

Orogenic gold and geologic time: a global synthesis

R.J. Goldfarb^{a,*}, D.I. Groves^b, S. Gardoll^b

^a *U.S. Geological Survey, Box 25046, M.S. 964, Denver Federal Center, Denver, CO 80225, USA*

^b *Centre for Global Metallogeny, Department of Geology and Geophysics, University of Western Australia, Nedlands, WA 6907, Australia*

Received 16 February 2000; accepted 18 December 2000

Abstract

Orogenic gold deposits have formed over more than 3 billion years of Earth's history, episodically during the Middle Archean to younger Precambrian, and continuously throughout the Phanerozoic. This class of gold deposit is characteristically associated with deformed and metamorphosed mid-crustal blocks, particularly in spatial association with major crustal structures. A consistent spatial and temporal association with granitoids of a variety of compositions indicates that melts and fluids were both inherent products of thermal events during orogenesis. Including placer accumulations, which are commonly intimately associated with this mineral deposit type, recognized production and resources from economic Phanerozoic orogenic-gold deposits are estimated at just over one billion ounces gold. Exclusive of the still-controversial Witwatersrand ores, known Precambrian gold concentrations are about half this amount.

The recent increased applicability of global paleo-reconstructions, coupled with improved geochronology from most of the world's major gold camps, allows for an improved understanding of the distribution pattern of orogenic gold in space and time. There are few well-preserved blocks of Middle Archean mid-crustal rocks with gold-favorable, high-strain shear zones in generally low-strain belts. The exception is the Kaapvaal craton where a number of orogenic gold deposits are scattered through the Barberton greenstone belt. A few > 3.0 Ga crustal fragments also contain smaller gold systems in the Ukrainian shield and the Pilbara craton. If the placer model is correct for the Witwatersrand goldfields, then it is possible that an exceptional Middle Archean orogenic-gold lode-system existed in the Kaapvaal craton at one time. The latter half of the Late Archean (ca. 2.8–2.55 Ga) was an extremely favorable period for orogenic gold-vein formation, and resulting ores preserved in mid-crustal rocks contain a high percentage of the world's gold resource. Preserved major goldfields occur in greenstone belts of the Yilgarn craton (e.g., Kalgoorlie), Superior province (e.g., Timmins), Dharwar craton (e.g., Kolar), Zimbabwe craton (e.g., Kwekwe), Slave craton (e.g., Yellowknife), Sao Francisco craton (e.g., Quadrilatero Ferrifero), and Tanzania craton (e.g., Bulyanhulu), with smaller deposits exposed in the Wyoming craton and Fennoscandian shield. Some workers also suggest that the Witwatersrand ores were formed from hydrothermal fluids in this period.

The third global episode of orogenic gold-vein formation occurred at ca. 2.1–1.8 Ga, as supracrustal sedimentary rock sequences became as significant hosts as greenstones for the gold ores. Greenstone–sedimentary rock sequences now exposed in interior Australia, northwestern Africa/northern South America, Svecofennia, and the Canadian shield were the

* Corresponding author.

E-mail address: goldfarb@usgs.gov (R.J. Goldfarb).

focus of gold veining prior to final Paleoproterozoic cratonization. Many of these areas also contain passive margin sequences in which BIFs provided favorable chemical traps for later gold ores. Widespread gold-forming events included those of the Eburnean orogen in West Africa (e.g., Ashanti); Ubendian orogen in southwest Tanzania; Transamazonian orogen in the Rio Itapicuru greenstone belt of the Sao Francisco craton, west Congo craton, and Guyana shield (e.g., Las Cristinas); Tapajós–Parima orogen on the western side of the Amazonian shield; Trans-Hudson orogen in North America (e.g., Homestake); Ketalidian orogen in Greenland; and Svecofennian orogen on the southwestern side of the Karelian craton. Where Paleoproterozoic tectonism included deformation of older, intracratonic basins, the resulting ore fluids were anomalously saline and orogenic lodes are notably, in some cases, base metal-rich. Examples include ore-hosting strata of the Transvaal basin in the Kaapvaal craton and the Arunta, Tennant Creek, and Pine Creek inliers of northern Australia.

The Mesoproterozoic through Neoproterozoic (1.6 Ga–570 Ma) records almost 1 b.y. of Earth history that lacks unequivocal evidence of significant gold-vein formation. To a large extent, the preserved geological record of this time indicates that this was a period of worldwide major extension, intracontinental rifting, and associated anorogenic magmatism. Some juvenile crust was, nevertheless, added to cratonic margins in this period, particularly during the growth of the Rodinian supercontinent at ca. 1.3–1.0 Ga. Some early Neoproterozoic dates are reported for important orogenic gold ores within the older mobile belts around the southern Siberian platform (e.g., Sukhoi Log), but it is uncertain whether these dates are correct or, in many cases, are ages of country rocks to the main lodes that may have formed later. Late Neoproterozoic collisions, which define the initial phases of Gondwana formation, mark the onset of the relatively continuous, orogenic gold-vein formation in accretionary terranes that has continued to the Tertiary and probably to the present day. Ore formation first occurred during Pan-African events in the Arabian–Nubian shield, within the Trans-Saharan orogen of western Africa and extending into Brazil's Atlantic shield, within the Brasilia fold belt on the western side of the Sao Francisco craton, and within the Paterson orogen of northwestern Australia.

Paleozoic gold formation, accompanying the evolution of Pangea, occurred along the margins of Gondwana and of the continental masses around the closing Paleo-Tethys Ocean. In the former example, orogenic lodes extend from the Tasman orogenic system of Australia (e.g., Bendigo–Ballarat), to Westland in New Zealand, through Victoria Land in Antarctica, and into southern South America. Early Paleozoic gold-forming Caledonian events in the latter example include those associated with amalgamation of the Kazakstania microcontinent (e.g., Vasil'kovsk) and closure of the Iapetus Ocean between Baltica, Laurentia and Avalonia (e.g., Meguma). Variscan orogenic gold-forming events in the middle to late Paleozoic correlate with subduction-related tectonics along the western length of the Paleo-Tethys Ocean. Resulting gold ores extend from southern Europe (e.g., in the Iberian Massif, Massif Central, Bohemian Massif), through central Asia (e.g., Muruntau, Kumtor), and into northwest China (e.g., Wulashan). The simultaneous Kazakstania–Euamerica collision led to gold vein emplacement within the Uralian orogen (e.g., Berezosk).

