©2005 Society of Economic Geologists, Inc.
Economic Geology 100th Anniversary Volume
pp. 407–450

Distribution, Character, and Genesis of Gold Deposits in Metamorphic Terranes

RICHARD J. GOLDFARB,†

U.S. Geological Survey, Box 25046, Mail Stop 964, Denver Federal Center, Denver, Colorado 80225-0046, and Department of Geological Sciences, University of Colorado, Campus Box 399, Boulder, CO 80309

TIMOTHY BAKER,

Economic Geology Research Unit, School of Earth Sciences, James Cook University, Townsville, 4811, Queensland, Australia

BENOÎT DUBÉ,

Geological Survey of Canada, 490 de la Couronne, Quebec, Canada G1K 9A9

DAVID I. GROVES,

Centre for Global Metallogeny, School of Earth and Geographical Sciences, University of Western Australia, Crawley, Western Australia 6009, Australia

CRAIG J. R. HART,

Yukon Geological Survey, Box 2703, (F-3), Whitehorse, Yukon, Canada Y1A 2C6, and Centre for Global Metallogeny, School of Earth and Geographical Sciences, University of Western Australia, Crawley, Western Australia 6009, Australia

AND PATRICE GOSSELIN

Geological Survey of Canada, 490 de la Couronne, Quebec, Canada G1K 9A9

Abstract

Epigenetic gold deposits in metamorphic terranes include those of the Precambrian shields (approx 23,000–25,000 t Au), particularly the Late Archean greenstone belts and Paleoproterozoic fold belts, and of the late Neoproterozoic and younger Cordilleran-style orogens (approx 22,000 t lode and 15,500 t placer Au), mainly along the margins of Gondwana, Laurentia, and the more recent circum-Pacific. Ore formation was concentrated during the time intervals of 2.8 to 2.55 Ga, 2.1 to 1.8 Ga, and 600 to 50 Ma. Prior to the last 25 years, ores were defined by grades of 5 to 10 g/t Au in underground mines; present-day economics, open-pit mining, and improved mineral processing procedures allow recovery of ores of ≤1 g/t Au, which has commonly led to the recent reworking of lower grade zones in many historic orebodies. Most of these deposits formed synchronously with late stages of orogeny and are best classified as orogenic gold deposits, which may be subdivided into epizonal, mesozonal, and hypozonal subtypes based on pressure-temperature conditions of ore formation. A second type of deposit, termed intrusion-related gold deposits, developed landward of Phanerozoic accreted terranes in the Paleozoic of eastern Australia and the Mesozoic of the northern North American Cordillera. These have an overall global distribution that is still equivocal and are characterized by an intimate genetic association with relatively reduced granitoids.

The majority of gold deposits in metamorphic terranes are located adjacent to first-order, deep-crustal fault zones, which show complex structural histories and may extend along strike for hundreds of kilometers with widths of as much as a few thousand meters. Fluid migration along such zones was driven by episodes of major pressure fluctuations during seismic events. Ores formed as vein fill of second- and third-order shears and faults, particularly at jogs or changes in strike along the crustal fault zones. Mineralization styles vary from stockworks and breccias in shallow, brittle regimes, through laminated crack-seal veins and sigmoidal vein arrays in brittle-ductile crustal regions, to replacement- and disseminated-type orebodies in deeper, ductile environments (i.e., a continuum model). Most orogenic gold deposits occur in greenschist facies rocks, but significant orebodies can be present in lower and higher grade rocks. Deposits typically formed on retrograde portions of pressure-temperature-time paths and thus are discordant to metamorphic features within host rocks. Spatial association between gold ores and granitoids of all compositions reflects a locally favorable structural trap, except in the case of the intrusion-related gold deposits where there is a clearer genetic association.

World-class orebodies are generally 2 to 10 km long, about 1 km wide, and are mined downdip to depths of 2 to 3 km. Most orogenic gold deposits contain 2 to 5 percent sulfide minerals and have gold/silver ratios from 5 to 10 and gold fineness >900. Arsenopyrite and pyrite are the dominant sulfide minerals, whereas pyrrhotite is more important in higher temperature ores and base metals are not highly anomalous. Tungsten-, Bi-, and Te-bearing mineral phases can be common and are dominant in the relatively sulfide poor intrusion-related gold deposits. Alteration intensity, width, and assemblage vary with the host rock, but carbonates, sulfides,

† Corresponding author: e-mail, goldfarb@usgs.gov

muscovite, chlorite, K-feldspar, biotite, tourmaline, and albite are generally present, except in high-temperature systems where alteration halos are dominated by skarnlike assemblages.

The vein-forming fluids for gold deposits in metamorphic environments are uniquely CO_2 and ^{18}O rich, with low to moderate salinities. Phanerozoic and Paleoproterozic ores show a mode of formation temperatures at 250° to 350°C, whereas Late Archean deposits cluster at about 325° to 400°C. However, there are also many important lower and higher temperature deposits deposited throughout the continuum of depths that range between 2 and 20 km. Ore fluids were, in most cases, near-neutral pH, slightly reduced, and dominated by sulfide complexes. Globally consistent ore-fluid $\delta^{18}O$ values of 6 to 13 per mil and δD values of –80 to –20 per mil generally rule out a significant meteoric water component in the gold-bearing hydrothermal systems. Sulfur isotope measurements on ore-related sulfide minerals are concentrated between 0 and 10 per mil, but with many higher and much lower exceptions, indicating variable sulfur sources and an unlikely dominant role for mantle sulfur. Drastic pressure fluctuations with associated fluid unmixing and/or desulfidation during water/rock interaction are the two most commonly called-upon ore precipitation mechanisms.

The specific model(s) for gold ore genesis remains controversial. Although the direct syngenetic models of the 1970s are no longer applicable, the gold itself may be initially added into the volcanic and sedimentary crustal rock sequences, probably within marine pyrite, during sea-floor hydrothermal events. Gold transport and concentration are most commonly suggested to be associated with metamorphic processes, as indicated by the volatile composition of the hydrothermal fluids, the progressive decrease in concentration of elements enriched in the gold deposits with increasing metamorphic grade of the country rocks, and the common association of ores with medium-grade metamorphic environments. Gold deposits of typically relatively low grade, which formed directly from fluid exsolution during granitoid emplacement within metamorphic rocks, are now also clearly recognized (i.e., intrusion-related gold deposits), but there are limited definitive data to implicate such an exsolved fluid source for most gold deposits within orogenic provinces. The fact that orogenic gold deposits are associated with all types of igneous rocks is a problem to a pure magmatic model. Hybrid models, where slab-derived fluids may generate rising melts that drive devolatilization reactions in the lower crust, are also feasible. Although involvement of a direct mantle fluid presents geochemical difficulties, the presence of lamprophyres and deep-crustal faults in many districts suggests potential mantle influence in the overall, large-scale tectonic event controlling the hydrothermal flow system.

Introduction

THE PAST 25 years have seen a major change in the classification of gold deposits in metamorphic terranes (i.e., belts of supracrustal rocks that have been regionally deformed and metamorphosed, typically to greenschist or higher grades; Fig. 1, App. Fig. A1), mainly reflecting the emerging understanding of plate tectonics and crustal evolution. These deposit types have historically been classified by depth and temperature of formation, structural style, age, host rock, geographic area, or genetic model. Recent workers (e.g., Groves et al., 2003) have begun to recognize that most gold deposits within these unroofed parts of Phanerozoic orogenic belts and Precambrian cratons may be grouped within two deposit types. Orogenic gold deposits, as defined by Groves et al. (1998), are predominant and are recognized to be broadly synchronous with deformation, metamorphism, and magmatism during lithospheric-scale continental-margin orogeny (Fig. 2). Reduced intrusion-related gold deposits, suggested as an additional significant class of gold deposits by workers in the 1990s (e.g., Thompson and Newberry, 2000), typically form landward of the orogenic gold deposits in a near-craton environment (Fig. 2).

Because most deposits recognized and exploited to date in these metamorphic terranes can be classified as orogenic deposits, the descriptive material in the first two-thirds of this paper focuses on them, unless otherwise noted. A subsequent section then highlights which of the deposits in these terranes might be unequivocally classified within the intrusion-related gold deposits model and the supporting evidence for such a distinction. A few significant, yet anomalous deposits in metamorphic terranes, such as Boddington, Bousquet, and Hemlo, which are mainly within the Yilgarn and Superior cratons, are not discussed in this paper; their possible relationships to deposits discussed here are examined in Groves et al. (2003) and Robert et al. (2005).

Classification, Distribution, and Size of Deposits

Classification of gold deposits in metamorphic terranes—historic overview

Classification based on deduced temperature and depth was common throughout the first half of the 20th century. Lindgren (1933) and Emmons (1937) divided gold deposits in metamorphic rocks into mesothermal and hypothermal groups. The former group (mainly Phanerozoic) was taken to reflect those ores formed between 1.5 and 3 km and 150° or 200° to 300°C, whereas the latter (mainly Precambrian) were defined as lodes developed at higher temperatures and greater depths. The mineralogical character of the ores and related alteration assemblages were also commonly used to classify a deposit. For example, the presence of scheelite and tourmaline was taken to indicate a hypothermal gold deposit. Buddington (1935), recognizing that some high-temperature gold lodes could have been deposited at very shallow depth, coined the phrase "xenothermal" for those deposits that today might include the intrusion-related gold deposits. Throughout this time period, there remained a general assumption that gold deposits in metamorphic rocks were intimately associated with magmatic processes (e.g., Emmons, 1937). Niggli (1929), for example, divided epigenetic gold systems into volcanic and plutonic groups, with the latter containing mesothermal and hypothermal deposits.

During the 1930s and 1940s, these well-accepted mesothermal and hypothermal gold groupings were subdivided based upon ore-forming process or deposit style. Niggli's (1929) plutonic gold deposits were subdivided into orthomagmatic,

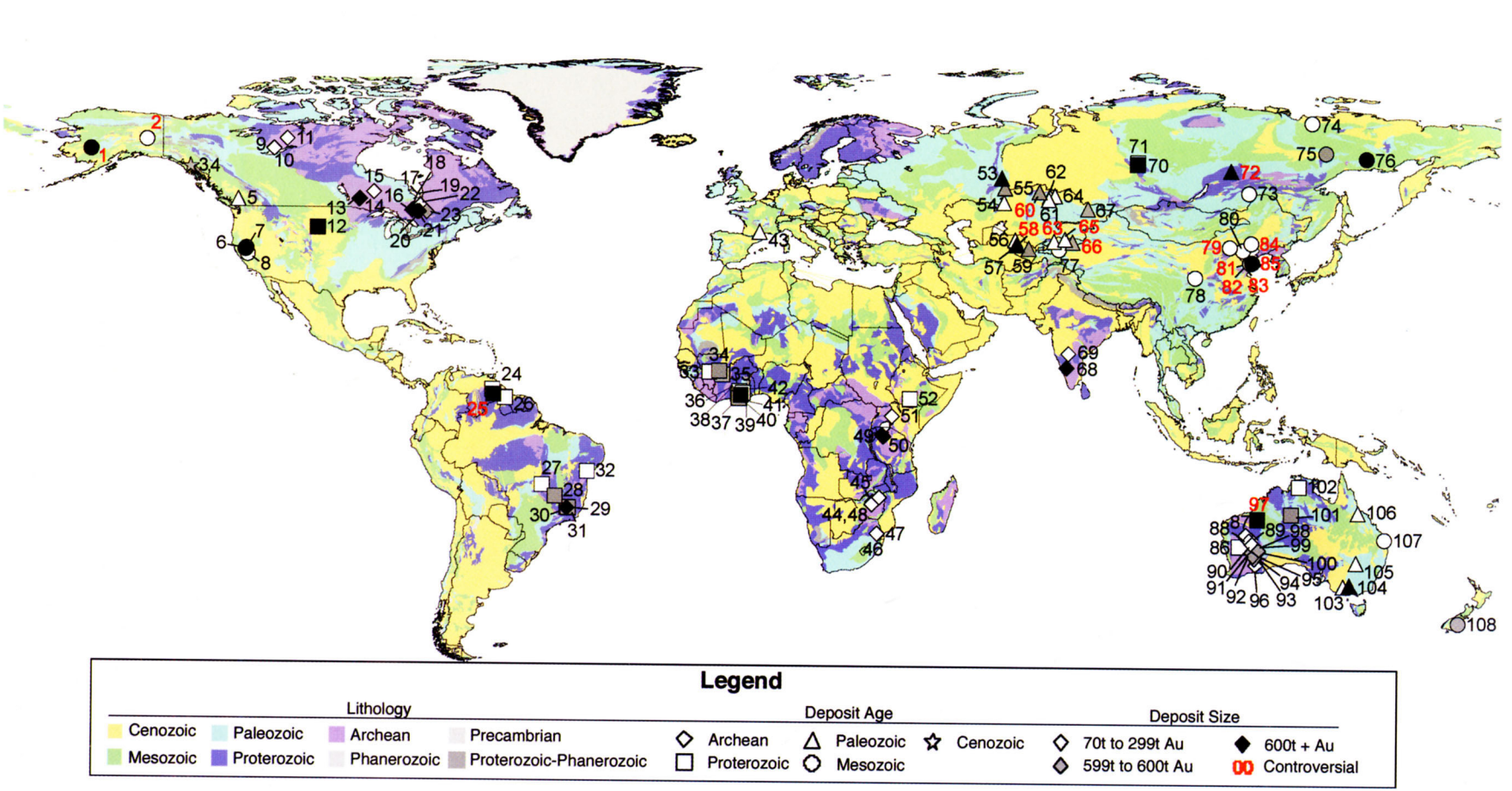


FIG. 1. World map showing the distribution of orogenic gold deposits in metamorphic terranes with production + resources >70 t. Those labeled as "controversial" have also been classified as reduced intrusion-related gold deposits by some workers. Data from the Geological Survey of Canada world gold database. (Chorlton, L.B., comp., 2004, Generalized Geology of the World: Age and Rock Type Domains; Geological Survey of Canada, unpub.). Numbers in figure are as follows: 1 = Donlin Creek; 2 = Pogo; 3 = Treadwell; 4 = Alaska-Juneau; 5 = Bralorne-Pioneer; 6 Grass Valley-Nevada City; 7 = Alleghany district; 8 = Jackson-Plymouth (Motherlode); 9 = Giant; 10 = Con; 11 = Lupin; 12 = Homestake; 13 = Madsen; 14 = Campbell-Red Lake; 15 = Musselwhite; 16 = McIntyre-Hollinger; 17 = Aunor; 18 = Dome; 19 = Pamour; 20 = Kirkland Lake; 21 = Kerr Addison; 22 = Casa Berardi; 23 = Sigma-Lamaque; 24 = El Callao; 25 = Las Cristinas; 26 = Omai; 27 Crixas; 28 = Brasilia (Morro do Ouro); 29 = Morro Velho; 30 = Raposos; 31 = Cuiaba; 32 = Fazenda Brasileiro; 33 = Siguiri; 34 = Morila; 35 = Syama; 36 = Bibiani; 37 = Prestea; 38 = Marlu-Bogoso; 39 = Damang; 40 = Ahafo; 41 = Ashanti; 42 = Konongo; 43 = Salsigne; 44 = Globe and Phoenix; 45 = Cam & Motor; 46 = New Consort; 47 = Sheba-Fairview; 48 = Shamva; 49 = Geita; 50 = Bulyanhulu; 51 = North Mara; 52 = Lega Dembi; 53 = Berezovkoe; 54 = Svetlinskoe; 55 = Kochkar; 56 = Kokpatas; 57 = Amantaitau; 58 = Muruntau; 59 = Zarmitan; 60 = Vassilkovskoye; 61 = Zholymbet; 62 = Aksu-Kvartsytovye Gorki; 63 = Jeroy; 64 = Bestobe; 65 = Taldybulak-Levoberezhny; 66 = Kumtor; 67 = Bakyrchik; 68 = Kolar; 69 = Hutti; 70 = Olimpiada; 71 = Sovetskoe; 72 = Sukhoi Log; 73 = Klyuchevsk; 74 = Kyuchus; 75 = Nezdahniskoye; 76 = Natalka; 77 = Sawuyaerdun; 78 = Baguamiao; 79 = Dongping; 80 = Jinchangyu; 81 = Sanshandao; 82 = Jiaojia; 83 = Xincheng; 84 Jinchanggouliang; 85 = Linglong; 86 = Hill 50; 87 = Plutonic; 88 = Wiluna; 89 = Jundee; 90 Bronzewing; 91 = Tarmoola; 92 = Sons of Gwalia; 93 = Mount Charlotte; 94 = Golden Mile; 95 = Kanowna Belle; 96 = Norseman; 97 = Telfer; 98 = Wallaby; 99 = Sunrise Dam; 100 = Granny Smith; 101 = The Granites; 102 = Mount Todd; 103 = Stawell; 104 = Bendigo; 105 = Cobar; 106 = Charters Towers; 107 = Gympie; 108 = Macraes Flat.

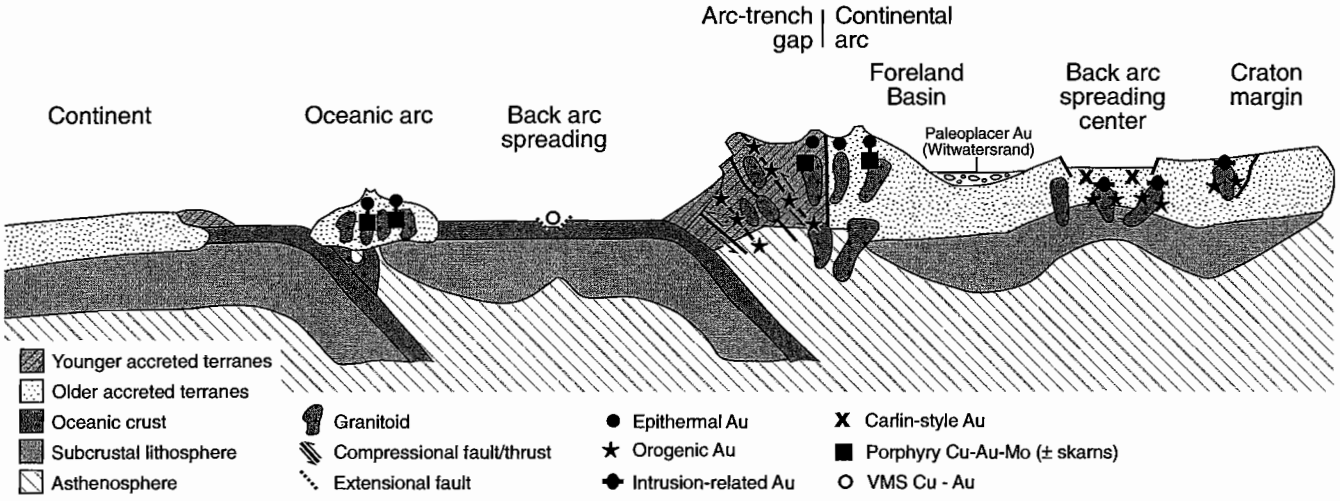


FIG. 2. Schematic diagram showing the tectonic setting of various gold deposit types. Orogenic gold deposits develop in the forearc region of a convergent continental margin over a wide range of crustal depths and may also develop in deformed back-arc sedimentary sequences seaward of the craton margin. Reduced intrusion-related gold deposits form inland of accreted terranes along shelf sequences of a craton margin. After Groves et al. (2005).

pneumatolytic to pegmatitic, and hydrothermal classes. Schneiderhohn (1941) further categorized the plutonic hydrothermal gold deposits as hypothermal veins, impregnations, replacements, and mesothermal Au-Pb-Se ores. Structural style, including fissure fillings, shear zones, saddle reefs, and stockworks, was used by Bateman (1950) to subdivide gold deposits. Nevertheless, the general Lindgren (1933) terminology provided the overriding classification for gold deposits in metamorphic rocks until the late 1970s.

In the late 1970s, and into the early 1980s, gold deposits in metamorphic terranes commonly were classified as to host-rock type, rather than being widely referred to as mesothermal or hypothermal deposits. Boyle (1979) subdivided these gold deposits into those hosted by volcanic rocks, sedimentary rocks, and complex "lithologies." Other workers referred to turbidite-hosted gold deposits (Keppie et al., 1986) in Phanerozoic rocks or greenstone-hosted gold deposits for those mainly in Precambrian cratons (e.g., Hutchinson and Burlington, 1984). However, development of a more unifying terminology was critical, because host-rock type is not a logical discriminator for epigenetic mineral deposit types. Similar problems also characterized attempted classification of these deposits by rock age (e.g., Archean gold deposits), location (e.g., Homestake and Mother Lode gold deposits), and hydrothermal process (e.g., metamorphic gold deposits).

Classification of gold deposits in metamorphic terranes—the last 25 years

The effort in the early 1980s by many geological surveys to develop mineral deposit models led to a renewed classification effort. Workers at the U.S. Geological Survey initially termed the epigenetic, structurally hosted lode gold deposits in metamorphic rocks as orogenic gold deposits (e.g., Böhlke, 1982), although later mineral deposit models divided these into low sulfide gold-bearing quartz (Phanerozoic) and Homestake (Precambrian) gold deposit types (e.g., Berger, 1986). Nesbitt et al. (1986) reemphasized the Lindgren terminology, grouping all these gold deposits into a mesothermal classification; however, as pointed out by Groves et al. (1998), many gold deposits in metamorphic rocks formed at higher pressure-temperature conditions than the mesothermal conditions defined by Lindgren. Therefore, following Böhlke (1982), this relatively diverse group of deposits, which are inherent to many of the world's orogenic belts, is now most widely referred to as "orogenic" gold deposits. If subdivided by depth and temperature (Fig. 3), as suggested originally by Lindgren (1907, 1933), then the terms epizonal (≤6 km, 150°–300°C), mesozonal (6–12 km, 300°–475°C), and hypozonal (>12 km, >475°C), following Gebre-Mariam et al. (1995), are useful discriminators.

Much of this paper reviews current understanding of the orogenic gold deposits. With the increase in the gold price at the start of the 1980s, and a renewed interest in the geology of gold itself, there was a flood of new research on this type of ore deposit. Subsequent results constitute large parts of numerous comprehensive, international meeting volumes from the 1980s that were solely devoted to gold deposits (e.g., Foster, 1984; Keppie et al., 1986; Ho and Groves, 1987; Macdonald, 1987; Bursnall, 1989; Keays et al., 1989; Ladeira, 1991b; Robert et al., 1991).

Sillitoe (1991) defined a "broad spectrum of gold mineralization styles" within the epizonal to mesozonal environment that showed clear evidence of being intrusion related. Sillitoe and Thompson (1998) and Thompson et al. (1999) further refined this model (coined the intrusion-related gold deposits model by Lang et al., 2000) and discussed the most obvious differences from and similarities to orogenic gold deposits. Many of the intrusion-related gold deposits are notable by their very late orogenic timing, commonly postregional deformation, as opposed to the orogenic gold deposits that most consistently develop in the latter stages of still ongoing regional deformation in the host metamorphic terranes. Stockwork and disseminated gold ores in country rocks adjacent to plutons (i.e., Muruntau, Uzbekistan), as well as epigenetic

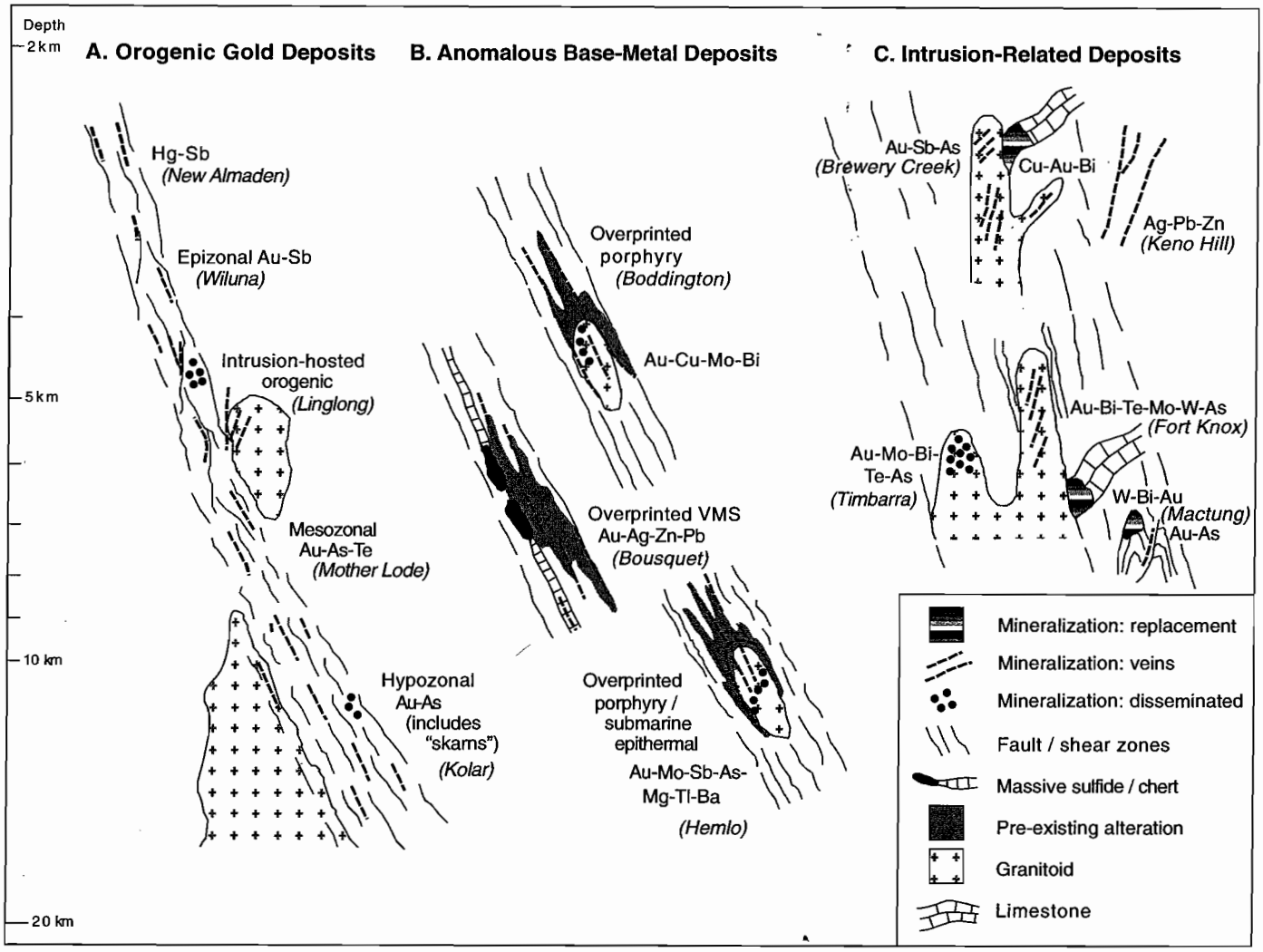


FIG. 3. Epigenetic gold deposit types in metamorphic terranes. Epizonal, mesozonal, and hypozonal orogenic gold deposits are associated with regional fluid flow along major deep-crustal fault zone and form at depths of 2 to 20 km. Reduced intrusion-related gold deposits are genetically related to local fluid exsolution from magmas in the upper half of this depth interval. Remobilization and overprinting of older, more base metal-rich VMS or porphyry deposits in the same metamorphic terranes can sometimes also form a variety of styles of base metal-rich epigenetic lode gold deposits, which, nonetheless, possess some of the characteristics of orogenic or intrusion-related gold deposits. After Groves et al. (2003).

quartz veins cutting magmatic rocks ranging in size from batholiths (i.e., Linglong, Jiaodong, China) to sills and dikes (i.e., Donlin Creek, Alaska), represent deposit styles in metamorphic terranes that commonly remain problematic in classification (Groves et al., 2003). They show characteristics of both orogenic gold deposits and deposits that are grouped by some workers into the intrusion-related gold deposits model. An important link between the orogenic and intrusion-related gold deposits types is the generation of ores from a distinct hydrothermal fluid of an aqueous-carbonic and ^{18}O-enriched nature.

Deposit distribution in space

A more global approach applied to exploration by the minerals industry in the late 1900s has led to an improved understanding of the spatial distribution of gold ores in metamorphic terranes (e.g., Goldfarb et al., 2001a, b; Fig. 1; Table 1). In particular, the last 10 to 20 years have seen the first comprehensive recognition of the distribution of epigenetic gold ores in China (e.g., Zhou et al., 2002), as well as in Russia and adjacent central Asian countries (e.g., Yakubchuk et al., 2002, 2005). All English-language global gold maps and compilations published prior to this recent period are notable for their limited information on gold resources throughout much of Asia.

The spatial association between Precambrian shield areas and epigenetic gold (Hagemann and Cassidy, 2000) has been recognized for 100 years (cf. Lindgren, 1909). Exposed areas of Late Archean, Paleoproterozoic, and, to a lesser extent, Middle Archean rocks (exclusive of the Witwatersrand deposits) throughout the world's Precambrian platforms (i.e., exposed shields and buried basements) are characterized by approximately 23,000 to 25,000 t Au in past production and defined resources (Goldfarb et al., 2001a). The majority of

TABLE 1. Orogenic Gold Deposits and/or Districts with Production + Resource ≥250 t Au
(those deposits and/or districts with an asterisk have been alternatively classified by some workers as intrusion-related gold deposits; references for each deposit are included in electronic App. 1)

Deposit name	Orogen or craton	Host rocks	Au (t)	Grade (g/t)	Mining
Muruntau*	Tien Shan	Ordovician-Silurian metasedimentary (mudstone-carbonate-sandstone-siltstone-conglomerate)	5290	3.5-4.0	1967-present
Ashanti	West African craton	Paleoproterozoic metasedimentary and mafic volcanics, schists	2070	4.73	1897-present
Golden Mile	Yilgarn craton	Late Archean dolerite and tholeiitic basalt	1984	1.98	1890-present
Telfer*	Paterson orogen	Middle to Late Proterozoic sediments (quartzite-mudstone-sandstone-siltstone)	1564	1.50	1977-2000
Homestake	Trans-Hudson orogen	Paleoproterozoic BIF and metasediments	1237	8.34	1876-2001
Sukhoi Log*	Siberian craton	Neoproterozoic carbonaceous shales, mudstone-sandstone	1048	2.70	Undeveloped
McIntyre-Hollinger	Canadian Shield	Late Archean tholeiitic basalt, unclassified granitoid rocks;unclassified sedimentary rocks	987	9.47	1910-1988
Las Cristinas*	Transamazonian orogen/ Amazon craton	Paleoproterozoic felsic to intermediate metavolcanics and metasedimentary, margins of ca. 2.15 ca felsic intrusions	964	1.11	Undeveloped
Kolar	Dharwar craton	Middle to Late Archean tholeiithic basalt and komatiitic basalt	838	14.47	1880-1998
Campbell-Red Lake	Canadian Shield	Late Archean mafic/ultramafic volcanic rocks	799	21.28	1948-present
Kirkland Lake	Canadian Shield	Late Archean syenite stock, unclassified volcanic rocks	797	14.97	1912-1999
Donlin Creek*	Cordilleran (Alaska) orogen	L Cretaceous granite porphyry dikes;sandstone	793	3.05	Undeveloped
Geita	Tanzanian craton	Late Archean BIFand andesite; carbonatite-lamprophyre association	788	4.01	1938-1966, 2000-present
Natalka	Russian Far East	Permian carbonaceous and hornfelsed metasedimentary (mudstone-sandstone-siltstone-conglomerate)	716	4.20	1944-present
Berezovkoe	Uralide orogen	Late Devonian andesite and dacite, Early Silurian granite-syenite porphyries	715	2.50	1750-1993
Olimpiada	SE Siberian craton	Neoproterozoic schists and carbonaceous slates	700	10.90	1997-present
Grass Valley-Nevada City District	Cordilleran (California) orogen	Late Paleozoic metavolcanics, serpentinites, and 127 Ma granodiorite	664	16.92	1850-1957
Morro Velho	Sao Francisco craton	Late Archean "lapa seca" (e.g., altered igneous rock-volcanic rocks?)	654	9.51	1834-present
Bulyanhulu	Tanzanian craton	Late Archean felsic and intermediate volcanics, mudstone	543	14.50	1980-present
Bendigo goldfield	Tasman orogen	Ordovician metasedimentary, granodiorite-tonalite suite	533	12.91	1853-1954
Dome	Canadian shield	Late Archean tholeiitic basalt-komatiite, mudstone-sandstone-conglomerate, porphyries	509	4.57	1910-present
Linglong camp*	Yanshanian orogen	Jurassic and Cretaceous quartz monzonite-monzogabbro suite; granite suite	500	9.70	>1,000 years of mining
Zarmitan	Tien Shan	Silurian metasedimentary-Late Carboniferous syenite-syenogabbro suite?	470	9.53	2000-2000
Sigma-Lamaque	Canadian shield	Late Archean andesitic flows and granodiorite-tonalite intrusions	444	4.88	1935-2001
Prestea	West African craton	Paleoproterozoic metasedimentary schist and tholeiithic volcanics	390	6.13	1885-present
Kochkar	Uralide	Early Carboniferous granodiorite-tonalite; mafic-intermediate dikes	380	3.50	1750-1998
Vasilkovskoye*	Tien Shan	Ordovician gabbro, diorite, granodiorite	375	2.76	1991-present
The Granites	North Australia Orogenic Province(?)	Paleoproterozoic BIF	369	4.65	1932-present
Bakyrchik	Tien Shan	Carboniferous carbonaceous metasedimentary	361	6.79	1956-1997
Morila	West African craton	Paleoproterozoic siltstone-sandstone-quartzite-mudstone-conglomerate	350	4.88	2000-present
Kerr Addison	Canadian Shield	Late Archean mafic/ultramafic volcanics; unclassified sedimentary rocks	327	9.10	1938-1995
Cuiaba	Sao Francisco craton	Late Archean BIF and mafic volcanic rocks	318	7.42	1877-present
Brasilia, Morro do Ouro	Brasiliano orogen/ Sao Francisco craton	Neoproterozoic carbonaceous phyllite	313	0.43	1987-present
Nezhdaninskoye	Verkhoyansk-Kolyma	Early Permian carbonaceous siltstones-sandstones, granite suite	311	5.39	1975-2000
Syama	West African craton	Paleoproterozoic basalts and sediments	289	3.16	1990-2000
Amantaitau	Tien Shan	Ordovician-Silurian carbonaceous flysch	288	3.70	Undeveloped
Kumtor*	Tien Shan	Neoproterozoic metasedimentary (mudstone-sandstone-siltstone)	284	4.41	1996-present
Alaska-Juneau	Cordillera	Late Jurassic to Early Cretaceous metasediments	281	1.42	1895-1944
Sunrise Dam-Cleo	Yilgarn craton	Archean volcaniclastics, andesite, BIF, granodiorite-tonalite-diorite suite	268	3.68	1997-present
Sons of Gwalia	Yilgarn craton	Late Archean tholeiitic basalt	255	4.02	1898-1963, 1983-present
Macraes Flat	Otago	Jurassic schists	251	1.20	1990-present
Pamour	Canadian shield	Late Archean conglomerate, sandtone-graywacke, basalt and komatiite	250	2.89	1915-1999
Giant-Lolor-Supercrest	Slave craton	Late Archean basalt	248	15.74	1948-present

these resources are localized within greenschist facies zones of Late Archean greenstone belts, with about 25 percent of the ores in Paleoproterozoic supracrustal rock sequences.

More than 50 percent of the entire Precambrian gold endowment is concentrated in Late Archean greenstone belts of the eastern Yilgarn craton (Australian platform) and the southern Superior province of the Canadian Shield (North American platform). Almost all other extensive areas of exposed Archean crust host similar gold deposits.

