that some quartz-sulfide-gold veins cut all fabrics and that some gold is in textural equilibrium with retrograde assemblages (Poulsen and Hannington, 1996).

The Paleoproterozoic Boliden Cu-Au-As deposit, within the 1.9-Ga Skellefte volcanic succession of northern Sweden (Allen et al., 1996; Hannington et al., 1999), is another, somewhat enigmatic deposit. The Boliden deposit consisted of two large, subvertical pyrite lenses enveloping several smaller arsenopyrite-rich lodes surrounded by a narrow aluminous alteration envelope rich in andalusite and quartz. The metal association of the ore was unusual, comprising Cu-Au-As (avg As grade 6.9%) with significant Ag, Bi, and Se. Most of the gold (95%) was contained within fine-grained massive pyrite and arsenopyrite, although bonanza-type gold mineralization was developed locally in arsenopyrite lenses (>200 g/t Au) and large, crosscutting quartz-tourmaline veins (>600 g/t Au). Such deposits could represent orogenic gold overprints, but Bergman Weihed et al. (1996) showed that all ore bodies have been affected by all phases of deformation and by regional metamorphism, and suggested that coarse-grained gold was derived from refractory gold in arsenopyrite during D_1 brecciation. Currently, the Boliden deposit is considered to represent coincident submarine epithermal-style and subsurface replacement-style mineralization developed in a shallow-water environment (Allen et al., 1996).

The latest Proterozoic to earliest Paleozoic gold-rich volcanic-hosted massive sulfide deposits of the Carolina slate belt, southeastern United States, are similarly enigmatic. Deposits such as Ridgeway, Haile, and Brewer are associated with metamorphosed felsic volcanic units, which had previously been altered on the sea floor to propylitic, argillic, and advanced argillic assemblages surrounding pyrite-rich zones with minor base metals, enargite, and arsenopyrite. The gold ores in these massive sulfide bodies could represent sea-floor hot springs or epithermal mineralization superimposed on volcanic-hosted massive sulfide deposits (Worthington et al., 1980; Crowe, 1995; Bierlein and Crowe, 2000). As with many volcanic-hosted massive sulfide deposits, those of the Carolina slate belt occur in accreted terranes also characterized by postaccretionary orogenic lode gold deposits. This has led to suggestions that the larger, low-grade gold resources within the felsic volcanic rock sequences are also later syntectonic orogenic gold deposits related to ductile shear zones (e.g., Tomkinson, 1988; Hayward, 1992). Dating of gold-stage molybdenite in these deposits by Re-Os (Stein et al., 1997), however, indicates that ore formation was pre-accretionary and approximately 200 m.y. prior to deformation and regional metamorphism.

A number of the volcanic-hosted massive sulfide deposits of the Cambrian Mount Read volcanic belt, western Tasmanian, are also anomalous in gold. At the Henty deposit, gold ores in late brittle fractures have been related to remobilization from sea-floor concentrations during Devonian deformation, more than 100 m.y. subsequent to the original volcanic-hosted massive sulfide deformation and prior to emplacement of nearby post-tectonic granitoids (Halley and Roberts, 1997). In contrast, at the Rosebery deposit, Zaw et al. (1999) suggested that fluids exsolved from the post-tectonic Devonian granitoids remobilized gold into auriferous replacement zones. Huston (2001) favors an Ordovician age for the Cu-Au deposits throughout the Mount Lyell district and indicates these may not be modified volcanic-hosted massive sulfide deposits at all, but rather porphyry Cu deposits and associated high-sulfidation epithermal ores.

Even some of the youngest orogens show some evidence of orogenic gold formation that can be related in places to remobilization of the volcanic-hosted massive sulfide deposits during metamorphism and deformation. In the Cordilleran orogen, the very high levels of H_2S in gold-bearing quartz veins of the Sumdum Chief gold deposit at the southern end of the Eocene Juneau gold belt, and in an area of extensive sea-floor sulfide mineralization, suggest that some of the volatiles in the epigenetic ores were derived from syngenetic sources (Goldfarb et al., 1988). At the northern end of the same gold belt, Newberry et al. (1997) used Pb isotope data to show that components from volcanic-hosted massive sulfide deposits were remobilized into veins during the Eocene gold-forming event.

Less equivocal field, textural, and geochronological evidence of overprinting of a weak volcanic-hosted massive sulfide system by an orogenic gold system is recorded at the small Mount Gibson deposit in Western Australia (Yeats et al., 1996). The realization that volcanic-hosted massive sulfide deposits can be overprinted by later orogenic gold systems should initiate reexamination of anomalously Au-rich volcanic-hosted massive sulfide systems in orogenic gold provinces, such as the Horne deposit in the Abitibi belt.

Outstanding problems

Despite considerable research effort, many of these deposits with atypical metal associations remain enigmatic, with little consensus on their affinities and genesis. In many cases, there is a lack of the well integrated, field-based structural, alteration, geochemical, isotopic, and fluid inclusion studies needed to define the total history of the deposits and provide potential mass balances of metal introduction (or removal) or remobilization at each stage of deposit evolution. In almost all cases, there is a lack of knowledge regarding the precise timing constraints on the stages of ore development needed to resolve models, mainly because of the apparent lack of ore-related minerals suitable for dating by robust isotopic techniques. In general, each deposit within this loosely defined group has been studied in isolation, such that there is little recognition of a potential grouping of deposits with specific metal associations, alteration, fluid characteristics, and overprinting relationships. For other deposit styles, the ability to recognize genetically related groups, and to integrate relationships across those groups, has led to more robust deposit and genetic models, but this is lacking in this group of deposits because of the complex and controversial nature of each of the deposits discussed above.