Mesozoic break-up of Pangea and development of the Pacific Ocean basin included the establishment of a vast series of circum-Pacific subduction systems. Within terranes on the eastern side of the basin, the subsequent Cordilleran orogen comprised a series of Middle Jurassic to mid-Cretaceous orogenic gold systems extending along the length of the continent (e.g., Mother Lode belt, Bridge River, Klondike, Fairbanks, Nome). A similar convergent tectonic regime across the basin was responsible for immense gold resources in the orogens of the Russian Far East, mainly during the Early Cretaceous (e.g., Natalka, Nezhdaninskoe). Simultaneously, important orogenic gold systems developed within uplifted basement blocks of the northern (e.g., Dongping deposit), eastern (e.g., Jiaodong Peninsula), and southern (e.g., Qinling belt) margins of the Precambrian North China craton. Orogenic gold veining continued in the Alaskan part of the Cordilleran orogen (e.g., Juneau gold belt) through the early Tertiary, and was also associated with Alpine uplift in southern Europe, and strike–slip events during Indo-Asian collision in southeastern Asia, through the middle, and into the late, Tertiary.

The important periods of Precambrian orogenic gold-deposit formation, at ca. 2.8–2.55 and 2.1–1.8 Ga, correlate well with episodes of growth of juvenile continental crust. Similar characteristics of the Precambrian orogenic gold ores to those of Phanerozoic age have led to arguments that “Cordilleran-style” plate tectonics were also ultimately responsible for the older lodes. However, the episodic nature of ore formation prior to ca. 650 Ma also suggests significant differences in overall tectonic controls. The two broad episodes of Precambrian continental growth, and associated orogenic gold-veining, are presently most commonly explained by major mantle overturning in the hotter early Earth, with associated plumes causing extreme heating at the base of the crust. This subsequently led to massive melting, granitoid emplacement, depleted lower crust and resultant extensive buoyant continental crust. The resulting Late Archean and Paleoproterozoic crustal blocks are large and relatively equi-dimensional stable continental masses. Importantly for mineral resources, such blocks are thermally and geometrically most suitable for the long-term preservation of auriferous mid-crustal orogens, particularly distal to their margins.

More than 50% of the exposed Precambrian crust formed between 1.8 and 0.6 Ga, yet these rocks contain few orogenic gold deposits, therefore indicating that more than volume of preserved crust controls the distribution of these ores. Despite much of this appearing to have been a time of worldwide extension and anorogenic magmatism in cratonic interiors, significant continental growth was still occurring along cratonic margins (e.g., Albany–Fraser and Musgravian orogens in Australia, growth of North America on southern side of Hudsonian craton, collisions on southwestern margin of Amazonian craton, etc.), culminating with the formation of Rodinia by ca. 1.0 Ga. Beginning at the end of the Paleoproterozoic, however, there was a change in crustal growth patterns, such that juvenile crust began to be added as long narrow microcontinents and accretionary complexes around the margins of older cratons. This probably reflects the gradual change from strongly plume-influenced plate tectonics to a less-episodic, more-continuous present-day style of slab subduction and plate tectonics as a more homogeneous, less layered mantle convection evolved. The long and narrow strips of juvenile crust younger than 1.8 Ga would have been relatively susceptible to continual reactivation and reworking during Mesoproterozoic through Phanerozoic collisions, and the high metamorphic-grade of most 1.8–0.6 Ga crustal sequences indicates unroofing of core zones to the orogens. These schist and gneiss sequences would have been beneath the levels of most-productive orogenic gold-vein formation within most orogens.

The distribution of orogenic gold ores formed during the last 650 m.y. of Earth history is well-correlated with exposures of the greenschist-facies mobile belts surrounding 1.8 Ga cratonic masses. Reworking of cratonic margins has eroded away most indications of orogenic gold older than ca. 650 Ma in these crustal belts, whereas younger lode systems are especially well preserved from the last 450 m.y. The immense circum-Pacific placer goldfields collectively suggest a short lifespan for many of the lode systems; veins are apparently recycled into the sedimentary rock reservoir within ≤ 100 –150 m.y. of their initial emplacement if continental margins remain active. Where continent–continent collisions preserved Phanerozoic orogens in a “craton-like” stable continental block (e.g., central Asia) during supercontinent growth, gold lodes (e.g., Muruntau) could be better preserved. The lack of any exposed, large orogenic gold-systems younger than about 55 Ma indicates that, typically, at least 50 m.y. are required before these mid-crustal ores are unroofed and exposed at the Earth’s surface. Crown Copyright © 2001 Published by Elsevier Science B.V. All rights reserved.

Keywords: Orogenic gold; Geochronology; Precambrian; Phanerozoic; Tectonics

1. Introduction

Economic geologists have continually contemplated the basic questions of metallogenic epochs. Why are some parts of the globe permissive for a given mineral deposit type of a certain age, whereas others are not? As far back as the turn of the 20th century, Lindgren (1909), in his classic paper on “metallogenic” epochs, admitted that he was satisfied with the state of classification of many mineral deposits, but critical questions remained concerning the reason for their geographic locations. He concluded that favorable conditions for ore formation or richer source rocks for ore components characterized these areas. Turneure (1955) noted the re-occurrence of the same ore deposit types in rocks of different ages in different parts of the world, such as lode-gold in the Precambrian shields and young orogenic belts (“orogenic gold deposits”, as discussed below), and therefore stressed uniform processes of ore concentration over time.

Orogenic, or the so-called “mesothermal”, gold deposits are a distinctive class of mineral deposit (e.g., Bohlke, 1982; Groves et al., 1998) that has been the source for much of world gold production. The ores are widely recognized in both Phanerozoic mobile belts and older cratonic blocks (Fig. 1). Consistent geological characteristics include deformed and variably metamorphosed host rocks; low sulfide volume; carbonate–sulfide \pm sericite \pm chlorite alteration assemblages in greenschist-facies host rocks; low salinity, CO₂-rich ore fluids with $\delta^{18}\text{O}$ values of 5–10‰; and, normally, a spatial association with large-scale compressional to transpressional structures (e.g., Colvine et al., 1984; Hodgson, 1993; Robert, 1996). The orogenic gold deposits normally consist of abundant quartz \pm carbonate veins and show evidence for formation from fluids at supralithostatic pressures. The mineralized lodes formed over a uniquely broad range of upper to mid-crustal pressures and temperatures, between about 200–650°C and 1–5 kbar (Groves, 1993).