The relatively huge gold endowment in the Archean rocks of Australia and North America is spread across areas that represent about 7 and 27 percent, respectively, of the > 2.5 Ga exposed crust (e.g., Goodwin, 1991). Given that Africa contains the largest volume of exposed Archean cratonic rocks (32%), mainly in greenschist facies greenstone belts, perhaps the greatest overall future potential for Archean epigenetic lode gold resources should be expected in that platform. Although significant exposures of Archean rocks occur in areas such as the three main cratons of China, they are generally deficient in significant gold deposits because of their high metamorphic grade. This also applies to other gold-poor shield areas. In Antarctica, the lack of known Precambrian gold may simply be due to the platform being closed for exploration.

Paleoproterozoic fold belts that surround the Archean cratonic nuclei, which have themselves become parts of the cratons subsequent to ca. 2.1 to 1.8 Ga deformation, are recognized to have contained about 4,500 to 6,000 t of the Precambrian epigenetic lode gold resource (e.g., Partington and Williams, 2000). In contrast to the Late Archean gold ores that are almost solely in greenstone belts, the greenschist facies parts of these auriferous folded belts comprise both greenstones and sequences of quartzite, carbonate, banded iron formation (BIF), and pelite that together define platform to slope-rise facies. Almost two-thirds of the exposed Paleoproterozoic crust is located in the African and North American platforms (Goodwin, 1991), which also host most of the gold deposits of that era. The gold ores are concentrated in the lower metamorphic grade domains of the belts, which include the Birimian greenstones and turbidites in West Africa (e.g., Ashanti) and BIF at the Homestake deposit in the Trans-Hudson belt of North America. Other major gold provinces include those in northern Australia (e.g., Pine Creek and Tanami) and in the Brazilian Amazonian and Sao Francisco cratons. Significant gold occurrences are not present in those Paleoproterozoic belts that are almost entirely dominated by amphibolite- and granulite-grade rocks, which characterize about 83 percent of the exposed Paleoproterozoic crust (Goodwin, 1991).

The majority of the Neoproterozoic and Phanerozoic orogens also contain important epigenetic lode gold deposits within mainly greenschist facies terranes with a total gold endowment exceeding 37,000 t. Approximately 40 percent of this gold was recovered from the great placers fields of the circum-Pacific (e.g., Sierra foothills of California, Russian Far East, Alaska and Yukon, South Island of New Zealand, Victoria province of Australia), Baikal fold belt, and Ural Mountains during the mid 1800s to mid 1900s, and during historic times in the Arabian Nubian Shield and the Iberian Massif (Goldfarb et al., 2001b). The post-800 Ma lode deposits comprise roughly 9,300 t of past production and 12,500 t of remaining resources defined by present-day economics. At present, the largest resources are recognized in central Asia, eastern Russia, interior Alaska, and eastern China.

Deposit distribution in time

The distribution of lode gold deposits in metamorphic terranes over geologic time has become fairly well established during the last few decades, as summarized by Kerrich and Cassidy (1994) and Goldfarb et al. (2001a, b), and with details and references for specific deposits mentioned here listed in Appendix Table A1. These compilations reflect, in large part, the abundance of new absolute age data that have become available for the gold ores during the last two decades. Through much of Earth history, epigenetic gold formation in metamorphic belts was episodic, with almost all pre-Neoproterozoic events occurring between 2800 and 2550 or 2100 and 1800 Ma (Fig. 4A; Table 2). The oldest epigenetic gold deposits include those of the Barberton greenstone belt (ca. 3.1 Ga) and northern Pilbara craton (ca. 3.4–3.0 Ga), but combined these account for less than two percent of the pre-1.8 Ga gold resource. Obviously, if Witwatersrand is considered to be a paleoplacer derived from a Middle Archean greenstone-belt sequence (Frimmel et al., 2005), then the importance of the Middle Archean must be reevaluated. But ignoring this one exceptional and still controversial (i.e., Law and Phillips, 2005) anomaly, and thus restricting this discussion to the other Precambrian lode gold provinces, most of the gold resource concentrated during the first 3 b.y. of Earth history was heterogeneously deposited over 20 percent of that time period. Subsequent to the Paleoproterozoic, there was a time gap of approximately 1200 m.y. (ca. 1.8–0.6 Ga) from which no significant gold resources are known.

Economically important gold resources formed relatively continuously between about 600 and 50 Ma (Fig. 4B). The oldest part of this range reflects collisional events on the active margins of Gondwana and Laurentia (Fig. 5), subsequent to the breakup of Rodinia. The ca. 725 to 500 Ma Pan African-Brasiliano orogeny, during assembly of the Gondwana supercontinent, was characterized by gold-forming events in the Arabian-Nubian Shield (e.g., Sukhaybarat, Umm Rus, El Sid, and Lega Dembi deposits), Hoggar Shield (e.g., Amesmessa and Tirek deposits), and Brasilia fold belt (e.g., Morro do Ouro deposit) of West Gondwana. The Paterson orogen of East Gondwana (e.g., Telfer deposit) contains the only recognized important gold ores formed during construction of that Gondwanan block, although subduction and/or accretion leading to the development of the Ross-Delamarian orogen along much of the length of Antarctica at the start of the Cambrian may have initiated other gold events in a vast region closed to mineral exploration. Coevally, although Laurentia and Baltica are generally characterized by lengthy Neoproterozoic-early Paleozoic rift margins, the Siberian block during this time was dominated by collisional margins. Resulting fold belts are the host for large syntectonic gold deposits (e.g., Olympiada and Sovetsk in the Yenisei fold belt, and Zun-Kholba in the East Sayan fold belt, eastern Russia: Yakubchuk et al., 2005).

The Paleozoic was dominated by subduction and/or accretion along much of the margin of the two evolving supercontinents

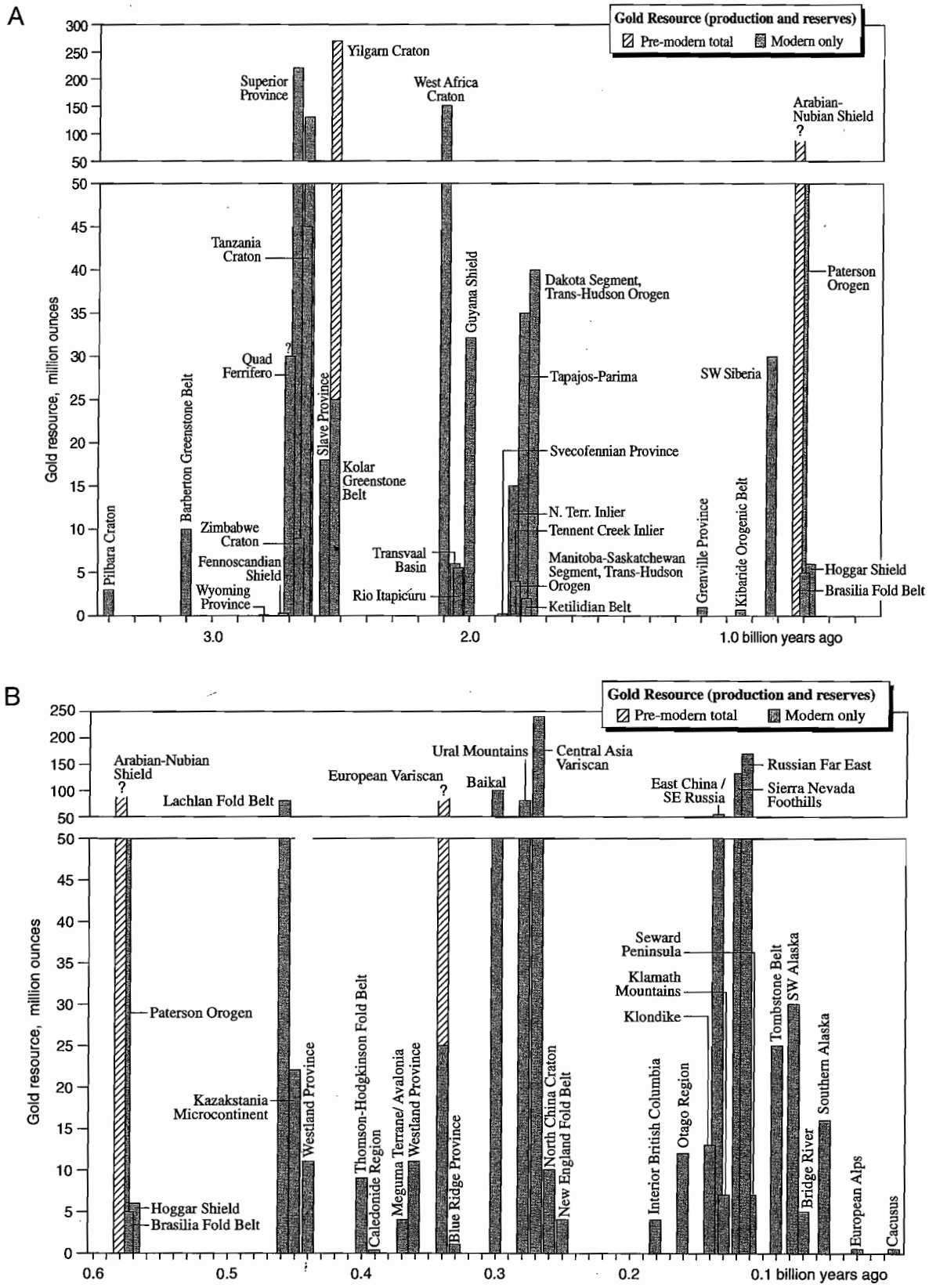


FIG. 4. Distribution of gold resources in orogenic gold deposits, and related placer gold endowment, over geologic time. A. Precambrian gold resources are mainly the product of ore-forming events clustered between 2.8 and 2.55 and 2.1 and 1.8 Ga. B. Phanerozoic gold resources indicate relatively continuous gold-forming events during orogenic events along the margins of Gondwana, Laurentia, and the Mesozoic-Tertiary circum-Pacific. After Goldfarb et al. (2001a).

TABLE 2. Age of Mineralization and Associated Magmatism for the 25 Largest Orogenic Gold Deposits (references for each deposit are included in electronic App. I)

Deposit name	Ore mineralization (Ma)	Intrusions
Muruntau	279±18 (Sm-Nd on scheelite), 286±5 (Re-Os on aspy)	Sardarin granite pluton 15 km SE (286.2±1.8, Rb-Sr); Murun alaskite, 4 km below (287.1±4.6, Rb-Sr); alkaline syenite and lamprophyre dikes to N and S, and granite to granodiorite dikes (277-270, Rb-Sr) that both cut and are cut by ores
Ashanti	2100-2090 (U-Pb on titanite)	2116-2088 Ma granitoids in adjacent basin
Golden Mile	2628, 2600 (Ar-Ar mica)	Ores hosted in 2674 Ma dolerite; province-wide 2690-2655 Ma voluminous granite magmatism and 2650-2630 syenitic magmatism
Telfer	Inferred 700-600	633±13 to 617±64 Ma monzogranite, syenogranite, and alkali-feldspar granite plutons within a few tens of kms of deposit
Homestake	Inferred ca. 1774-1720	ca. 1.72 Ga granite 11 km NE
Sukhoi Log	380-365 (±12, Rb-Sr), 345 (Ar-Ar mica)	354 Ma(?) quartz monzonite stock and felsic porphyry dikes located 6 km SW; part of 340-280 Ma Angara-Vitim batholith; inferred pluton at 3 km below deposit
McIntyre-Hollinger	<2673	Pre-ore 2689 Ma qtz-feldspar porphyry stocks (Pearl Lake, Acme and Miller Lake porphyries) and pre-ore 2673 Ma albitite dikes
Las Cristinas	2139±24 to 2064±9 (five Ar-Ar mica dates)	Intermediate to felsic dikes and stocks throughout the district; granite near deposits dated at 2087±21 Ma
Kolar	≥2550	ca. 2.55-2.53 Ga graniodiorite/quartz monzanite plutons surrounding lodes
Campbell-Red Lake	<2870, >2714; 2721 (Re-Os on molybdenite)	2714 Ma quartz-feldspar-porphyry dike cutting ores
Kirkland Lake	<2677	Syenite ore host
Donlin Creek	74-68 (Ar-Ar mica)	76-66 Ma granite porphyry dikes and sills host ore
Geita	≤2644±3	Pre-, syn-, and post-tectonic ca. 2.7-2.4 Ga granitoids in greenstone belt; abundant mafic and intermediate ca 2.6-2.5 Ga dikes
Natalka	135 (Ar-Ar mica)	Small Late Cretaceous rhyolite body 10 km to SE; Jurassic-Cretaceous felsic and mafic dikes; inferred pluton at depth
Berezovkoe	≤328	2 km above buried part of 328 Ma Shartash quartz monzonite/granodiorite pluton; granite porphyry dikes extend into ores
Olympiada	800-600 (range of Rb-Sr dates)	Regional 760-750 Ma granites of the Tatarka-Ayakhta complex in surrounding area (a few km SW) and inferred at depth
Grass Valley-Nevada City District	144 (K-Ar mica), 141 (Rb-Sr)	Ores in and adjacent to 127 Ma (K-Ar hornblende) granodiorite; felsic to mafic dikes
Morro Velho	≤2710	2.8-2.7 Ga granitoids in region
Bulyanhulu	<2640,>2550	ca. 2550 Ma Bugarama granitoid 2 km SW of deposit; mafic dikes cut ore veins
Bendigo goldfield	ca. 440 (Ar-Ar mica); 438±6 (Re-Os on arsenopyrite-pyrite)	370 Ma felsic dikes in deposit; regional ca. 370 Ma granitoids
Dome	<2679	ca. 2690 Ma quartz-feldspar Preston and Paymaster porphyries
Linglong camp	123-122 (Rb-Sr pyrite)	Ores hosted by 165-150 Ma granite/granodiorite (Linglong suite) and syenogranite (Luanjiahe suite) and 130-126 Ma granodiorite (Guojialing suite)
Zarmitan	≤269	Ore-hosting 269 Ma syenitic Koshrabad massif batholith; felsic dikes in deposit
Sigma-Lamaque	2682 (U-Pb zircon), 2596±33 (Sm-Nd scheelite)	Adjacent to and hosted by 2700-2685 Ma dioritic/tonalitic batholith
Prestea	Probably ca. 2100 Ma	2116-2088 Ma granitoids in adjacent basin

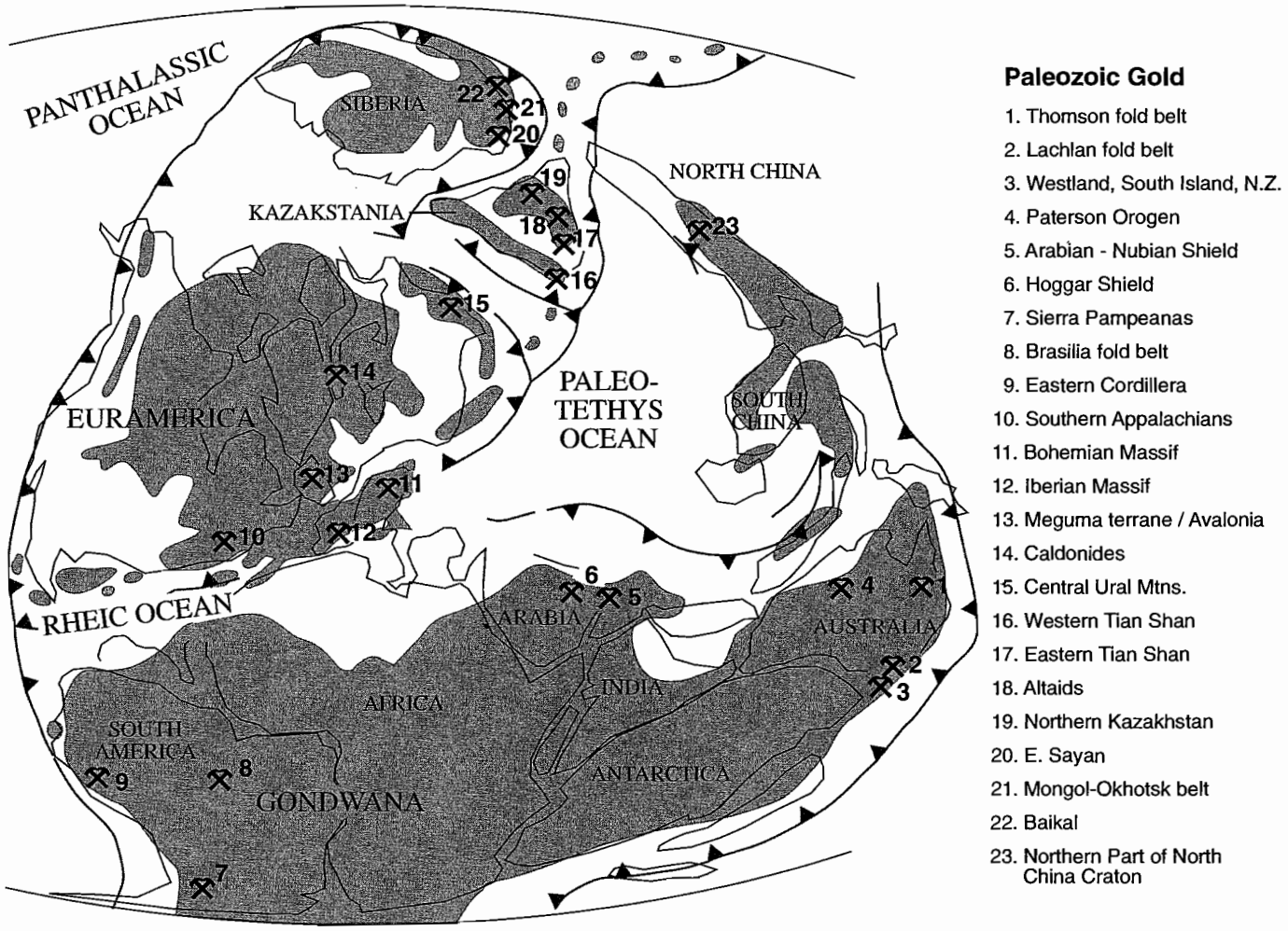


FIG. 5. The Gondwana and Laurentia supercontinents and the distribution of Paleozoic gold provinces along their associated marginal orogenic belts. After Goldfarb et al. (2001a).

(Fig. 5). From Ordovician to Carboniferous, gold events were diachronously widespread along the proto-Pacific margin of Gondwana. Important gold provinces developed within the Lachlan, Thomson, and Hodgkinson-Broken River fold belts of eastern Australia; Westland area of South Island, New Zealand; and the eastern Andean Cordillera from northern Peru to northern Argentina. At the same time, along the northern margin of the Paleotethys Ocean and adjacent Uralian Sea, Ordovician to Permian tectonism, in places extending into Triassic, was associated with gold deposit formation in the Appalachians of eastern North America (e.g., Blue Ridge belt to Meguma terrane), Caledonides of the United Kingdom (e.g., Dolgellau, Tyndrum, and Clontibret goldfields), Iberian Massif, Massif Central, and Bohemian Massif of southern Europe, the east-central Ural Mountains of Russia (e.g., Berzovsk and Kochkar deposits), and across central Asia, Mongolia, and southern Russia (e.g., Muruntau, Kumtor, Sukhoi Log, and Zaamar deposits).

Mesozoic to early Tertiary ore systems are almost exclusively concentrated around the circum-Pacific (Fig. 1), within orogenic belts that define the most active continental margins subsequent to Pangea breakup. Many of these are particularly significant for their immense placer production. On the eastern side of the Pacific basin, important gold provinces include the Sierra foothills (e.g., Mother Lode belt and Alleghany district) of central California, the Klondike in Yukon, Bridge River in British Columbia, the Juneau gold belt of southeastern Alaska, the Fairbanks region (e.g., Fort Knox and Pogo deposits) and Kuskokwim basin (e.g., Donlin Creek deposit) of interior Alaska, and the Nome district of northwestern Alaska. Simultaneously, on the western side of the Pacific basin, gold provinces formed in terranes seaward of craton margins in the Verhoyansk fold belt, Yana-Kolyma superterrane, Amur district, and Sikhote-Alin fold belt of the Russian Far East, and in the New England fold belt and Otago schist belt (e.g., Macraes Flat deposit) adjacent to the Australian platform. In between these two areas, Yanshanian (Jurassic-Cretaceous) orogenic events along the margins of the eastern half of the North China craton led to the widespread distribution of gold ores within high-grade metamorphic rocks of the Precambrian block itself, representing the only large Phanerozoic gold endowment in Mesoproterozoic or older crustal blocks.

Goldfarb et al. (2001b) relate the gaps in time within the distribution of gold deposits as reflecting both processes of

preservation and crustal growth. Crustal growth was episodic throughout much of the Precambrian, perhaps reflecting plume-influenced mantle overturn events; the gold ores correlate with these periods of greenstone belt evolution at mainly 2.8 to 2.5 and 2.1 to 1.8 Ga. The roughly equidimensional cratonic blocks, with buoyant subcontinental mantle lithosphere, included vast areas that were protected from subsequent tectonism and, as a result, these areas of gold-bearing greenstones and associated supracrustal sequences at subamphibolite grade metamorphic facies have remained uneroded for 2 to 3 b.y. Subsequent to the Archean, a more recent, but still highly debated, style of plate tectonics gradually became dominant on the cooling Earth and resulting new crust was mainly a product of terrane accretion surrounding the Paleoproterozoic and older cratonic nuclei. The linear, narrow volcano-sedimentary terranes added to the platforms were more susceptible to reworking and deep erosion; many of the Mesoproterozoic and Neoproterozoic orogens, thus, have been unroofed down to their high-grade metamorphic cores, which reflect depths commonly far below those (2–20 km: cf. Groves et al., 1998) that host most gold deposits in metamorphic belts. Post-600 Ma orogenic belts that formed during the growth of Gondwana and/or Laurentia and during circum-Pacific tectonism typically exhibit broad zones of greenschist facies rocks that are more gold favorable. Although there are some small gold provinces in metamorphic belts that are younger than 50 Ma (e.g., European Alps, Greater Caucasus of the Georgia Republic, Southern Alps of New Zealand), these are generally uneconomic and thus suggest that it takes significant time until a major gold resource is exposed within most orogens.

Grades and tonnages of gold ore in metamorphic belts

There are about 100 world-class gold deposits, which are considered here as defined by at least 70 t Au (Figs. 1, 6; App. Table A1; Gosselin and Dubé, 2005a, b), with 17 of these being truly giants (>500 t Au; Table 1). There seems to be little association of deposit size with age (Fig. 7A) or with geographic region. The six largest examples include Late Archean gold deposits in the Canadian Shield (e.g., McIntyre-Hollinger) and Yilgarn craton (e.g., Golden Mile), Paleoproterozoic deposits in North America (e.g., Homestake) and West Africa (e.g., Ashanti), and Paleozoic deposits in the Central Asian orogen (e.g., Muruntau) and the Baikal fold belt (e.g., Sukhoi Log). Lode productivity versus age shows a relatively significant drop in the Mesozoic-Cenozoic (Fig. 7B), but this does not take into consideration the huge endowment

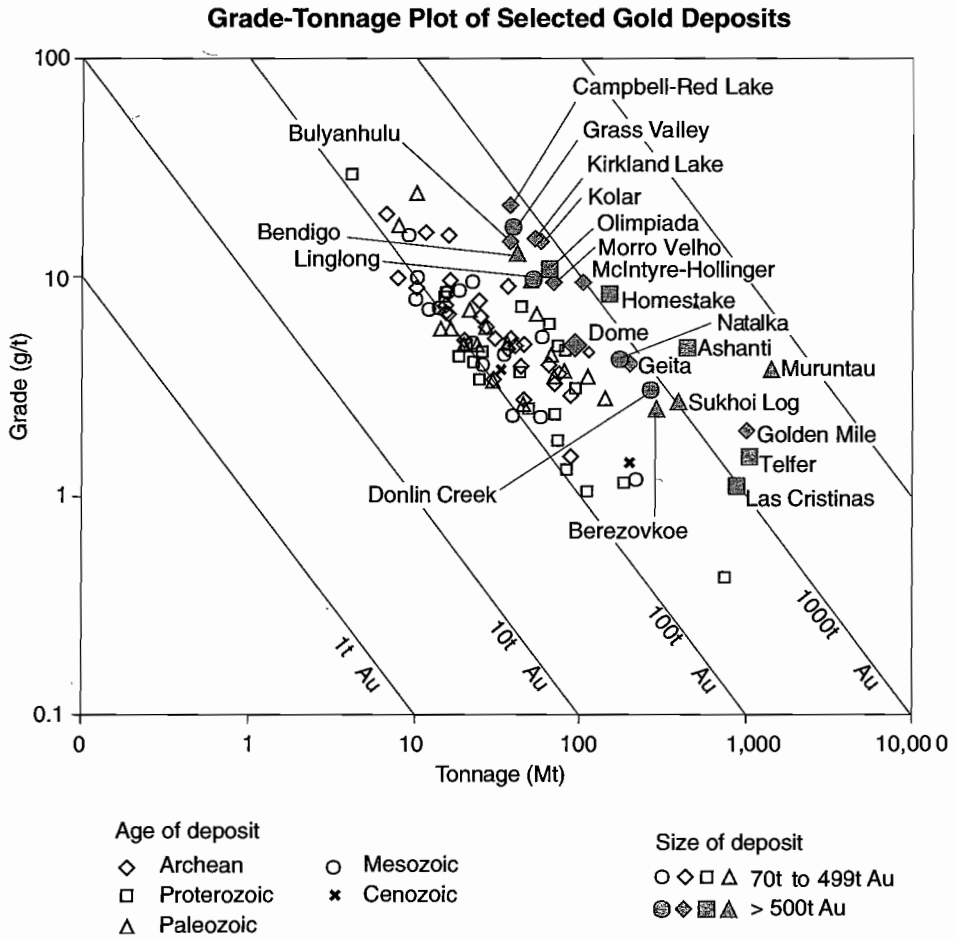
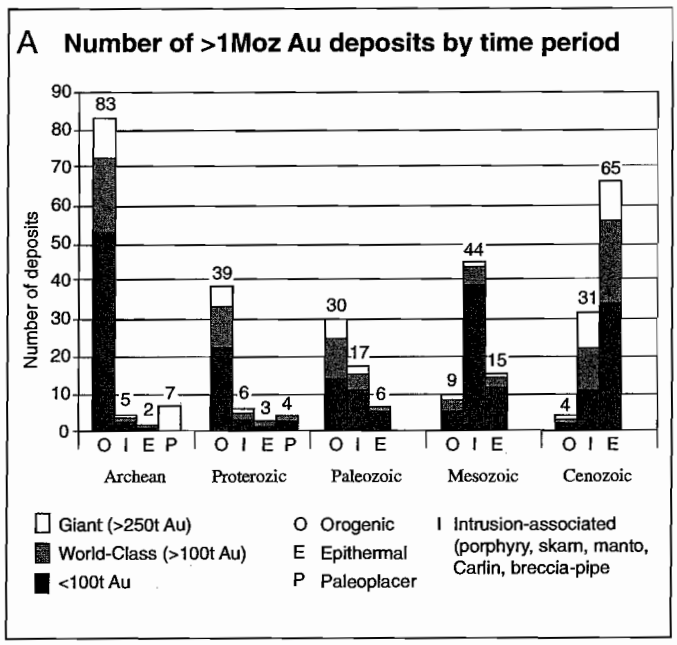


FIG. 6. Grade vs. tonnage for orogenic gold deposits and those deposits of controversial affinity (have been referred to as either orogenic or intrusion-related) that contain at least 70 t Au (production + reserves). These are subdivided by age. Data from Gosselin and Dubé (2005a).



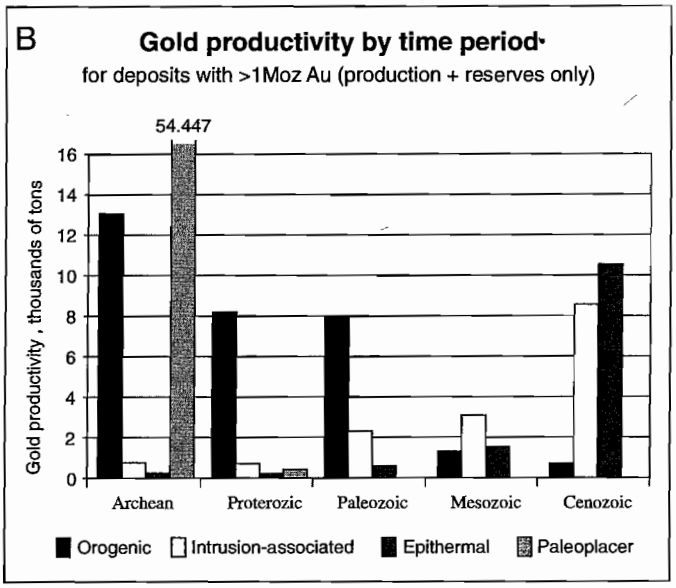


FIG. 7. A. Number of gold deposits containing at least 31 t Au as defined by time period and deposit type. B. Gold productivity by time period and deposit type. Data from Gosselin and Dubé (2005a).

of gold in placers developed from erosion of the circum-Pacific orogenic gold deposits.

Many uneconomic gold occurrences were transformed into significant gold resources and reserves during the previous 25 years, because of the peak in the gold price at the start of the 1980s, the move, in some cases, to open-pit mining, and metallurgical breakthroughs (i.e., heap leaching). Thus, long-recognized intrusion-related gold deposits and orogenic gold prospects have been put into production as world-class deposits (e.g., Fort Knox) or are being evaluated as giant resources (e.g., Sukhoi Log, Donlin Creek). At the same time, "mined-out" deposits are commonly being redeveloped for production from previously subeconomic zones. For example, gold ore was initially mined from the Golden Mile deposit at the start of the 1900s at average grades of 41 g/t, and mining from underground workings and small pits ceased in 1975. However, with the rise in the price of gold, alteration envelopes surrounding the previously mined high-grade lodes are now exploited at average grades of 2 to 3 g/t within the Fimiston superpit.

Regional Controls on Localization of Gold Districts

Structural environments

First-order regional fault zones: Most productive gold provinces in metamorphic belts are linked to major crustal structures, although the ores themselves are not directly hosted by these faults. First-order deformation zones, which are spatially associated with gold ores, include those of the Golden Mile adjacent to the Boulder-Lefroy shear zone (App. Fig. A2A), the Abitibi belt deposits alongside the Porcupine-Destor and Larder Lake-Cadillac breaks (App. Fig. A3, Fig. 8A, C), the Kolar mines with the major shear zones of the Champion Reef system, the Ashanti deposits along the Obuasi-Ashanti shear zone, the Yellowknife ores associated with the Campbell-Giant shear zone (Fig. 8B), Muruntau adjacent to the Tamdytau-Sangruntau fault system that may be a part of the continental-scale Turkestan suture (Yakubchuk et al., 2005, fig. 13), the Mother Lode deposits along the Melones fault zone, the Jiaodong deposits near the Tan-Lu fault system, and the Juneau gold belt deposits along the Fanshaw-Sumdum fault system (App. Fig. A4). Although many of these spatial associations have been noted for more than 50 years (e.g., Turneaure, 1955), it is only during the last 20 years that this relationship has been studied in detail.

The first-order, ore-controlling regional faults are typically several hundred kilometers in length by a few hundred meters in width. Many are not single faults but segmented structures that show multiple deformation events. They tend to be parallel to subparallel to volcanic stratigraphy in Precambrian greenstone environments and to accreted terrane margins in Phanerozoic settings. In the latter, they may commonly mark the collisional suture zones (e.g., Fig. A4), whereas in the older volcanic sequences they commonly occur between lithologic units (Kerrich and Wyman, 1990; Hodgson, 1993). The faults represent near-vertical, major crustal dewatering conduits (Kerrich, 1986) that likely become listric at depth within the mantle lithosphere (Wyman and Kerrich, 1988). They have a complex and long-lived structural history, which commonly begins as shortening and high-angle reverse motion, in some cases on older basin-forming faults, and subsequently changes to strike-slip motion, (Kerrich, 1989; McCuaig and Kerrich, 1998; Robert and Poulsen, 2001). This change in regional stress fields may be critical for fluid migration (Fig. 9; Goldfarb et al., 1991b) during extreme pressure fluctuations associated with major seismic events (Fig. 10; Sibson et al., 1988; Cox et al., 2001).

Lower order faults: The first-order faults, although conduits for the massive volume of auriferous fluids needed to form the world-class gold lodes, rarely host the ores; rather, second- and third-order faults are the sites of mineral deposition (Gunning and Ambrose, 1937; Robert et al., 2005, fig. 8).

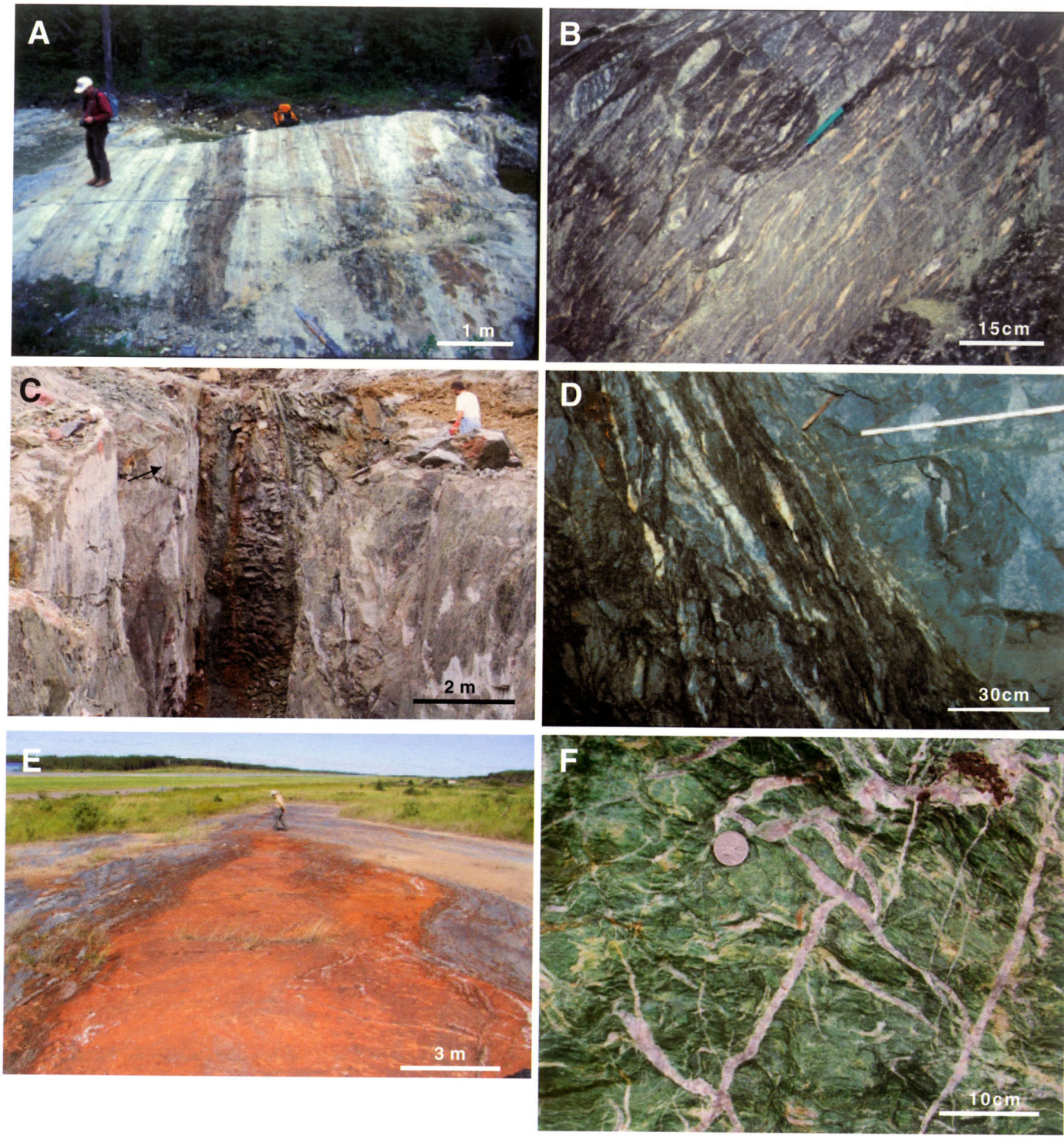


FIG. 8. A. Larder Lake-Cadillac fault zone, Val d'Or area. B. Campbell shear zone, Con mine, Yellowknife. C. Kirkland Lake Main Break, Kirkland Lake. D. High-angle reverse shear zone deforming a gabbro sill, Cooke mine, Chibougamau area, section view. E. Iron carbonate vein, Red Lake. F. Fuchsite-rich, green carbonate rock, Larder Lake area.