Giant Gold Deposits in Metamorphic Belts

The defining parameters and origins of giant ore deposits of all deposit classes are currently the most important topic for large exploration companies. Studies of giant mineral deposits, in general, reveal that there is no simple explanation for their giant size relative to adjacent deposits in similar settings (e.g., Hodgson et al., 1993). It is more likely that giant deposits form via the conjunction of a number of favorable physical and chemical processes, rather than as a result of special processes (Phillips et al., 1996; Sillitoe, 2000). For example, a study of the distribution of large versus small gold deposits in the Norseman-Wiluna belt of Western Australia, using an empirical approach within a GIS, showed that there are no significant differences in individual parameters. However, only 15 percent of the deposits, containing more than 80 percent of known gold resources, lie in zones of greatest overlap of the critical defining parameters (Groves et al., 2000).

A brief discussion of those gold deposit types that contain significant giant deposits, or even clusters of world-class deposits, is given below, together with a brief overview of those special features that are potential defining parameters of giant deposits. The precise definition of those parameters, however, remains one of the outstanding problems, not only of gold deposits in metamorphic rocks in many of the world's major orogens, but also of mineral deposits of all types globally.

Affiliation of giant gold deposits in metamorphic belts

If 2,500 t Au ($\approx$75 Moz) is taken as the lower resource limit of supergiant gold deposits (e.g., Laznicka, 1999), then it is evident that only the unique Witwatersrand deposits, possibly Muruntau, and perhaps the undeveloped and poorly understood Sukhoi Log deposit, qualify as supergiants, although the Kalgoorlie and Timmins gold fields are close to this limit as districts. A large number of the giant deposits containing $\geq$250 t Au (some as clusters of world-class deposits—e.g., the Mother lode belt) in metamorphic belts are orogenic gold deposits (see Table A1, Appendix). There are also numerous world-class deposits (>100 t Au or 3 Moz) within gold provinces in metamorphic belts worldwide. There are also some giant deposits in the category of deposits with atypical metal associations.

There are no individual, giant intrusion-related gold deposits (unless the classification of Sillitoe, 2000, is used for Muruntau, Boddington, and Hemlo, or the inferred resource at Donlin Creek, Alaska proves to be economic), and the provinces that contain deposits ascribed to this class are generally less well endowed than others (Fig. 3). In fact, there are few world-class deposits of this type, despite the enormous tonnage of some of them, because the ore grade is generally low. Exceptions include Fort Knox and Pogo in the Alaskan side of the Tombstone gold province, if Pogo is indeed an intrusion-related deposit, and perhaps Cosmo-Howley and Telfer in northern Australia. Although debatable, the 27-Moz gold resource of the Jiaodong Peninsula in eastern China is considered by some workers to be an example of a giant intrusion-related gold province (Poulsen et al., 1990; Sillitoe and Thompson, 1998). Only three individual deposits in this cluster of hydrothermal systems, however, fit the world-class category (e.g., Zhou et al, 2002). Within the syenite-associated group of Abitibi belt deposits, only Malartic is world-class; all others are relatively small.

Definition of special features

As shown in Table 2, there are no easily discernable single factors that uniquely define giant gold deposits at the deposit scale within broad belts of metamorphic rocks, as pointed out by Sillitoe (2000) for gold deposits of any type. For example,

TABLE 2. Comparison of Some Giant Orogenic Gold Deposits in Terms of Deposit-Scale Parameters

Giant gold deposits	Major host rock			Major structural control		Metamorphic grade		Granitoids		Fluid oxidation state			Overprinting	
(Oldest to youngest)	m	f	s	Shears	Folds	Green.	Amph.	Prox.	Dist.	Ox.	n	Red.	Strong	Weak
Hollinger-McIntyre	X	X		XX		XX		X	X		XX		XX	
Golden Mile	XX			XX		XX			X	XX			XX	
Morro Velho			XX		XX	XX			X			XX	X	
Kolar	XX			XX			XX	XX			X	X	X	
Ashanti	X		X	XX		X			X			XX	X	
Homestake			XX	X	X	X	X	X	X			XX	XX	
Bendigo			XX		X	X			X			XX	X	
Muruntau			XX	X	X	X	X	X	X		X	X	XX	
Mother Lode	X		X	XX		X	X	X	X		X	X	X	

Note: Listed in order of decreasing age
Certainty of interpretation: XX = very certain, X = less certain
Abbreviations: amph. = amphibolite, dist. = distal, f = felsic, green. = greenschist, m = mafic, n = normal, ox. = oxidized, prox. = proximal, red. = reduced, s = sedimentary

among orogenic gold deposits, parameters such as deposit age, host-rock lithology, structural control, type of spatially associated intrusive rocks, and redox state of the ore fluid are variable. It is perhaps more beneficial to examine the far-field tectonic controls on those gold provinces that contain giant orogenic and other gold deposits, which is to say, examine the problem at a larger scale (Table 3).