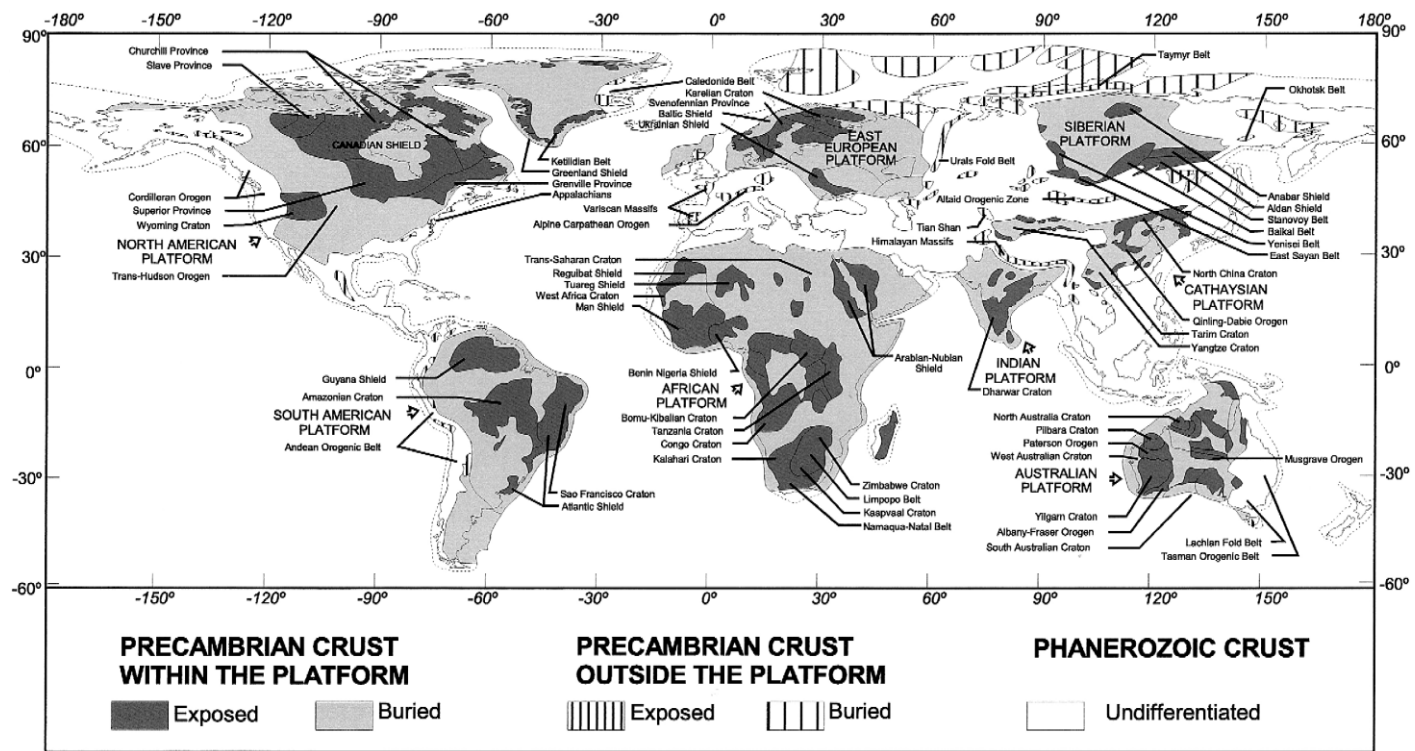


Fig. 1. Distribution of Precambrian cratons and shields, and Phanerozoic mobile belts.

Orogenic lode-gold deposits are the typical source for many of the great placer districts, including the enormous circum-Pacific placer fields of the California foothills belt, Russian Far East, and central Victoria (Goldfarb et al., 1998).

It is critical to note that the *orogenic gold deposit* type terminology in this paper is used to describe a distinctive type of mineral deposit. Gold deposits of this type are a coherent group characterized by the above geological and geochemical features. The

hydrothermal systems are typically widespread throughout an orogen and represent a *regional* fluid type inherent to tectonism along convergent margins (Groves et al., 1998). Certainly, other auriferous deposit types, including epithermal precious metal-bearing veins and gold-bearing porphyries, also exist in orogens. These other deposit types, however, are closely associated with magmatic–meteoric hydrothermal systems of *more local* extent and have characteristics that differ from those of the orogenic