Fluid focusing into lower order faults is most effective in areas of jogs, changes in strike, or bifurcations of the first-order systems (Colvine et al., 1984; Weinberg et al., 2004b). Additional favorable areas with low or minimum mean stress zones include regional fault intersections, areas of regional uplift or anticlines, and zones of competency contrast (App. Fig. A5), such as along granitoid margins (Robert, 1989; Vearncombe et al., 1989; Groves et al., 2000). In compressional regimes, reverse faults in these zones (Fig. 8D) have the highest degree of misorientation (Fig. 10) and the highest

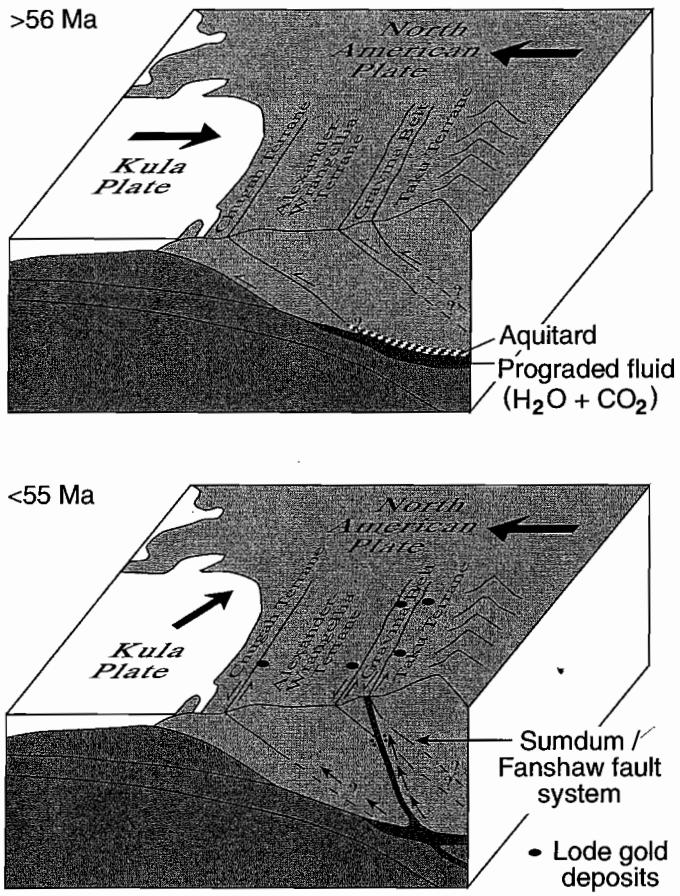


FIG. 9. Change in plate motions in the northern Pacific basin at ca. 56 to 55 Ma. This change from orthogonal (thrusting) to oblique (strike-slip motion) far-field stress was critical for seismicity, fluid migration, and gold deposition along the Sumdum-Fanshaw deep-crustal fault system of the Juneau gold belt. Modified from Goldfarb et al. (1991).

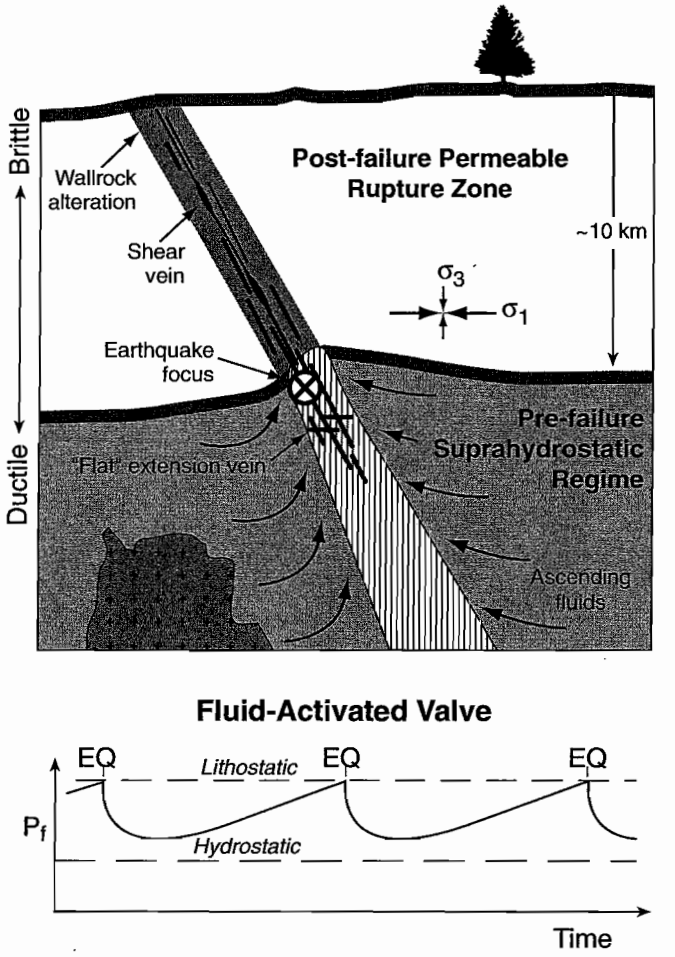


FIG. 10. Strong fluid pressure cycling near the base of the seismogenic zone will lead to episodic hydraulic fracturing and deposition of gold along high-angle reverse fault systems. After Sibson et al. (1988).

levels of fluid overpressure, making them most susceptible to a high fluid flux and the deposition of auriferous veins (e.g., Sibson et al., 1988). These mineralized splays are several tens of meters long by several meters wide, with the second-order faults generally parallel to the regional grain, whereas the smaller, third-order structures are oblique (Robert and Poulsen, 2001).

Mineralized bodies have a variety of geometries and styles, with brittle-ductile and ductile shears being more common ore hosts than extensional quartz carbonate vein systems. Most gold-bearing veins in metamorphic belts occur as fault-fill shears or fractures. Such veins are commonly laminated (Fig. 11A-D), in places contain breccia fragments or large blocks of wall rock, exhibit relatively high grade and elongate ore shoots, and mainly fill moderate- to steep-dipping faults. Less commonly, stacked fault-fill veins occupy shallow structures, such as in the Grass Valley district of the Sierra foothills, Victory-Defiance and Sunrise-Cleo deposits in the Yilgarn craton, Macraes Flat in New Zealand (Teagle et al., 1990), or Pogo in eastern Alaska (Rhys et al., 2003). Vein density is greatest near the centers of the shears or fault zones and decreases rapidly away from these structures (Cox et al., 1991). In many turbidite-hosted gold provinces, such as the Victorian goldfields (Cox et al., 1991; Phillips and Hughes, 1996) and the Meguma terrane (Kontak et al., 1990), veins are associated with faults in fold hinge areas.

Robert and Poulsen (2001) noted that extensional veins and vein arrays are overall of lower economic significance but can be important ore hosts in competent host rocks or in areas adjacent to fault-fill vein systems (Fig. 11A-B). These gently dipping vein types (Fig. 11E-F), with parallel planar walls and open-space filling textures, can occur as en echelon arrays, stacked planar veins, or isolated tabular veins (Hodgson, 1989). Finally, sheeted veins, stockworks, and breccia may also be common in competent rock types (Fig. 12A-D) and vary in geometry from well-ordered vein stockworks (e.g., Mt. Charlotte in the Golden Mile) to dense, more randomly ordered veinlet networks (e.g., Kensington in Juneau gold belt; Miller et al., 1995).

Chemical environments

Although structural traps localize gold deposits in many metamorphic terranes, particular lithogeochemistries are critical for concentration of gold ores in some provinces. Iron- or carbon-rich rocks along a flow path prove to be important sinks for the release of gold from hydrothermal solutions. In

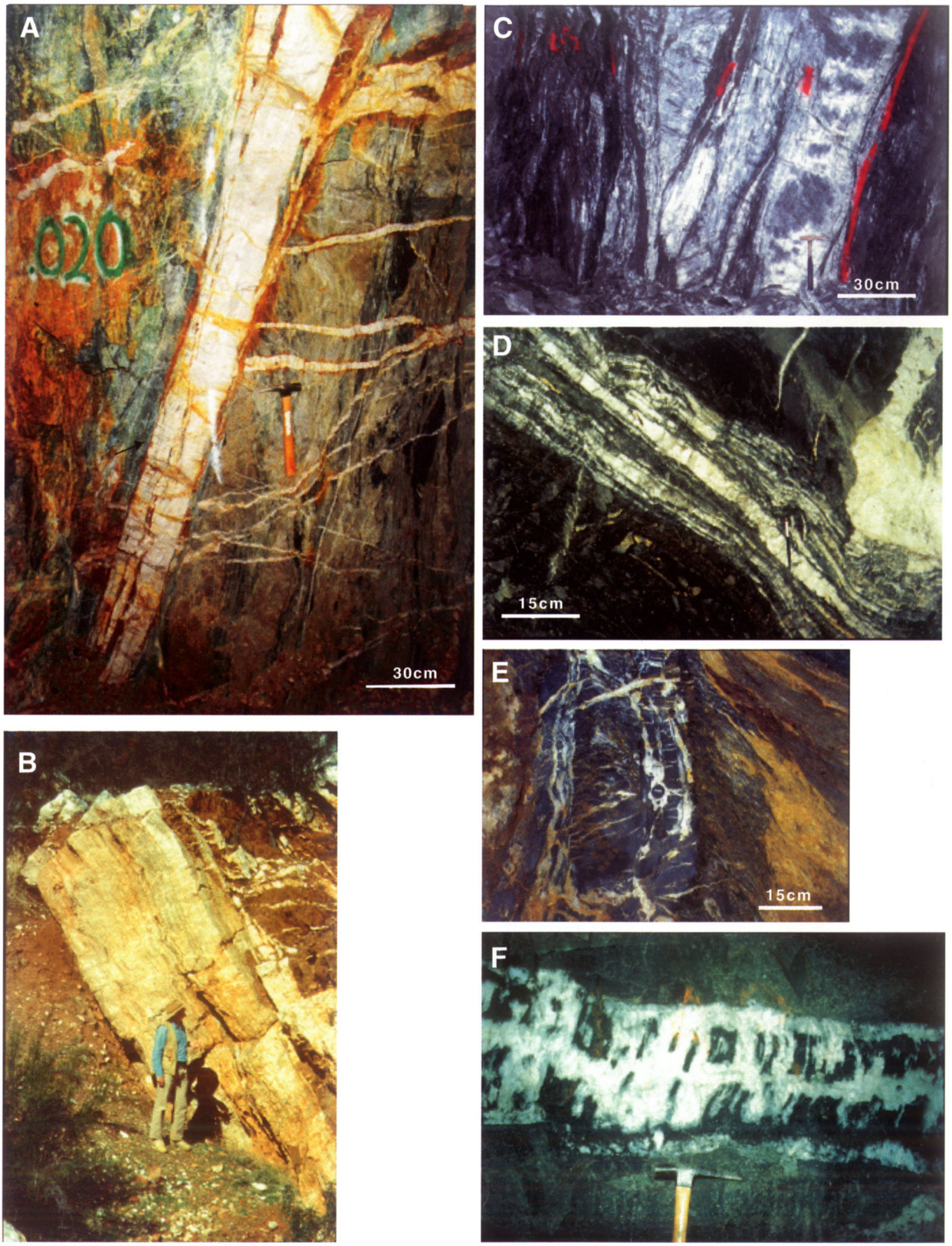


FIG. 11. A. Mother Lode fault-fill laminated vein with associated flat extensional vein, California. B. Mother Lode fault-fill laminated vein with associated flat extensional vein in iron-carbonatized hanging wall, California. C. Laminated fault-fill quartz vein, Con mine, Northwest Territories, Canada, section view. D. Bedding-parallel laminated fault-fill quartz vein, Bendigo, Australia. From Poulsen et al. (2000). E. Quartz-tourmaline vein, Clearwater deposit, James Bay, Quebec. F. Shallow-dipping quartz-tourmaline extensional vein, Sigma mine, Val d'Or, Quebec.

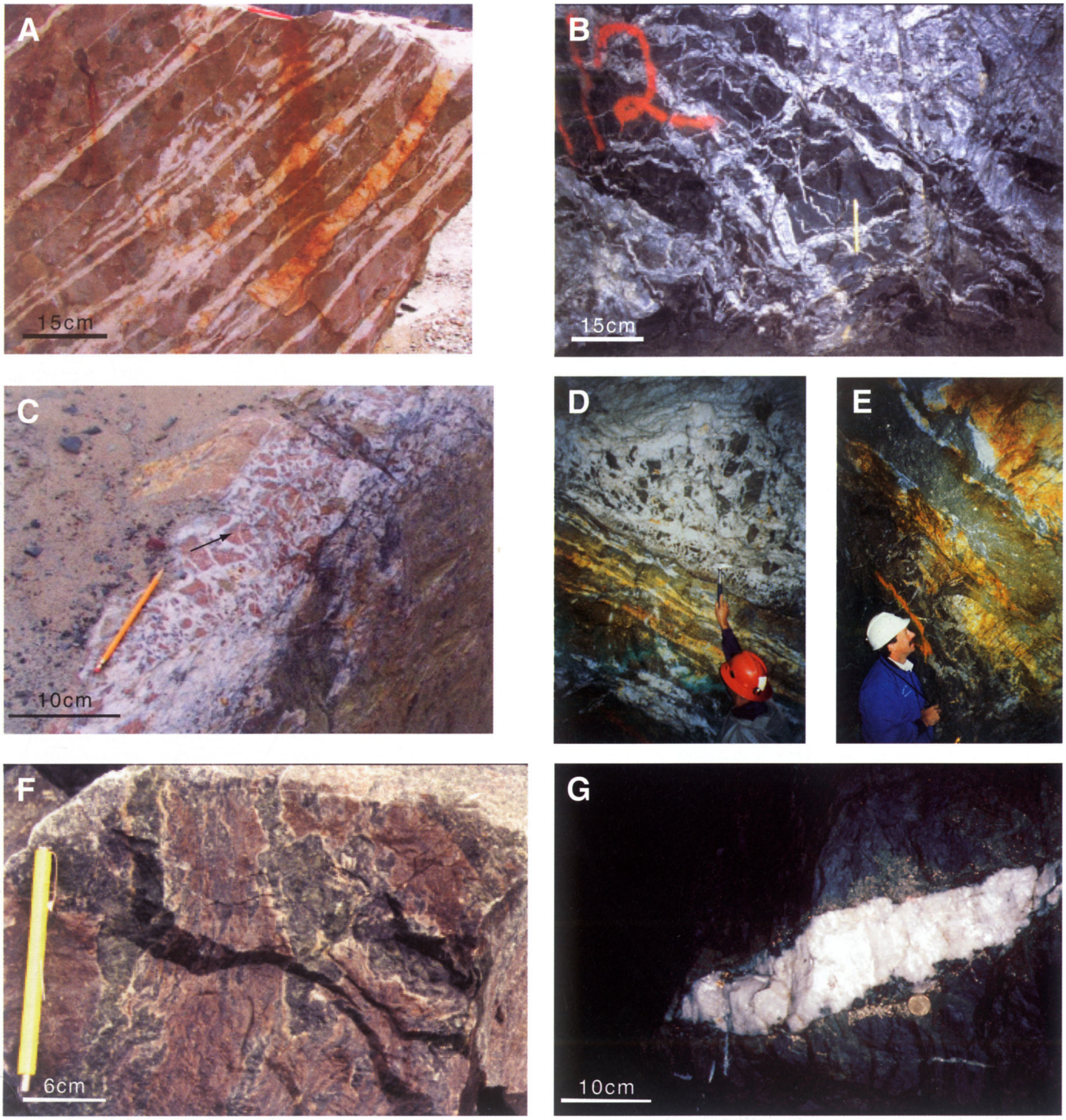


FIG. 12. A. Sheeted quartz vein in carbonatized Timiskaming conglomerate, Pamour mine, Timmins. B. Iron carbonate breccia vein, Red Lake mine, Ontario. C. Fault-fill breccia vein, Kirkland Lake. D. Kensington fault-fill breccia vein, Juneau gold belt. E. Kensington massive pyrite fault-fill vein. F. Amphibolite-grade replacement-style gold deposit, Madsen mine, Red Lake. G. Sulfidation along margins of quartz vein, Victory mine, Yilgarn craton.

many Phanerozoic sedimentary rock-dominant terranes, carbonaceous pelitic sequences serve as important reductants of the fluids and, thus, sites for high-grade epigenetic ores (Cox et al., 1991). Iron-rich tholeiites in Archean greenstone belts also form important ore sinks because of desulfidation reactions with the gold-transporting fluids (Fig. 12G). The iron-rich parts of the ore-hosting dolerites at the Golden Mile preferentially contain much of the gold resource (Phillips,

1986), and most of the ore in the Campbell-Red Lake deposit is hosted by basalt (Dubé et al., 2004).

Precambrian BIF are important hosts to orogenic gold deposits, and the disseminated style of mineralization suggested to many workers that these ores are syngenetic (e.g., Homestake: Sawkins and Rye, 1974; Morro Velho: Ladeira, 1991a; Lupin: Kerswill, 1993). However, the gold-bearing, disseminated- to massive sulfide-style strata-bound ores likely formed as epigenetic replacements in oxide-, sulfide-, or carbonate-facies BIF. For example, Phillips et al. (1984) showed clear macroscopic and microscopic evidence for an epigenetic origin of gold ores by sulfidation of BIF oxide facies at Mount Magnet. Fyon et al. (1983) and Poulsen et al. (2000) showed similar relationships for auriferous BIF in the Timmins camp and Lupin, respectively.

Thus, although structural environment certainly must be considered for focusing large fluid volumes, rock types of a specific chemical composition also can be targeted as favorable ore-hosting environments. In general, units that are characterized by high Fe/Fe + Mg ratios are good traps for epigenetic gold deposits (Böhlke, 1988). These rocks would most commonly include iron formations, iron-rich tholeiites, ferruginous shales, and some felsic igneous rock types. Previously iron-metasomatized rocks may also be important host rocks (e.g., Wallaby, Western Australia: Salier et al., 2004).

Relative timing of hydrothermal events

Most gold deposits within metamorphic belts formed late in the orogenic process, during the last increments of crustal shortening, but commonly postdating regional metamorphism of the host rocks (Boyle, 1975; Groves et al., 1984; Powell et al., 1991). However, the relative timing of gold ores to structural evolution in amphibolite and higher grade rocks is typically equivocal, and there are important examples where high-grade regional metamorphic events have overprinted gold ores (Challenger, South Australia, and Renco, Zimbabwe: Phillips et al., 2003). In some important provinces, multiple mineralization events (e.g., Golden Mile: Clout et al., 1990; Sigma-Lamaque: Couture et al., 1994; Muruntau: Kempe et al., 2001) make determination of a simple relationship between hydrothermal events and regional tectonic processes challenging (Groves et al., 2003).

Magmatism can predate, be relatively synchronous with, or postdate gold events. Where synchronous, strong arguments can, in some places, be made for classification of ores as intrusion-related gold deposits, with melts and fluids being derived from the same magma sources. Typically, however, magmatism occurs over a distinctly broader period than that representative of orogenic gold formation within an evolving orogenic belt. The ores of the Juneau gold belt in are mainly 56 to 53 Ma in age, whereas the majority of the magmatism forming the Coast batholith, located a few kilometers inland of the deposits, occurred between 70 and 55 Ma (App. Fig. A4; Goldfarb et al., 1997). In contrast, the ca. 125 Ma Mother Lode deposits formed at the start of a 30- to 40-m.y. period of magmatism immediately inland that marked the formation of the Sierra Nevada batholith.

In evolving metamorphic belts that show a characteristic D_1 to D_4 deformation sequence, gold deposits generally form during D_2 to D_4 deformation and perhaps 20 to 100 m.y. after sedimentation and submarine volcanism that led to formation of the country rock terranes (Groves et al., 2000). Combining the above D_2 and D_3 events, Robert and Poulsen (2001) simplified the deformation sequence into D_1 (low-angle, thin-skin thrusting, and related isoclinal folding), D_2 (thick-skinned horizontal shortening), and D_3 (strike-slip regime along preexisting regional shears). They argue that it is the high-angle D_2 reverse faulting that correlates with gold deposition. In contrast, Allibone et al. (2002) presented a D_1 to D_5 sequence in the Ashanti goldfields, with D_2 to D_3 and D_4 to D_5 correlating with D_2 and D_3 of Robert and Poulsen (2001), respectively. The Ashanti ores are interpreted by Allibone et al. (2002) to have formed during D_5 strike-slip motion, although in reactivated D_2 thrusts. Commonly it is the broadly constrained shift from high-angle reverse to strike-slip motion (e.g., the D_2 to D_3 transition using the D_1 to D_3 sequence of Robert and Poulsen, 2001) that is most favorable for voluminous fluid flux and ore genesis (e.g., Goldfarb et al., 1991b; de Ronde and de Wit, 1994; Bierlein et al., 2004). There are, however complications with any generalization as more than one terrane-deformation episode may correlate with gold-forming events that are tens of millions of years apart (e.g., Meguma terrane: Morelli et al., 2003).

Relationship to metamorphic grade

The spatial association of gold deposits with greenschist-grade belts within many Precambrian greenstone belts and Phanerozoic orogens has been well known for many decades (e.g., Boyle, 1979) and has been heavily stressed in the economic geology literature from the 1980s (e.g., Keays et al., 1989). Such a setting for the majority of the economic gold deposits in these metamorphic terranes (Table 3) is an indication of the ambient pressure-temperature conditions within the mid-crustal environments where the gold ores are precipitated (Bierlein and Crowe, 2000). The specific reason(s) for the gold-greenschist–grade association remains uncertain. Suggestions include: (1) the fact that a large fluid volume is created during the amphibolite and/or greenschist transition and is released into the greenschist zone, (2) the structurally favorable brittle-ductile zone lies just above this transition, (3) fluid focusing and phase separation are most likely to occur as fluids ascend into the greenschist facies pressure-temerature regime, and/or (4) gold solubility shows a sharp drop under greenschist facies temperatures (Phillips, 1991). Brittle shear or extensional fractures, and veins that fill them, will form more readily under the brittle-ductile conditions of greenschist grade than under those of middle to upper amphibolite grade, which may be a critical factor for the close association of vein-type ores with greenschist-grade rocks worldwide (F. Robert, writ. commun., 2005)

Many of the relatively young Cretaceous-Tertiary deposits in the metamorphic terranes of Alaska, in particular, highlight this consistent spatial association (Goldfarb et al., 1997). In the Juneau gold belt, all lode gold deposits occur within a few kilometers of two regional shear zones and solely within lower- to upper-greenschist facies rocks of a narrow (10–20 km), inverted Barrovian metamorphic sequence. Although the shears continue far to the south of the gold belt, there are no additional significant gold ores adjacent to the structures and they cut a more deeply unroofed part of the orogen; rocks

TABLE 3. Metamorphic Facies for Host Rocks for the 25 Largest Orogenic Gold Deposits (references for each deposit are included in electronic App. I)

Deposit name	Metamorphic facies of host rocks
Muruntau	Greenschist (muscovite-chlorite; 440-403 Ma); overprinted by contact mm cordierite, biotite, and andalusite porphyroblasts
Ashanti	Greenschist (chlorite-sericite; 2092 Ma)
Golden Mile	Greenschist (muscovite-chlorite; ≥2674 Ma)
Telfer	Lower to subgreenschist (ca. 700 Ma)
Homestake	Greenschist-amphibolite transition (1840 Ma)
Sukhoi Log	Greenschist (chlorite-sericite)
McIntyre-Hollinger	Greenschist (2677-2643 Ma)
Las Cristinas	Lower greenschist (chlorite)
Kolar	Middle to upper amphibolite
Campbell-Red Lake	Middle greenschist-lower amphibolite (2677-2643 Ma)
Kirkland Lake	Lower greenschist (2677-2643 Ma)
Donlin Creek	Unmetamorphosed to very low grade
Geita	Upper greenschist (≥2578±72 Ma)
Natalka	Greenschist (chlorite-sericite); contact overprint (cordierite, andalusite, pyrrhotite, ilmenite)
Berezovkoe	Greenschist
Olimpiada	Amphibolite contact facies
Grass Valley-Nevada City District	Greenschist
Morro Velho	Greenschist
Bulyanhulu	Greenschist (chlorite; 2700-2650 Ma)
Bendigo goldfield	Middle greenschist
Dome	Greenschist (2677-2643 Ma)
Linglong camp	High grade
Zarmitan	Greenschist/amphibolite
Sigma-Lamaque	Greenschist (biotite) to lower amphibolite (2677-2643 Ma)
Prestea	Greenschist (chlorite-sericite)

along the shears are generally amphibolite and granulite grade. The same spatial distribution characterizes the Valdez Creek district of central Alaska, where gold-bearing veins are localized within greenschist facies rocks of a narrow, well-developed Barrovian sequence. In terranes with broader metamorphic zones, similar relationships apply.

Examination of many significant Phanerozoic provinces further emphasizes localization of ores in greenschist-grade rocks. In the Victorian goldfields, most of the gold endowment is within gold systems in greenschist-grade rocks; large areas of subgreenschist and amphibolite facies turbidites are gold poor (Phillips et al., 2003). Deposits in the Meguma terrane occur in dominantly greenschist-grade rocks, although they are in areas of local contact metamorphism to slightly higher grade assemblages (Kontak et al., 1990). Lode gold deposits in the Bohemian Massif occur for 100 km along the sheared and intruded fault boundary between high-grade gneisses and migmatites of the Moldanubian block and greenschist-grade rocks of the Barrandian block. Exclusive of the Kasperske Hory gold deposits, the economically significant deposits are all located along the length of the margin of the greenschist-grade block within an inverted metamorphic sequence (Moravek et al., 1996; Bouchot et al., 2003). Auriferous Archean greenstone belts show the same patterns, with the majority of the productive gold lodes, including the giant Golden Mile and Hollinger-McIntyre deposits, in middle to upper greenschist-grade domains (Groves and Foster, 1991).

Studies in the 1990s began to point out that, although there was a typical greenschist-gold association, some significant orogenic gold deposits occur in higher or lower grade rocks. Colvine (1989) noted in the Abitibi belt that the Campbell-Red Lake, Dupont, and Musselwhite deposits were hosted in amphibolite-grade rocks. He emphasized that mineralogy and style varied between deposits in the different metamorphic zones and that this reflected differences in the pressure-temperature of the hydrothermal system, rather than a metamorphic overprint of selective deposits that all initially formed under relatively similar conditions (see below). In fact, epigenetic gold deposits in metamorphic belts seemed, as a rule, to have formed at temperatures that were quite similar to the maximum temperatures experienced by surrounding volcanic and sedimentary rocks during regional metamorphism.

This concept was further developed by Groves (1993), whose crustal continuum model for orogenic gold deposits summarized the changes in alteration, ore mineralogy, and structural style with varying metamorphic zones (Fig. 13). Within the Yilgarn craton, these included gold deposits from within subgreenschist- (e.g., Wiluna) to amphibolite-grade (e.g., Norseman, Frasers, Marvel Loch, Westonia) rocks. As many of these gold deposits formed during peak or just slightly postpeak metamorphism, those in greenschist rocks are typically of mesozonal character and in higher grade rocks are hypozonal in nature (Gebre-Mariam et al., 1995). Those ores of epizonal character occur in subgreenschist-grade rocks (e.g., Wiluna: Hagemann et al., 1992), in very low grade rocks, or even in broad unmetamorphosed tracts of accretionary orogens (e.g., Donlin Creek: Goldfarb et al., 2004).

Although orogenic gold deposits are hosted by metamorphic rocks and exhibit variable features with different metamorphic grades, ore formation most commonly postdates metamorphism of the immediate host rocks. This characteristic reflects the "deep-later" temperature-depth regimes that are inherent to Barrovian-type sequences in many collisional orogens (Stuwe, 1998). In such regimes, subduction, prograde metamorphism of the newly underplated material, and

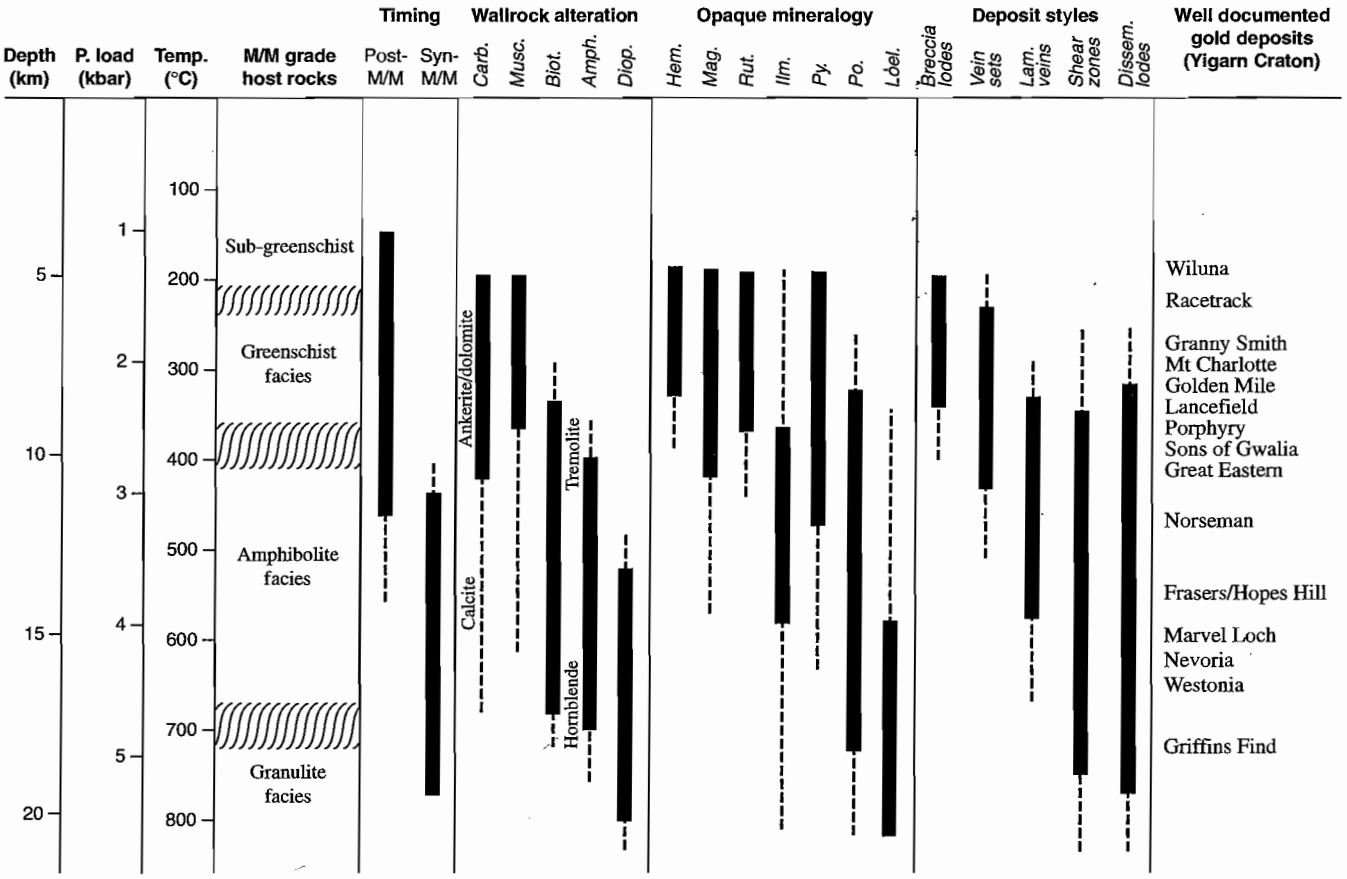


FIG. 13. Summary of features of the continuum model as applied to deposit examples from the Yilgarn craton. Features such as deposit style and ore and alteration mineral assemblages vary with pressure-temperature conditions of ore formation. These pressure-temperature conditions for the ore fluids also change with metamorphic grade of the country rocks. After Groves (1993). Abbreviations: Amph = amphibole, Biot = biotite, Carb = carbonate, Diop = diopside, Dissem = disseminated, Hem = hematite, , Lam = laminated, Lim = limonite, Loel = loellingite, Mag = magnetite, M/M = metamorphic, Musc = muscovite, Po = pyrrhotite, Py = pyrite, Rut = rutile.

significant magmatism all occur subsequent to metamorphism of shallower, overlying rocks defining older parts of the orogen. Thus, any deep-crustal hydrothermal fluids that advect through the crust will deposit gold ores in rocks already along retrograde pressure-temperature-time paths. Temporal patterns in most cratons and Phanerozoic slate belts show hydrothermal activity and magmatism to trail metamorphism of structurally thickened country rocks by 20 to 50 m.y. In areas, however, where gold formation is associated with crustal thinning and magmatic underplating (e.g., the "deep-earlier" concept of Stuwe, 1998), regional metamorphism and melt and/or fluid migration may be essentially coeval. Accretionary prisms that are subjected to ridge subduction are such an example (e.g., Chugach terrane, Alaska: Haeussler et al., 1995).

There are a minority of deposits that are exceptions to the above generalizations, reflective of the complex and multiple tectonic processes active during greenstone belt evolution and orogeny. The Big Bell deposit in upper amphibolite-grade rocks of the Yilgarn craton, the Kolar deposit in amphibolite-grade rocks of the Dharwar craton, and the Renco deposit in granulite-grade rocks of the Zimbabwe craton margin are controversial in regard to their relationship to metamorphic host rocks. Rather than gold ores formed under peak to postpeak metamorphic conditions, it has been suggested that these ores originally formed under greenschist, or slightly higher, grade on a prograde metamorphic path (Hamilton and Hodgson 1986; Phillips and DeNooy 1988; Phillips et al., 2003). The ores and country rocks are interpreted to have continued along a pressure-temperature-time path to higher peak metamorphic conditions, thus leading to the high-temperature mineral assemblages and mineralization styles. However, the documentation of postpeak metamorphism gold-hosting microstructures (Wilkins, 1993), the replacement of lowest amphibolite grade metamorphic minerals by hydrothermal minerals similar to those formed during uppermost greenschist conditions (Clark et al., 1989; Colvine, 1989), and the consistent rimming of loellingite by arsenopyrite (McCuaig and Kerrich, 1998) have led many workers to conclude that these deposits did not form on a prograde metamorphic path. Where there are multiple metamorphic events in a region, relationships are more complex but overprinting is much clearer (e.g., Challenger, South Australia: Tomkins and Mavrogenes, 2002).