It is clear from modern, arc-related mineral deposit types, such as porphyry Cu-Au and epithermal Ag-Au deposits, that the geometry of subduction systems in convergent margin settings is important in controlling the location of giant metallogenic provinces (e.g., Sillitoe, 1997; Kerrich et al., 2000; Kay and Mpodozis, 2001). There are indications that there may be similar tectonic controls on orogenic gold deposits, with Goldfarb et al. (1991) first demonstrating a relationship to changing plate motions in the generation of such deposits in the relatively young accretionary collisional events of southern Alaska. Subsequently, other workers have interpreted structural data to suggest that similar tectonic events controlled formation of some of the oldest orogenic gold deposits (e.g., de Ronde and de Wit, 1994). Wyman et al. (1999) demonstrated that the giant Abitibi gold province probably formed in an environment where subduction reversal occurred, and Kerrich et al. (2000) and Goldfarb et al. (2001) summarized a number of other scenarios where subducted spreading ridges, subduction roll back, and other crustal processes leading to asthenospheric upwelling or crustal thickening, and consequent thermal anomalies, played a key role in the generation of giant orogenic gold provinces in metamorphic belts. Similarly, the presence of komatiites in Archean and Paleoproterozoic belts that contain giant gold provinces signals the interaction of plumes with subduction-related environments, again potentially producing anomalous plate geometries (Dalziel et al., 2000) and thermal anomalies. A challenge is to develop criteria to recognize some of these specific processes in the volcanic and intrusive rock record in terranes where there is only indirect evidence of subduction.

The presence of crustal-scale deformation zones in linear volcanosedimentary belts appears a factor common to most gold provinces containing giant gold deposits of all ages. Such crustal-scale structures also localize porphyry and lamprophyre dike swarms, and commonly juxtapose volcanic and sedimentary sequences. Perhaps most important is that without such structures, it is questionable whether enough fluid

TABLE 3. Comparison of Some Giant Orogenic Gold Deposits in Terms of Province-Scale Parameters

Giant gold deposits	Tectonic setting		Crustal-scale faults		Complexity of geometry		Metamorphic grade		Felsic porphyries/ lamprophyres	
(Oldest to youngest)	Accretion	Collision/ delamin.	Present	Absent	Complex	Simple	Green.	Amph.	Common	Rare
Hollinger-McIntyre	XX		XX		XX		XX		XX	
Golden Mile	X	X	XX		XX		XX		XX	
Morro Velho	XX		X		XX		XX			X
Kolar	X		XX		XX			XX	X	
Ashanti	XX		XX		XX		XX		X	
Homestake	X		X		X		X	X		X
Bendigo	X	X	X		X		XX		X	
Muruntau	X	X	XX		XX		X	X	XX	
Mother Lode	XX		XX		XX		X	X	XX	

Note: Listed in order of decreasing age
Certainty of interpretation: XX = very certain, X = less certain
Abbreviations: amph. = amphibolite, delamin. = delamination, green. = greenschist

can be focused to form a giant gold deposit. Unlike many sedimentary basins and carbonate platforms, where inherent permeability of the rock sequences can favor migration of major fluid volumes, highly deformed, metamorphosed greenstone belts and marine sedimentary sequences will have a low primary permeability and major fluid flow must be along secondary structures (e.g., Jamtveit and Yardley, 1997).

The giant orogenic gold deposits consistently have a complex regional-scale geometry, commonly due to the reactivation or reorientation of complex thrust, commonly duplex, structures (e.g., Timmins, Kalgoorlie, Ashanti), which may juxtapose competent and incompetent segments of lithostratigraphy (Groves et al., 2000). In other cases, the deposits are situated close to the closures of domal structures (e.g., Bendigo) in sequences situated in the hanging wall of sole thrusts in thin-skinned tectonic belts (e.g., Gray, 1997). These controlling geometries are large, complex, and commonly well sealed by relatively incompetent rocks, making them zones of heterogeneous stress that focused fluid flux. Reactivation of suitably oriented structures late in the deformational history of an orogen, commonly during regional uplift and retrograde metamorphism (Groves et al., 1988), appears to be a common factor.

In all cases, complex lithostratigraphy provides paired strength and chemical contrasts that allow very selective failure and consequent fluid flux into chemically reactive rocks (Phillips et al., 1996; Groves et al., 2000). These rocks commonly have high Fe/Fe + Mg (± Ca) ratios (e.g., tholeiitic dolerites or basalts at Kalgoorlie, Timmins, Kolar, and some Mother lode deposits; BIF at Homestake) and/or anomalous carbon contents (e.g., Ashanti), although these may be volumetrically minor (e.g., indicator slates in Victorian gold fields; Bierlein et al., 2001c).

Finally, many giant deposits are the sites of multiple generations of gold mineralization. In this case, the most obvious deposits are those in the category of deposits with atypical metal associations, such as Hemlo and Boddington, where, in all probability, earlier mineralization styles have been overprinted and/or remobilized during later events. The Hollinger-McIntyre system at Timmins also fits into this category. At Kalgoorlie, the Golden Mile lode systems are overprinted by the Oroya and Flat lode systems that, in turn, are overprinted by the Mount Charlotte-style mineralization (Mueller et al., 1988; Clout et al., 1990; Bateman et al. 2001). At Bendigo, early, commonly Au poor, quartz saddle reefs are remineralized by high-grade gold (Cox et al., 1991). A complex series of mineralization styles at Muruntau is also suggestive of multiple, chemically distinct fluid-flow events (Graupner et al., 2001).

Summary of Outstanding Problems for Classification and Genetic Models

Classification

Many authors of recent papers appear to accept the classification of most lode gold deposits in metamorphic belts as orogenic gold deposits (Bouchot and Moritz, 2000; Hagemann and Brown, 2000), although specific examples are controversial (Sillitoe and Thompson, 1998). However, the definition of intrusion-related gold deposits varies between papers and, because this model has been proposed only recently, comprehensive lists of provinces or deposits ascribed to this type are lacking. Most of these deposits are Phanerozoic, but Proterozoic (e.g., Pine Creek, Telfer) and Archean examples (e.g., syenite-associated class of Robert, 2001) may be included in this type. It is probable that there are several subtypes within this class of intrusion-related deposits, and this requires better resolution and classification. The deposits with atypical metal associations are, to some extent, unique. These different deposit types are well classified in the scheme proposed by Poulsen et al. (2000).