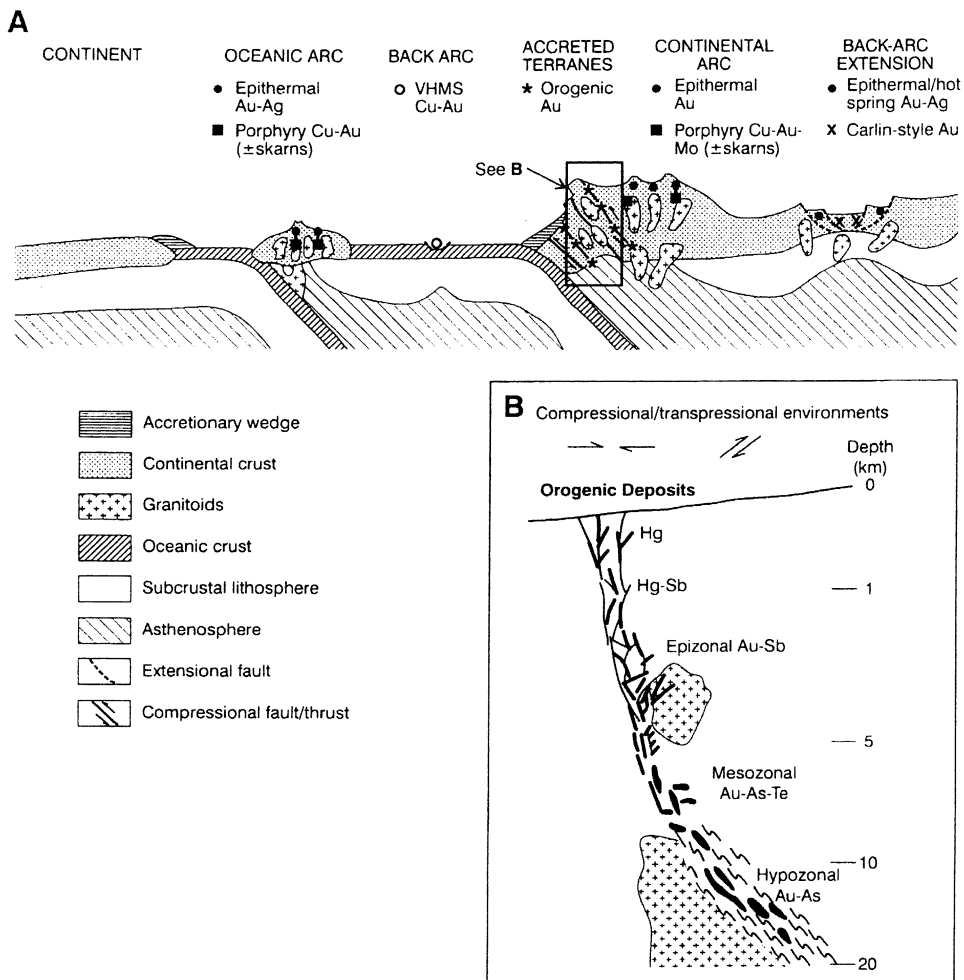


Fig. 2. The tectonic settings of gold-rich epigenetic mineral deposits. Epithermal veins and gold-rich porphyry and skarn deposits, form in the shallow (≤ 5 km) parts of both island and continental arcs in compressional through extensional settings. The epithermal veins, as well as the sedimentary rock-hosted Carlin-like ores, are also emplaced in the shallow regions of back-arc crustal thinning and extension. In contrast, orogenic gold deposits are emplaced during collisional events throughout much of the middle to upper crust (after Groves et al., 1998).

gold deposits. As described below, the distinction between orogenic gold deposits and some Carlin-like and intrusion-related gold deposits remains problematic. Furthermore, there appears to be little point in further subdividing what are classified here as orogenic gold deposits into categories such as “Korean” intrusion-related, “Motherlode” volcanic-hosted, “Grass Valley” plutonic-hosted, “Bendigo” turbidite-hosted, and “Homestake” iron-formation-hosted (e.g., Poulsen, 1996). Such divisions based on host rock type and/or formation depth provide little additional advantage; that is, even a single hydrothermal system can evolve over a broad depth range or interact with a variety of country rock types.

Meyer (1981) discussed the apparent lack of formation of orogenic gold lodes between 2.4 and 0.3 Ga. Gold-bearing quartz veins were stated to have been deposited throughout southern Africa at about 3 Ga and in other greenstone belts at about 2.5 Ga. Subsequently, these ore systems were protected from erosion during stabilization of Precambrian crust. Meyer (1981) hypothesized that the 2000-m.y.-long gap in ore formation may reflect a lack of gold-enriched source areas in host terranes or the lack of the required type of hydrothermal process throughout most of the Proterozoic and into the Phanerozoic. These hypotheses may still be valid, but, with the increased understanding of the orogenic gold-deposit type that has developed over the last 20 years (Groves et al., 1998; Goldfarb et al., 1998), it is now possible to better evaluate all factors that determine why some rocks of some eras in certain locations contain gold ores, and rock of other eras lack gold ores.

Many key questions regarding tectonics, source rocks, thermal regimes, and structure need to be addressed in understanding the distribution of metallogenic epochs for orogenic gold formation. Orogenic gold shows a spatial association with collisional orogens (Fig. 2). Therefore, did Phanerozoic-style collisional plate tectonics continue back into the Archean, and, if so, why does much of the Proterozoic lack orogenic gold? Are transcrustal structures, the obvious conduits for large-scale ore fluid flow, notably lacking in gold-poor orogens? It is now recognized that dissolved sulfur and gold in the ore-forming fluids (Loucks and Mavrogenes, 1999), and overall fluid volumes (Fyfe and Kerrich, 1984), are critical for the formation of economic

orogenic gold deposits. Could any of these critical ingredients have been lacking in orogenic belts that do not contain significant gold ores? Could the increased thermal gradient needed to drive crustal fluid migration have been lacking in certain orogens over space and time? Or, simply, is the observed distribution a consequence of non-preservation of gold-mineralized orogens at particular times in Earth history? The more information that can be obtained to answer these and related questions, the better the possibilities of targeting gold-enriched tracts of the crust.

2. Orogenic gold through time

Since the mid-1980s, one of the main advances in our knowledge of orogenic gold deposits has been the abundance of high-precision geochronological studies. These studies, with a few exceptions, have narrowed the 2000-m.y. gap (2.4–0.3 Ga) defined in Meyer’s (1981) classic work to a period of approximately 1200 m.y., continuing from 1.8 to 0.6 Ga (Fig. 3). Post-Archean orogens, concentrated mainly between 2.1 and 1.8 Ma, in present-day north-central Australia, western Africa–northeastern South America, the Trans-Hudson of Canada, southern Greenland, and Scandinavia are now recognized gold ore hosts. Also, younger gold ores are now known to have formed as far back as the Caledonian orogen in the early Paleo-Tethys ocean basin and the Pan-African orogen of the latest Proterozoic (Fig. 4). Nevertheless, rocks of the Mesoproterozoic, and most of the Neoproterozoic, remain extremely noteworthy in terms of their almost total absence of orogenic gold vein systems. The 400-m.y.-long period between about 2.5 and 2.1 Ma is also characterized by a lack of gold (Fig. 3).

2.1. Middle Archean (3.4–3.0 Ga)

There are very few well-preserved blocks of Middle Archean rocks remaining on Earth, particularly any that contain abundant volcanic rocks with subduction-type petrochemical signatures and with generally low degrees of strain, which are most amenable to gold-carrying fluids being focused along narrow, high-strain shear zones during a major deformation.