In addition to deposits that appear in equilibrium with high-grade surrounding rocks, there are also a few important epigenetic gold deposits in such rocks that precipitated

gangue and metals at temperatures hundreds of degrees below peak metamorphic temperatures experienced by these rocks. The Pogo deposit in Alaska, with features of both intrusion-related gold deposits and orogenic gold deposits, is characterized by ores that show a brittle- to ductile-style deformation in high-grade orthogneiss and paragneiss. Geochronological constraints indicate ore formation about 15 to 20 m.y. postpeak metamorphism of the host rocks (Rhys et al., 2003). Gold deposits in the high-grade rocks of the North China craton, in provinces such as Jiaodong and Qinling, and also of controversial classification formed more than 1.5 to 2.0 b.y. subsequent to maximum metamorphic temperatures (Zhou et al., 2002). The Renabie deposit in the Abitibi belt is characterized by brittle-ductile features and mineralization assemblages that overprint gneissic features in Archean tonalite (Colvine, 1989).

Relationship to magmatism.

A spatial association between intrusions and orogenic gold deposits (i.e., gold hosted within, along the sheared margins of, or within a few kilometers of igneous rocks) in metamorphic belts has been long recognized (Emmons, 1933); in the last few decades, improved geochronological methodology has also shown there to be a distinct broad temporal association (Table 2; Goldfarb et al., 2001a). In fact, there are very few auriferous Archean greenstone belts or productive Phanerozoic orogens that contain gold provinces without nearby intrusions of roughly the same age. Whether or not any of these igneous bodies are the source of fluids and metals that become a part of the gold-forming systems is often a highly debated issue; the other obvious scenario is that both melts and fluids may be products of the same deep-crustal or even mantle-generated, thermal event.

The emplacement of batholiths, stocks, and sills and dikes is well documented in the literature as being coeval with the evolution of many lode gold districts. Most of the intrusions are felsic to intermediate in composition (e.g., Hodgson and MacGeehan, 1982; Cassidy et al., 1998). The common occurrence, however, of lamprophyres in productive gold districts (e.g., Rock and Groves, 1988) likely indicates involvement of deep mantle processes in the overall tectonic regime (e.g., Perring et al., 1989). There is little argument that the reported source of melts in auriferous parts of metamorphic belts can range from mantle magmas to bodies that are almost pure flysch melts. For example, many gold deposits are associated with both high to low Ca monzogranites to granodiorites in the Yilgarn craton (Cassidy et al., 1998), trondhjemite-tonalite-granodiorite complexes in Zimbabwe (Foster, 1989); both trondhjemite-tonalite-granodiorite systems and felsic porphyries in the Superior province (Card et al., 1989), Li-, F-, and B-rich leucogranites in the Massif Central (Bouchot et al., 2000), and S-type granites and granodiorites in the Chugach terrane of southern Alaska (Goldfarb et al., 1997). There is no single melt composition that has been identified as consistently associated with orogenic gold deposits. A more important association is the likelihood that both gold and many melts are controlled by the same high-order structural systems (e.g., Hodgson and Hamilton, 1989), as supported by the common en cornue shape of syntectonic plutons (Weinberg et al., 2004a).

Although most gold deposits in metamorphic belts are hosted by volcanic and sedimentary rocks, a significant minority of deposits are hosted by, or adjacent to, granitoids. For example, 25 percent of the gold deposits in the Abitibi subprovince are hosted by felsic intrusions, whereas such quartz-feldspar dikes and stocks are exposed over only 4 percent of the belt (Colvine et al., 1988). Almost 75 percent of the other Abitibi deposits have small porphyritic intrusions in their mined areas (Hodgson and Troop, 1988). Crosscutting relationships between dikes and mineralization have led to suggestions that magmatism continued from pre- to postore times (e.g., Kerr Addison deposit: Poulsen et al., 2000; Campbell-Red Lake: Dubé et al., 2004). Commonly, regional deformation is an ongoing process during the magmatism and hydrothermal activity, such that ore-bearing veins may cut both deformed and undeformed igneous rocks in a given gold province (e.g., Peters and Golding, 1989).

Pre-ore igneous bodies, within or adjacent to major structures, provide critical competency contrasts in the metamorphic belts (App. Fig. A5; Groves et al., 2000). In southern Alaska, such igneous bodies can be ≥50 to 100 m.y. older than (Juneau gold belt), 10 m.y. older than (Willow Creek), or essentially coeval with (Chugach terrane) the orogenic gold deposits that they host. Such granitoids are also tens of millions of years older than their contained gold resources in most Precambrian terranes (e.g., Cassidy et al., 1998). Although some important orogenic gold deposits may be in reverse shears that overprint igneous bodies (e.g., Sigma: Robert and Brown, 1986) or along shears that transect major igneous complexes (e.g., Linglong: Qiu et al., 2002; Charters Towers: Peters and Golding, 1989), the sheared margins of stocks are typically the most prospective zones (e.g., Bourlamaque batholith, Sigma-Lamaque: Robert, 1994; Tarmoola: Duuring et al., 2001). Where large batholith complexes define a massive magmatic arc, the exterior (seaward) margins of the batholith tend to be favorable for vein development (e.g., Willow Creek district: Goldfarb et al., 1997; Pataz district: Haeberlin et al., 2004). There are some deposits where gold veins occur in the roof of a coeval pluton (e.g., Salave, Fort Knox, Timbarra) and this characteristic has been used as one important criterion to classify such deposits as intrusion-related gold deposits.

Examples of lode gold provinces in metamorphic rocks without spatial and temporal associations with igneous rocks are rare. The Otago region on the eastern side of the South Island of New Zealand is perhaps the best example of such, where the Haast schists lack any melts that are coeval with the Late Jurassic-Early Cretaceous gold (e.g., Macres Flat: Craw, 2002). The closest known significant igneous rocks of overlapping age are hundreds of kilometers west in the Fiordlands region of the island, but these rocks were probably emplaced into their different host terrane before amalgamation of the South Island and at a time when the gold-bearing rocks were far to the north (Goldfarb et al., 2001a). Crustal temperatures during Barrovian metamorphism of the Haast schist obviously reached values capable of causing widespread medium-grade metamorphism, but extremely high (>600°–700°C) temperatures were never experienced by any areas of the presently exposed crust.

Deposit Geology

Mineralization styles and orebody dimensions

Gold deposits in metamorphic belts can show a variety of styles (Fig. 13; Robert et al., 2005, fig. 8), which, to a large degree, relate to overriding ductile, brittle-ductile, or brittle regimes. Under brittle conditions, mineralization is dominated by stockworks and breccias (Fig. 12B-D) that reflect cataclastic deformation; in igneous rocks (i.e., Fort Knox) or hornfels (i.e., Mt. Todd), sheeted-vein systems may also be characteristic (Fig. 12A). Relatively undeformed quartz grains tend to show anhedral features in metasedimentary host rocks but are commonly euhedral in more competent igneous hosts (Dowling and Morrison, 1989). Microstructures may include stylolites, fault gouge, and spider veinlets. Laminated crack-seal quartz carbonate veins, most commonly discordant (Fig. 11A-B) but in places concordant (Fig. 11D), and sigmoidal vein arrays are common under higher pressure-temperature, brittle-ductile conditions. The crack-seal textures are indicative of hydraulic fracturing during multiple fluid-flow events. Numerous vein types have been distinguished by Hodgson (1989) and Robert and Poulsen (2001), such as those occurring in shears (i.e., central shear, oblique shear); as fault-fill veins, extensional vein systems (i.e., between shears, as en echelon gash veins), oblique-extension veins, vein stockworks, and breccia veins; and within anticlinal hinges (i.e., saddle reef, leg reef, neck). Boudinage and folding of some veins reflect their prekinematic to, more commonly, synkinematic timing (e.g., Alaska-Juneau, Yellowknife, Bendigo, Meguma). In the highest pressure-temperature environments (≥400°C and 2.5 kbars), mineralization styles are dominated by ductile deformation within broad shear zones, a dominance of bedding-parallel deformed veins, replacement textures (Fig. 12F), and common disseminated lodes (e.g., Groves and Phillips, 1987). Quartz grains are characteristically highly recrystallized.

The above changes in gold mineralization style correlate with both variations in pressure-temperature conditions of host rocks and related change in metamorphic grade (e.g., the crustal continuum model of Groves, 1993; Fig. 13); the textures of vein quartz also vary with depth (Vearncombe, 1993). For example, in the Abitibi belt, deposit styles change from brittle breccias and lodes in lower greenschist-grade rocks at Kirkland Lake, to brittle-ductile laminated veins in the middle to upper greenschist-grade rocks at Sigma, and to vein-poor, foliation-parallel mineralization along ductile shears in the amphibolite-grade rocks of the Red Lake area (Colvine, 1989). Changes in structural regime at the same depth, with fluctuating brittle to ductile conditions, can even commonly lead to different ore styles in adjacent parts of the same orebody. The adjacent Jiaojia (disseminated) and Linglong (brittle vein) styles of gold deposits in the Jiaodong peninsula of eastern China (Qiu et al., 2002) are such an example, as are parts of the Dome and Kerr-Addison deposits in the Abitibi belt, and of the Mother Lode belt in central California, which may contain as much as 10 percent disseminated pyrite lodes. In the lowest metamorphic grades, brittle styles and vein textures may, in places, resemble those commonly characteristic of epithermal precious metal veins in unmetamorphosed rocks. For example, gold deposits in the Yilgarn craton (e.g., Mount Pleasant, Wiluna) may show open-space filling features that include comb, cockade, crustiform, and colliform textures, with precursor chalcedony (Gebre-Mariam et al., 1993). Despite these textures that also are characteristic of epithermal vein deposits, it is important that these local features do not lead to misclassification of the system as a low-sulfidation epithermal deposit (e.g., Fimiston ores, Golden Mile: Bateman and Hagemann, 2004). Also, within a single metamorphic grade, more competent granitoid host rocks may show more brittle vein features, whereas adjacent country rocks could concentrate ores in more ductile structures (Cassidy et al., 1998)

Masses of high-grade, gold-rich rock occurring along shears, bedding, or lithologic contacts define geometric and kinematic ore shoots (e.g., Peters, 1993; Robert et al., 1994; Robert and Poulsen, 2001). Changes in strike of orebodies, contacts between rock types, structural intersections, or dilation at high angle to the slip vector can all generate such ore shoots in large dilational zones. The resultant ore shoots may reach lengths of >1 km, continue downplunge for as much as 0.5 km, and have a typical mass of 2×10^4 to 1×10^6 t (Peters, 1993). Replacement-style orebodies may define some ore shoots that occur over widths of as much as 60 m.

Gold orebodies in metamorphic rocks are relatively extensive both along strike and downdip. Single veins, or more commonly groups of veins, are generally continuous for hundreds of meters. Individual, giant gold deposits may continue along strike for as much as 2 to 5 km. In India, the shear zone that hosts the productive Champion Lode at Kolar has been mined along an 8-km strike length (Radhakrishna and Curtis, 1999). Widths of individual veins vary from meters to tens of meters, although entire deposits may be wider than 1 km (i.e., Dome, Hollinger-MacIntyre, Golden Mile, Muruntau). Many of the most productive orebodies exceed 1 km in vertical extent, with little change in gold grade or gold fineness with depth. The largest gold deposits in metamorphic belts have been economically mined to depths of 1 to 3 km (e.g., Sigma-Lamaque, Kirkland Lake, Hollinger-McIntyre, Campbell-Red Lake, Golden Mile, Kolar, Bralorne-Pioneer). Theoretically, the entire hydrothermal system developed within a deep-crustal fault zone and might occur in such over a depth range of 10 to 15 km (e.g., Colvine, 1989), although economic ores only are present over a small part of the range. The orebodies commonly occur in belts, as districts, being somewhat regularly spaced along a zone many hundreds of kilometers long and several tens of kilometers wide that delineates a regional fault system or a group of such subparallel faults. The spacing may reflect focusing of crustal fluid-flow cells into structurally favorable zones, such that there are large areas lacking any mineralization or hydrothermal alteration between the orebodies and their surrounding altered rocks (e.g., Goldfarb et al., 1986; Paterson, 1986; Weinberg et al., 2004a).

Ore mineralogy and paragenesis

The ore mineralogy of lode gold deposits in metamorphic belts is consistent and predictable among most deposits, with variations mainly reflecting the more complex mineralogy of many intrusion- or hornfels-hosted ores (Bierlein and Crowe, 2000) or temperature and depth of ore formation (Groves, 1993). Abundance of sulfide minerals in quartz carbonate

veins or altered wall-rock ranges from trace amount, particularly in the intrusion-related gold deposits, to a maximum of 3 to 5 vol percent within most orogenic gold deposits. Locally, however, massive sulfide clots (Fig. 12E-G) may be present in some veins or replacement zones, and BIF-hosted ores can, in places, show total replacement of much of the original iron-rich minerals by sulfide grains (e.g., Lupin: Bullis et al., 1994).

Arsenopyrite is the dominant sulfide mineral in deposits that are hosted by metasedimentary rocks, whereas pyrite is the most common sulfide phase in deposits hosted by mafic rocks and granitoids. At temperatures above about 400°C, loellingite and pyrrhotite may dominate over arsenopyrite and pyrite, particularly in the more reduced hydrothermal systems. An abundance of arsenopyrite in the Salsigne gold deposit in the French Massif Central, mined out in 1998, made it the world's leading producer of arsenic for many years (e.g., Le Guen et al., 1992). Stibnite is a common sulfide phase, typically late in the paragenesis, in deposits hosted by metasedimentary rocks (e.g., West Gore, Meguma terrane; Hillgrove, New South Wales; Reefton, South Island, New Zealand). Provinces of epizonal orogenic gold deposits may characterize low-grade metamorphic rocks (i.e., Kuskokwim basin, southwestern Alaska; Melbourne zone, Victoria). These deposits may also be enriched in mercury, reflecting the association of Hg, as well as Sb, As, and Au, with sulfur ligands in low-salinity hydrothermal fluids. In deeper, higher temperature deposits, anomalous mercury is also reported, typically concentrated in sphalerite and/or sulphosalts (Boyle, 1979). The base metals are generally present in trace amounts, being economically insignificant geochemical anomalies (Kerrich and Hodder, 1982). Platinum-group elements are reported to be anomalous in many deposits, in Archean greenstone belts (e.g., Dome: Fryer et al, 1979), Proterozoic iron formations (e.g., Caue, Brazil: Olivo et al., 1995), and Phanerozoic orogens (e.g., central Asia and eastern Russia: Wilde and Bierlein, 2003), and these enrichments may be a consequence of the interaction of the gold-transporting fluids with mafic oceanic rocks.

Tungsten, predominantly in the form of scheelite, is characteristic of deposits hosted in igneous or metasedimentary rocks that are not strongly reduced. The tungsten has been recovered in some deposits (i.e., central Otago lodes, New Zealand; Hollinger-McIntyre, Abitibi subprovince; Moose River, Meguma terrane). Tellurium- and bismuth-bearing mineral phases are widely recognized in many deposits. Along with tungsten-bearing minerals, these minerals are notably enriched in the intrusion-related gold deposits (Thompson et al., 1999), although tellurides and bismuthinides also can be conspicuous within orogenic gold deposits (e.g., Boyle, 1979; Kerrich and Hodder, 1982). In general, most lode gold deposits in metamorphic belts are anomalous in W, Te, and/or Bi (Goldfarb et al., 2000; Groves et al., 2003). In igneous rocks, Bi-dominant mineral phases are most common (e.g., Freda-Rebecca, Zimbabwe); in metasedimentary host rocks, bismuth most typically correlates with anomalous lead, suggesting substitution of bismuth into the galena structure. Tellurides are commonly gold rich in granitoid host rocks, but the fact that this association occurs in pre-ore and syn-ore granitoids indicates a spatial, rather than solely genetic, relationship. Tellurides are also not unusual in many nongranitoid-hosted ores (e.g., Golden Mile). Very minor amounts of molybdenite are found in some gold orebodies hosted by granitoids (e.g., Kirkland Lake, Treadwell) and more significant quantities in some anomalous deposits (e.g., Hemlo).

Most lode gold deposits in metamorphic rocks have Au/Ag ratios of 5/1 to 10/1. Ratios typically do not change significantly with depth nor is there any other distinct metal zoning with depth, unlike the characteristics of epithermal gold deposits. Boyle (1979) suggested that ratios of about 5 characterize Precambrian deposits, whereas a slightly lower ratio of about 3.5 is common for Phanerozoic ores. Gold fineness typically averages 920 to 940, with higher, more consistent values and a narrower overall range than VMS, porphyry, and epithermal gold deposits (Morrison et al., 1991). High gold grades commonly appear to be associated with carbonaceous rocks, and carbonaceous material in many quartz carbonate veins is the site of much of the visible gold in hand samples or microscopic studies. The high-grade ores are not necessarily associated with greatest abundances of sulfide minerals. The gold can occur in the quartz carbonate veins, in alteration halos surrounding barren to low-grade quartz carbonate veins (i.e., Hollinger-McIntyre), or in both environments (i.e., Sigma-Lamaque, Campbell-Red Lake, Mother Lode, Golden Mile), depending on the ore precipitation mechanism

Paragenetic descriptions traditionally describe gold as late in the vein formation and, in fact, some workers argue that there may be a consistent separate, second hydrothermal event in these systems as a whole (e.g., "Variscan-type" gold deposits: Vallance et al., 2004). However, although gold occurs consistently in late fractures cutting sulfide grains and gangue phases, this most likely reflects local remobilization of the ductile metal during subsequent deformation and/or vein recrystallization (e.g., Romberger, 1986; Mumin et al., 1994; Dubé et al., 2004). This is not surprising given the long-lived period of deformation and uplift during which the gold ores have been exhumed. However, in epizonal systems, some gold may have precipitated late with stibnite as the hydrothermal system cooled below about 200° to 220°C (i.e., Wiluna: Hagemann et al., 1992; Donlin Creek: Goldfarb et al., 2004). Cathelineau et al. (1989) suggested an early stage of native gold and a second, low-temperature (170°–250°C) deposition of gold-rich arsenopyrite in deposits of the European massifs. In some relatively high temperature orogenic gold and intrusion-related gold deposits systems, scheelite may be part of a pregold, calc-silicate–forming event (e.g., Uspensky et al., 2000; Mair et al., in prep.).

The gangue phases in most gold deposits in metamorphic rocks are identical to the more proximal alteration phases described in detail below. Quartz, albite, white mica/fuchsite/roscoelite, chlorite, tourmaline, biotite, and carbonate minerals are most common in gold orebodies. Carbonate, the most abundant gangue phase after quartz, rarely exceeds 5 to 15 vol percent of the gold-bearing veins. Oxidized hydrothermal phases, such as magnetite, hematite, and/or anhydrite, are present in some large orebodies (i.e., Golden Mile, Kirkland Lake, Renabie, North China craton deposits, Campbell-Red Lake). Very minor monazite, xenotime, and rutile have proven to be important mineral phases for which to apply modern dating techniques (e.g., Ayer et al., 2003; Vielreicher

et al., 2003). Graphite and amorphous carbon are reported from deposits in relatively reduced wall rocks.

Hydrothermal alteration

Hydrothermal alteration assemblages in wall rocks that host orogenic gold deposits and intrusion-related gold deposits reflect the interaction of an H_2O-CO_2-H_2S ($\pm CH_4$ and N_2) fluid with different rock types at various temperatures (e.g., Böhlke, 1989; Ridley and Diamond, 2000). Because fluids that form orogenic gold deposits are typically in equilibrium with the dominant rock types of their host terranes, having formed close to the ambient metamorphic pressure-temperature conditions (Boyle, 1961; Goldfarb et al., 1986; Clark et al., 1989), alteration halos are commonly relatively cryptic, and they are less well developed than in many other hydrothermal mineral deposit types. Such alteration is particularly subtle in clastic metasedimentary hosts because these rocks are typically less reactive. An exception is that alteration may become better developed where fluids interact with a chemically anomalous lithology in the ore-hosting terrane (i.e., a granitoid in a slate belt or an iron formation). The alteration minerals generally overprint metamorphic mineral phases.

In greenschist facies rocks, alteration is dominated by a variety of carbonate phases (Figs. 8E, 11B, 12B), sulfide minerals in the form of pyrite (Fig. 12G), pyrrhotite, or arsenopyrite, and alkali metasomatism that leads to formation of sericite, biotite, albite, and/or chlorite. The latter metasomatism is, however, notably absent in BIF-hosted gold deposits due to insufficient aluminum for the stabilization of any potassium-bearing phases (Phillips and Powell, 1992). Geochemical analyses, as well as mineralogical observations, support the addition of sulfur, H_2O, and CO_2 into wall rocks surrounding the orebodies. Although quartz veinlets and silicification are common features of most orebodies, the silica may just be remobilized, rather than having been added from the hydrothermal fluids, particularly given its retrograde solubility relative to temperature. Major element and lithophile components, such as K_2O, Na_2O, Rb, Sr, Li, Cs, Tl, and Ba, are reported to be enriched in places (e.g., Kerrich, 1989) but this seems to be a consistent pattern only for K_2O.

Ankerite and/or ferroan dolomite, with pyrite and gold, is the dominant carbonate in middle greenschist-grade wall rocks where initial molar Fe/(Fe + Mg) $\geq$0.5, whereas for lower ratios, almost all iron is incorporated into the magnesite-siderite series of carbonates. This is important because, in the latter case, there is no pyritization of iron-bearing mineral phases and this hinders deposition of disseminated gold orebodies via desulfidation reactions (Böhlke, 1988). In other words, degree of sulfidation and volume of disseminated gold are not proportional to total iron content of the rocks, and even low iron rock types such as metasedimentary rocks, granitoids, and intermediate volcanic rocks can be characterized by such ankerite formation and pyritization (Böhlke, 1988, 1989). Similarly, magnesium-rich rocks, such as ultramafic bodies and some argillaceous metasedimentary units, are unlikely to undergo pyritization and thus will not contain disseminated-style mineralization. Except in felsic rocks, calcite is rarely stable with ore-stage minerals proximal to the orebodies; rather, it is stable in distal parts to the alteration, where lower water/rock conditions prevail and/or as lower temperature barren veins superimposed on older orebodies and proximal alteration zones. In many turbidite-hosted gold deposits, carbonate porphyroblasts and patches are well developed in proximal alteration zones (Bierlein et al., 1998). In some relatively reactive rock types, extensive replacement may be dominated by pervasive carbonatization, such as that forming the so-called "lapa-seca" rock in the Quadrilatero Ferrifero ores (e.g., Morro Velho: Lobato et al., 2001). Broad zones of carbonate alteration, commonly an early product of the hydrothermal system, may also increase the competency of the country rocks and enhance brittle fracture and gold veining (e.g., Poulsen et al., 1986).

The width of alteration halos surrounding a given vein can vary from a few centimeters to several kilometers (Colvine, 1989; Eilu et al., 1998), depending on rock type, orientation of bedding relative to a vein, metamorphic grade, permeability, and porosity (Bierlein and Crowe, 2000). The widths generally show little variation along strike unless one of these variables changes significantly. Repeated deformation along part of an ore-forming structure may generate areas of increased fracture permeability and can locally widen segments of halos (e.g., Christie and Brathwaite, 2003).

Proximal alteration zones ($\leq$50 m) in middle greenschist facies and lower grade rocks are commonly strongly bleached, due to the sericitization of feldspars, breakdown of metamorphic chlorite, and rarely the presence of kaolinite, although this latter phase may be of secondary origin (e.g., Phillips et al., 2003). The most common assemblage in proximal alteration zones in greenschist-grade sedimentary and mafic igneous rocks is ankerite and/or dolomite-quartz-muscovite-pyrite $\pm$ paragonite, arsenopyrite, albite (Eilu et al., 1998). Sericite and muscovite are notably K or Na rich closest to the lodes; they become more phengitic (Mg or Fe rich) at greater distances (e.g., Christie and Brathwaite, 2003). Chlorite may or may not be stable, in places having been replaced by tourmaline. In ultramafic rocks, talc and fuchsite (Fig. 8F; or related Cr- and V-bearing micas) occur rather than muscovite, and siderite and magnesite are the main carbonates. Biotite forms with, or in lieu of, sericite in many deposits hosted in uppermost greenschist-grade rocks.

More intermediate zones of alteration, extending as far as 100 m from gold orebodies and with an inner boundary marked by the outer edge of bleaching (Eilu et al., 1998), are characterized by more stable metamorphic minerals, such as albite and chlorite, and a lesser degree of sericitization. Calcite may be present along with the Fe- and Mg-bearing carbonates. Sulfide minerals are rare. The most distal alteration, identified by mainly secondary chlorite, calcite, quartz and epidote, lacks hydrothermal sulfide minerals, dolomite and/or ankerite, and white mica or fuchsite. Any preexisting primary or metamorphic albite, K-feldspar, amphibole, and magnetite are likely to be preserved and easily recognized. Hydrothermal calcite may define the outermost boundary of altered rocks to an orebody (Eilu et al., 1998).

For slightly hotter fluids (400°–500°C) present in upper greenschist-grade rocks, biotite becomes as important as, or dominates over, white mica (i.e., Muruntau, Alaska-Juneau, eastern Campbell-Red Lake). Pyrrhotite also is more widespread than pyrite. The occurrence of pyrrhotite correlates with the typical absence of tellurides in ore zones, reflecting

the limited solubility of tellurium in reduced ore fluids at sulfur fugacities above the pyrrhotite-pyrite buffer (Afifi et al., 1988). Calcite is commonly an additional stable carbonate phase. Potassium-feldspar occurs not only in the wall rocks but also within auriferous quartz veins, leading to their description as "peg veins" in some intrusion-related gold deposits (e.g., Fort Knox).

In the minority of gold deposits that occur in amphibolite-grade rocks, alteration assemblages reflect interaction of a higher temperature (≥500°C) fluid with country rocks (Colvine, 1989; Ridley and Barnicoat, 1990; Mueller and Groves, 1991). Halos themselves are much narrower than those in greenschist-grade rocks; maximum widths to the outer edge of the distal zones may be only 10 m (Eilu et al., 1998). Amphibole, garnet, and diopside are common silicate alteration phases adjacent to the ductile orebodies in these rocks and calcite is the stable carbonate phase. Biotite continues to be a stable alteration phase under lower amphibolite-grade conditions; a 10-m-wide biotite halo surrounds ore at the Kolar deposit (Hamilton and Hodgson, 1986). Under higher temperature conditions, biotite is only recorded in the distal parts of the alteration halos. Calcic plagioclase and K-feldspar may be parts of the alteration assemblage, particularly in lower amphibolite rocks, whereas albite is no longer stable. Pyrrhotite and loellingite, in places rimmed by arsenopyrite, are the stable sulfide phases developed within the inner zones to these lower sulfur-fugacity hydrothermal systems.

Geochemical Characteristics of Orogenic Gold Deposits

Stable isotopes

The uniformity in measured oxygen isotope composition of orogenic gold-forming hydrothermal systems (App. Table A2) has been well documented (Kerrich, 1987; Nesbitt, 1991). Estimates for ore-fluid $\delta^{18}O$ values range between 6 to 11 per mil for the Precambrian (McCuaig and Kerrich, 1998) and 7 and 13 per mil for the Phanerozoic (App. Fig. A6; Bierlein and Crowe, 2000). The slight variation between ranges probably reflects differences in the lithogeochemistry of fluid source areas and/or of units along fluid pathways, with some of the spread in each range due to uncertainties in temperature estimates for quartz deposition and/or fractionationation during fluid unmixing events. These data are most typically interpreted to suggest that isotopically heavy fluids originated within the middle to deeper levels of the crust and were channeled upward.

Nesbitt et al. (1986) and Nesbitt (1990) argued alternatively that isotopically light meteoric waters would freely circulate downward from the upper crust under relatively low water/rock ratios, would be shifted in $\delta^{18}O$ by 25 to 30 per mil, and thus would obtain isotopic compositions characteristic of the greenstone and metasedimentary host rocks. Such a hypothesis was mainly invoked to help explain very light δD measurements of fluid inclusion waters from auriferous quartz but which are themselves of questionable significance (see below). There are, however, rare examples where isotopically light $\delta^{18}O_{quartz}$ measurements suggest that surface waters may have mixed with deeper aquo-carbonic crustal fluids in gold-forming hydrothermal systems (e.g., French Massif Central: Fourcade et al., 2000; Omai deposit, Guiana Shield: Voicu et al., 1999). In the Yilgarn province, Hagemann et al. (1994) calculated $\delta^{18}O_{fluid}$ values of about 3 to 4 per mil for the Late Archean epizonal Wiluna deposit and suggested that these values may indicate Archean meteoric water involvement, but subsequently Hagemann and Luders (2003) stated that isotope data do not support significant surface water influx.

Hydrogen isotope analyses, for identification of fluid sources, have been interpreted in a variety of ways, with controversy in the late 1980s to early 1990s as to what type of analysis is most meaningful. Nesbitt et al. (1986), working in the Canadian Cordillera, stressed that very light hydrogen isotope values consistently measured from extraction of inclusion fluids supported the argument that gold deposits in metamorphic belts owed their origin to deeply circulating surface waters. However, as pointed out by Pickthorn et al. (1987), such bulk extraction techniques include contributions of many generations of postore inclusions that were trapped in the host quartz grains during tens of millions of years of subsequent deformation and regional uplift. For many gold deposits, including those of the Canadian Cordillera, calculations of δD using measurements on hydrothermal micas differ significantly from measurements on fluid inclusion waters, and the former are the best estimate of ore-fluid compositions (e.g., Goldfarb et al., 1991a; Taylor et al., 1991; Simon, 2001). Most δD fluid estimates, when using micas, range between about –80 and –20 per mil (Fig. A6; Bierlein and Crowe, 2000; Hagemann and Cassidy, 2000). Based on the data from northern latitudes, this range rules out meteoric water as a significant component to the hydrothermal systems, as the relatively low hydrogen concentration of crustal rocks makes extensive exchange of a strongly D depleted surface water with crustal rocks highly unlikely. Rare outliers from the –80 to –20 per mil range, particularly from very low δD measurements, are best interpreted as reflective of exchange effects in a very CH_4 rich reduced fluid (e.g., Rye and Rye, 1974; Craw, 2002).

Sulfur isotope measurements are extremely variable between deposits (App. Table A2) and a definitive source for the gold-transporting sulfur ligands within the ore-forming aqueous-carbonic fluids is equivocal. For the most part, $\delta^{34}S$ values for sulfide minerals in Archean terranes range from about 0 to 9 per mil (Kerrich, 1987, 1989; Golding et al., 1990), are quite varied in Proterozoic rock-hosted deposits (Partington and Williams, 2000), and also range from about 0 to 10 per mil for many deposits in Phanerozoic rocks (Nesbitt, 1991). However, there are important examples where measured $\delta^{34}S$ are as light as –20 or as heavy as +25 per mil.

Extremely anomalous positive $\delta^{34}S$ values, such as defined by the range of 9 to 24 per mil in the Meguma terrane (Kontak and Smith, 1989), are products of a ^{34}S-enriched wall-rock source reservoir (Sangster, 1992), with differences between deposits interpreted as reflecting some degree of provinciality in the source region and/or variations along the flow path. Goldfarb et al. (1997) showed that $\delta^{34}S$ for sulfide minerals in gold deposits in Alaska is a function of the age of the rocks of the hosting terrane, with variations in the seawater sulfate curve correlating with variations of sulfur in the terranes (App. Fig. A7). This supports the notion that the sulfur source

reservoir for many deposits is the ore-hosting allochthonous block itself (e.g., Sangster, 1992). Traditionally, a $\delta^{34}S$ value of about 0 per mil was taken as indicative of a magmatic fluid, but if a large crustal component is added to a mantle melt, then greater variability in ore-fluid $\delta^{34}S$ is possible. Thus, the broad range in $\delta^{34}S$ for gold deposits in metamorphic belts does not eliminate a magmatic source for sulfur in the ores; it does, however, weigh heavily against a mantle contribution for a large component of the sulfur.

Fluids responsible for ^{34}S-depleted sulfides, particularly described for Archean (some Golden Mile ores, Victory-Defiance, Canadian Arrow: Hagemann and Cassidy, 2000) and Paleoproterozoic (some Ashanti ores: Partington and Williams, 2000) environments, are interpreted by some workers as having undergone some degree of oxidation during their history. More than likely, in many cases, very depleted $\delta^{34}S$ may be simply a source-inherited feature, particularly in carbonaceous metasedimentary rock environments (e.g., Oberthur et al., 1996). Thus, $\delta^{34}S$ values as negative as –10 to –20 per mil could be products of devolatilization or of exsolution of a very low fo_2 fluid from S-type melts within very reduced source strata (e.g., Donlin Creek: Goldfarb et al., 2004).

The use of carbon isotopes to define the source of the ubiquitous CO_2 within gold deposits in metamorphic terranes has also been unable to provide definitive results, with the same data open to a variety of very different interpretations. Most $\delta^{13}C$ data for ore-related carbonates in Phanerozoic terranes typically range from near 0 to about –10 per mil, but deposits are as depleted as –25 per mil in the Meguma terrane and Lachlan fold belt (Table A2; Bierlein and Crowe, 2000). Archean and Paleoproterozoic deposits also are characterized by $\delta^{13}C$ values of about 0 to –10 per mil (Table A2), but there are also older outliers such as Ashanti and Pine Creek, with measurements at the latter being as depleted as –32 per mil (Kerrich, 1989; Partington and Williams, 2000). The bulk of the measurements (i.e., those >–10‰) could be products of devolatilization of the greenstone belts or metasedimentary rock terranes (Kerrich and Fyfe, 1981; Groves and Phillips, 1987). Some workers have suggested that these measurements are characteristic of mantle carbon (e.g., Fyon et al., 1984; Cameron, 1988), whereas other studies suggest a crustal magmatic carbon source to explain the slightly negative $\delta^{13}C$ values (e.g., Burrows et al., 1986; Callnan and Spooner, 1989). In fact, there are also numerous models calling upon variable degrees of mixing of mantle, oxidized crustal, and/or reduced crustal carbon reservoirs, with superimposed local variations indicative of wall-rock reactions or fluid immiscibility (McCuaig and Kerrich, 1998). Additional arguments have been put forward that $\delta^{13}C$ values of 0 to –10 per mil cannot be solely products of a mantle nor of a magmatic reservoir (Kerrich, 1989, 1991). The more negative $\delta^{13}C$ data are most readily interpreted as products of a devolatilization in a sequence where there is a large component of biogenic carbon (Kontak et al., 1988, 1997). Broad ranges in $\delta^{13}C$ within a given region might reflect contributions from a variety of carbonate mineral species and or variable contributions of carbon from seawater, mantle, and/or organic sources (e.g., Golding et al., 1989).

Nitrogen isotopes have recently been proposed as useful for identification of fluid source reservoir or, at the least, for any N_2 in a hydrothermal system. Ammonium ions, which commonly substitute for potassium in hydrothermal micas in the gold deposits, are the source of the measured nitrogen. Reported values of $\delta^{15}N$ range from about 10 to 24 per mil for Late Archean gold deposits (Jia and Kerrich, 1999), and from about 0.5 to 5.5 per mil for younger orogenic gold deposits of western North America (Jia et al., 2003) and New Zealand (Pitcairn et al., 2005). The few data are compatible with nitrogen derivation from devolatilization of metamorphic rocks; data are interpreted as not supporting a fluid, or at least nitrogen in the fluid, being derived from meteoric, mantle-derived, nor granitoid-related sources (Jia et al., 2003). The $\delta^{15}N$ database for rocks and minerals is still quite limited and thus further work is required to prove the reliability of this isotope system as a fluid tracer (Ridley and Diamond, 2000).