Orogenic gold deposits

The major outstanding problems in the understanding of orogenic gold deposits are as follows: (1) the precise timing of many deposits with respect to magmatic, metamorphic, and deformational events in the host terranes; (2) the exact nature and release mechanisms of the deeply sourced ore fluids that dominate these systems; (3) the configuration of the regional, crustal-scale hydrothermal conduits and fluid flow within them; (4) the precise transport and depositional mechanisms, particularly in S-poor systems, where As, Bi, Sb, W, and/or Te may be abundant; and (5) the precise controls on the generation of world-class to giant examples. A specific problem is the distinction between orogenic gold deposits and intrusion-related deposits with similar ore-element associations and ore fluid types in the same metamorphic belts. Another is the distinction between skarns and hypozonal orogenic gold deposits in high metamorphic-grade settings.

Intrusion-related gold deposits

A major problem in the classification of intrusion-related gold deposits is the wide variety of deposits included in this category by different authors. Outstanding problems in the understanding of this deposit type include the following: (1) unequivocal evidence that connects individual deposits to their proposed source intrusions, (2) the large range of granitic compositions and redox states that are ascribed to source intrusions, (3) the mechanism for exsolution of aqueous-carbonic fluids from shallow-level (<7 km deep) granitoids late in the differentiation history of the source magmas, and (4) the structural timing and the structural and tectonic controls on deposit style.

Gold deposits with atypical metal associations

It is difficult to treat these deposits as a group because of their highly diverse characteristics and the complications imparted by the overprinting deformation and metamorphism. For these atypical deposits, major outstanding problems include the following: (1) the possible existence of multiple mineralizing events and their variable importance, (2) the timing of alteration and mineralization relative to their host penetrative structures and to metamorphism, (3) the distinction between local remobilization of gold and introduction of gold during an overprinting hydrothermal event, and (4) the geometry of the deposits and host rocks in the case of severely deformed deposits (e.g., Lin, 2001). Resolution of the nature and origin of these complex deposits requires integration of all geometric, structural, alteration, mineralogical, and geochemical features of the deposits and their host rocks. This will provide the basis for recognizing factors leading to the formation of giant examples of this anomalous group.

Temporal distribution of gold deposits in terms of crustal evolution

Goldfarb et al. (2001) have drawn together all published, robust age data for orogenic gold deposits, to define their global temporal distribution. There are, however, outstanding uncertainties in the age of some large deposits and gold provinces that, particularly in Brazil, Kolar, the Baikal region, and the orogens surrounding the southern Siberian craton, northern Africa, and China, need resolution. Goldfarb et al. (2001) have also made some suggestions on the links between the formation of orogenic gold provinces, the evolution of plate-tectonic processes, and the periods of major continental-crust formation. However, these models need to be further tested and refined by examination of the temporal distribution of other ore deposit styles strongly influenced by tectonic processes. Economic porphyry Cu-Au-Mo deposits and associated epithermal systems are generally very rare beyond the Mesozoic. However, they do appear, albeit in a somewhat modified form (e.g., possibly Hollinger-McIntyre, Boddington, Hemlo), in Archean terranes. This anomalous temporal distribution requires explanation.

Future Research to Resolve Classification and Genetic Problems

Integrated province-scale and deposit-scale research

Modern ore deposit research is based on sophisticated techniques using expensive research equipment, and tackles small, specific research problems within an ore deposit or province. What is required to resolve the problems related to gold deposits in metamorphic belts is an integrated approach, combining thorough, field-based studies with careful structural and petrographic studies, before more sophisticated geochemical and isotopic analysis is applied. Such studies are available for some deposits or districts (e.g., Sigma-Lamaque: Robert and Brown, 1986a, b; northern Juneau gold belt: Miller et al., 1995; central Victorian gold fields: Bierlein et al., 2001b), but there are few integrated studies of the giant gold deposits carried out by a single research team working in concert, in part contributing to current lack of knowledge of the deposits' defining characteristics.

For many deposits or provinces, the lack of precise dating of the mineralization, using robust isotopic systems within the context of the regional events, limits the development of viable genetic models. Such dating should be a priority, particularly for the giant and world-class deposits. Particularly useful methodologies include SHRIMP U-Pb dating of zircon, monazite, titanite, allanite, rutile, apatite, and xenotime to bracket both intrusive phases and ore-related mineral assemblages; Re-Os analysis of molybdenite, other sulfide minerals, and gold itself; Sm-Nd measurements of ore-related tungstates, fluorides, and uranium-rich oxides; and Ar-Ar studies on hydrothermal micas and amphiboles, particularly if their robustness in specific provinces can be confirmed using other methodologies (Richards and Noble, 1998).

Research on fluid source

There is clearly a need to better constrain the source of ore fluids in gold systems in metamorphic belts. This can be achieved in three ways: (1) using the geochemistry and stable isotope compositions of relevant fluid inclusions in well constrained ore-related minerals, (2) using radiogenic and stable isotope compositions of ore-related minerals as tracers, and (3) applying better models of the mechanisms and P-T conditions for release of fluid of appropriate compositions from proposed source rocks or magmas. These approaches should be integrated.