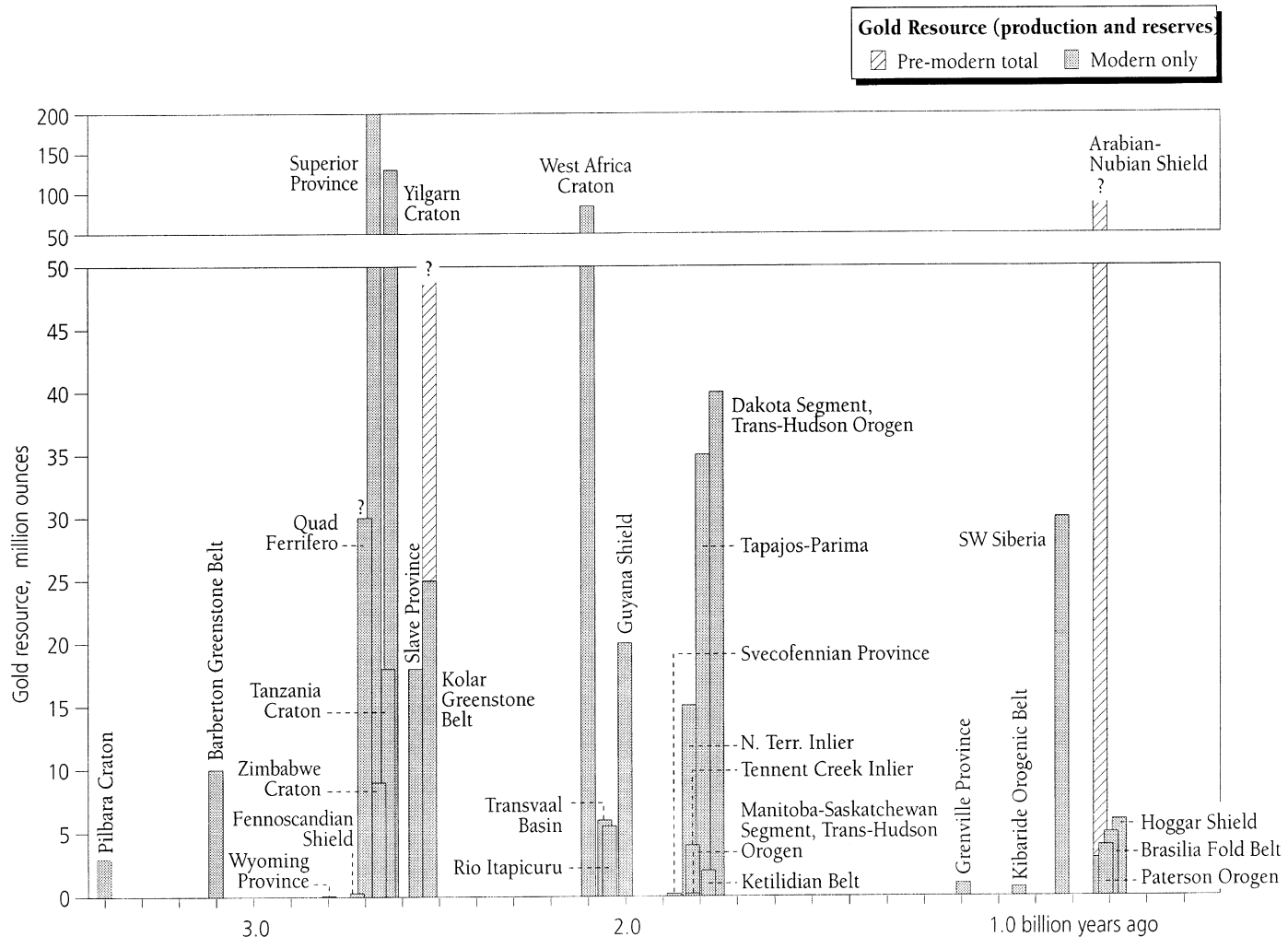


Fig. 3. Gold production vs. best approximation for the age of gold vein formation for Precambrian orogenic gold deposits. For many of the gold-bearing regions, there are commonly a variety of conflicting dates determined by a variety of isotopic systematics. The most reliable age of gold mineralization is chosen on the basis of available published information on the timing of other tectonic events in the appropriate orogen. Great uncertainties in gold production values from the Kolar greenstone belt and Arabian-Nubian Shield reflect extensive pre-modern day lode and placer workings. The age for SW Siberia ores is very uncertain and could be 200 m.y. younger.