Radiogenic isotopes and noble gases

The application of radiogenic isotope and noble gas techniques, to help define sources for gold and other metals, has been widespread, but the results have also been quite equivocal. Lead and strontium are the most commonly applied isotopic systems but they rarely define solely source regions. Noble gases and halogens potentially may best identify fluid sources, but, as mentioned below, there are still significant concerns.

In studies of Phanerozoic deposits, lead isotope signatures of sulfide minerals typically match those of their host rocks. For example, Goldfarb et al. (1997) showed how lead values for gold ores in many Alaskan districts with multiple host rocks varied significantly. This was particularly noticeable in the extreme difference in lead values for sulfide minerals from the Alaska-Juneau and Treadwell gold deposits, two coeval world-class gold orebodies only a few kilometers apart but on opposite sides of a terrane-bounding fault. Haeberlin et al. (2003, 2004) defined a similar situation in the Eastern Cordillera of South America, where lead isotope values of sulfides in the gold ores at Pataz approximate those of the host batholith, which itself predates gold deposition by about 20 m.y. Although workers have stressed that Precambrian lead ratios for ore-stage sulfide minerals are uniform for a given camp and rarely match country-rock ratios (e.g., Ridley and Diamond, 2000), this does not seem to be a good generalization for Phanerozoic orogens. One exception may be the Monte Rosa gold ores in the Alps, where ore-stage lead data have a signature typical of more distal Caledonian metapelites, rather than proximal greenstones (Curti, 1987).

Precambrian lode gold deposits show less host-rock control of lead isotope values. The measured values for ore-related sulfide minerals are interpreted to indicate a deeper, more radiogenic lead source than the greenstone host rocks (Browning et al., 1987; McCuaig and Kerrich, 1998). Although less radiogenic than coeval granitoids, granite-gneiss basement rocks may be the most feasible lead source in the Late Archean ore systems, perhaps with some mixture of greenstone lead (Perring and McNaughton, 1992; Qiu and McNaughton, 1999). The difference between Precambrian and Phanerozoic lead systematics seems to be real and is difficult to explain. Perhaps a key point is that background lead concentrations in greenstone are significantly lower than those in most metasedimentary rocks (e.g., 5 vs. 10–70 ppm Pb). Low-salinity ore fluids of both ages would be capable of only minor degrees of lead

transport, but the mobilized lead still would make a relatively significant contribution to the total lead in ores deposited in the greenstones. In contrast, total lead in turbidite-hosted ores might overwhelm the exotic lead, such that lead isotope ratios for the small amount of lead entering the sulfide ore assemblage would mainly reflect ratios of host rocks.

Interpretation of strontium ratios is even more complex (Ridley and Diamond, 2000) and ratios do not preserve source character. Kerrich (1989) and Mueller et al. (1991) pointed out how most initial strontium ratios for ore fluids differ from those of host rocks and are also clearly more radiogenic than mantle and greenstone reservoirs, again leading to the conclusion that basement rocks below greenstone belts were an important source for at least some components in the hydrothermal system. Similarly, in the Meguma deposits, initial strontium ratios do not indicate a simple contribution from the turbiditic host rocks but rather some of the strontium reservoir being the underlying gneissic unit (Kontak et al., 1988; Kontak and Kerrich, 1997). The Mother Lode deposits in California yield data from many of the ores that indicate an external strontium reservoir and with fluids that have interactered with a variety of rock types (Böhlke and Kistler, 1986). Somewhat similarly, Pettke et al. (2000) noted that for small gold deposits in the Alps, the strontium signatures of fluid inclusion extractions and hydrothermal minerals varied between deposits, reflecting the degree of armoring of fluid conduits from interaction with adjacent country rocks. Nevertheless, Miller et al (1995) reported consistent, relatively primitive initial $^{87}Sr/^{86}Sr$ values, as well as εNd values, for highly altered versus unaltered diorite host rocks at the Kensington deposit in southeastern Alaska, again providing an example that isotopic signatures of some ores may clearly just define those of the surrounding host rocks and not source regions. A similar conclusion was reached by Kempe et al. (2001) at Muruntau, where Sr-Nd signatures were concluded to represent local wall-rock control.

Other applied tracers have included osmium and neodymium isotopes, halogens such as Cl, Br, and I, and noble gas isotopes of species such as argon and helium. Osmium and neodymium have so far been even less definitive than strontium and lead in understanding metal sources, with again a lot of the uncertainty reflecting the question of how much of the total concentration measured for the isotopes of each element was actually transported to the site of ore deposition in the hydrothermal fluid and how much was already present locally in deposit host rocks. Yardley et al. (1992) noted that halogens extracted from fluid inclusions in gold veins of the Italian Alps had signatures characteristic of surface waters, which contradicts various deep-crustal fluid models (e.g., Pettke et al., 2000), and, taken together, again highlight problems inherent to bulk extraction techniques for analytical study of fluid inclusion waters. Laser microanalyses of individual fluid inclusions for halogen species in ore-bearing quartz from the California Mother Lode goldfields, in contrast, have been used to indicate a fluid that interacted with organic-rich metasedimentary rocks (Bohlke and Irwin, 1992). Noble gases extracted from fluid inclusions have been shown to have apparent mantle signatures at the Dongping deposit along the northern margin of the North China craton, but the significance of such is uncertain, given that sulfur isotope data are incompatible with any type of mantle source reservoir (Mao et al., 2003). As a whole, whereas all these above species have potential as fluid and metal tracers, systematics for each have been, to date, too poorly understood to have made them valuable contributors to our understanding of the evolution of such gold-rich hydrothermal systems.

Ore-fluid volatile species

Hundreds of papers written during the previous 25 years have documented the composition of gold-bearing hydrothermal systems in metamorphic rocks through the application of fluid inclusion studies. Almost universally, workers have identified a mixed aqueous-carbonic fluid in gold-bearing quartz, generally of low salinity, which, in most cases, is the suggested ore-forming fluid (App. Fig. A8, Table A3). The consistent occurrence of ankerite and ferroan dolomite in proximal alteration zones to orebodies and the associated CO_2-rich nature of many fluid inclusions in auriferous quartz (Letnikov, 1975; Kerrich and Fyfe, 1981; Roedder, 1984) are now well-established features that typify this group of gold deposits.

Reported ore-fluid concentrations of H_2O and CO_2 are quite variable among gold provinces (Table A3) and even within a given gold district, but a majority of the gold deposits show mixed parent fluids with ranges of between about 4 and 30 mol percent CO_2. In many cases where higher contents of CO_2 are suggested, there is a strong likelihood that unmixing has concentrated the nonaqueous gas species and gold relative to the original parent fluid within the hydrothermal system. Gold deposits with CO_2 contents in the lower end of the range, specifically those with 4 to 15 mol percent gas, are more commonly reported for Phanerozoic gold systems (e.g., Goldfarb et al., 1993), which typically formed at slightly lower temperatures (about 250°–350°C) than many of the more gas rich Precambrian deposits (about 325°–400°C). Also, within some gold districts, the more CO_2-rich fluids are reported in higher metamorphic grade rocks (e.g., Alaska-Juneau vs. Treadwell, Juneau gold belt: Goldfarb et al., 1989), although this may not be a consistent occurrence (e.g., Yilgarn craton: Mikucki and Ridley, 1993). In any given gold deposit, there can be a range of CO_2 concentrations between various fluid pulses if fluid unmixing accompanied ore deposition. Fluid pressures may vary significantly during hydraulic fracturing events and, as a result, compositions of unmixed compositional pairs must also fluctuate over time. In contrast to epithermal-type deposits in unmetamorphosed rocks, it is very rare to find gold deposits with <4 mol percent CO_2 in metamorphic belts; one exception may be Macraes Flat (de Ronde et al., 2000)

Pure carbonic fluids have been reported as ore-forming fluids from a variety of Paleoproterozoic gold provinces, such as Ashanti in Ghana (Klemd et al., 1996), Rio Itapicura in Brazil (Xavier and Foster, 1999), and Limpopo in South Africa (Van Reenen et al., 1994), as well as from the Neoproterozoic of Africa (Garba and Akande, 1992). These carbonic fluids could reflect a crustal fluid formed at high temperatures where an aqueous component was preferentially concentrated in a coeval melt (e.g., Schmidt Mumm et al., 1997). However, as pointed out by Ridley and Diamond (2000), there are important concerns with such a fluid; most significantly, metal solubilities will not be adequate for the observed ore assemblages and such a fluid is not compatible

with the H_2O-bearing alteration phases or the quartz veins. They stress that the observed pure carbonic fluids might reflect either postentrapment modification of the studied fluid inclusions, such that the aqueous phase was preferentially leaked, or the extreme unmixing between carbonic and aqueous fluid phases during which the former fluid was preferentially entrapped. The Fimiston stage ores at the Golden Mile deposit might be one such example of the latter, where CO_2 concentrations in various ore veins can vary from between <5 to 100 mol percent (Ho, 1987; Ho et al., 1990; Hagemann and Cassidy, 2000). At Renco, Kolb et al. (2000) suggested that both immiscibility and postentrapment modification, perhaps occurring almost simultaneously, are responsible for the ore-stage carbonic inclusions.

Almost universally, CH_4, N_2, and H_2S are reported as additional nonaqueous volatile species in fluid inclusions from the gold-bearing veins. Their concentrations range from traces to values of CH_4 and/or N_2 that equal or exceed CO_2 levels in the fluid. Combined CH_4 and N_2 concentrations in most Phanerozoic gold deposits in metamorphic terranes generally are ≤5 mol percent (Goldfarb et al., 1993; Bierlein and Crowe, 2000). Most workers have attributed the concentrations of these two reduced gases in the ore fluids to variable interaction with reduced country rocks. Within a given gold province, some workers have shown that gold-bearing versus gold-barren quartz veins can be distinguished by the presence or absence, respectively, of CH_4 and/or N_2 (e.g., Shepherd et al., 1991; Sherlock et al., 1993; Jia et al. 2000); however, such a generalization does not seem to apply to these gold deposits as a whole. Reduced sulfur species are estimated to range between 10^{-3} to $10^{-0.5}$ molal for most deposits (Ridley and Diamond, 2000).

The salinity of the aqueous-carbonic fluids typically ranges from 3 to 12 wt percent NaCl equiv (App. Table A3). Daughter minerals are, thus, rare and cations are generally Na > K >> Ca and Mg, with Cl^- being the dominant anion (e.g., Ridley and Diamond, 2000). The typically low salinity has been interpreted to account for the low base metal concentrations of gold deposits in metamorphic belts. There are, however, notable exceptions of significantly higher salinity fluids, which may contain halite and other daughter salts. In many cases, these appear as a late, brine-bearing fluid inclusion generation that postdates gold deposition (e.g., Muruntau: Graupner et al., 2001; Abitibi subprovince: Boullier et al., 1998). Alternatively, extreme fluid unmixing might have led to formation of a highly saline aqueous end-member composition (e.g., Victory-Defiance: Clark et al., 1989; Meguma terrane: Kontak et al., 1996; Kolar: Mishra and Panigrahi, 1999). High-salinity fluids in gold deposits in Paleoproterozoic platforms (i.e., Telfer: Goellnicht et al., 1989; Pilgrim's Rest: Boer et al., 1995) remain poorly understood, although they have been suggested to reflect metamorphism of sequences with trapped pore waters (Goldfarb et al., 2001a). Yardley (1997) indicated that such brines trapped in pores, particularly in basinal settings, which can develop along craton margins and inland of accreted terranes, may persist in the crust during prograde events up to anatexis. In addition, high-salinity fluids have been interpreted, in some deposits, as the finger print of a fluid exsolved directly from a melt (e.g., Petrackova Hora, Bohemian Massif: Zacharias et al., 2001).

Chemical constraints on ore-forming fluids

Gold deposits in metamorphic rocks are well characterized by their precipitation from low-salinity, H_2O-CO_2-H_2S ± CH_4 ± N_2 fluids over a broad range of temperatures and pressures (Colvine, 1989; Groves, 1993). Most of the deposits are reported to range between about 200° and 500°C, and 1 and 4 kbars. There is generally a mode in temperatures of about 250° to 350°C for the Phanerozoic and Proterozoic deposits; many of the Archean deposits are reported to have formed at slightly higher temperatures of 325° to 400°C, although in both groups there are many significant lower and higher temperature outliers. Pressure estimates are more variable in the literature, in part due to large pressure fluctuations associated with hydraulic fracturing and mineral precipitation and also due to the greater difficulties in estimating absolute pressure values.

Mineral assemblages and fluid inclusion compositions are mainly consistent with a relatively reduced fluid. Estimated values of f_{O_2} are typically within two orders of magnitude of the fayalite-magnetite-quartz buffer, although some deposits with abundant magnetite or hematite may be more oxidized (Mikucki and Ridley, 1993). It is unclear whether the more oxidized nature of some deposits reflects an inherently more oxidized fluid-source region, a phase separation event, a period of fluid mixing, the overprinting of an earlier magmatic hydrothermal system, or simply oxidation of the fluids by local wall rocks. McCuaig and Kerrich (1998) suggested that there is a redox-temperature trend such that typically the most anomalously oxidized hydrothermal systems were active at relatively high temperatures. The pH of the ore fluids is generally near-neutral (App. Fig. A9), consistent with the sericite-carbonate ± paragonite-albite associations in many proximal alteration zones.

Gold in these deposits is thought to have been transported in the near-neutral pH and relatively reduced fluid as a bisulfide complex (e.g., Seward 1973, 1989). The AuHS° species tends to predominant in gold-bearing hydrothermal systems below about 300°C; $Au(HS)_2^-$ is generally considered the more significant complex throughout more mesozonal environments (App. Fig. A10; Mikucki, 1998). However, Loucks and Mavrogenes (1999) noted that $AuHS(H_2S)_3^0$ may be most important for controlling gold solubility. Although chloride is present, it is not a significant gold complex under the low f_{O_2} conditions at low to moderate temperatures. Wood and Samson (1998) suggested that As-, Sb-, and Te-bearing species may also be gold-transporting ligands, although their importance relative to sulfide is unclear. Douglas et al. (2000) indicated that liquid Bi might be an important gold mobilizer in the reduced hydrothermal fluids.

Controls on metal precipitation

There are a variety of processes that may be responsible for precipitation of gold ores from their hydrothermal solutions to form orebodies in metamorphic terranes (App. Fig. A11). Fluid–wall-rock reaction is most commonly accepted as driving mineral precipitation where orebodies are of disseminated and replacement style. The sulfidation of wall rocks with high Fe/Fe + Mg ratios, including many BIF, mafic igneous rocks, and argillites, will destabilize gold as the sulfur-bearing ligands are broken down to precipitate pyrite and

other sulfide minerals (e.g., Phillips and Groves, 1984; Böhlke, 1988). Gold grades may thus, in some cases, correlate with sulfide mineral abundance. Through exchange with carbonaceous metasedimentary, resultant changes in fluid fo_2 and/or pH can also facilitate breakdown of the gold-transporting complexes. McCuaig and Kerrich (1998) suggested that potassium and CO_2 metasomatism of wall rocks, and subsequent release of hydrogen ions causing a decrease in pH, may further destabilize gold from the fluid phase.

Pressure fluctuations, particularly for quartz vein-hosted orebodies, provide important controls on gold deposition. Hydraulic fracturing, to a large degree explained by the fault-valve concept of Sibson et al. (1988), will lead to major shifts from supralithostatic to near-hydrostatic pressure conditions. As veins are precipitated and pathways resealed and refractured, pressures will continue to change dramatically. In many cases, particularly when parent fluid CO_2 contents are above about 5 to 8 mol percent, i.e., initially not in the two-phase field, fluids will unmix when the two-phase field is expanded during the transient pressure decreases. Fluid unmixing may be a significant process in localizing high-grade ore shoots with abundant coarse-grained gold (Groves and Foster, 1991). As reduced gases are the least stable among the nonaqueous volatile species, the sulfur of gold-bearing complexes may be lost from the parent fluid during hydraulic fracturing events. Recent data from Loucks and Mavrogenes (1999) confirmed that pressure decreases alone may be effective to cause gold precipitation.

A number of other processes appear less important to the ore-forming process. In these relatively reduced solutions, gold solubility is recognized to be inversely related to temperature (e.g., Mikucki, 1998), although some recent experimental data suggest that temperature declines could lower gold solubility in such hydrothermal solutions (Loucks and Mavrogenes, 1999). Fluid mixing has been proposed by some workers for Archean (e.g., Hagemann et al., 1994; Walshe et al., 2003) and Phanerozoic (Cox et al., 1995; Graupner et al., 2001) systems, but, in most deposits, evidence for two distinct and coeval fluids is lacking. Some studies have argued that the presence of oxidized phases (i.e., hematite, magnetite, anhydrite) in some of the hydrothermal, metal-bearing stages (Craw and Chamberlain, 1996; Walshe et al., 2003) provides such evidence, but the general uniform composition of ore-stage fluids and consistent $\delta^{18}O_{quartz}$ measurements weigh against such a two-fluid argument (McCuaig and Kerrich, 1998). Knipe et al. (1992) stressed that sulfide mineral surfaces might be critical substrates for gold precipitation, but whether adsorption-reduction mechanisms are by themselves a major cause of gold deposition remains unclear (Mikucki, 1998). In deposits with abundant arsenopyrite, dissolution of the sulfide grains may generate a local redox trap that can be effective in extracting gold from the ore fluids and depositing it along grain boundaries and in cracks within the preexisting arsenopyrite (Pokrovski et al., 2002).

Reduced Intrusion-Related Gold Deposits

Introduction

During the last decade, a type of gold deposit commonly associated with reduced felsic intrusions has been distinguished from orogenic gold deposits within metamorphic belts. Although many orogenic gold deposits have spatial and temporal, yet equivocal genetic associations with felsic plutons, reduced intrusion-related gold deposits have a clearer genetic relationship with host or adjacent plutons. These differ from other gold deposits that also have well-recognized genetic associations with igneous bodies (e.g., gold-rich porphyry, epithermal gold, and gold skarns; Hagemann and Brown, 2000, and papers therein) by (1) the association of intrusion-related gold deposits with granitoids that have a reduced primary oxidation state (App. Fig. A12), relative to arc magmas associated with gold and copper-gold porphyry deposits; (2) their formation in shallow to moderate crustal settings (2–8 km) that lack extensive coeval volcanism; and (3) their development late in the orogenic cycle (Thompson et al., 1999; Thompson and Newberry, 2000). These characteristics are, however, similar to those of many orogenic gold deposits, and, as a result, categorization of many deposits is controversial, warranting a more specific discussion of reduced intrusion-related gold deposits.

Thompson et al. (1999) defined a distinct intrusion-related gold deposits class based on the recognition of several deposits with the following characteristics: (1) an anomalous metal suite that includes some combination of Bi, W, As, Sn, Mo, Te, and Sb; (2) occurrence within magmatic provinces characterized by tungsten and/or tin mineralization; (3) a genetic relationship to felsic intrusions of intermediate oxidation state; (4) location in continental margins but in a landward position relative to continental margin arcs; (5) a low sulfide content (<3%), with gold commonly intimately associated with bismuth and a paucity of base metals; (6) greisen, disseminated, sheeted vein, stockwork, and breccia styles of mineralization in igneous host rocks, with gold also concentrated in the surrounding metasedimentary rocks in skarns (reduced), disseminated and replacement zones, and veins; (7) quartz, K-feldspar, albite, sericite and carbonate alteration; and (8) low- to high-salinity, CO_2-rich, ore-forming fluids. Widespread arrays of parallel quartz veins (sheeted veins) are the most characteristic deposit style associated with this classification (Fig. 14B-D, H). Thompson et al. (1999) interpreted seven deposits (Fort Knox, Mokrsko, Salave, Vasilkovskoe, Timbarra, Kidston, and Kori Kollo) as typical intrusion-related gold deposits. Lang et al. (2000) emphasized the exploration potential of these gold systems and highlighted their vertical and lateral zonation patterns. They expanded the intrusion-related gold deposits class to include shallow-level, dike- and sill-hosted systems (e.g., Brewery Creek, Donlin Creek), metasedimentary rock-hosted deposits including skarns (Rio Narcea, Spain; Marn, Yukon) and deeper, structurally controlled veins (Pogo).

Prior to the global classification of Thompson et al. (1999) and Lang et al. (2000), several other workers had noted the distinct characteristics of individual deposits or districts now within the intrusion-related gold deposits class. Hollister (1992) ascribed a gold "porphyry" model for the Fort Knox deposit; however, as similarities with copper "porphyry" deposits were few, the term never gained acceptance. Nonetheless, Rowins (2000) included some of the gold deposits within his newly defined reduced porphyry copper-gold deposit model but that classification is misleading for deposits such as

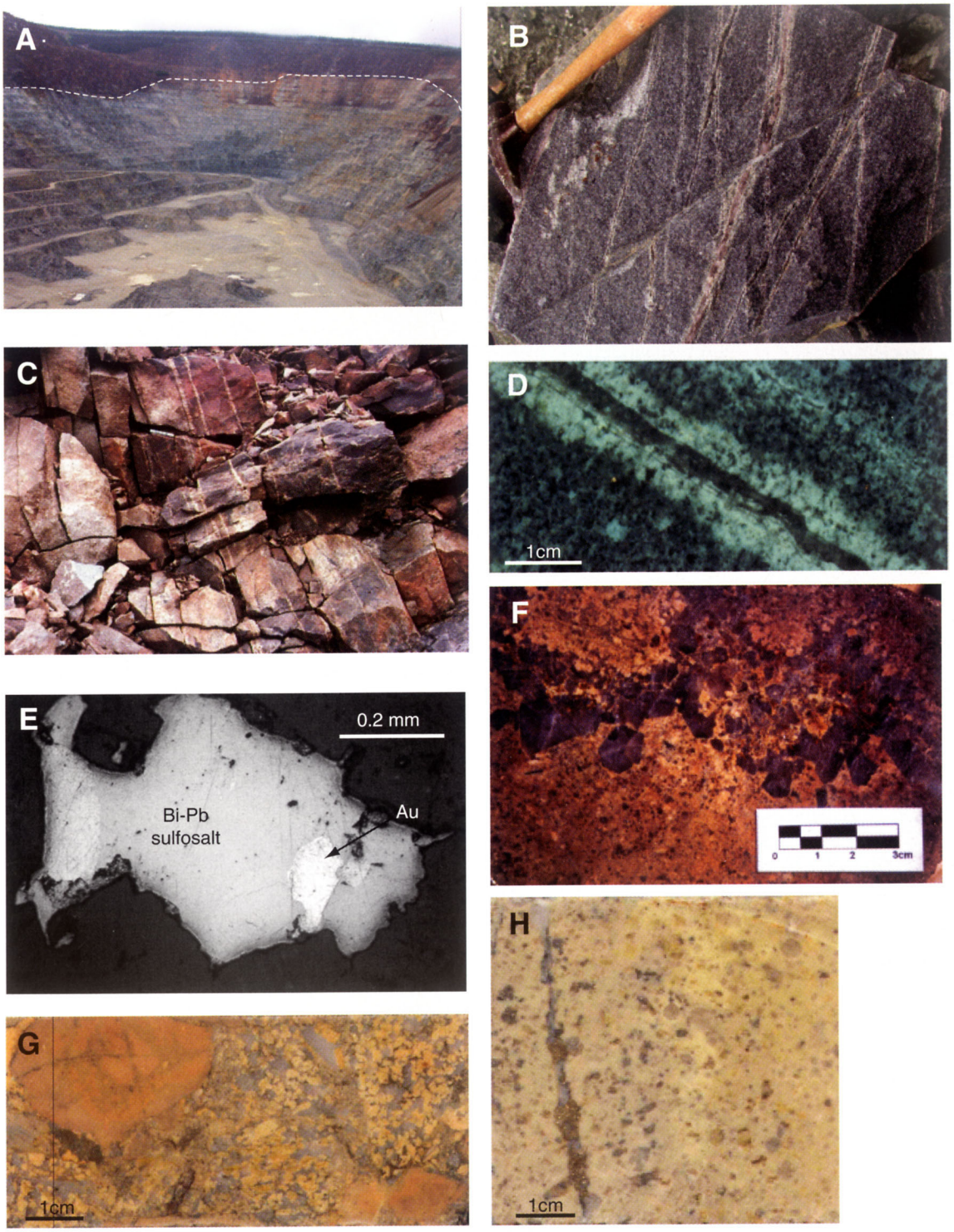


FIG. 14. A. Looking toward the eastern end of the Fort Knox, Alaska, open pit (July 2003). The deposit is hosted in the apex of a slightly peraluminous biotite > hornblende granite pluton. The roof of the pluton is outlined at its contact with the darker schist country rock. B. Highly fractured and veined ore from Fort Knox showing dominant "sheeted" veins and intersecting cross veins. This is unlike typical stockworks in porphyry deposits. The larger central vein also contains alkali feldspar. Note the limited alteration selvages adjacent to the veins. C. Typical gold- and scheelite-bearing, sheeted quartz ± feldspar ± muscovite veins cutting granite at Clear Creek occurrence in Yukon. D. Gold-bearing sheeted vein sample from Dublin Gulch with K-feldspar–rich alteration envelope and low sulfide, quartz-rich infill. E. Exsolution textures of Au, Bi, and Te from Dublin Gulch. F. Coarse unidirectional solidification texture that caps the disseminated gold mineralization at the Timbarra deposit (photograph courtesy of R. Mustard). G. Clast-supported breccia from Kidston comprising gold-bearing quartz, pyrite and carbonate fill surrounding round to subangular clasts of prebreccia rhyolite and granodiorite. H. Sheeted gold-bearing quartz-pyrite-ankerite vein from Kidston hosted by postbreccia rhyolite porphyry dike.

Fort Knox, which totally lack copper. Newberry et al. (1995) used the term intrinsic gold deposits to distinguish Alaskan granite-hosted gold deposits from orogenic (or extrinsic; Newberry et al., 1995) gold deposits. McCoy et al. (1997) removed the porphyry connection altogether and used the term plutonic-related gold deposits for a range of deposits in east-central Alaska and emphasized their deep-level nature (including Fort Knox) compared to typical porphyry copper systems. Goldfarb et al. (2000) classified gold deposits associated with middle to Late Cretaceous intrusions of Alaska and Yukon as granitoid-related lode gold deposits, highlighting the fractionated nature of the intrusions, whereas Thompson and Newberry (2000) emphasized the reduced nature of the associated granites and suggested the term reduced intrusion-related gold deposits. Hart et al. (2002) separated the intrusion-related gold deposits into subtypes that are unequivocally (1) intrusion related, (2) have an epizonal character, and (3) are shear related (Fig. 15). The term reduced intrusion-related gold deposits (Thompson and Newberry, 2000) is used here to distinguish these deposits from other more oxidized intrusion-related gold deposits as defined by Sillitoe (1991).

Examples of reduced intrusion-related gold deposits

The Tintina gold province and the Tasman fold belt are the two regions where intrusion-related gold deposits, with somewhat different characteristics than most of the other deposits described above from metamorphic terranes, are best documented. The intrusion-related gold deposits in these two regions have unequivocal geologic and geochronologic evidence to indicate that ore formation was synchronous with granitoid crystallization. Other potentially significant metamorphic belts for recognition of reduced intrusion-related gold deposits are not discussed in detail here, as the assignment of deposits as intrusion-related gold deposits or orogenic in these areas is much less certain. These include the Tien Shan (Jilau: Cole et al., 2000), the Altai Shan (Vasilkovskoe: Yakubchuk et al., 2002), the Bohemian Massif (Mokrsko and Petrackova hora: Moravek, 1995; Zacharias et al., 2001), the Hercynian of Spain and Portugal (Salave: Harris, 1980), and the Miocene polymetallic belt of Bolivia (Kori Kollo: Thompson and Newberry, 2000).

Tintina gold province, Yukon and Alaska: This province is a broad arc-shaped belt that continues for >1,500 km, from southwestern Alaska, across central Alaska and Yukon, to the westernmost Northwest Territories (App. Fig. A13; Smith et al., 2000; Hart et al., 2002). The province contains several gold districts and belts that are mostly coincident with middle (110–85 Ma) and Late (70–65 Ma) Cretaceous magmatic suites that are spatially, temporally, and, in some cases, genetically associated with the gold mineralization. The deposits in the province that are clearly genetically associated with magmatism include Fort Knox, Dublin Gulch, Brewery Creek, and Shotgun, whereas other deposits have a more equivocal origin (e.g., Pogo and Donlin Creek). In Yukon and eastern Alaska, 97 to 90 Ma plutons are genetically associated with the Fort Knox, Brewery Creek, Scheelite Dome, and Dublin Gulch gold deposits, as well as the very large tungsten skarns at Mactung and Cantung. Despite their similarity in age and tectonic setting, plutons vary from metaluminous to peraluminous, include associated aplite, pegmatite, and lamprophyre dikes, have low magnetic susceptibilities and Fe_2O_3/FeO ratios, and are mainly ilmenite series (Hart et al., 2004). Radiogenic isotope data indicate a significant crustal component to the magmas (Lang et al., 2000), but, locally, there are also important contributions from ancient metasomatized mantle

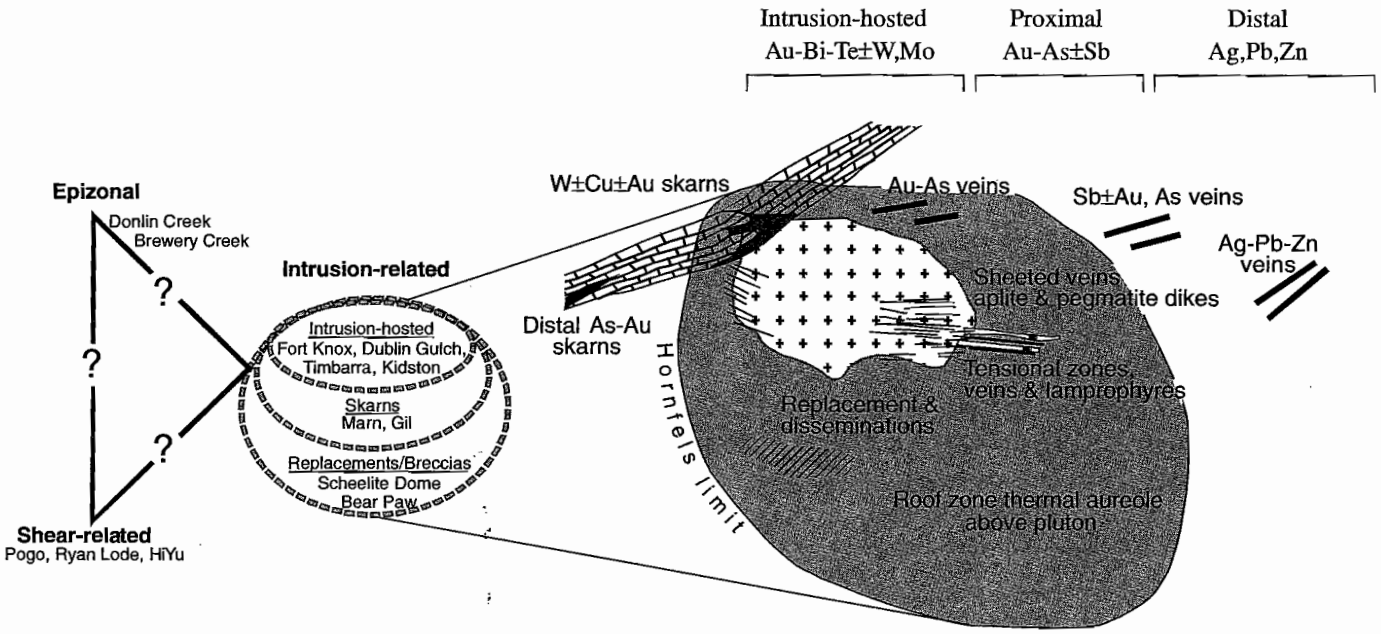


FIG. 15. Mineral deposits and occurrences associated with Cretaceous intrusions in the Tintina gold province are divisible into those that are epizonal, associated with shear zones and those that are clearly intrusion related (modified from Hart et al., 2002). Intrusion-related mineralization can be characterized by a model that has differing deposit styles, metallogeny, and geochemistry, which vary depending on whether lodes are intrusion hosted or within to beyond the hornfelsed aureole.

(Hart et al., 2004). In southwestern Alaska, plutons are ca. 70 Ma but are more remote and thus less well studied.

Fort Knox (168 t Au, 0.93 g/t) is the largest tonnage, widely accepted, intrusion-related gold deposit in the world (Bakke, 1995; McCoy et al., 1997; Bakke et al., 2000). The deposit (Fig. 14A), located near Fairbanks in eastern Alaska, is hosted by a small (1-km^2), biotite- and hornblende-bearing, variably porphyritic granite to granodiorite stock. Low magnetic susceptibilities and low Fe_2O_3/FeO ratios (0.15–0.3) suggest a reduced oxidation state (Hart et al., 2004). The Fort Knox deposit comprises several vein and related hydrothermal alteration stages (Fig. 14B; Bakke, 1995; McCoy et al. 1997), which include early quartz-feldspar veins, sheeted quartz-K-feldspar veins, and planar, milky quartz veins that occur as stockworks and in late-stage, gently to moderately dipping shear zones (Bakke et al., 2000). Gold occurs in all vein stages, has a high fineness (>960), averages 110 mm in diameter, and is commonly intergrown with native bismuth, bismuthinite, and tellurobismuth. The volume of sulfide minerals in the quartz veins is low (<1%) and ore-related minerals include pyrite, marcasite, pyrrhotite, arsenopyrite, bismuthinite, scheelite, tellurides, and molybdenite. An Re-Os age of 92.6 ± 0.9 Ma from molybdenite intergrown with gold in the Fort Knox ore (Selby et al., 2002) is similar to the U-Pb zircon age (in Bakke, 1995) of 92.5 ± 0.2 Ma for the intrusive host. Fluid inclusions in the auriferous quartz veins contain CO_2-rich, low-salinity (2–8 wt % NaCl equiv) fluids trapped at 1.25 to 1.5 kbars and 270° to 330°C (McCoy et al., 1997).

The Dublin Gulch deposit (127 t Au resource; 1.19 g/t), central Yukon, is hosted by the larger (10 km^2) Dublin Gulch pluton that, unlike the widely mineralized Fort Knox pluton, is only locally mineralized (Hitchens and Orssich, 1995; Maloof et al., 2001). The main gold resource, the Eagle zone, occurs in a thin, apical part (~200 m) of an elongate, east-northeast–trending, biotite > hornblende granodiorite body. The subalkaline granodiorite has Fe_2O_3/FeO ratios of 0.15 to 0.3 that indicate a moderately reduced oxidation state (Brown, 2001). The Eagle ore zone includes broad arrays of steep-dipping, thin (several cm), sheeted veins of early quartz-scheelite ± pyrrhotite, pyrite, and arsenopyrite, with K-feldspar ± albite–dominant alteration envelopes (Fig. 14D; Maloof et al., 2001). Locally, these early veins show along-strike transitions from late-stage magmatic vein dikes, which comprise aplite selvages and quartz infill with irregular margins. The quartz-scheelite-feldspar veins also grade into, and are overprinted by, sericite-carbonate-quartz-chlorite veinlets and alteration. Most gold occurs with sparse older (?) molybdenite, lead-bismuth ± antimony sulfosalts, galena, and bismuthinite in these veinlets. Baker and Lang (2001) documented an evolving fluid inclusion history above 1.1 kbars, from early higher homogenization temperature (250°– 350°C), low-salinity (<7 wt % NaCl equiv), and high X_{CO_2} fluids, to lower homogenization temperature (141°–219°C), higher salinity (2.1–15.7 wt % NaCl equiv) aqueous fluids with low to no detectable CO_2 component. The Dublin Gulch gold ores are zoned outward through a proximal tungsten skarn (Ray Gulch), and beyond the ~2-km-wide contact aureole, to silver-bearing, base metal-rich veins (Rex and Peso: Hitchens and Orssich, 1995).