In order to characterize ore fluids, it is now possible to carry out sophisticated analysis of fluid inclusions, for example by multi-element laser-ablation ICP-MS to measure Au, Ag, As, Bi, Sb, and other trace-element concentrations, gas, and ion chromatographic analyses to constrain fluid compositions and halogen element ratios, and Os isotope and noble gas analyses. However, these techniques should be applied only when the inclusion and the host minerals are unequivocally related to the gold mineralization phase. It must also be recognized that fluid pathways may be extensive, leading to the possibility of fluid reaction with a variety of wall rocks, and that fluid immiscibility is common, making any analyzed fluid only representative of the fluid evolution at a particular moment in a particular location in the hydrothermal system.

Although a wide range of isotopic tracers can be measured in both fluid inclusions and hydrothermal minerals (e.g., Pb, Sr, Nd, O, H, C, N, S, B, Br, Cl), most of these will not be diagnostic of a fluid and/or metal source because of fluid-rock interactions along extensive fluid pathways and/or postentrapment modification of the fluid inclusions. Jia and Kerrich (1999) introduced N isotope signatures as superior fluid-source tracers, and Ridley and Diamond (2000) emphasized that only N, Br, and Cl isotopes may be truly representative of source, but that isotopic composition of potential source rocks is poorly characterized. Further investigations of the isotopic compositions of these elements in potential source rocks are needed to allow these systems to be used effectively.

Where granitoid magmas are inferred to be the source of ore fluids, melt inclusion (e.g., Thomas et al., 2000), as well as fluid inclusion, studies on the proposed source intrusions are necessary to determine whether or not they are compatible with ore fluids inferred on the basis of fluid inclusion studies of the ore-associated minerals. High-precision, ultra-low background analyses of the granitoids for ore elements (e.g., Au, Ag, As, Bi, Sb, Te, W) would also help determine if these granitoids were anomalous in terms of metal contents and ratios, and would help document their behavior during fractionation and volatile phase separation.

In many cases, models are unconstrained by experimental studies or theoretical calculations of fluid release from source rocks. For example, the release of aqueous-carbonic fluids from granitic magmas at different crustal levels needs to be quantitatively modeled. Similarly, scenarios where degassing of subducted oceanic crust (e.g., gently dipping subduction zones), or flow of the residue of previously partially melted subducted crust, can contribute volatiles into subsequently formed melts, need to be established.

Research on fluid flow conduits

If deeply sourced ore fluids are accepted as necessary for the genesis of orogenic gold deposits, then the conduits for fluid flux must be understood. As many giant gold provinces are located near crustal-scale deformation zones in metamorphic belts, there is a need for thorough and integrated studies of the structural evolution and associated magmatic activity, if any, along the structures, combined with integrated fluid inclusion and isotopic studies. The nature of the connectivity and fluid flow between the crustal-scale and lower-order structures that host the gold deposits must be better understood in terms of their respective structural evolution (e.g., Neumayr et al., 2000; Neumayr and Hagemann, 2002).

Although many orogenic gold deposits are situated in faults or shear zones, many others are hosted in adjacent rock bodies as stockworks, vein arrays, or disseminations. Following from the studies of Sibson (1990), the precise mechanisms for fluid flux in this type of ore deposit need to be more clearly understood. Similarly, whether the presence of ultra-effective cap rocks or seals to the system can cause local convective flow (e.g., Etheridge et al., 1983) is still uncertain, as most ore systems show evidence of changes in mineralogy, and, therefore, probably fluid composition, with time. Such features are difficult to explain in a one-pass advecting fluid system.

Research on background gold concentrations

Although several authors (e.g., Kerrich, 1986; Phillips et al., 1987) have shown that even giant gold deposits can form from leaching and metal extraction of realistic volumes of any crustal rock type, other authors have suggested that specific rocks (e.g., iron formations, exhalative sedimentary rocks, komatiites, subducted oceanic crust, some granitoids) may be particularly enriched sources (Keays and Scott, 1976; Bierlein et al., 1998). However, there is a dearth of high-precision, ultra-low–level background analyses of Au and related elements in potential source rocks. Such background studies need to be carefully planned to avoid measuring gold in dispersion haloes related to the ore deposits. This is particularly important for proposed sources for intrusion-related deposits; that is, can we tell if a pluton hosting such deposits is, itself, inherently gold rich away from the ore bodies?

Transport and deposition of gold

Our understanding of gold solubility in thiosulfide and chloride complexes is now adequate for modeling of transport and deposition of gold complexes of this type, particularly below 300°C and 1 kbars (e.g., Seward, 1991). However, in some deposits, Au may show an equally strong or even stronger correlation to As, Te, Sb, or Bi. Initial research on the Bi-Au association (Douglas et al., 2000) explains the strong Bi-Au correlation in some deposits, potentially those formed in environments with low fluid/rock ratios. There is an equal need to investigate Au-As, Au-Sb, and Au-Te complexes as alternative transport mechanisms for Au in systems rich in these elements (e.g., Wood and Samson, 1998).