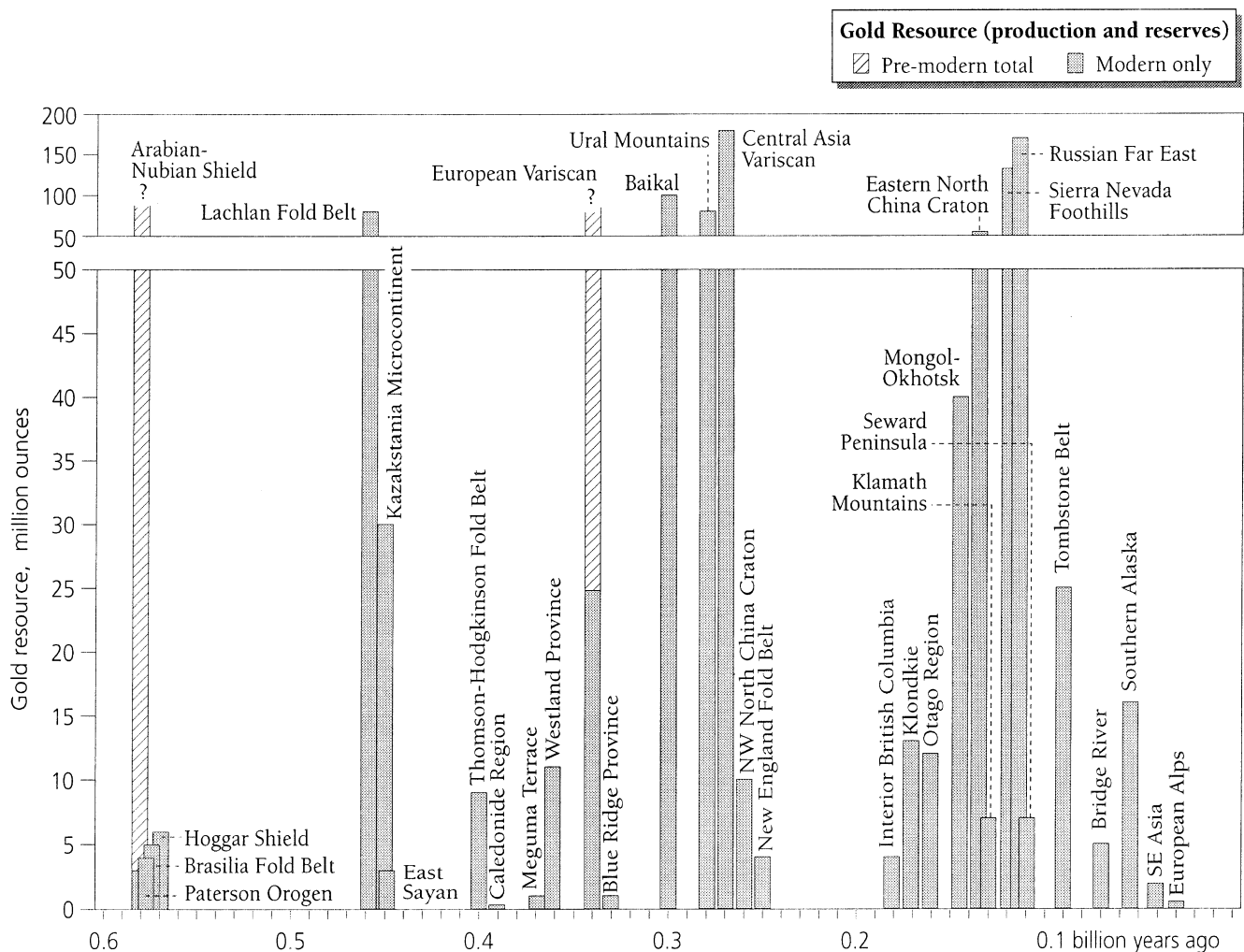


Fig. 4. Gold production vs. best approximation for the age of gold vein formation for Phanerozoic orogenic gold deposits. For many of the gold-bearing regions, there are commonly a variety of conflicting dates determined by a variety of isotopic systematics. The most reliable age of gold mineralization is chosen on the basis of available published information on the timing of other tectonic events in the appropriate orogen. Great uncertainties in gold production values from the European Variscan reflect extensive lode and placer workings by the Romans in the northern Iberian Peninsula.

The Kaapvaal craton of South Africa is an exception, composed of a series of amalgamated crustal fragments that were stabilized by about 3.1 Ga and include 10 distinct greenstone belts (Brandl and de Wit, 1997). The 3.57–3.08 Ga Barberton greenstone belt formed much of the early nucleus for the craton. More significantly, these greenstones, now towards

the eastern margin of the craton, host the oldest recognized orogenic gold ores.

Economically significant gold-bearing quartz veins of the Barberton greenstone belt (Fig. 5a) are recognized to have formed at about 3126–3084 Ma by de Ronde et al. (1991) and at > 3040 Ma by Harris et al. (1993). Studies by de Ronde and de Wit