The ca. 70 Ma Shotgun deposit (34 t Au resource, 0.93 g/t Au) is the clearest example of an intrusion-related gold deposit in southwestern Alaska and is hosted by an ilmenite series (low to very low magnetic susceptibility), biotite-bearing granite porphyry (Rombach and Newberry, 2001). The ore zone comprises gold-bearing quartz stockwork and breccia with both a hydrothermal and granite matrix. In the low sulfide (<1%) mineralization, gold correlates strongly with Bi, Te, Mo, and Ag. Coexisting brine and CO_2-rich vapor inclusions indicate fluid unmixing at 350° to 650°C and ~ 0.5 kbar (Rombach and Newberry, 2001). Bundtzen and Miller (1997) and Ebert et al. (2000) described ca. 70 Ma porphyritic rhyodacite and rhyolite dikes and sills that host a 778 t Au resource at the Donlin Creek deposit, but the genetic relationship of the gold-rich stockworks to magmatism is unclear (e.g., Goldfarb et al., 2004).

Tasman fold belt, Australia: The Tasman fold belt of eastern Australia is a complex region comprising five Paleozoic orogenic belts that host a wide variety of gold deposits (Walshe et al., 1995), including Kidston and Timbarra. The Kidston gold deposit, in a Proterozoic inlier, is associated with the Permo-Carboniferous Kennedy igneous province (Bain and Draper, 1997). The province is characterized by predominantly subalkaline and metaluminous, intermediate to highly fractionated I-type felsic rocks, which are moderately oxidized to reduced and contain a significant crustal component (Richards, 1980; Champion and Chappel, 1992). Timbarra is located in the New England fold belt and is hosted by magnetite- and ilmenite-bearing, I-type granites of Late Permian to Early Triassic age (Mustard, 2001a, b).

The Kidston gold deposit (Baker and Andrew, 1991), mined out in 2001 (62 t Au, 1.6 g/t), is spatially and temporally related to a swarm of Permo-Carboniferous rhyolite dikes that cut Mesoproterozoic metamorphic rocks and Siluro-Devonian granodiorite. Gold mineralization at Kidston (Fig. 14G, H) occurs within a funnel-shaped, breccia-filled diatreme that extends to a ≥1,300-m depth, with gold mineralization best developed in the uppermost 250 m, with quartz in concentric, inward-dipping sheeted fractures and as cavity fill in breccia (Baker and Tullemans, 1990). Kidston is zoned with an upper gold- and base metal-rich zone and a deeper, early molybdenum-tungsten stockwork developed within a rhyolite porphyry stock (Morrison et al., 1996). The gold occurs with approximately 4 percent pyrite, pyrrhotite, and minor sphalerite, chalcopyrite, molybdenite, galena, arsenopyrite, and bismuthinite, and quartz-sericite-carbonate alteration (Baker and Tullemans, 1990). Early high-temperature brines are associated with molybdenum-tungsten mineralization, as indicated by high-salinity (20–50 wt % NaCl equiv), high homogenization temperature (340°–600°C) fluid inclusions. A low-salinity fluid containing appreciable CO_2 is associated with quartz veins that formed prior to the main stage of gold introduction. The main gold stage is related to a low-salinity (2–10 wt % NaCl equiv), low-temperature (170°–350°C) aqueous fluid, interpreted to have formed 3.5 km beneath the paleosurface from condensation of vapor generated during phase separation from a high-temperature magmatic brine (Baker and Andrew, 1991). Mineralization is coeval with magmatism at 332 Ma (Perkins and Kennedy, 1998) and confirms a magmatic affiliation for the deposit. Although mineralization style and gold-transporting fluid chemistry differ from deposits in the Tintina gold province, the presence of anomalous Bi, Mo, and

W, the occurrence of a CO_2-rich hydrothermal event and tin-tungsten deposits within the region led Thompson et al. (1999) to define Kidston as an intrusion-related gold deposit.

Timbarra is a small deposit (12 t Au, 0.73 g/t) that was only mined briefly during the late 1990s, but it is significant because it shows some of the most compelling evidence for a magmatic genesis of reduced intrusion-related gold deposits (Mustard, 2001, 2003; Mustard et al., 2003). The composite Permo-Triassic (252–249 Ma) granite host has an identical age to gold mineralization (Re-Os of molybdenite) and alteration (Ar-Ar of sericite; Mustard, 2001). Most gold is hosted within the areally extensive, highly fractionated Stanthorpe leuco-monzogranite pluton as lenticular to tabular bodies. The outer carapace, defined by an upper strongly porphyritic to very fine grained granite, lacks gold, whereas minor gold (<0.2 ppm) occurs in the lowermost miarolitic portion. The bulk of the gold is hosted immediately beneath this carapace by medium- to coarse-grained granite that is pervasively altered to muscovite-chlorite-albite-carbonate. The granite is oxidized, but its low total oxide content allows it to be classified as ilmenite series. The average sulfide content of the ore is low (<1%) and includes arsenopyrite, pyrite, molybdenite, and bismuth and silver-lead tellurides. Gold is either disseminated in the host granite, occurs in microfractures in pegmatites and veins, and as infill in miarolitic cavities. Mustard (2003) and Mustard et al. (2003) have documented a well-defined melt-fluid evolution, where melt inclusions trapped in the late stages of magmatic devolatilization contain significant CO_2 and coexist with CO_2-bearing, low-salinity fluid inclusions. Subsequent fluid inclusions trapped progressively less CO_2. The main gold event occurred at 260° to 320°C and ~2 kbars.

A consensus of reduced intrusion-related gold deposit characteristics

The deposits described above share consistent characteristics, some of which are distinct from those of orogenic gold deposits. Detailed dating on well-documented systems confirms that ore formation was essentially synchronous with granitoid emplacement, with fluid likely exsolved from deeper, partly crystallized melts. The intrusions are granodioritic to granitic, subalkaline, and metaluminous to weakly peraluminous, but the magmas have a significant crustal component that likely gave rise to their reduced oxidation state, which may be a critical factor for gold concentration in the melts. The majority of deposits are associated with reduced granitoids that typically have associated tungsten mineralization, but those of the Tasman fold belt are clearly more oxidized (Blevin, 2004). At the camp scale, they show intrusive-centered metallogenic zonation (Fig. 15). Deposits such as Fort Knox, Dublin Gulch, and Timbarra contain compelling geologic evidence for a magmatic origin with features that represent the magmatic to hydrothermal transition, such as aplites, pegmatites, vein dikes, miarolitic cavities, and unidirectional solidification textures (Fig. 14F). The deposits typically evolved from early high-temperature magmatic stages to lower temperature hydrothermal veins. The ore assemblage consistently contains gold intergrown with bismuth- and tellurium-bearing phases and locally molybdenum and/or scheelite. The low sulfide content consists of a reduced mineral assemblage (pyrrhotite, pyrite, loellingite, and arsenopyrite), which is consistent with a source related to reduced magmas. Most deposits formed at mesozonal depths (4–8 km), but epizonal examples are known (e.g., Kidston and Shotgun) and these typically have higher base metal contents. Baker (2002) argued that the variation in fluid inclusion characteristics between mesozonal and epizonal deposits resulted from fluid trapping at different crustal levels subsequent to being exsolved from felsic melts.

Although there is a general acceptance that deposits such as Fort Knox, Timbarra, and Kidston are distinctly different from orogenic gold deposits, the overall geographic and economic importance of intrusion-related gold deposits is still uncertain (e.g., Goldfarb et al., 2000; Groves et al., 2003). The most important differences between these reduced intrusion-related gold deposits and orogenic gold deposits may be (1) their low grades (i.e., <1 g/t vs. >5–10 g/t in orogenic deposits, although if Pogo is classified as an intrusion-related gold deposit, as one of us believes [T.B], then this does not hold); (2) their location in deformed shelf sequences inland of accreted terranes; (3) a regional association with tungsten and/or, less consistently, tin lodes; (4) a postdeformational timing relative to more of a late synorogenic timing for orogenic gold deposits; and (5) anomalous granitoid systems reflecting some input from mantle-derived mafic alkaline magmas into the base of the crust. The low grades, which became realistic targets during the recently changing economics and mining efficiencies, help explain why intrusion-related gold deposits have really just become a second type of gold deposit defined in metamorphic belts during the previous 10 to 15 years. Many deposits mentioned within the intrusion-related gold deposits classification (e.g., Thompson and Newberry, 2000), however, lack unequivocal evidence of a magmatic origin and, therefore, remain controversial (e.g., Pogo and Donlin Creek in the Tintina gold province, Linglong in eastern China, and Muruntau, Vasilikovskoye, and Jilau in central Asia). Kidston, described above as part of the intrusion-related gold deposits group, has alternatively been described as a "porphyry-related" mineral deposit type (Solomon and Groves, 1994) or a breccia pipe (Poulsen et al., 2000). Importantly, features not suitable to discriminate between the two deposit types include (1) anomalous Bi, W, and Te, and reduced sulfide assemblages, (2) low-salinity, CO_2-bearing fluid inclusions, (3) lodes formed subsequent to peak metamorphism of the host rocks, (4) shallow vein systems, and (5) spatial and/or temporal association with granitoids, as these features also may characterize orogenic gold deposits in metamorphic rocks.

Genetic Models

There have been numerous models proposed during the past 25 years for the genesis of gold deposits in metamorphic terranes (see discussion in App.) and yet there is still no consensus. In the late 1970s, a syngenetic sea-floor exhalative origin was very commonly applied to many of the gold deposits in these environments (Hutchinson and Burlington, 1984), but, exclusive of gold-rich VMS deposits, such a model is now considered inappropriate by most workers. However, the gold might initially be concentrated in crustal rocks in a syngenetic environment. That is, although the gold lodes themselves are clearly epigenetic, there is a strong likelihood that gold was

initially added into crustal rocks as an uneconomic syngenetic trace component many tens of millions of years prior to its concentration in productive lodes (e.g., Henley et al., 1976; Hodgson, 1993).

During the mid 1980s through the early 1990s, deep convection of meteoric fluids was often implicated as the source of the hydrothermal systems (Nesbitt et al., 1986; Shelton et al., 1988). This model was mainly based upon hydrogen isotope data from fluid inclusions in quartz samples of orogenic gold deposits in the North American Cordillera. However, as discussed above, the significance of such data is questionable. Thus, the meteoric water model is viewed today, by most workers, as unlikely.

A majority of workers relate ore genesis to processes of crustal devolatilization; yet, significant debate continues as to exactly how processes proceed and focus metalliferous fluids. Originally, such a model was focused on lateral secretion mechanisms (e.g., Boyle 1979, 1986), by which fluids and metals were mainly derived from metamorphic events in the host terrane but not from subducted material. The bulk of the data are indeed compatible with most fluids being produced from prograde metamorphic events (Kerrich and Fyfe, 1981; Phillips and Groves, 1983: Phillips et al., 1987) but with subducted material in the middle to lower crust being a likely source. Fluid produced at metamorphic facies boundaries (Fyfe et al., 1978; Powell et al., 1991), and released during relative increases in pore pressure (e.g., Fyfe and Henley, 1973; Norris and Henley, 1976), become channelized into major structures and move upward in the crust, particularly during seismic events (Sibson et al., 1988). Gold deposition occurs at shallower crustal levels in rocks that were likely on a retrograde metamorphic path for the previous 10 to 50 m.y. (Goldfarb et al., 1986; Kontak et al., 1990; Stuwe et al., 1993). In addition, metamorphism of a subducted slab may also be critical to volatile release, as perhaps required by Phanerozoic gold in the high-grade Precambrian rocks of the North China craton. In most cases, as this would occur at depths of 80 to 120 km (e.g., Jarrard, 2003), fluids would not migrate directly into the lower crust but get carried within rising melts formed in an overlying mantle wedge.

Although the importance of emplacement of mantle or crustal melts with the release of significant metals or volatiles is unclear, there seems to have been a swing in the recent literature back to the possibility that many gold deposits in metamorphic rocks are products of magmatic exsolution. Such an idea was popular throughout much of the first three-quarters of the 20th century (e.g., Lindgren, 1933; Bateman, 1950) and certainly the intrusion-related gold deposits model provides evidence that at least some granitoids are capable of producing at least low-grade economic gold deposits along craton margins. If controversial deposits such as Pogo and Muruntau are indeed intrusion-related gold deposits, then magmatic models may also explain some high-grade and very high tonnage gold systems. Both early (e.g., Spooner, 1993) and late (e.g., MacDonald and Hodgson, 1986; McCoy et al., 1997) magmatic fluids have been suggested by various workers. Universal application of a magmatic model for most gold systems in an evolving orogen is unlikely based upon a spatial and temporal association of gold with a variety of magma compositions, geochronological arguments, trace element geochemistry characteristics, and spatial distribution of ores and gangue typically restricted to sheared pluton margins (details in Appendix).

Involvement of mantle contributions has also been widely considered during the last two decades. The spatial association of gold with lamprophyres led Rock and Groves (1988) to suggest a mantle connection to the ore-forming process, although Wyman and Kerrich (1989), Kerrich and Wyman (1994), and Dubé et al. (2004) summarize evidence why this is likely to be solely a spatial association and without genetic implications. Nonetheless, mantle melts at the base of the crust (e.g., Powell et al., 1991), subduction of a mantle window (e.g., Haeussler et al., 1995), or mantle plume activity (Murphy et al., 1999) may provide the needed thermal energy to help drive crustal devolatilization episodes.

It appears, at times, that the more numerous the studies of a given deposit, the more data lead to conflicting genetic models. For example, as described by Kempe et al. (2001), syngenetic, metamorphic, magmatic, and mantle outgassing have all been applied to Muruntau in various studies during the last one-half century. The pros and cons of the various models that have been applied to these hydrothermal systems are discussed in detail in the Appendix. The fact that fluids from multiple sources are mobile in these actively deforming tectonic belts (Fig. 16, App. Fig. A14) leads to a variety of permissive scenarios that can be critical for ore genesis. Numerous tectonic events, including crustal thickening, plume input, slab rollback, ridge subduction, and the loss of the subcontinental mantle lithosphere, can all provide the thermal driving force for fluid migration (App. Fig. A15; Goldfarb et al., 2001a; Groves et al., 2005).

Geological, Geochemical, and Geophysical Exploration Signatures

Given the extensive advances in understanding of gold deposits in metamorphic belts during the last 25 years, the ability to target favorable ground for gold ores in these environments has improved significantly. An understanding of the regional and local structural geology is perhaps the most critical geologic feature in defining an exploration strategy (e.g., Sibson et al., 1988; Hodgson, 1989). Complex geometries along major fault zones provide recognized target areas in regional exploration programs. Features such as dilational zones where shears or faults may be more gently dipping or anomalous in strike, flower structures, dilational jogs, heterogeneous stress fields, irregular pluton margins, and pressure shadows at termination zones of elongate batholiths are examples of such favorable complexities (Groves et al., 2000). Definition of the apical portions of barely unroofed plutons may also be important in targeting large-tonnage intrusion-related gold deposits (Hart et al., 2002) rather than orogenic gold deposits. It is clear that specific competent rock types in a complex stratigraphy are likely to be favorable traps for deep-crustal fluids, although competency contracts and layer anisotropy induced by these stiff units add significant structural complexity (Dubé et al. 1989; Robert et al., 1994). This is particularly true for such rock types that occur at high angles to principal far-field stresses during progressive deformation (e.g., Ridley, 1993). Not only are jogs and bends within major faults likely areas to host ores, but the intersection of

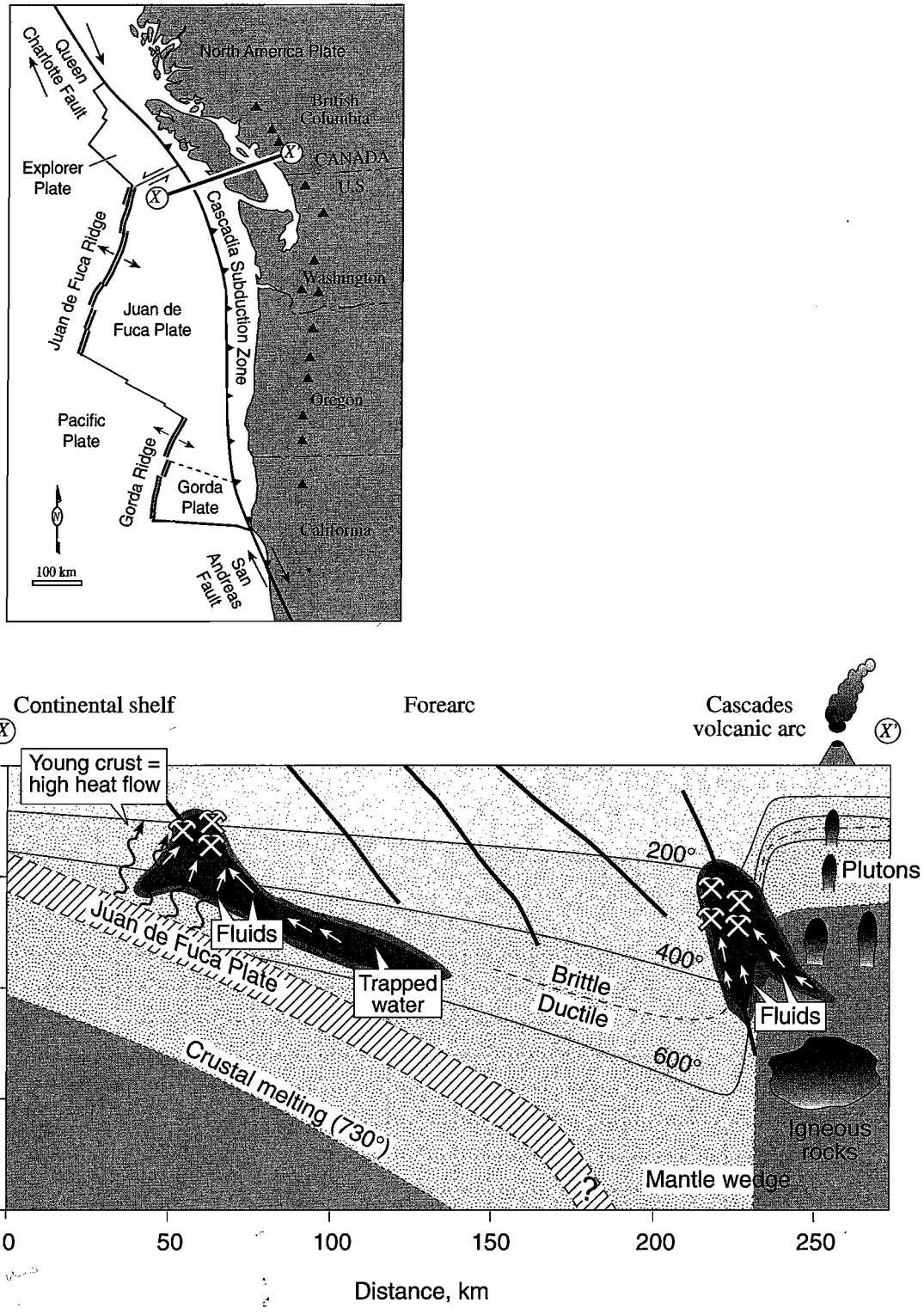


FIG. 16. Present-day subduction off the western coast of North America shows two zones of high heat flow and potential fluids at depth seaward of the Cascades magmatic arc. These fluids may be eventual ore-forming solutions, with deposits developed at depth during seismic events associated with future changes in the stress regimes (from collisional to strike-slip margin). Major potential fluid reservoirs would include the deeper parts to the accreted terranes, the synkinematic plutons, and the slab itself. Whether one of these in particular, or possibly all three, contributed to ore formation is unclear. After Goldfarb et al. (2001a).

different fault generations, perhaps early thrusts and later transpressional structures, can isolate curvilinear blocks, such as at the Golden Mile deposit and Timmins district, which will focus fluids (Groves et al., 2000). Major anticlinal fold hinge zones, particularly in post-Archean fold belts and commonly existing as domal culminations, are additional key targets (e.g., Kontak et al., 1990; Cox et al., 1991; Dubé et al., 2002). The association of gold with high paleogeotherms (Phillips and Powell, 1992) and Barrovian metamorphic sequences, particularly greenschist facies zones, suggests that metamorphic facies maps are invaluable for exploration programs in metamorphic belts (e.g., Ridley and Diamond, 2000). Regional unconformities, such as the Timiskaming in southern Abitibi and that at Red Lake, show an empirical relationship to large gold deposits and represent key exploration targets (Hodgson, 1993, Dubé et al., 2004).

The application to exploration of Geographic Information Systems (GIS), using regional and structural geologic data, has become commonplace during the previous decade. This reflects, in large part, the late, repetitive, and thus predictable geologic controls on lode gold systems (Groves et al., 2000). Important information for such modeling is likely to include distance to nearest regional fault and/or unconformity, nearest anticline, rheological contrasts between contacts, differences between observed and expected strikes, etc. Stress mapping techniques, which use such data, indicate where critical dilational jogs are likely to develop along regional fault systems (e.g., Holyland et al., 1993; Vearncombe and Holyland, 1995). On a local scale, such models then use strength parameters to define rock competency contrasts. Computer-based prospectivity mapping using such GIS approaches (Knox-Robinson and Wyborn, 1997) may either be conceptual (i.e., using genetic concepts) or empirical (i.e., using data from well-studied deposits). The former approach has been used as part of the U.S. Geological Survey's three-step mineral resource assessment strategy (Barton et al., 1995). The latter, as noted by Knox-Robinson and Wyborn (1997), may involve identifying the critical spatial relationships, quantifying such information, and then integrating these results with approaches such as Boolean methods, weights of evidence, fuzzy logic, and neural networks (e.g., Knox-Robinson and Groves, 1997; Brown et al., 2000).

Geochemical and mineralogical signatures, particularly within a favorably defined block, have been documented by many workers. Potassic alteration, silicification, sulfidation, and carbonation are all well-proven signatures for lode gold exploration in metamorphic belts (e.g., Boyle, 1979; Eilu et al., 1998). Bleaching of metasedimentary or metavolcanic rocks, due to breakdown of mafic minerals, consistently indicates proximity to ore zones, and carbonate spotting and sulfide porphyroblasts are commonly well developed in such bleached rocks (Bierlein et al., 1998). Rock, stream sediment, and soil geochemical surveys have tended to indicate a very consistent group of pathfinder elements. Trace elements that are consistently enriched include Ag, As, Au, B, Bi, Hg, Sb, Te, and W (e.g., Kerrich, 1983; Nesbitt, 1991), although this geochemical signature may vary depending on the nature of the host rocks. For example, As, Hg, and Sb may be less important for deposits, both orogenic and intrusion-elated gold deposits, hosted by felsic igneous rocks (Goldfarb, unpub. data). Lithogeochemical surveys are generally variable as to which trace elements give the broadest halos, but Sb and As appear to be most consistently effective (e.g., Eilu and Mikucki, 1998; Christie and Brathwaite, 2003). Some surveys also note that enrichments in ore-fluid volatile species (CO_2, H_2O, N_2, S) or major element anomalies (increase in K, decrease in Na) are good indicators of proximity to ore (e.g., Boyle, 1979; Bierlein et al., 1998; Eilu et al., 1998).

Although geophysical methodology has advanced considerably in the past few decades, these evolving techniques have typically not been directly useful to the recognition of new gold ore deposits. Rather, most applications have focused on identifying potentially favorable structures or rock types (e.g., BIF, granitoids, etc.; Moore, 1996) for ore, subsequent to which geological, geochemical, and structural approaches have been applied on the more local scale. Such regional geophysical work is particularly critical in poorly exposed, gold-rich terranes, such as those in the shield areas of Canada and Australia or the tundra of interior Alaska and eastern Russia. Linear magnetic lows can identify regional faults and trends, where alteration along fault zones has broken down regional magnetite or where felsic dikes or massive quartz veins fill major fault zones (Paterson and Hallof, 1991). For intrusion-related gold deposits, radiometric surveys to identify more highly fractionated, K-rich intrusions or the typical "doughnut-like" features in magnetic data, where pyrrhotite-rich alteration halos surround plutons intruding carbonaceous metasedimentary rocks, are likely to be valuable (Hart et al., 2002). Remote sensing surveys, where airborne hyperspectral data are used to produce mineral abundance maps (e.g., Bierwith et al., 2002), have become more common in recent years. In areas where gold deposits are likely in highly reactive country rocks, induced polarization (IP) surveys can define zones of disseminated or replacement style mineralization; local resistivity highs also may be geophysical signatures of zones of intense silicification or veining (Paterson and Hallof, 1991).

Relationship to Other Epigenetic Mineral Deposit Types

Intuitively, there must be locations where the fluids that form the epizonal to hypozonal gold deposits in metamorphic belts vent at the surface and precipitate minerals within the upper few kilometers of the crust. The tops to these hydrothermal systems are almost certainly epizonal mercury and/or antimony deposits common in the less eroded parts of orogenic belts (e.g., Studmeister, 1984; Dill, 1998). Thus, there is a clear metallogenic continuum in the upper crust from mercury- to antimony- to gold-rich zones with increasing depth in the epizonal environment (e.g., Nesbitt and Muehlenbachs, 1989). This zoning reflects low-temperature solubility controls on these sulfide-complexed metals, such that most gold is no longer soluble below about 225°C and most antimony has precipitated by about 175°C, whereas highly volatile mercury is carried to shallowest depths. In fact, it has been suggested for almost 40 years that the mercury ores in westernmost North America (e.g., California Coast Ranges, Pinchi belt, Kuskokwim basin) are the products of fluids produced during lower grades of metamorphism (e.g., White, 1967; Barnes, 1970), a process described above as commonly related to the genesis of many gold deposits in

metamorphic belts. As with gold deposits at deeper crustal levels, the fluids responsible for forming the Hg- and Sb-rich brittle veinlets were enriched in ^{18}O and CO_2; the isotopically heavy fluids are much different than those associated with most shallow gold deposits of epithermal or Carlin classification (Goldfarb et al., 1990). The typical lack of these deposits in Precambrian environments reflects their shallow levels of formation and thus a lack of preservation (e.g., Groves et al., 2005). The presence of such mercury and antimony deposits in unmetamorphosed to low-grade parts of orogenic belts may define important gold pathfinders.

The relationship between the hypozonal orogenic gold deposits that occur in metamorphic belts and skarn deposits has been controversial (e.g., see Groves et al., 1998). As noted by Mueller and Groves (1991), the higher pressure-temperature gold deposits in these belts have many features that resemble skarns in the descriptive sense of Einaudi and Burt (1982). Meinert (1989) noted that, in contrast to most other skarns, gold skarns contain only minor base metals, have an Au-As-Bi-Te signature, are characterized by host rocks with a significant clastic component, and have gangue and sulfide mineralogies dominated by garnet-pyroxene ± K-feldspar and arsenopyrite-pyrrhotite, respectively. Nevertheless, he defined greenstone belt-hosted deposits such as Southern Cross and Marvel Loch as "other classes of deposits," perhaps because of the absence of other features characteristic of gold skarns that include proximity to copper-rich skarns, an association with mafic plutons, and some degree of igneous or carbonate host-rock material. In addition, in contrast to most intrusion-related gold deposits and orogenic gold deposits, including those of hypozonal nature, true gold skarns form from a saline to hypersaline fluid (Meinert, 2000). Mueller (1992) argued that many of the hypozonal features of gold deposits are identical to those of skarn deposits, but the fact that economic mineralization is commonly in quartz reefs makes it difficult to determine whether deposits such as Norseman and Kolar should be classified as types of skarns. It is recommended that, because there seems to be a continuum of deposit styles and hydrothermal minerals within a given gold province, and commonly along the same deep crustal structure, these deeply formed deposits in greenstone and slate belts, despite their skarnlike calc-silicate mineralogy, be continued to be termed hypozonal orogenic gold deposits rather than skarn deposits.

Many epigenetic silver-lead-zinc quartz-carbonate veins in clastic metasedimentary rock terranes show features (e.g., Beaudoin and Sangster, 1992) that are remarkably similar to those of gold deposits in the same environments. Although possessing an argentiferous base metal-rich metallogeny, Neoproterozoic through Mesozoic vein systems in districts such as Coeur d'Alene, Idaho; Kokanee Range, British Columbia; Cobar, NSW; and Harz Mountains, Germany, occur in metamorphic belts, were emplaced near major faults during late orogenesis, and formed from H_2O-CO_2 ± CH_4 ± N_2 fluids at moderate pressure-temperature conditions, which are typically more saline than many orogenic gold systems, and commonly subsequent to any recognized magmatism (Leach et al., 1988; Beaudoin and Sangster, 1992; Stegman, 2001). Models similar to those expressed for gold deposits in metamorphic belts have been applied to these ores; for Coeur d'Alene metamorphic and magmatic arguments have been proposed (Leach et al., 1988; Fleck et al., 2002). It is conceivable that these deposits reflect mobilization of basinal fluids at moderate- to high-metamorphic temperature conditions (e.g., Yardley, 1997) within a fine-grained sedimentary rock sequence that has an inherently high background enrichment of silver and base metals from older sea-floor and/or diagenetic processes. In other words, they are analogs to orogenic gold deposits in metamorphic belts but are the product of more saline fluid migration in metalliferously favorable strata.

Conclusions

What has been learned during the last 25 years?

The economic geology literature from post-1980 shows clearly the advances over the last few decades in understanding of gold ores in metamorphic settings. It now appears to us that these deposit types are of epigenetic origin and mostly continue to define a coherent group, despite attempts to split the ores into a variety of distinct classes. The gold ores are related to major tectonic episodes within specific geodynamic environments; their preservation and global distribution reflect the evolving plate tectonic processes of Earth. Accurate and precise dating techniques have, for the first time in many provinces, allowed a thorough understanding of temporal patterns and relationships. Formation of these ores over a broad temperature-depth range has led to the development of a "continuum" of deposit styles and mineral assemblages. Nevertheless, a generally consistent, complex fluid chemistry stresses the need for a deep-crustal fluid source that is typically distal to gold lodes. Unlike other gold deposit types, these regional hydrothermal systems are dominated by a low-salinity, aqueous-carbonic fluid with consistently heavy $\delta^{18}O$. The understanding of structure, as well as host-rock rheology, composition, and distribution, are clearly realized to be keys for development of an exploration strategy within Precambrian and Phanerozoic permissive terranes. Given the late kinematic setting of most ores, such that only limited changes have affected many of the overall structural relationships within large gold districts, and the present understanding of geochemical alteration patterns, application of computer-based GIS approaches are becoming commonplace in selecting exploration sites.

What are the key problems to solve in the next 25 years?

The most critical needs for future research have been recently well addressed in reviews by Bierlein and Crowe (2000), Hagemann and Brown (2000), Thompson and Newberry (2000), and Groves et al. (2003). Compared to many other gold deposit types, particularly those developed in the surrounding thermal aureoles to shallowly emplaced plutons in unmetamorphosed environments, a clear and comprehensive genetic model of gold deposits in metamorphic rocks remains elusive. Geochemical data continue to be equivocal in defining fluid source; the same data are commonly interpreted by various workers to be indicative of magmatic, metamorphic, or mantle origins. Some of the confusion reflects fluid interaction with rocks over a broad crustal stratigraphy causing the complex geochemical signature (D. Kontak, oral commun., 2004). If a metamorphic model is selected as

appropriate for the formation of many orogenic gold deposits, then where do the fluids come from—deeper crustal rocks or a subducted slab? Future laser developments for analyzing trace elements in melt and fluid inclusions, rare gas studies, and application of new isotope systems may all eventually help fingerprint different fluid sources. This, in turn, and coupled with new hydrologic models for the deeper crust, may help determine how fluids are initially focused into regional structures (Cox, 2005). Low-level measurements of gold and related metal species in different minerals may help to eventually solve the long-debated source rock problem.

Exploration is likely to continue to be aided by application of evolving GIS-based prospectivity mapping techniques to carefully collected field measurements. Much of this work will address the problems of recognizing global gold giants, which are more consistently the focused targets of exploration. Detailed field mapping to establish key chronological relationships, combined with absolute dating of ore minerals in complex hydrothermal systems, should elucidate questions regarding the duration of hydrothermal events and relationships with spatially associated magmatic and structural events. Finally, the significance of intrusion-related gold deposits is likely to be more completely addressed during the next few decades. Can specific pluton types emplaced in metamorphic rocks be consistently fingerprinted for their association with large-tonnage gold resources or are the few economic intrusion-related gold deposits simply relative anomalies that will not prove to be a type of widespread global target?

Acknowledgments

This paper benefited from careful reviews by Kevin Cassidy, Connie Nutt, and Dan Kontak and insightful comments also from Francois Robert. Although presented by a small group of us, it is obvious that this material reflects the contributions of many individuals during the last few decades. We specifically would like to acknowledge the contributions of our colleagues, Rob Kerrich, Jay Hodgson, Neil Phillips, and François Robert, who have been true leaders in this field and have helped shape many of our ideas here. In addition, collaborations with and concepts introduced by Frank Bierlein, Dwight Bradley, Sandy Colvine, Steve Cox, David Leach, Ed Mikucki, Bruce Nesbitt, Bill Pickthorn, Howard Poulsen, John Ridley, Rick Sibson, and Noreen Vielreicher have also led to an improved understanding of many of the deposits and districts discussed in this paper. Interactions with John Thompson and Jim Lang have been critical to the evolving model for intrusion-related gold deposits. Organizational help with the manuscript by Erin Marsh is greatly acknowledged. Finally, we thank Jeff Hedenquist and John Thompson for the invitation to write this review on orogenic and intrusion-related gold deposits. This paper is also Geological Survey of Canada contribution no. 2005069.

REFERENCES

Afifi, A.M., Kelly, W.C., and Essene, E.J., 1988, Phase relations among tellurides, sulfides, and oxides: I. Thermochemical data and calculated equilibria: Economic Geology, v. 83, p. 377–394.

Allibone A.H., McCuaig, T.C., Harris, D., Etheridge, M., Monroe, S., Byrne, D., Amanor, J., and Gyapong, W., 2002 Structural controls on gold mineralization at the Ashanti gold deposit, Obuasi, Ghana: Society of Economic Geologists Special Publication 9, p. 65–93.

Ayer, J.A., Barr, E., Bleeker, W., Creaser, R.A., Hall, G., Ketchum, J.W.F., Powers, D., Salier, B., Still, A., and Trowell, N.F., 2003, Discover Abitibi: New geochronologieal results from the Timmins area: Implications for the timing of late-tectonic stratigraphy, magmatism and gold mineralization: Ontario Geological Survey Open-file Report 6120, p. 33.1–33.10.

Bain, J.H.C., and Draper, J.J., eds., 1997, North Queensland geology: AGSO Bulletin 240, 600 p., geologic map scale 1:1,000,000, atlas 1:300,000.

Baker, E.M., and Andrew, A.S., 1991, Geologic, fluid inclusion, and stable isotope studies of the gold-bearing breccia pipe at Kidston, Queensland, Australia: Economic Geology, v. 86, p. 810–830.

Baker, E.M., and Tullemans, F.J., 1990, Kidston gold deposit: Australasian Institute of Mining and Metallurgy Monograph 14, p. 1461–1465.

Baker, T., 2002, Emplacement depth and CO_2-rich fluid inclusions in intrusion-related gold deposits: Economic Geology, v. 97, p. 1109–1115.

Baker, T., and Lang, J.R., 2001, Fluid inclusion characteristics of intrusion-related gold mineralization, Tombstone tungsten magmatic belt, Yukon Territory, Canada: Mineralium Deposita, v. 36, p. 563–582.