Orogenic and intrusion-related gold deposits commonly show evidence for H_2O-CO_2 phase separation, but the precise chemical changes that lead to precipitation of gold during this process are poorly understood, with competing processes complicating a thorough understanding of many hydrothermal systems (e.g., Mikucki, 1998). Establishing the influence of volatile immiscibility on the deposition of gold and associated elements is a priority to better understand orogenic gold systems, particularly in vein-style ores. In the many cases where H_2O-CO_2 phase immiscibility does not accompany gold precipitation, it is critical to examine in more detail how other mechanisms, especially fluctuations in pressure, without H_2O-CO_2 phase separation, may lead to destabilization of gold-transporting complexes. In fact, the gold solubility experiments of Loucks and Mavrogenes (1999) show that at 400°C, a 2-kbars pressure drop during hydrofracturing of metamorphic rocks would cause desulfidation of a supercritical fluid and an associated 90 percent decrease in gold solubility. The role of fluid mixing or back mixing also needs to be carefully assessed.

The processes by which gold can be remobilized during metamorphism of preexisting deposits and overprinting hydrothermal events must also be determined. The scales at which such processes operate require more detailed documentation.

Research on temporal distribution of gold deposits

More robust dating of problematic gold deposits and provinces in Brazil, Russia, China, and some parts of Africa is required to improve understanding of the distribution of gold deposits through time, defined by Goldfarb et al. (2001). At the same time, Precambrian tectonic processes and environments, and supercontinent geometries, must be better studied, in order to interpret the temporal distribution of gold deposits in terms of the evolution of the earth.

Development of four-dimensional models

What is ultimately required is to develop four-dimensional space-time models for gold deposits in metamorphic belts. This can be aided by the rapid improvements in physical modeling packages (e.g., ELLIPSIS; Moresi et al., 2001) that can eventually be used to produce realistic, three-dimensional models of the complex fluid-flow systems. When these are combined with chemical modeling packages into integrated models, real progress will be made in the understanding of the total systems, as has been done for sedimentary basins.

Seismic traverses have proved exceptionally useful in delineating crustal structure and assisting better understanding of the crustal-scale architecture of gold mineralizing systems, both in the Abitibi belt (e.g., Wyman et al. 1999; Hynes and Ludden, 2000) and Western Australia (Drummond and Goleby, 1993), as have maps of mantle thermal anomalies in younger belts (e.g., de Boorder et al., 1998). Such data are vital if breakthroughs are to be made in this area of research.

Significance to Gold Exploration

Critical parameters for giant gold deposits

The desire for giant gold deposits of superior size and/or grade dominates exploration by major mining and exploration companies at the beginning of the twenty-first century. However, to date, there is no clear identification of the key parameters or conjunction of parameters that dictate their formation. It appears, at the province to deposit scale, that a conjunction of several factors, rather than one or two dominant factors, controls the siting of giant orogenic gold deposits (Phillips et al., 1996). A promising approach is to define those factors that control those provinces hosting numerous world-class to giant deposits, and then apply these and more local parameters at the gold-field or deposit scale. A database of the geophysical signatures of giant gold deposits would also be most useful where GIS-based prospectivity analysis can facilitate the definition of factors which, in conjunction, control giant deposits. Better definition of these factors has obvious benefits in terms of the choice of terranes to explore and assignment of priorities to exploration target areas within them.

Better temporal and tectonic models

Better models for the temporal distribution of gold deposits, particularly giant examples, would allow better definition of these terranes of most interest to explorationists. For exploration, defining the distribution of gold ores in metamorphic belts on the reconstructed Rodinian supercontinent, defining gold-favorable tracts on such a reconstruction, and then rotating these tracts onto present-day coordinates may present a novel approach to assessing Precambrian gold-resource potential. When combined with improved tectonic models and better Precambrian supercontinent reconstructions, they allow refined predictive capacity for ground selection on a global scale. The capacity to overlay global geological, geophysical, and geochemical databases on superior supercontinent reconstructions can be a powerful regional exploration tool.

Improved genetic models for gold deposits in metamorphic belts

Clearly, improved genetic models provide better understanding of the controls on deposit styles, which can, in turn, improve exploration models. In the case of orogenic gold deposits, knowledge of the fluid-flow systems is far more critical to concept-driven exploration than is knowledge of the fluid source, at least at the gold-field scale. Better definition of the fluid conduits would allow more quantitative, coupled modeling of fluid flow and Au deposition, bringing a predictive capability to concept-driven exploration. Furthermore, because orogenic gold deposits are typically formed late in the structural evolution of host terranes (Groves et al., 2000), better definition of flow conduits improves the capacity of computer-based techniques, such as stress mapping (e.g., Holyland and Ojala, 1997), and GIS-based prospectivity mapping using fuzzy logic (e.g., D'Ercole et al., 2000; Knox-Robinson, 2000) and artificial neural-network (e.g., Brown et al., 2000) techniques, because the parameters selected to be tested depend on the quality of the models, as well as the quality of input data.

In the case of intrusion-related gold deposits, improved geologic and, in turn, genetic models will highlight key controls for the location of the deposits that will assist area selection in exploration. In addition, recognition of the specific type(s) of granitoid intrusions responsible for the formation of these systems becomes critical in area selection in provinces containing these deposits, if a magmatic origin is valid.

Improved understanding of deposit overprinting

As overprinted deposits may combine the metal budgets of two separate mineralization episodes of different style, they may be superior exploration targets (e.g., Hollinger-McIntyre, Hemlo, Boddington). Even where two or more orogenic gold episodes overprint each other, because of reactivation of controlling structures and/or change in physical-chemical parameters relating to the earlier mineralization or alteration episode, superior ore bodies may be developed (e.g., Golden Mile, Kalgoorlie). Remobilization alone, without any input of new metal during that latter hydrothermal event, may also increase grade and or improve the metallurgical qualities of the ore. Thus, overprinting and remobilization are processes that need to be better recognized and understood in order to improve target generation in gold exploration.