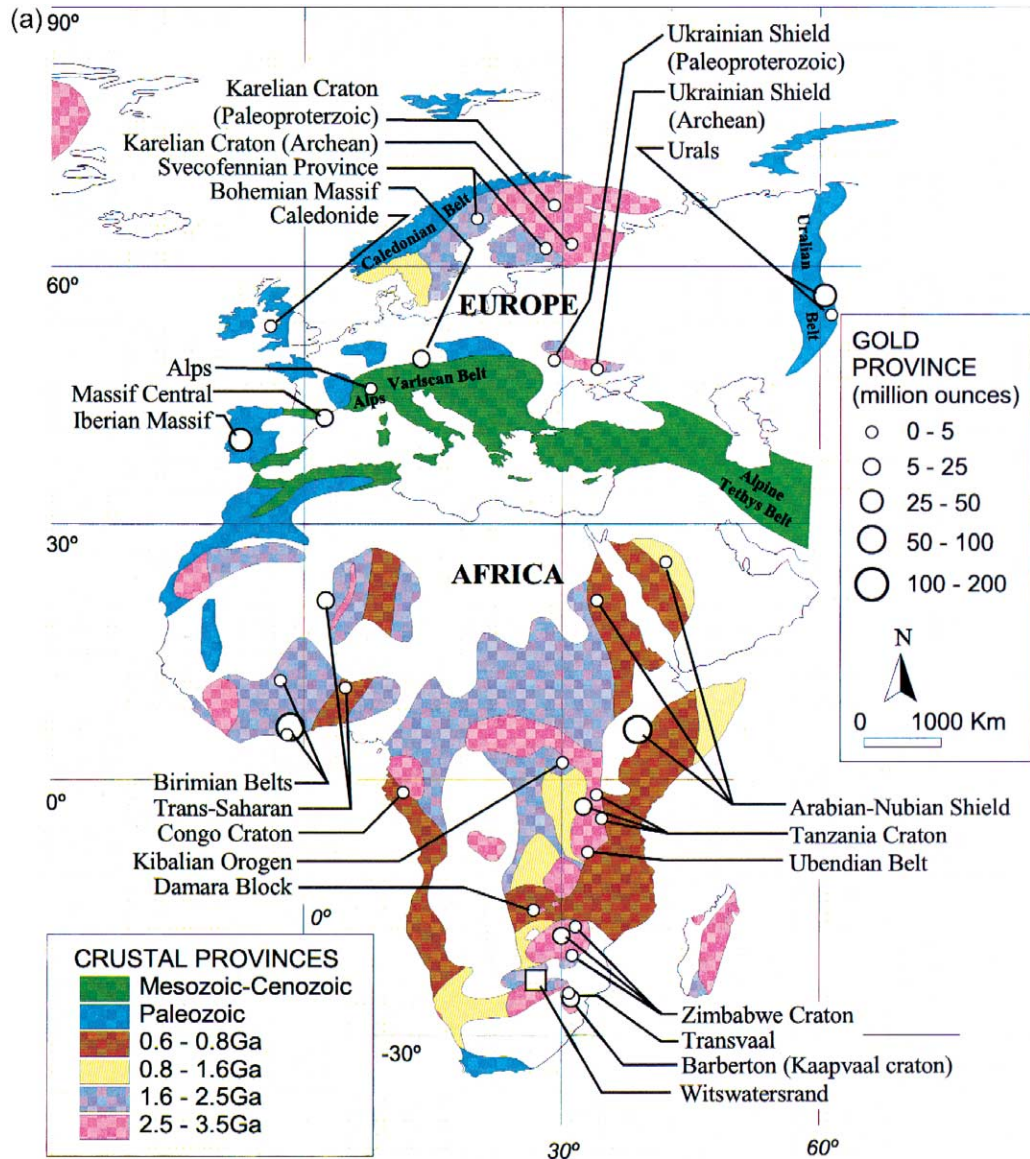


Fig. 5. Maps showing the distribution of crust of a given age and the distribution of significant orogenic gold lodes hosted within such crust. Figures include Africa/Europe (a), Australia/New Zealand/India/Asia (b) and North America/South America (c).

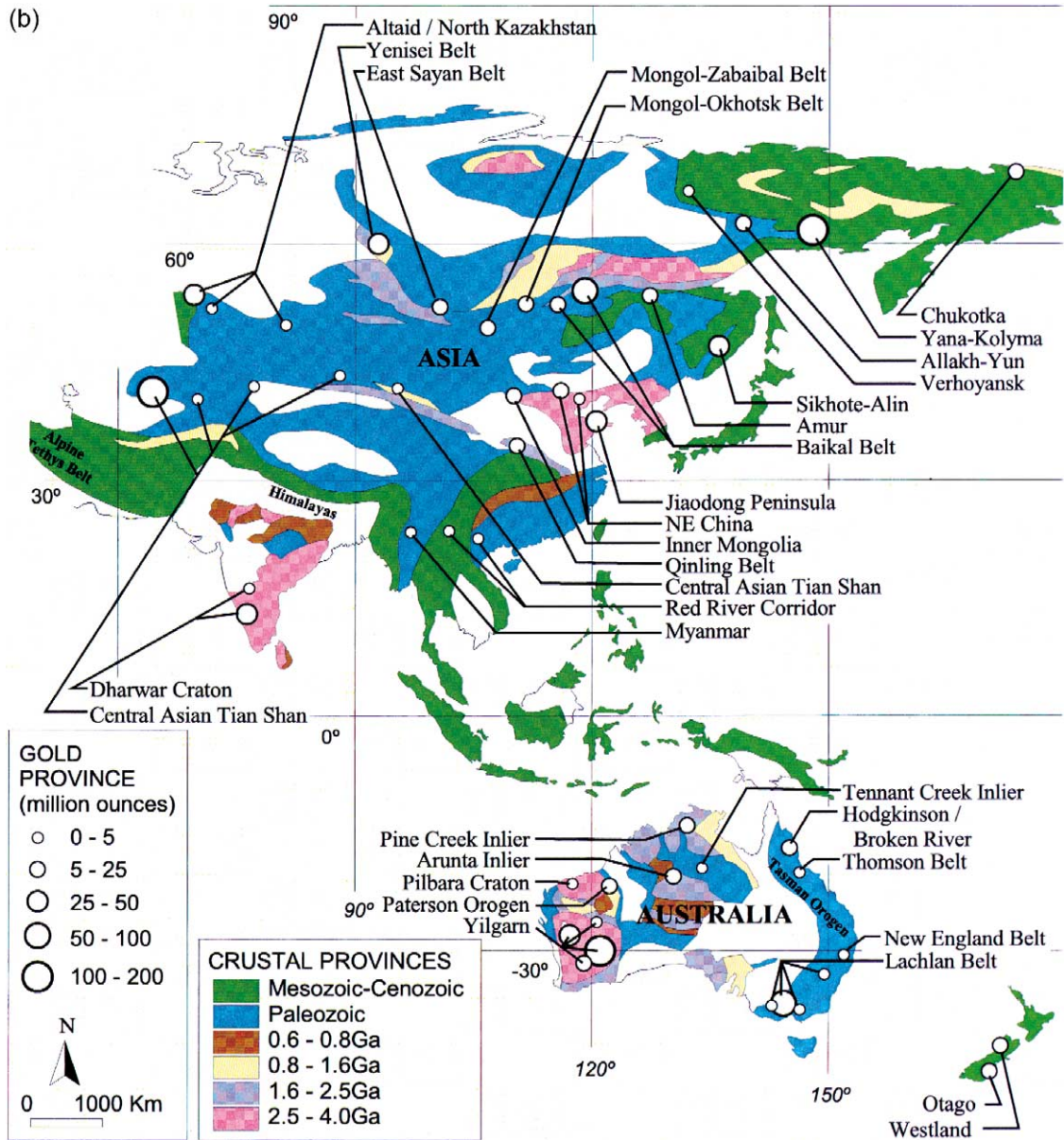


Fig. 5 (continued).

(1994) indicate present-day type accretionary and subduction events from about 3230–3080 Ma, followed by a change to transtensional tectonics simultaneous with gold vein formation. The main gold deposits, combining to produce about 10 million ounces of gold (Moz Au), are located in secondary

structures only a few kilometers from the suture between the major colliding blocks. Vein emplacement post-dates greenstone-belt metamorphism and was coeval with large-scale plutonism in areas adjacent to the greenstone belt. Other greenstone belts farther north within the Kaapvaal craton, such as the