Bakke, A.A., 1995, The Fort Knox "porphyry" gold deposit—structurally controlled stockwork and shear quartz vein, sulphide-poor mineralization hosted by Late Cretaceous pluton, east-central Alaska: Canadian Institute of Mining and Metallurgy Special Volume 46, p. 795–802.

Bakke, A., Morrell, B., Odden, J., Bergstrom, T., and Woodman, J., 2000, Kinross Gold USA's activities in the Fairbanks mining district, K2K: British Columbia and Yukon Chamber of Mines Special Volume 2, p. 89–98.

Barnes, I., 1970, Metamorphic waters from the Pacific tectonic belt of the west coast of the United States: Science, v. 168, p. 973–975.

Barton, P.B., Brew, D.A., Ludington, S., Lindsey, D.A., Ayuso, R.A., Force, E.R., Gamble, B.M., Goldfarb, R.J., John, D.A., and Johnson, K.M., 1995, Forecasting undiscovered mineral resources: U.S. Geological Survey Open-file Report 95–82, 90 p.

Bateman, A.M., 1950, Economic mineral deposits, 2nd ed.: New York, John Wiley and Sons, 916 p.

Bateman, R., and Hagemann, S., 2004, Gold mineralisation throughout about 45 Ma of Archaean orogenesis—protracted flux of gold in the Golden Mile, Yilgarn craton, Western Australia: Mineralium Deposita, v. 39, p. 536–559.

Beaudoin, G., and Sangster, D.F., 1992, A descriptive model for silver-lead-zinc veins in clastic metasedimentary terranes: Economic Geology, v. 87, p. 1005–1021.

Beirwith P., Huston, D., and Blewett, R.S., 2002, Hyperspectral mapping of mineral assemblages associated with gold mineralizationin the central Pilbara, Western Australia: Economic Geology, v. 97, p. 819–826.

Belt, T., 1861, Mineral veins—an enquiry into their origin founded on a study of the auriferous quartz veins of Australia: London, John Weale Publisher, 52 p.

Berger, B.R., 1986, Descriptive model of low-sulphide Au-quartz veins: U.S. Geological Survey Bulletin 1693: p. 183–186.

Bierlein, F.P., Christie, A.B., and Smith, P.K., 2004, A comparison of orogenic gold mineralization in central Victoria (AUS), western South Island (NZ) and Nova Scotia (CAN)—implications for variations in the endowment of Paleozoic metamorphic terrains: Ore Geology Reviews, v. 25, p. 125–168.

Bierlein, F.P., and Crowe, D.E., 2000, Phanerozoic orogenic lode gold deposits: Reviews in Economic Geology, v. 13, p. 103–139.

Bierlein, F.P., Fuller, T., Stuwe, K., Arne, D.C., and Keays, R.R., 1998, Wall-rock alteration associated with turbidite-hosted gold deposits—examples from Central Victoria, Australia: Ore Geology Reviews, v. 13, p. 345–380.

Blevin, P.L., 2004, Redox and compositional parameters for interpreting the granitoid metallogeny of eastern Australia—implications for gold-rich ore systems: Resource Geology, v. 54, p. 241–252.

Boer, R.H., Meyer, F.M., Robb, L.J., Graney, J.R., Vennemann, T.W., and Kesler, S.E., 1995, Mesothermal-type mineralization in the Sabie-Pilgrim's Rest gold field, South Africa: Economic Geology, v. 90, p. 860–876.

Böhlke, J.K., 1982, Orogenic (metamorphic-hosted) gold-quartz veins: U.S. Geological Survey Open-file Report 82–795, p. 70–76.

——1988, Carbonate-sulfide equilibria and "stratabound" disseminated epigenetic gold mineralization: A proposal based on examples from Alleghany, California, U.S.A: Applied Geochemistry, v. 3, p. 499–516.

——1989, Comparison of metasomatic reactions between a common CO_2–rich vein fluid and diverse wall rocks: Intensive variable, mass transfers, and Au mineralization at Alleghany, California. Economic Geology, v. 89, p. 291–327.

Böhlke, J.K., and Irwin, J.J., 1992, Laser microprobe analyses of Cl, Br, I, and K in fluid inclusions—implications for sources of salinity in some ancient hydrothermal fluids: Geochimica et Cosmochimica Acta, v. 56, p. 203–225.

Böhlke, J.K., and Kistler, R.W., 1986, Rb-Sr, K-Ar, and stable isotope evidence for ages and sources of fluid components of gold-bearing quartz veins in the northern Sierra Nevada foothills metamorphic belt, California: ECONOMIC GEOLOGY, v. 81, p. 296–322.

Bouchot, V., Milesi, J. P., Ledru, P., Lerouge, C., Roig, J.Y., Bellot, J.P., Becq-Giraudon, J.F., and Truffert, C., 2000, Orogenic gold veins and W, Li-F mineralizations related to "specialised" granites: Two markers of the crustal scale Au-W-Sb metalliferous peak at 310–305 Ma (French Variscan belt): Documents du Bureau de Recherches Geologiques et Minieres 297, p. 53–55.

Bouchot, V., Faure, M., Feybesse, J.L., Correia, P., and Zacharias, J., 2003, Variscan orogenic gold districts related to a regional scale Visean detachment in the Central Bohemian metallogenic province (Czech Republic)—a geodynamic reassessment, *in* Eliopoulos, D.G., et al., eds, Mineral exploration and sustainable development: Rotterdam, Millpress, p. 747–750.

Boullier, A.-M., Firdaous, K., and Robert, F., 1998, On the significance of aqueous fluid inclusions in gold-bearing quartz vein deposits from the southeastern Abitibi subprovince (Quebec, Canada): ECONOMIC GEOLOGY, v. 93, p. 216–223.

Boyle, R.W., 1961, The geology, geochemistry, and origin of the gold deposits of the Yellowknife district: Geological Survey of Canada, Memoir 310, 193 p.

——1975, Mineralization processes in Archean greenstone and sedimentary belts: Geological Survey of Canada, Paper 75–15, 45 p.

——1979, The geochemistry of gold and its deposits: Geological Survey of Canada Bulletin 280, 584 p.

——1986, Gold deposits in turbidite sequences—their geology, geochemistry and history of the theories of their origin: Geological Association of Canada Special Paper 32, p. 1–13.

Brown, V., 2001. The geology and genesis of the Ray Gulch tungsten skarn, Yukon Territory, Canada: Unpublished B.Sc. thesis, Townville, Australia, James Cooke University, 164 p.

Brown, W.M., Gedeon, T.D., Groves, D.I., and Barnes, R.G., 2000, Artificial neural networks—a new method for mineral prospectivity mapping: Australian Journal of Earth Sciences, v. 47, p. 757–770.

Browning, P., Groves, D.I., Blockley, J.G., and Rosman, K.J.R., 1987, Lead isotope constraints on the age and source of gold mineralization in the Archean Yilgarn block, Western Australia: ECONOMIC GEOLOGY, v. 82, p. 971–986.

Buddington, A.F., 1935, High-temperature mineral associations at shallow to moderate depths: ECONOMIC GEOLOGY, v. 30, p. 205–222.

Bullis, H.R., Hureau, R.A., and Penner, B.D., 1994, Distribution of gold and sulfides at Lupin, Northwest Territories: ECONOMIC GEOLOGY, v. 89, p. 1217–1227.

Bundtzen, T.K., and Miller, M.L., 1997, Precious metals associated with Late Cretaceous-early Tertiary igneous rocks of Southwestern Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 242–286.

Burrows, D.R., Wood, P.C., and Spooner, E.T.C., 1986, Carbon isotope evidence for a magmatic origin for Archaean gold-quartz vein ore deposits: Nature, v. 321, p. 851–854.

Bursnall, J.T., ed., 1989, Mineralization and shear zones: Geological Association of Canada Short Course Notes Volume 6, 299 p.

Cameron, E.M., 1988, Archean gold: Relation to granulite formation and redox zoning in the crust: Geology, v. 16, p. 109–112.

Card, K.D., Poulsen, K.H., and Robert, F., 1989, The Archean Superior province of the Canadian Shield and its lode gold deposits: ECONOMIC GEOLOGY MONOGRAPH 6, p. 19–36.

Cassidy, K.F., Groves, D.I., McNaughton, N.J., and Arne, D.C., 1998, Late-Archean granitoid-hosted lode-gold deposits, Yilgarn craton, Western Australia—deposit characteristics, crustal architecture and implications for ore genesis: Ore Geology Reviews, v. 13, p. 65–102.

Cathelineau, M., Boiron, M-C., Holliger, P., Marion, P., and Denis, M., 1989, Gold in arsenopyrites—crystal chemistry, location and state, physical and chemical conditions of deposition: ECONOMIC GEOLOGY MONOGRAPH 6, p. 328–341.

Champion, D.C., and Chappell, B.W., 1992, Petrogenesis of felsic I-type granites—an example from Queensland: Transactions of the Royal Society of Edinburgh, Earth Sciences, v. 83, p. 115–126.

Christie, A.B., and Brathwaite, R.L., 2003, Hydrothermal alteration in metasedimentary rock-hosted orogenic gold deposits, Reefton goldfield, South Island, New Zealand: Mineralium Deposita, v. 38, p. 87–107.

Clark, M.E., Carmichael, D.M., Hodgson, C.J., and Fu, M., 1989, Wall-rock alteration, Victory gold mine, Kambalda, Western Australia: Processes and P-T-X_{CO_2} conditions of metasomatism: ECONOMIC GEOLOGY MONOGRAPH 6, p. 445–459.

Clout, J.M.F., Cleghorn, J.H., and Eaton, P.C., 1990, Geology of the Kalgoorlie gold field: Australasian Institute of Mining and Metallurgy Monograph 14, p. 411–431.

Cole, A., Wilkinson, J.J., Halls, C., and Serenko, T.J., 2000, Geological characteristics, tectonic setting and preliminary interpretations of the Jilau gold-quartz vein deposit, Tajikistan: Mineralium Deposita, v. 35, p. 600–618.

Colvine, A.C., 1989, An empirical model for the formation of Archean gold deposits—products of final cratonization of the Superior province, Canada: ECONOMIC GEOLOGY MONOGRAPH 6, p. 37–53.

Colvine, A.C., Andrews, A.J., Cherry, M.E., Durocher, M.E., Fyon, J.A., Lavigne, M.J., Macdonald, A.J., Marmont, S., Poulsen, K.H., Springer, J.S., and Troop, D.G., 1984, An integrated model for the origin of Archean lode gold deposits: Ontario Geological Survey, Open-File Report 5524, 98 p.

Colvine, A.C., Fyon, J.A., Heather, K.B., Marmont, S., Smith, P.M., and Troop, D.G., 1988, Archean lode gold deposits in Ontario: Ontario Geological Survey Miscellaneous Paper 139, 136 p.

Couture, J.F., Pilote, P., Machado, N., and Desrochers, J.-P., 1994, Timing of gold mineralization in the Val-d'Or district, southern Abitibi belt: Evidence for two distinct mineralizing events: ECONOMIC GEOLOGY, v. 89, p. 1542–1551.

Cox, S.F., Wall, V.J., Etheridge, M.A., and Potter, T.F., 1991, Deformational and metamorphic processes in the formation of mesothermal vein-hosted gold deposits: Examples from the Lachlan fold belt in central Victoria, Australia: Ore Geology Reviews, 6, p. 391–423.

Cox, S.F., Sun, S.S., Etheridge, M.A., Wall, V.J., and Potter, T.F., 1995, Structural and geochemical controls on the development of turbidite-hosted gold quartz vein deposits, Wattle Gully mine, central Victoria, Australia: ECONOMIC GEOLOGY, v. 90, p. 1722–1746.

Cox, S.F., Knackstedt, M.A., and Brown, J., 2001, Principles of structural control on permeability and fluid flow in hydrothermal systems: Reviews in Economic Geology, v. 14, p. 1–24.

Craw, D., 2002, Geochemistry of late metamorphic hydrothermal alteration and graphitisation of host rock, Macraes gold mine, Otago Schist, New Zealand: Chemical Geology, v. 191, p. 257–275.

Craw, D., and Chamberlain, C.P., 1996, Meteoric incursion and oxygen fronts in the Dalradian metamorphic belt, Southwest Scotland: A new hypothesis for regional gold mobility: Mineralium Deposita, v. 31, p. 365–373.

Curti, E., 1987, Lead and oxygen isotope evidence for the origin of the Monte Rosa gold lode deposits (Western Alps, Italy)—a comparison with Archaean lode deposits: ECONOMIC GEOLOGY, v. 82, p. 2115–2140.

de Ronde, C.E.J., and de Wit, M.J., 1994, Tectonic history of the Barberton greenstone belt, South Africa—490 million years of Archean crustal evolution: Tectonics, v. 13, p. 983–1005.

de Ronde, C.E.J., Faure, K., Bray, C.J., and Whitford, D.J., 2000, Round Hill shear zone-hosted gold deposit, Macraes Flat, Otago, New Zealand—evidence of a magmatic ore fluid: ECONOMIC GEOLOGY, v. 95, p. 1025–1048.

Dill, H.G., 1998, Evolution of Sb mineralisation in modern fold belts—a comparison of the Sb mineralization in the Central Andes (Bolivia) and the Western Carpathians (Slovakia): Mineralium Deposita, v. 33, p. 359–378.

Douglas, N., Mavrogenes, J., Hack, A., and England, R., 2000, The liquid bismuth collector model: An alternative gold depositional mechanism [abs]: Geological Society of Australia Abstract 59, p. 135.

Dowling, K., and Morrison, G., 1989, Application of quartz textures to the classification of gold deposits using North Queensland examples: ECONOMIC GEOLOGY MONOGRAPH 6, p. 342–355.

Dubé, B., Poulsen K.H., and Guha, J., 1989, The effects of layer anisotropy on auriferous shear zones—the Norbeau mine, Quebec: ECONOMIC GEOLOGY, v. 84, p. 871–878.

Dubé, B., Williamson, K., and Malo, M., 2002, Geology of the Goldcorp Inc. high-grade zone, Red Lake mine, Ontario—an update: Geological Survey of Canada Current Research 2001–C26, 13 p.

Dubé, B., Williamson, K., McNicoll, V., Malo, M., Skulski, T., Twomey, T., and Sanborn-Barrie, M., 2004, Timing of gold mineralization in the Red Lake gold camp, northwestern Ontario, Canada: New constraints from U-Pb geochronology at the Goldcrop High-grade zone, Red Lake mine and at the Madsen mine: ECONOMIC GEOLOGY, v. 99, p. 1611–1641.

Duuring, P., Hagemann, S.G., and Love, R.J., 2001, A thrust ramp model for gold mineralization at the Archean trondhjemite-hosted Tarmoola deposit: The importance of heterogeneous stress distributions around granitoid contacts: ECONOMIC GEOLOGY, v. 96, p. 1379–1396.

Ebert, S., Dodd, S., Miller, L., and Petsel, S., 2000, The Donlin Creek Au-As-Sb-Hg deposit, southwestern Alaska: Geology and Ore Deposits 2000—The Great Basin and Beyond, Geological Society of Nevada Symposium Proceedings, p. 1069–1081.

Eilu, P., and Mikucki, E.J., 1998, Alteration and primary geochemical dispersion associated with the Bulletin lode-gold deposit, Wiluna, Western Australia: Journal of Geochemical Exploration, v. 63, p. 73–103.

Eilu, P., Mikucki, E.J., and Groves, D.I., 1998, Wallrock alteration and primary geochemical dispersion in lode-gold exploration: Society for Geology Applied to Mineral Deposits Short Course Series, v. 1, 65 p.

Einaudi, M.T., and Burt, D.M., 1982, Introduction—terminology, classification, and composition of skarn deposits: ECONOMIC GEOLOGY, v. 77, p. 745–754.

Eisenlohr, B.N., Groves, D., and Partington, G.A., 1989, Crustal-scale shear zones and their significance to Archaean gold mineralization in Western Australia: Mineralium Deposita, v. 24, p. 1–8.

Emmons, W.H., 1933, On the mechanism of the deposition of certain metalliferous lode systems associated with granitic batholiths, *in* Ore deposits of the western States: New York, American Institute of Mining and Metallurgical Engineers, p. 327–349.

——1937, Gold deposits of the world: New York, McGraw Hill, 562 p.

Fleck, R.J., Criss, R.E., Eaton, G.F., Cleland, R.W., Wavra, C.S., and Bond, W.D., 2002, Age and origin of base and precious metal veins of the Coeur d'Alene mining district, Idaho: ECONOMIC GEOLOGY, v. 97, p. 23–42.

Foster, R.P., ed., 1984, Gold '82—the geology, geochemistry and genesis of gold deposits: Rotterdam, Balkema, 753 p.

——1989, Archean gold mineralization in Zimbabwe: Implications for metallogenesis and exploration: ECONOMIC GEOLOGY MONOGRAPH 6, p. 54–70.

Fourcade, S., Boiron, M.C., Cathelineau, M., Guerrot, C., Lerouge, C., Marignac, C., Martineau, F., and Vallance, J., 2000, Fluids and Late Carboniferous Variscan gold mineralizations in the French Massif Central—the bearing of stable isotopes: Documents du Bureau de Recherches Geologiques et Minieres 297, p. 58–59.

Fryer, B.J., Kerrich, R., Hutchinson, R.W., Peirce, M.G., and Rogers, D.S., 1979, Archaean precious-metal hydrothermal systems, Dome mine, Abitibi greenstone belt; I. Patterns of alteration and metal distribution: Canadian Journal of Earth Sciences, v. 16, p. 421–439.

Fyfe, W.S., and Henley, R.W., 1973, Some thoughts on chemical transport processes, with particular reference to gold: Minerals Science Engineering, v. 5, p. 295–303.

Fyfe, W.S., Price, N.J., and Thompson, A.B., 1978, Fluids in the Earth's crust: Amsterdam, Elsevier, 383 p.

Fyon, J.A., Crocket, J.H., and Schwarcz, H.P., 1983, The Carshaw and Malga iron-formation hosted gold deposits of the Timmins area: Ontario Geological Survey, Miscellaneous Paper 110, p. 98–110.

Fyon, J.A., Schwarcz, H.P., Crocket, J.H., and Fyfe, W.S., 1984, Carbonatization and gold mineralization in the Timmins area, Abitibi greenstone belt—genetic links with Archean mantle CO_2; degassing and lower crustal granulitization [abs]: Geological Association of Canada-Mineralogical Association of Canada, Program with Abstracts, p. 65.

Garba, I., and Akande, S. O., 1992, The origin and significance of non-aqueous CO_2 fluid inclusions in the auriferous veins of Bin Yauri, northwestern Nigeria: Mineralium Deposita, v. 27, p. 249–255.

Gebre-Mariam, M., Groves, D.I., McNaughton, N.J., Mikucki, E.J., and Vearncombe, J.R., 1993, Archaean Au-Ag mineralisation at Racetrack, near Kalgoorlie, Western Australia: A high crustal-level expression of the Archaean composite lode-gold system: Mineralium Deposita, v. 28, p. 375–387.

Gebre-Mariam, M., Hagemann, S.G., and Groves, D.I., 1995, A classification scheme for epigenetic Archaean lode-gold deposits: Mineralium Deposita, v. 30, p. 408–410.

Goellnicht, N.M., Groves, D.I., McNaughton, N.J., and Dimo, G., 1989, An epigenetic origin for the Telfer gold deposit, Western Australia: ECONOMIC GEOLOGY MONOGRAPH 6, p. 151–167.

Goldfarb, R.J., Leach, D.L., Miller, M.L. and Pickthorn, W.J., 1986, Geology, metamorphic setting, and genetic constraints of epigenetic lode-gold mineralization within the Cretaceous Valdez Group, south-central Alaska: Geological Association of Canada Special Paper 32, p. 87–105.

Goldfarb, R.J., Leach, D.L., Pickthorn, W.J., and Paterson, C.J., 1988, Origin of lode-gold deposits of the Juneau gold belt, southeastern Alaska: Geology, v. 16, p. 440–443.

Goldfarb, R.J., Leach, D.L., Rose, S.C., and Landis, G.P., 1989, Fluid inclusion geochemistry of gold-bearing quartz veins of the Juneau gold belt, southeastern Alaska—implications for ore genesis: ECONOMIC GEOLOGY MONOGRAPH 6, p. 363–375.

Goldfarb, R.J., Gray, J.E., Pickthorn, W.J., Gent, C.A., and Cieutat, B.A., 1990, Stable isotope systematics of epithermal mercury-antimony mineralization, southwestern Alaska: U.S. Geological Survey Bulletin 1950, p. E1–E9.

Goldfarb, R.J., Newberry, R.J., Pickthorn, W.J., and Gent, C.A., 1991a, Oxygen, hydrogen, and sulfur isotope studies in the Juneau gold belt, southeastern Alaska—constraints on the origin of hydrothermal fluids: ECONOMIC GEOLOGY, v. 86, p. 66–80.

Goldfarb, R.J., Snee, L.W., Miller, L.D., and Newberry, R.J., 1991b, Rapid dewatering of the crust deduced from ages of mesothermal gold deposits: Nature, v. 354, p. 296–299.

Goldfarb, R.J., Snee, L.W., and Pickthorn, W.J., 1993, Orogenesis, high-T thermal events, and gold vein formation within metamorphic rocks of the Alaskan Cordillera: Mineralogical Magazine, v. 57, p. 375–394.

Goldfarb, R.J., Miller, L.D., Leach, D.L., and Snee, L.W., 1997, Gold deposits in metamorphic rocks of Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 151–190.

Goldfarb, R.J., Phillips, G.N., and Nokleberg, W.J., 1998, Tectonic setting of synorogenic gold deposits of the Pacific Rim: Ore Geology Reviews, v. 13, p. 185–218.

Goldfarb, R.J., Hart, C., Miller, M., Miller, L., Farmer, G.L. and Groves, D.I., 2000, The Tintina gold belt—a global perspective: British Columbia and Yukon Chamber of Mines Special Volume 2, p. 5–34.

Goldfarb, R.J., Groves, D.I., and Gardoll, S., 2001a, Orogenic gold and geologic time: A global synthesis: Ore Geology Reviews, v. 18, p. 1–75.

——2001b, Rotund versus skinny orogens: Well-nourished or malnourished gold?: Geology, v. 29, p. 539–542.

Goldfarb, R.J., Ayuso, R., Miller, M.L., Ebert, S.W., Marsh, E.E., Petsel, S.A., Miller, L.D., Bradley, D., Johnson, C, McClelland, W., 2004, The Late Cretaceous Donlin Creek deposit, southwestern Alaska—controls on epizonal formation: ECONOMIC GEOLOGY, v. 99, p. 643–671.

Golding, S.D., Groves, D.I., McNaughton, N.J., Mikucki, E.J., and Sang, J.-h., 1990, Source of ore fluid and ore components—sulphur isotope studies: Geology Department and University Extension, University of Western Australia Publication 20, p. 259–262.

Golding, S.D., McNaughton, N.J., Barley, M.E., Groves, D.I., Ho, S.E., Rock, N.M.S., and Turner, J.V., 1989 Archean carbon and oxygen reservoirs: Their significance for fluid sources and circulation paths for Archean mesothermal gold deposits of the Norseman-Wiluna Belt, Western Australia: ECONOMIC GEOLOGY MONOGRAPH 6, p. 376–388.

Goodwin, A.M., 1991, Precambrian geology: London, Academic Press, 666 p.

Gosselin, P., and Dubé, B., 2005a, Gold deposits of the world: Distribution, geological parameters and gold content: Geological Survey of Canada Open File 4895, 271 p. (CD-ROM).

——2005b, Gold deposits of the world: Geological Survey of Canada Open File 4896, Map (CD-ROM).

Graupner, T., Kempe, U., Spooner, E.T.C., Bray, C.J., Kremenetsky, A.A., and Irmer, G., 2001, Microthermometric, laser Raman spectroscopic, and volatile-ion chromatographic analysis of hydrothermal fluids in the Paleozoic Muruntau Au-bearing quartz vein ore field, Uzbekistan: ECONOMIC GEOLOGY, v. 96, p. 1–23.

Groves, D.I., 1993, The crustal continuum model for late-Archaean lode-gold deposits of the Yilgarn block, Western Australia: Mineralium Deposita, v. 28, p. 366–374.

Groves, D.I., and Foster, R.P., 1991, Archaean lode gold deposits, *in* Foster, R.P., ed., Gold metallogeny and exploration: London, Blackie, p. 63–103.

Groves, D.I., and Phillips, G.N., 1987, The genesis and tectonic control on Archaean gold deposits of the Western Australian Shield—a metamorphic replacement model: Ore Geology Reviews, v. 2, p. 287–322.

Groves, D.I., Phillips, G.N., Ho, S.E., Henderson, C.A., Clark, M.E., and Wood, G.M., 1984, Controls on distribution of Archaean hydrothermal gold deposits in Western Australia, *in* Foster, R. P., ed., Gold '82—The geology, geochemistry and genesis of gold deposits: Rotterdam, Balkema, p. 689–712.

Groves, D.I., Goldfarb, R.J., Gebre-Mariam, M., Hagemann, S.G., and Robert, F., 1998, Orogenic gold deposits: A proposed classification in the context of their crustal distribution and relationship to other gold deposit types: Ore Geology Reviews, v. 13, p. 7–27.

Groves, D.I., Goldfarb, R.J., Knox-Robinson, C.M., Ojala, J., Gardoll, S., Yun, G., and Holyland, P., 2000, Late-kinematic timing of orogenic gold

deposits and its significance for computer-based exploration techniques with emphasis on the Yilgarn block, Western Australia: Ore Geology Reviews, v. 17, p. 1–38.

Groves, D.I., Goldfarb, R.J., Robert, F., and Hart, C.J.R., 2003, Gold deposits in metamorphic belts: Overview of current understanding, outstanding problems, future research, and exploration significance: ECONOMIC GEOLOGY, v. 98, p. 1–29.

Groves, D.I., Condie, K.C., Goldfarb, R.J., Hronsky, J.M.A., and Vielreicher, R.M., 2005, Secular changes in global tectonic processes and their influence on the temporal distribution of gold-bearing mineral deposits: ECONOMIC GEOLOGY, v. 100, p. 203–224.

Gunning, H.C., and Ambrose, J.W., 1937, Cadillac-Malartic area Quebec: Canadian Institute of Mining and Metallurgy Transactions, v. 40, p. 341–362.

Haeberlin, Y., Moritz, R., and Fontbote, L., 2003, Paleozoic orogenic gold deposits in the eastern Central Andes and its foreland, South America: Ore Geology Reviews, v. 22, p. 41–59.

Haeberlin, Y., Moritz, R., Fontbote, L., and Cosca, M., 2004, Carboniferous orogenic gold deposits at Pataz, eastern Andean Cordillera, Peru—geological and structural framework, paragenesis, alteration, and $^{40}Ar/^{39}Ar$ geochronology: ECONOMIC GEOLOGY, v. 99, p. 73–112.

Haeussler, P., Bradley, D., Goldfarb, R., Snee, L., and Taylor, C. 1995, Link between ridge subduction and gold mineralization in southern Alaska: Geology, v. 23, p. 995–998.

Hagemann S.G., and Brown, P.E., eds., 2000, Archean orogenic lode gold deposits: Reviews in Economic Geology, v. 13, 559 p.

Hagemann S.G., and Cassidy, K.F., 2000, Archean orogenic lode gold deposits: Reviews in Economic Geology, v. 13, p. 9–68.

Hagemann, S.G., and Luders, V., 2003, P-T-X conditions of hydrothermal fluids and precipitation mechanism of stibnite-gold mineralization at the Wiluna lode-gold deposits, Western Australia: Conventional and infrared microthermometric constraints: Mineralium Deposita, v. 38, p. 936–952.

Hagemann, S.G., Groves, D.I., Ridley, J.R., and Vearncombe, J.R., 1992, The Archean lode gold deposits at Wiluna, Western Australia—high-level brittle-style mineralization in a strike-slip regime: ECONOMIC GEOLOGY, v. 87, p. 1022–1053.

Hagemann, S.G., Gebre-Mariam, M., and Groves, D.I., 1994, Surface-water influx in shallow-level Archean lode-gold deposits in Western Australia: Geology, v. 22, p. 1067–1070.

Hamilton, J.V., and Hodgson, C.J., 1986, Mineralization and structure of the Kolar gold field, India, *in* Macdonald, A. J., ed. Gold '86: Willowdale, Ontario, Konsult International Inc., p. 270–283.

Harris, M., 1980, Gold mineralization at Salave gold prospect, Northwest Spain: Institution of Mining and Metallurgy Transactions, v. B89, p. 1–4.

Hart, C.J.R., McCoy, D., Goldfarb, R.J., Smith, M., Roberts, P., Hulstein, R., Bakke, A.A., and Bundtzen, T.K., 2002, Geology, exploration and discovery in the Tintina gold province, Alaska and Yukon: Society of Economic Geologists Special Publication 9, p. 241–274.

Hart, C.J.R., Mair, J.L., Goldfarb, R.J., and Groves, D.I., 2004, Source and redox controls on metallogenic variations in intrusion-related ore systems, Tombstone-Tungsten belt, Yukon Territory, Canada: Transactions of the Royal Society of Edinburgh, v. 95, p. 339–356.

Henley, R.W., Norris, R.J., and Paterson, C.J., 1976, Multistage ore genesis in the New Zealand geosyncline: A history of post-metamorphic lode emplacement: Mineralium Deposita, v. 11, p. 180–196.

Hitchins, A.C., and Orssich, C.N., 1995, The Eagle zone gold-tungsten sheeted vein porphyry deposit and related mineralization, Dublin Gulch, Yukon Territory: Canadian Institute of Mining and Metallurgy Special Volume 46, p. 803–810.

Ho, S.E., 1987, Fluid inclusions; their potential as an exploration tool for Archaean gold deposits: Geology Department and University Extension, University of Western Australia Publication 11, p. 239–263.

Ho S.E., and Groves, D.I., eds., 1987, Recent advances in understanding Precambrian gold deposits: Geology Department and University Extension, University of Western Australia Publication 11, 368 p.

Ho, S.E., Bennett, J.M., Cassidy, K.F., Hronsky, J.M.A., Mikucki, E.J., and Sang, J.H., 1990, Fluid inclusion studies: Geology Department and University Extension, University of Western Australia Publication 20, p. 198–211.

Hodgson, C.J., 1989, Patterns of mineralization: Geological Association of Canada Short Course Notes v. 6, p. 51–88.

——1993, Mesothermal lode-gold deposits: Geological Association of Canada Special Paper 40, p. 635–678.

Hodgson, C.J., and Hamilton, J.V., 1989, Gold mineralization in the Abitibi greenstone belt: End-stage results of Archean collisional tectonis?: ECONOMIC GEOLOGY MONOGRAPH 6, p. 86–100.

Hodgson, C.J., and MacGeehan, P.J., 1982, Geological characteristics of gold deposits in the Superior province of the Canadian Shield: Canadian Institute of Mining and Metallurgy Special Volume 24, p. 211–229.

Hodgson, C.J., and Troop, D.G., 1988, A new computer-aided methodology for area selection in gold exploration—a case study from the Abitibi greenstone belt: ECONOMIC GEOLOGY, v. 83, p. 952–977.

Hollister, V.F., 1992, On a proposed plutonic porphyry gold deposit model: Nonrenewable Resources, v. 1, p. 293–302.

Holyland, P.W., Ridley, J.R., and Vearncombe, J.R., 1993, Stress mapping technology (STMTM), *in* Parnell, J., Ruffell, A.H., and Moles, N.R., eds., Geofluids '93: Belfast, Queens University, p. 272–275.

Hutchinson, R.W., and Burlington, J.L., 1984, Some broad characteristics of greenstone belt gold lodes, *in* Foster, R. P., ed., Gold '82—the geology, geochemistry and genesis of gold deposits: Rotterdam, Balkema, p. 339–372.

Jarrard, R.D., 2003, Subduction fluxes of water, carbon dioxide, chlorine, and potassium: Geochemistry, Geophysics, Geosystems (G^3), v. 4, no. 5, 50 p.

Jia, Y., and Kerrich, R., 1999, Nitrogen isotope systematics of mesothermal lode gold deposits—metamorphic, granitic, meteoric water, or mantle origin?: Geology, v. 27, p. 1051–1054.

Jia, Y., Li, X., and Kerrich, R., 2000, A fluid inclusion study of the Au-bearing quartz vein systems in the Central and North Deborah deposits of the Bendigo gold field, central Victoria, Australia—constraints on the origin of ore-forming fluids: ECONOMIC GEOLOGY, v. 95, p. 467–496.

Jia, Y., Kerrich, R., and Goldfarb, R.J., 2003, Metamorphic origin of ore-forming fluids for orogenic gold-bearing quartz vein systems in the North American Cordillera: Constraints from a reconnaissance study of $\delta^{15}N$, δD, and $\delta^{18}O$: ECONOMIC GEOLOGY, v. 98, p. 109–123.

Keays, R.R., Ramsay, W.R.H., and Groves, D.I., eds., 1989, The geology of gold deposits—the perspective in 1988: ECONOMIC GEOLOGY MONOGRAPH 6, 667 p.

Kempe, U., Belyatsky, B.V., Krymsky, R.S., Kremenetsky, A.A., and Ivanov, P.A., 2001, Sm-Nd and Sr isotope systematics of scheelite from the giant Au(-W) deposit Muruntau (Uzbekistan)—implications for the age and sources of Au mineralization: Mineralium Deposita, v. 36, p. 379–392.

Keppie, J.D., Boyle, R.W., and Haynes, S.J., eds., 1986, Turbidite-hosted gold deposits: Geological Association of Canada Special Paper 32, 186 p.

Kerrich, R., 1983, Geochemistry of gold deposits in the Abitibi greenstone belt: Canadian Institute of Mining and Metallurgy Special Volume 27, 75 p.

——1986, Fluid transport in lineaments: Philosophical Transactions of the Royal Society of London, Series A, v. 317, p. 219–251

——1987, The stable isotope geochemistry of Au-Ag vein deposits in metamorphic rocks: Mineralogical Association of Canada Short Course Handbook, v. 13, p. 287–336.

——1989, Lithophile element systematics of gold vein deposits in Archean greenstone belts: Implications for source processes: ECONOMIC GEOLOGY MONOGRAPH 6, p. 508–519.

——1991, Mesothermal gold deposits—a critique of genetic hypotheses, *in* Robert, F., Sheahan, P.A., and Green, S., eds, Greenstone gold and crustal evolution: St. John's, Geological Association of Canada, p. 13–31.

Kerrich, R., and Cassidy, K.F., 1994, Temporal relationships of lode gold mineralization to accretion, magmatism, metamorphism and deformation: Archean to present: A review: Ore Geology Reviews, v. 9, p. 263–310.

Kerrich, R., and Fyfe, W.S., 1981, The gold-carbonate association: Source of CO_2, and CO_2 fixation reactions in Archaean lode deposits: Chemical Geology, v. 33, p. 265–294.

Kerrich, R., and Hodder, R. W., 1982, Archean lode gold and base metal deposits—chemical evidence for metal fractionation into independent hypothermal reservoirs: Canadian Institute of Mining and Metallurgy Special Volume 24, p. 144–160.

Kerrich, R., and Wyman, D., 1990, Geodynamic setting of mesothermal gold deposits: An association with accretionary tectonic regimes: Geology, v. 18, p. 882–885.

——1994, The mesothermal gold-lamprophyre association: Significance for an accretionary geodynamic setting, supercontinent cycles, and metallogenic processes: Mineralogy and Petrology, v. 51, p. 147–172.