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APPENDIX

The paper contains a large number of deposit descriptions. For ease of reference, these are listed alphabetically in Table A1 and their locations are shown in Figure A1. Only orogenic and gold-dominant intrusion-related gold deposits and gold-rich deposits with atypical metal associations are listed. References to other deposit types are given in the text.

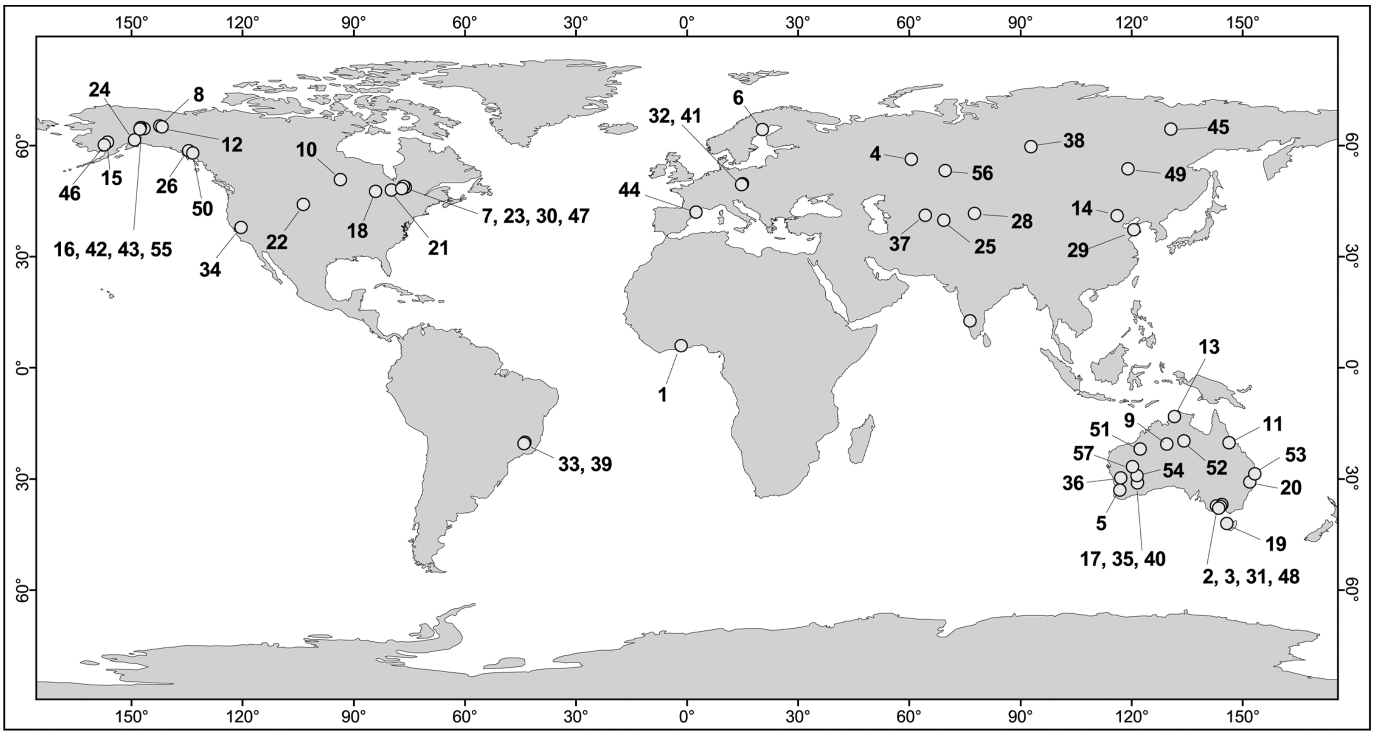

Fig. A1. Location of orogenic and intrusion-related gold deposits and deposits with atypical metal associations discussed in the text and listed in Table A1.

TABLE A1. List, in Alphabetical Order, of the Orogenic and Intrusion-Related Gold Deposits and Deposits with Atypical Metal Associations that are Discussed in the Text