Kerrich, R., Goldfarb, R.J., Groves, D.I., and Garwin, S., 2000, The geodynamics of world-class gold deposits: Characteristics, space-time distribution, and origins: Reviews in Economic Geology, v. 13, p. 501–551.

Kerswill, J.A., 1993, Models for iron-formation-hosted gold deposits: Geological Association of Canada, Special Paper 40, p. 171–199.

Kirk, J., Ruiz, J., Chesley, J., Titley, S, and Walshe, J., 2001, A detrital model for the origin of gold and sulfides in the Witwatersrand basin based on Re-Os isotopes: Geochimica et Cosmochimica Acta, v. 65, p. 2149–2159.

Klemd, R., Huenken, U., and Olesch, M., 1996, Fluid composition and source of early Proterozoic lode gold deposits of the Birimian volcanic belt, West Africa: International Geology Review, v. 38, p. 22–32.

Knipe, S.W., Foster, R.P., and Stanley, C.J., 1992, Role of sulphide surfaces in sorption of precious metals from hydrothermal fluids: Institution of Mining and Metallurgy Transactions, v. 101, p. B83–B88.

Knox-Robinson, C.M., and Groves, D.I., 1997, Gold prospectivity mapping using a Geographic Information System (GIS) with examples from the Yilgarn block of Western Australia: Chronique de la Recherche Miniere, v. 65, p. 127–138.

Knox-Robinson, C.M., and Wyborn, L.A.I., 1997, Towards a holistic exploration strategy; using geographic information systems as a tool to enhanced exploration: Australian Journal of Earth Sciences, v. 44, p. 453–463.

Kolb, J., Kisters, A.F.M., Hoernes, S., and Meyer, F.M., 2000, The origin of fluids and nature of fluid-rock interaction in mid-crustal auriferous mylonites of the Renco mine, southern Zimbabwe: Mineralium Deposita, v. 35, p. 109–125.

Kontak, D. J., and Kerrich, R., 1997, An isotopic (C, O, Sr) study of vein gold deposits in the Meguma Terrane, Nova Scotia; implication for source reservoirs: ECONOMIC GEOLOGY, v. 92, p. 161–180.

Kontak, D. J., and Smith, P. K., 1989, Sulphur isotopic composition of sulphides from the Beaver Dam and other Meguma-Group-hosted gold deposits, Nova Scotia—implications for genetic models: Canadian Journal of Earth Sciences, v. 26, p. 1617–1629.

Kontak, D.J., Smith, P.K., and Kerrich, R., 1988, Meguma gold studies—V, Carbon, strontium, oxygen and sulphur isotopic compositions of vein minerals: Implications for source reservoirs and fluid-rock ratios attending vein formation: Nova Scotia Dept. of Mines and Energy Report 88–1, p. 101–110.

Kontak, D.J., Smith, P.K., Kerrich, R., and Williams, P.F., 1990, Integrated model for Meguma Group lode gold deposits, Nova Scotia, Canada: Geology, v. 18, p. 238–242.

Kontak, D.J., Horne, R.J., and Smith, P.K., 1996, Hydrothermal characterization of the West Gore Sb-Au deposit, Meguma terrane, Nova Scotia, Canada: ECONOMIC GEOLOGY, v. 91, p. 1239–1262.

Ladeira, E.A., 1991a, Genesis of gold in the Quadrilatero Ferrifero—a remarkable case of permanency, recycling and inheritance—a tribute to Djalma Guimaraes, Pierre Routhier, and Hans Ramberg, *in* Ladeira, E.A., ed., Brazil Gold '91—the geology, geochemistry and genesis of gold deposits: Rotterdam, Balkema, p. 11–30.

——1991b, Brazil Gold '91—The geology, geochemistry and genesis of gold deposits: Rotterdam, Balkema, 823 p.

Lang, J.R., Baker, T., Hart, C.J.R., and Mortensen, J.K., 2000, An exploration model for intrusion-related gold systems: Society of Economic Geology Newsletter 40, p. 1, 6–15.

Leach, D.L., Landis, G.P., and Hofstra, A.H., 1988, Metamorphic origin of the Coeur d'Alene base- and precious-metal veins in the Belt basin, Idaho and Montana: Geology, v. 16, p. 122–125.

Le Guen, M., Lescuyer, J.L., and Marcoux, E., 1992, Lead-isotope evidence for a Hercynian origin of the Salsigne gold deposit (southern Massif Central France): Mineralium Deposita, v. 27, p. 129–136.

Letnikov, F.A., Vibor, N.V., Gantimurova, T.P., Konovalov, I.V., Shkandriy, B.O., and Shkarupa, F.A., 1975, Transport forms of gold and fluid evolution in the production of gold-bearing metamorphogenic quartz veins: Geochemistry International, v. 12, p. 126–134.

Lindgren, W., 1907, The relation of ore deposition to physical conditions: ECONOMIC GEOLOGY, v. 2, p. 105–127.

——1909, Metallogenic epochs: ECONOMIC GEOLOGY, v. 4, p. 409–420.

——1933, Mineral deposits, 4th ed.: New York, McGraw-Hill, 930 p.

Lobato, L.M., Ribeiro-Rodrigues, L.C., Vieira, F.W.R., Groves, D.I., Goldfarb, R.J., and da Silva, L.C., 2001, Brazil's premier gold province: Part II. Geology and genesis of gold deposits in the Archean Rio das Velhas greenstone belt, Quadrilatero Ferrifero: Mineralium Deposita, v. 36, p. 249–277.

Loucks, R.R., and Mavrogenes, J.A., 1999, Gold solubility in supercritical hydrothermal brines measured in synthetic fluid inclusions: Science, v. 284, p. 2159–2163.

Macdonald, A.J., ed., 1987, Gold'86: Willowdale, Ontario, Konsult International, Inc., 517 p.

Macdonald, A.J., and Hodgson, C.J., 1986, The case for the magmatic-hydrothermal origin of Archean lode gold deposits [abs.], *in* Chater, A. M., ed., Gold '86, An International Symposium on the Geology of Gold Deposits—Poster Paper Abstracts: Geological Association of Canada, Toronto, p. 98–99.

Maloof, T.L., Baker, T., and Thompson, J.F.H., 2001, The Dublin Gulch intrusion-hosted gold deposit, Tombstone plutonic suite, Yukon Territory, Canada: Mineralium Deposita, v. 36, p. 583–593.

Mao, J., Li, Y., Goldfarb, R.J., He, Y., and Zaw, K., 2003, Fluid inclusion and noble gas studies of the Dongping gold deposit, Hebei province, China: A mantle connection for mineralization?: ECONOMIC GEOLOGY. v. 98, p. 517–534

McCoy, D., Newberry, R.J., Layer, P.W., DiMarchi, J.J., Bakke, A.A., Masterman, J.S., and Minehane, D.L., 1997, Plutonic-related gold deposits of interior Alaska: ECONOMIC GEOLOGY MONOGRAPH 9, p. 191–241.

McCuaig, T.C., and Kerrich, R., 1998, P-T-t-deformation-fluid characteristics of lode gold deposits: Evidence from alteration systematics: Ore Geology Reviews, v. 12, p. 381–454.

Meinert, L.D., 1989, Gold skarn deposits: Geology and exploration criteria: ECONOMIC GEOLOGY MONOGRAPH 6, p. 537–552.

——2000, Gold in skarns related to epizonal intrusions: Reviews in Economic Geology, v. 13, p. 347–375.

Mikucki, E.J., 1998, Hydrothermal transport and depositional processes in Archean lode-gold systems: A review: Ore Geology Reviews, v. 13, p. 307–321.

Mikucki, E.J., and Ridley, J.R., 1993, The hydrothermal fluid of Archaean lode-gold deposits at different metamorphic grades: Compositional constraints from ore and wallrock alteration assemblages: Mineralium Deposita, v. 28, p. 469–481.

Miller, L.J., Goldfarb, R.J., Snee, L.W., Gent, C.A., and Kirkham, R.A., 1995, Structural geology, age, and mechanisms of gold vein formation at the Kensington and Jualin deposits, Berners Bay district, Southeast Alaska: ECONOMIC GEOLOGY, v. 90, p. 343–368.

Mishra, B., and Panigrahi, M.K., 1999, Fluid evolution in the Kolar Gold Field—evidence from fluid inclusion studies: Mineralium Deposita, v. 34, p. 173–181.

Moore, D.H., 1996. Geophysical signatures of gold deposits in Western Victoria: Australian Institute of Geoscientists Bulletin, v. 20, p. 19–23.

Moravek, P., 1995, Gold metallogeny of Central and Western European Variscides, *in* Pasava, J., Kribek, B., and Zak, K., eds., Mineral deposits—from their origin to their environment impacts: Rotterdam, A.A. Balkema, p. 67–70.

Moravek P., Pertold, Z., Puncochar, M., Studnicna, B., and Zacharias, J., 1996, Gold deposits in Bohemia: Prague, Czech Geological Survey, 96 p.

Morelli, R.M., Creaser, R.A., Kontak, D.J., Horne, R.J., and Selby, D., 2003, Re-Os arsenopyrite geochronology of quartz veining and Au mineralization, Meguma terrane, Nova Scotia, Canada [abs.]: Geological Society of America Abstracts with Programs, v. 34, no. 7, p. 401.

Morrison, G., Seed, M., Bobis, R., and Tullemans, F., 1996, The Kidston gold deposit, Queensland—a piston-cylinder model for gold mineralisation in a porphyry Mo system [abs]: Geological Society of Australia Abstracts, v. 41, p. 303.

Morrison, G.W., Rose, W.J., and Jaireth, S., 1991, Geological and geochemical controls on the silver content (fineness) of gold in gold-silver deposits: Ore Geology Reviews, v. 6, p. 333–364.

Mueller, A.G., 1992, Petrogenesis of amphibole-biotite-calcite-plagioclase alteration and laminated gold-silver quartz veins in four Archean shear zones of the Norseman district, Western Australia: Canadian Journal of Earth Science, v. 29, p. 388–417.

Mueller, A.G., and Groves, D.I., 1991, The classification of Western Australian greenstone-hosted gold deposits according to wallrock-alteration mineral assemblages: Ore Geology Reviews, v. 6, p. 291–331.

Mueller, A.G., Laeter, J.R., and Groves, D.I., 1991, Strontium isotope systematics of hydrothermal minerals from epigenetic Archean gold deposits in the Yilgarn block, Western Australia: ECONOMIC GEOLOGY, v. 86, p. 780–809.

Mumin, A.H., Fleet, M.E., and Chryssoulis, S.L., 1994, Gold mineralization in As-rich mesothermal gold ores of the Bogosu-Prestea mining district of the Ashanti gold belt, Ghana—remobilization of "invisible" gold: Mineralium Deposita, v. 29, p. 445–460.

Murphy, J.B., van Staal, C.R., and Keppie, J.D., 1999, Middle to late Paleozoic Acadian orogeny in the northern Appalachians—a Laramide-style plume-modified orogeny?: Geology, v. 27, p. 653–656.

Mustard, R., 2001, Granite-hosted gold mineralization at Timbarra, northern New South Wales, Australia: Mineralium Deposita, v. 36, p. 542–562.

——2003, The magmatic-hydrothermal transition at Timbarra—implications for the genesis of intrusion-related gold, *in* Eliopoulos D.G., et al., eds, Mineral exploration and sustainable development: Rotterdam, Millpress, p. 747–750.

Mustard, R., Kamenetsky, V.S., and Mernagh, T.P., 2003, Carbon dioxide bearing melt inclusions within a gold-mineralized felsic granite, *in* Eliopoulos D.G., et al., eds, Mineral exploration and sustainable development: Rotterdam, Millpress, p. 351–354.

Nesbitt, B.E., 1988, Gold deposit continuum—a genetic model for lode Au mineralization in the continental crust: Geology, v. 16, p. 1044–1048.

——1990, Fluid flow and chemical evolution in the genesis of hydrothermal ore deposits: Mineralogical Association of Canada Short Course Handbook, v. 18, p. 261–297.

——1991, Phanerozoic gold deposits in tectonically active continental margins, *in* Foster, R.P., ed., Gold metallogeny and exploration: London, Blackie, p. 63–103.

Nesbitt, B.E., and Muehlenbachs, K., 1989, Geology, geochemistry, and genesis of mesothermal lode gold deposits of the Canadian Cordillera—evidence for ore formation from evolved meteoric water: ECONOMIC GEOLOGY MONOGRAPH 6, p. 553–563.

Nesbitt, B.E., Murowchick, J.B., and Muehlenbachs, K., 1986, Dual origins of lode gold deposits in the Canadian Cordillera: Geology, v. 14, p. 506–509.

Newberry, R.J., McCoy, D.T., and Brew, D.A., 1995, Plutonic-hosted gold ores in Alaska—igneous versus metamorphic origin: Resource Geology Special Issue, 18, p. 57–100.

Niggli, P., 1929, Ore deposits of magmatic origin: London, Thomas Murby and Co.,

Norris, R.J., and Henley, R.W., 1976, Dewatering of a metamorphic pile: Geology, v. 4, p. 333–336.

Oberthur, T., Scmidt Mumm, A., Vetter, U., Simon, K., and Amanor, J.A., 1996, Gold mineralization in the Ashanti belt of Ghana—genetic constraints of the stable isotope geochemistry: ECONOMIC GEOLOGY, v. 91, p. 289–301.

Olivo, G.M., Gauthier, M., Bardoux, M., de Sa, E.L., Fonseca, J.T.F., and Santana, C., 1995, Palladium-bearing gold deposit hosted by Proterozoic Lake Superior-type iron-formation at the Caue iron mine, Itabira district, southern Sao Francisco craton, Brazil—geologic and structural controls: ECONOMIC GEOLOGY, v. 90, p. 118–134.

Partington, G.A., and Williams, P.J., 2000, Proterozoic lode gold and (iron)-copper-gold Deposits: A comparison of Australian and global examples: Reviews in Economic Geology, v. 13, p. 69–101.

Paterson, C.J., 1986, Controls on gold and tungsten mineralization in metamorphic-hydrothermal systems, Otago, New Zealand: Geological Association of Canada Special Paper 32, p. 25–39.

Paterson, N.R., and Hallof, P.G., 1991, Geophysical exploration for gold, *in* Foster, R.P., ed., Gold metallogeny and exploration: London, Blackie, p. 360–398.

Perkins, C., and Kennedy, A.K., 1998, Permo-Carboniferous gold epoch of Northeast Queensland: Australian Journal of Earth Sciences, v. 45, p. 185–200.

Perring, C.S., and McNaughton, N.J., 1992, The relationship between Archaean gold mineralization and spatially associated minor intrusions at the Kambalda and Norseman gold camps, Western Australia: Lead isotope evidence: Mineralium Deposita, v. 27, p. 10–22.

Perring, C.S., Barley, M.E., Cassidy, K.F., Groves, D.I., McNaughton, N.J., Rock, N.M.S., Bettenay, L.F., Golding, S.D., and Hallberg, J.A., 1989, The association of linear orogenic belts, mantle-crustal magmatism, and Archean gold mineralization in the eastern Yilgarn block of Western Australia: ECONOMIC GEOLOGY MONOGRAPH 6, p. 571–584.

Peters, S.G., 1993, Formation of oreshoots in mesothermal gold-quartz vein deposits; examples from Queensland, Australia: Ore Geology Reviews, v. 8, p. 277–301.

Peters, S.G., and Golding, S.D., 1989, Geologic, fluid inclusion, and stable isotope studies of granitoid-hosted gold-bearing quartz veins, Charters Towers, northeastern Australia: ECONOMIC GEOLOGY MONOGRAPH 6, p. 260–273.

Pettke, T., Diamond, L.W., and Kramers, J.D., 2000, Mesothermal gold lodes in the north-western Alps—a review of genetic constraints from radiogenic isotopes: European Journal of Mineralogy, v. 12, p. 213–230.

Phillips, G.N., 1986, Geology and alteration in the Golden Mile, Kalgoorlie: ECONOMIC GEOLOGY, v. 81, p. 779–808.

——1991, Pressure-temperature environments and the causes of gold deposition [abs], *in* Robert, F., Sheahan, P.A., and Green, S.B., eds, Greenstone gold and crustal evolution: St. John's, Geological Association of Canada, 193 p.

Phillips, G. N., and de Nooy, D., 1988, High-grade metamorphic processes which influence Archaean gold deposits, with particular reference to Big Bell, Australia: Journal of Metamorphic Geology, v. 6, p. 95–114.

Phillips, G. N., and Groves, D. I., 1983, The nature of Archaean gold-bearing fluids as deduced from gold deposits of Western Australia: Journal of the Geological Society of Australia, v. 30, p. 25–39.

——1984, Fluid access and fluid-wall rock interaction in the genesis of the Archaean gold-quartz vein deposit at Hunt mine, Kambalda, Western Australia, *in* Foster, R. P., ed., Gold '82—the geology, geochemistry and genesis of gold deposits: Rotterdam, Balkema, p. 389–416.

Phillips, G.N., and Hughes, M.J., 1996, The geology and gold deposits of the Victorian gold province: Ore Geology Reviews, v. 11, p. 255–302.

Phillips, G.N., and Powell, R., 1992, Gold only provinces and their common features: James Cook University, Contributions of the Economic Geology Research Unit, v. 43, 27 p.

Phillips, G.N., Groves, D.I., Clark, M.E., de Villiers, J.P.R., and Cawthorn, P.A., 1983, The importance of host-rock mineralogy in the location of Archaean epigenetic gold deposits: Geological Society of South Africa Special Publication 7, p. 79–86.

Phillips, G.N., Groves, D.I., and Martyn, J.E., 1984, An epigenetic origin for Archean banded iron-formation-hosted gold deposits: ECONOMIC GEOLOGY, v. 79, p. 162–171.

Phillips, G.N., Groves, D.I., and Brown, I.J., 1987, Source requirements for the Golden Mile, Kalgoorlie—significance to the metamorphic replacement model for Archean gold deposits: Canadian Journal of Earth Sciences, v. 24, p. 1643–1651.

Phillips, G.N., Hughes, M.J., Arne, D.C., Bierlein, F.P., Carey, S.P., Jackson, T., and Willman, C.E., 2003, Gold—historical wealth, future potential: Geological Society of Australia Special Publication 23, p. 377–432.

Pickthorn, W.J., Goldfarb, R.J., and Leach, D.L., 1987, Dual origins of lode gold deposits in the Canadian Cordillera—discussion: Geology, v. 15, p. 471–473.

Pitcairn, I.K., Teagle, D.A.H., Kerrich, R., Craw, D., and Brewer, T.S., 2005, The behavior of nitrogen and nitrogen isotopes during metamorphism and mineralization—evidence from the Otago and Alpine schists, New Zealand: Earth and Planetary Science Letters, v. 233, p. 229–246.

Pokrovski, G.S., Kara, S., and Roux, J., 2002, Stability and solubility of arsenopyrite, FeAsS, in crustal fluids: Geochimica et Cosmochimica Acta, v. 66, p. 2361–2378.

Poulsen, K.H., Ames, D.E., Lau, S., and Brisbin, W.C., 1986, Preliminary report on the structural setting of gold in the Rice Lake area, Uchi subprovince, southeastern Manitoba: Geological Survey of Canada Paper 86–1B, p. 213–221.

Poulsen, K.H., Robert, F., and Dube, B., 2000, Geological classification of Canadian gold deposits: Geological Survey of Canada Bulletin 540, 106 p.

Powell, R., Will, T.M., and Phillips, G.N., 1991, Metamorphism in Archaean greenstone belts: Calculated fluid compositions and implications for gold mineralization: Journal of Metamorphic Geology, v. 9, p. 141–150.

Qui, Y., and McNaughton, N. J., 1999, Source of Pb in orogenic lode-gold mineralisation: Pb isotope constraints from deep crustal rock from the southwestern Archaean Yilgarn craton, Australia: Mineralium Deposita, v. 34, p. 366–381.

Qiu, Y., Groves, D.I., McNaughton, N.J., Wang, L-G., and Zhou, T., 2002, Nature, age and tectonic setting of granitoid-hosted orogenic gold deposits at the Jiaodong Peninsular, eastern North China craton, China: Mineralium Deposita, v.37, p.283–305.

Radhakrishna, B.P., and Curtis, L.C., 1999, Gold in India: Bangalore, Geological Society of India, 301 p.

Rhys, D., DiMarchi, J., Smith, M., Friesen, R., and Rombach, C., 2003, Structural setting, style and timing of vein-hosted gold mineralization at the Pogo deposit, east central Alaska: Mineralium Deposita, v. 38, p. 863–875.

Richards, D.N.G., 1980, Paleozoic granitoids of northeastern Australia, *in* Henderson, R.A., and Stephenson, P.J., eds., The geology and geophysics of northeastern Australia: Brisbane, Geological Society of Australia, Queensland Division, p. 229–246.

Ridley, J., 1993, The relations between mean rock stress and fluid flow in the crust; with reference to vein- and lode-style gold deposits: Ore Geology Reviews, v. 8, p. 23–37.

Ridley, J.R., and Barnicoat, A.C., 1990, Alteration patterns—wallrock alteration in amphibolite-facies gold deposits: Geology Department and University Extension, University of Western Australia Publication 20, p. 79–86.

Ridley, J.R., and Diamond, L.W., 2000, Fluid chemistry of orogenic lode gold deposits and implications for genetic models: Reviews in Economic Geology, v. 13, p. 141–162.

Robert, F., 1989, Internal structure of the Cadillac tectonic zone southeast of Val d'Or, Abitibi greenstone belt, Quebec: Canadian Journal of Earth Sciences, v. 26, p. 2661–2675.

——1994, Vein fields in gold districts—the example of Val d'Or, southeastern Abtiti subprovince, Quebec: Geological Survey of Canada Current Research 1994–C, p. 295–302.

Robert, F., and Brown, A.C., 1986, Archean gold-bearing quartz veins at the Sigma Mine, Abitibi greenstone belt, Quebec; Part I, Geologic relations and formation of the vein system: ECONOMIC GEOLOGY, v. 81, p. 578–592.

Robert, F., and Poulsen, K.H., 2001, Vein formation and deformation in greenstone gold deposits: Reviews in Economic Geology, v. 14, p. 111–155.

Robert, F., Sheahan, P.A., and Green, S.B., eds, 1991, Greenstone gold and crustal evolution: St. John's, Geological Association of Canada, 252 p.

Robert, F., Poulson, K.H., and Dube, B., 1994, Structural analysis of lode gold deposits in deformed terranes: Geological Survey of Canada Open-file Report 2850, 140 p.

Rock, N.M.S., and Groves, D.I., 1988, Can lamprophyres resolve the genetic controversy over mesothermal gold deposits?: Geology, v. 16, p. 538–541.

Roedder, E., 1984, Fluid-inclusion evidence bearing on the environments of gold deposition, *in* Foster, R. P., ed., Gold '82—The geology, geochemistry and genesis of gold deposits: Rotterdam, Balkema, p. 129–164.

Rombach, C.S., and Newberry, R.J., 2001, Shotgun deposit: Granite porphyry-hosted gold-arsenic mineralization in southwestern Alaska, USA: Mineralium Deposita, v. 36, p. 607–621.

Romberger, S.B., 1986, The solution chemistry of gold applied to the origin of hydrothermal deposits: Canadian Institute of Mining and Metallurgy Special Volume 38, p. 168–186.

Rowins, S.M., 2000, Reduced porphyry copper-gold deposits: A new variation on an old theme: Geology, v. 28, p. 491–494.

Rye, D.M., and Rye, R.O., 1974, Homestake gold mine, South Dakota: I. Stable isotope studies: ECONOMIC GEOLOGY, v. 69, p. 293–317.

Salier, B.P., Groves, D.I., McNaughton, N.J., and Fletcher, I.R., 2004, The world-class Wallaby gold deposit, Laverton, Western Australia—an orogenic-style overprint on a magmatic-hydrothermal magnetite-calcite alteration pipe?: Mineralium Deposita, v. 39, p. 473–494.

Sangster, A.L., 1992, Light stable isotope evidence for a metamorphogenic orogen for bedding-parallel, gold-bearing veins in Cambrian flysch, Meguma Group, Nova Scotia: Exploration Mining Geology, v. 1, p. 69–79.

Sawkins, F.J., and Rye, D.M., 1974, Relationship of Homestake-type gold deposits to iron-rich Precambrian sedimentary rocks: Institution of Mining and Metallurgy, Transactions, v. 83, p. B56–B59.

Schmidt-Mumm, A. Oberthuer, T., Vetter, U., and Blenkinsop, TG., 1997, High CO_2 content of fluid inlusions in gold mineralization in the Ashanti belt, Ghana—a new category of ore forming fluids?: Mineralium Deposita, v. 32, p. 107–118.

Schneiderhohn, H., 1941, Lehrbuch der Erzlagerstattenkunde: Jena, Gustav Fischer.

Selby, D., Creaser, R.A., Hart, C.J.R., Rombach, C.S., Thompson, J.F.H., Smith, M.T., Bakke, A.A., and Goldfarb, R.J., 2002, Absolute timing of sulfide and gold mineralization—a comparison of Re-Os molybdenite and Ar-Ar mica methods from the Tintina gold belt, Alaska: Geology, v. 30, p. 791–794.

Seward, T.M., 1973, Thio complexes of gold and the transport of gold in hydrothermal ore solutions: Geochimica et Cosmochima Acta, v. 37, p. 379–399.

——1989, The hydrothermal chemistry of gold and its implications for ore formation—boiling and conductive cooling as examples: ECONOMIC GEOLOGY MONOGRAPH 6, p. 398–404.

Shelton, K.L., So, C-S., and Chang, J-S., 1988, Gold-rich mesothermal vein deposits of the Republic of Korea—geochemical studies of the Jungwon gold area: ECONOMIC GEOLOGY, v. 83, p. 1221–1237.

Shepherd, T.J., Bottrell, S.H., and Miller, M.F., 1991, Fluid inclusion volatiles as an exploration guide to black shale-hosted gold deposits, Dolgellau gold belt, North Wales, U.K.: Journal of Geochemical Exploration, v. 42, p. 5–24.

Sherlock, R.L., Jowett, E.C., Smith, B.D., and Irish, D.E., 1993, Distinguishing barren and auriferous veins in the Sigma mine, Val-d'Or, Quebec: Canadian Journal of Earth Sciences, v. 30, p. 413–419.

Sibson, R.H., Robert, F., and Poulsen, K.H., 1988, High-angle reverse faults, fluid-pressure cycling, and mesothermal gold-quartz deposits: Geology, v. 16, p. 551–555.

Sillitoe, R.H., 1991, Intrusion-related gold deposits, *in* Foster, R.P., ed., Gold metallogeny and exploration: Glasgow, Blackie and Son, p. 165–209.

Sillitoe R.H., and Thompson, J.F.H., 1998, Intrusion-related vein gold deposits—types, tectono-magmatic setting and difficulties of distinction from orogenic gold deposits: Resource Geology, v. 48, p.237–250.

Simon, K., 2001, Does δD from fluid inclusions in quartz reflect the original hydrothermal fluid?: Chemical Geology, v. 177, p. 483–495.

Smith, M., Thompson, J.F.H., Moore, K.H., Bressler, J.P., Layer, P., Mortensen, J.K., Abe, I., and Takaoka, H., 2000, The Liese zone, Pogo property—a new high-grade gold deposit in Alaska: British Columbia and Yukon Chamber of Mines Special Volume 2, p. 131–144.

Solomon, M., and Groves, D.I., 1994, The geology and origin of Australia's mineral deposits: Oxford Monographs on Geology and Geophysics, v. 24, 951 p.

Spooner, E.T.C., 1993, Magmatic sulphide/volatile interaction as a mechanism for producing chalcophile element enriched, Archean Au-quartz, epithermal Au-Ag and Au skarn hydrothermal ore fluids: Ore Geology Reviews, v. 7, p. 359–379.

Stegman, C.L., 2001, Cobar deposits—still defying classification: Society of Economic Geologists Newsletter 44, p. 1, 15–26.

Studemeister, P.A., 1984, Mercury deposits of western California—an overview: Mineralium Deposita, v. 19, p. 202–207.

Stuwe, K., 1998, Tectonic constraints on the timing relationships of metamorphism, fluid production and gold-bearing quartz vein emplacement: Ore Geology Reviews, v. 13, p. 219–228.

Taylor, B.E., Robert, F., Ball, M., and Leitch, C.H.B., 1991, Mesozoic "mother lode type" gold deposits in North America: Primary vs. secondary (meteoric) fluids [abs.]: Geological Society of America Abstracts with Programs, v. 23, p. 174.

Teagle, D.A.H., Norris, R.J., and Craw, D., 1990, Structural controls on gold-bearing quartz mineralization in a duplex thrust system, Hyde-Macraes shear zone, Otago Schist, New Zealand: ECONOMIC GEOLOGY, v. 85, p. 1701–1719.

Thompson, J.F.H., Sillitoe, R.H., Baker, T., Lang, J.R., and Mortensen, J.K., 1999, Intrusion-related gold deposits associated with tungsten-tin provinces: Mineralium Deposita, v. 34, p. 323–334.

Thompson, J.F.H., and Newberry, R.J., 2000, Gold deposits related to reduced granitic intrusions: Reviews in Economic Geology, v. 13, p. 377–400.

Tomkins, A.G., and Mavrogenes, J.A., 2002, Mobilization of gold as a polymetallic melt during pelite anatexis at the Challenger deposit, South Australia—a metamorphosed Archean gold deposit: ECONOMIC GEOLOGY, v. 97, p. 1249–1271.

Turneaure, F.S., 1955, Metallogenic provinces and epochs: ECONOMIC GEOLOGY 50TH ANNIVERSARY VOLUME, p. 38–98.

Uspensky, E., Cole, A., and Rassulov, V., 2000, REE geochemical systematics of scheelites from the Muruntau Complex gold deposit (Uzbekistan) using luminescence spectroscopy: Documents du Bureau de Recherches Geologiques et Minieres 297, p. 114–115.

Vallance, J., Boiron, M-C., Cathelineau, M., Fourcade, S., Varlet, M., and Marignac, C., 2004, The granite hosted gold deposit of Moulin de Cheni (Saint-Yrieix district, Massif central, France)—petrographic, structural, fluid inclusion and oxygen isotope constraints: Mineralium deposita, v. 39, p. 265–281.

Van Reenen, D.D., Pretorius, A.I., and Roering, C., 1994, Characterization of fluids associated with gold mineralization and with regional high-temperature retrogression of granulites in the Limpopo belt, South Africa: Geochimica et Cosmochimica Acta, v. 58, p. 1147–1159.

Vearncombe, J.R., 1993, Quartz vein morphology and implications for formation depth and classification of Archaean gold-vein deposits: Ore Geology Reviews, v. 8, p. 407–424.

Vearncombe, J.R., and Holyland, P.W., 1995, Rheology, stress-mapping, and hydrothermal mineralization—the example of structurally controlled gold-antimony deposits in South Africa: South African Journal of Geology, v. 98, p. 415–429.

Vearncombe, J.R., Barley, M.E., Eisenlohr, B.N., Groves, D.I., Houstoun, S.M., Skwarnecki, M.S., Grigson, M.W., and Partington, G.A., 1989, Structural controls on mesothermal gold mineralization: Examples from the Archean terranes of southern Africa and Western Australia: ECONOMIC GEOLOGY MONOGRAPH 6, p. 124–134.

Vielreicher, N.M., Groves, D.I., Fletcher, I.R., McNaughton, N.J., and Rasmussen, B., 2003, Hydrothermal monazite and xenotime geochronology—a new direction for precise dating of orogenic gold mineralization: Society of Economic Geologists Newsletter 53, p. 1, 10–15.

Voicu, G., Bardoux, M., Jebrak, M., and Crepeau, R., 1999, Structural, mineralogical and geochemical studies of the Paleoproterozoic Omai gold deposit, Guyana: ECONOMIC GEOLOGY, v. 94, p. 1277–1303.

Walshe, J.L., Heithersay, P.S., and Morrison, G.W., 1995, Toward an understanding of the metallogeny of the Tasman fold belt system: ECONOMIC GEOLOGY, v. 90, p. 1382–1401.

Walshe, J.L., Halley, S.W., Hall, G.A., and Kitto, P., 2003, Contrasting fluid systems, chemical gradients and controls on large-tonnage, high-grade Au deposits, Eastern Goldfields province, Yilgarn craton, Western Australia, *in* Eliopoulos D.G., et al., eds, Mineral exploration and sustainable development: Rotterdam, Millpress, p. 827–830.

Weinberg, R.F., Sial, A.N., and Mariano, G., 2004a, Close spatial relationship between plutons and shear zones. Geology, v. 32, p. 377–380

Weinberg, R.F., Hodkiewicz, P.F., and Groves, D.I., 2004b, What controls gold distribution in Archean terranes?: Geology, v. 32, p. 545–548

White, D.E. 1967, Mercury and base-metal deposits with associated thermal and mineral waters, *in* Barnes, H.L., ed., Geochemistry of hydrothermal ore deposits, 1st ed.: New York, Holt, Rhinehart, and Winston, p. 575–631.

Wilde, A.R., and Bierlein, F.P., 2003, Economic platinum concentrations in sediment-hosted orogenic gold deposits? *in* Eliopoulos D.G., et al., eds, Mineral exploration and sustainable development: Rotterdam, Millpress, p. 831–835.

Wilkins, C., 1993, A post-deformational, post-peak metamorphic timing for mineralization at the Archaean Big Bell gold deposit, Western Australia: Ore Geology Reviews, v. 7, p. 439–483.

Wood, S.A., and Samson, I.M., 1998, Solubility of ore minerals and complexation of ore metals in hydrothermal solutions: Reviews in Economic Geology, v. 10, p. 33–80.

Wyman, D., and Kerrich, R., 1988, Alkaline magmatism, major structures and gold deposits—implications for greenstobe belt gold metallogent: ECONOMIC GEOLOGY, v. 83, p. 454–461.

——1989, Archean shoshonitic lamprophyres associated with Superior province gold deposits, distribution, tectonic setting, noble metal abundances, and significance for gold mineralization: ECONOMIC GEOLOGY MONOGRAPH 6, p. 651–667.

Xavier, R.P., and Foster, R.P., 1999, Fluid evolution and chemical controls in the Fazenda Maria Preta (FMP) gold deposit, Rio Itapicuru greenstone belt, Bahia, Brazil: Chemical Geology, v. 154, p. 133–154.

Yakubchuk, A., Cole, A., Seltmann, R., and Shatov, V., 2002, Tectonic setting, characteristics, and regional exploration criteria for gold mineralization in the Altaid orogenic collage—the Tien Shan province as a key example: Society of Economic Geologists Special Publication 9, p. 177–201

Yardley, B.W.D., 1997, The evolution of fluids through the metamorphic cycle, *in* Jamtveit, B., and Yardley, B., eds., Fluid flow and transport in rocks—mechanisms and effects: London, Chapman and Hall, p. 99–121.

Yardley, B.W.D., Banks, D.A., and Munz, I.A., 1992, Halogen compositions of fluid inclusions as tracers of crustal fluid behaviour: International Symposium on Water-Rock Interaction, International Association of Geochemistry and Cosmochemistry and Alberta Research Council, Proceedings, v. 7, p. 1137–1140.

Zacharias, J., Pertold, Z., Pudilova, M., Zak, K., Pertoldova, J., Stein, H., and Markey, R., 2001, Geology and genesis of Variscan porphyry-style gold mineralization, Petrackova Hora deposit, Bohemian Massif, Czech Republic: Mineralium Deposita, v. 36, p. 517–541.

Zhou, T., Goldfarb, R.J., and Phillips, G.N., 2002, Tectonics and distribution of gold deposits in China: An overview: Mineralium Deposita, v. 37, p. 249–282.