No.	Deposit	Gold province	Classification	Size	Key reference
1	Ashanti (Obuasi)	Birimian belts	Orogenic	Giant	Allibone et al. (2002)
2	Ballarat	Lachlan fold belt	Orogenic	World class	Bierlein et al. (2001a)
3	Bendigo	Lachlan fold belt	Orogenic	Giant	Bierlein et al. (2001a)
4	Berezovsk	East-central Urals	Orogenic	Giant	Kisters et al. (1999)
5	Boddington	West Yilgarn	Atypical (porphyry)	World class	McCuaig et al. (2001)
6	Boliden	Svecofennian province	Atypical (VHMS)	World class	Hannington et al. (1999)
7	Bousquet	Southern Superior province	Atypical (VHMS)	World class	Tourigny et al. (1993)
8	Brewery Creek	Tombstone province	Intrusion-related	Sub-world class	Hart et al. (2000)
9	Calie	Northern Territory inliers	Orogenic	World class	Wygralak and Mernagh (2001)
10	Campbell-Red Lake	Uchi Subprovince	Orogenic	Giant	Dubé et al. (2002)
11	Charters Towers	Thomson fold belt	Orogenic or intrusion-related	World class	Sillitoe and Thompson (1998)
12	Clear Creek	Tombstone province	Intrusion-related	Sub-world class	Marsh et al. (2003)
13	Cosmo Howley	Northern Territory inliers	Orogenic or intrusion-related	World class	Matthai et al. (1995)
14	Dongping	Yan-Liao/Changbaishan	Orogenic or intrusion-related	Sub-world class	Sillitoe and Thompson (1998)
15	Donlin Creek	Tombstone province	Intrusion-related	Giant?	Ebert et al. (2000)
16	Fort Knox	Tombstone province	Intrusion-related	World class	Selby et al. (2002)
17	Golden Mile	Eastern Goldfields province	Orogenic	Giant	Bateman et al. (2001)
18	Hemlo	Southern Superior province	Atypical (epithermal)	Giant	Lin (2001)
19	Henty	Mt. Read belt	Atypical (VHMS)	Sub-world class	Halley and Roberts (1997)
20	Hillgrove	New England fold belt	Orogenic	Sub-world class	Boyle (1990)
21	Hollinger-McIntyre	Southern Superior province	Orogenic (+ porphyry)	Giant	Burrows et al. (1993)
22	Homestake	Dakota segment	Orogenic	Giant	Caddey et al. (1991)
23	Horne	Southern Superior province	Atypical (VHMS)	Giant	Hannington et al. (1999)
24	Independence	Southern Alaska	Orogenic	Sub-world class	Madden-McGuire et al. (1989)
25	Jilau	Southern Tian Shan	Intrusion-related	World class	Cole et al. (2000)
26	Juneau (Alaska-Juneau)	Juneau gold belt	Orogenic	World class	Goldfarb et al. (1997)
27	Kolar	E. Dharwar block	Orogenic	Giant	Radhakrishna and Curtis (1999)
28	Kumtor	Southern Tian Shan	Orogenic	Giant	Jenchuraeva et al. (2001)
29	Linglong	Jiaodong Peninsular	Orogenic or intrusion-related	Sub-world class	Qiu et al. (2002)
30	Malartic	Southern Superior province	Intrusion-related or orogenic	World class	Robert (2001)
31	Maldon	Lachlan fold belt	Orogenic	Sub-world class	Foster et al. (1998)
32	Mokrsko	Bohemian Massif	Orogenic or intrusion-related	World class	Cliff and Moravek (1995)
33	Morro Velho	Rio das Velhas	Orogenic	Giant	Lobato et al. (2001)
34	Mother Lode belt	Sierra Foothills	Orogenic	Giant	Bohlke and Kistler (1986)
35	Mt. Charlotte	Eastern Goldfields province	Orogenic	World class	Bateman et al. (2001)
36	Mt. Gibson	West Yilgarn	Orogenic (+ VHMS)	Sub-world class	Yeats et al. (1996)
37	Muruntau	Southern Tian Shan	Orogenic or intrusion-related	Super giant	Kempe et al. (2001)
38	Olympiada	Yenisei fold belt	Orogenic or intrusion-related	Giant	Genkin et al. (2002)
39	Ouro Preto	Quadrilatero Ferrifero	Orogenic	Sub-world class	Chauvet et al. (2001)
40	Oroya	Eastern Goldfields province	Orogenic	World class	Bateman et al. (2001)
41	Petrockhova Hora	Bohemian Massif	Orogenic or intrusion-related	World class	Zacharias et al. (2001)
42	Pogo	Tombstone province	Orogenic or intrusion-related	World class	Smith et al. (1999)
43	Ryan Lode	Tombstone province	Intrusion-related	Sub-world class	Sillitoe and Thompson (1998)
44	Salsigne	Massif Central	Orogenic	World class	Marignac and Cuney (1999)
45	Sarylakh	Yara-Kolyma	Orogenic	World class	Volkov et al. (2002)
46	Shotgun	Tombstone belt	Intrusion-related	Sub-world class	Rombach and Newberry (2001)
47	Sigma-Lamaque	Southern Superior province	Orogenic	World class	Robert and Brown (1986a, b)
48	Stawell	Lachlan fold belt	Orogenic	World class	Foster et al. (1998)
49	Sukhai Log	Baikal fold belt	Orogenic or intrusion-related	Giant	Laverov et al. (2000)
50	Sumdum Chief	Juneau gold belt	Orogenic	Sub-world class	Goldfarb et al. (1997)
51	Telfer	Paterson province	Intrusion-related or orogenic	World class	Rowins et al. (1997)
52	Tennant Creek	Tennant Creek province	Intrusion-related or orogenic	World class	Zaw et al. (1994)
53	Timbarra	New England fold belt	Intrusion-related	Sub-world class	Mustard (2001)
54	Tower Hill	Eastern Goldfields province	Intrusion-related or orogenic	Sub-world class	Witt (2001)
55	True North	Tombstone province	Intrusion-related or orogenic	Sub-world class	Hart et al. (2000)
56	Vasil'kovsk	Kipchak arc	Orogenic or intrusion-related	Giant	Spiridonov (1996)
57	Wiluna	Eastern Goldfields province	Orogenic	World class	Hagemann and Cassidy (2000)

Note: The gold province is taken from Goldfarb et al. (2001) for consistency; varying classifications are both given where uncertainty exists; for deposits with atypical metal associations the probable major deposit style is given in brackets; classification into super giant (>2,500 t Au), giant (>250 t Au), world class (>100 t Au) and sub-world class (<100 t Au) categories is based on best current knowledge of production and resources for primary resources: alluvial production is excluded; a key recent reference is given, which where possible, contains comprehensive reference lists: this is not possible for some deposits where there are limited publications in English; the locations of the deposits are shown in Figure A1; for other deposit types discussed in the text, references are given that provide critical geological and location data for individual deposits

Abbreviations: VHMS = volcanic-hosted massive sulfide