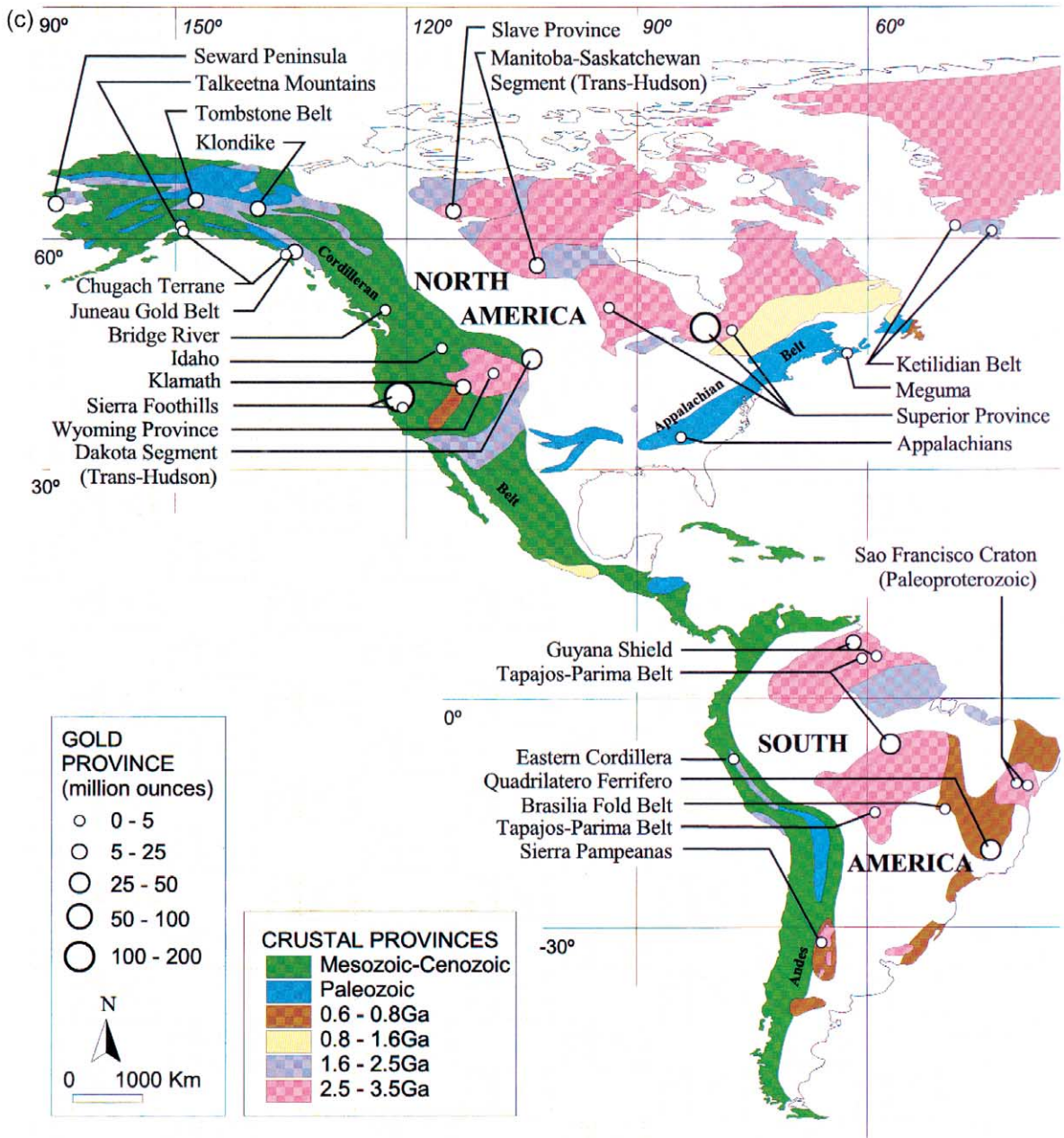


Fig. 5 (continued).

Murchison and Pietersburg belts, and the Sutherland (or Giyani) group of belts, contain some relatively small gold deposits (Foster and Piper, 1993). Although many of these deposits are undated, some clearly did not form until the Late Archean (Foster and Piper, 1993) during tectonism associated with

collision of the Kaapvaal and Zimbabwe cratons (see below).

Important Middle Archean orogenic gold deposits may have also formed in South Africa, but, if so, they were then eroded a few hundred million years later. Gold-rich conglomerates of the exceptional

Witwatersrand goldfields (1500 Moz Au production and > 600 Moz Au reserve) occur in a 2.89–2.71 Ga sedimentary rock sequence (Robb and Meyer, 1995) that filled a growing Witwatersrand basin. The origin of the Witwatersrand gold deposits is controversial, with both placer/modified placer (Minter et al., 1993) and hydrothermal models (Phillips and Myers, 1989; Barnicoat et al., 1997) being proposed, and recent ideas even favoring significant remobilization during a 2.02 Ga meteorite impact event (Frimmel et al., 1999).

The tectonic setting of the Witwatersrand basin, a retroarc foreland basin, is entirely consistent with derivation of the Witwatersrand gold ores as giant Late Archean paleoplacers that were eroded from Middle Archean lode sources. Important placers derived from orogenic lode-gold deposits are typical of many tectonically active Cenozoic environments. Some features of the Witwatersrand ores, such as their low fineness and anomalous mercury content, make it impossible to rule out erosion of epithermal vein systems in Archean arcs (cf. Hutchison and Viljoen, 1988), or notably shallow epizonal orogenic gold deposits, if a placer model is valid. New rhenium depletion ages of 3.5–2.9 Ga for gold and an isochron age of 2.99 ± 0.11 Ga on ore-related pyrite, as well as unradiogenic osmium isotope ratios, are very consistent with a detrital origin for gold in the Witwatersrand basin (Kirk et al., 2001, 2001). In terms of Late Archean hydrothermal models, the Witwatersrand ores show some similarities to orogenic lode-gold deposits in their gold–pyrite or gold–carbon association and their greenschist-facies host rocks (Phillips and Powell, 1993). Important differences, however, include the nature of alteration (e.g., pyrophyllite commonly present, and carbonate absent), the association of ores with a U–Ni–Co–Cr geochemical suite, the lack of ubiquitous gold-related quartz \pm carbonate veins, the overall lack of evidence for supralithostatic pressures (Groves et al., 1995), and the relative geometrical simplicity of the majority of structural settings in which gold is sited. The controversial nature of the origin of these ores precludes more detailed discussion in the present paper.

Some small gold occurrences in the Pilbara craton of northwestern Australia formed at about 3.4 Ga (Neumayr et al., 1998). It is not entirely certain, but

a number of smaller orogenic gold deposits in the Ukrainian shield of the East European platform (Fig. 5a) may also be of Middle Archean age. Most of these occur within the largest granite–greenstone terrane of the shield, termed the Pre-Dnieprovia craton (or block) that is mainly 3.34–3.25 Ga in age (Kushev and Kornilov, 1997). It is possible that the gold ores within the Middle Archean Pre-Dnieprovia craton, at deposits such as Balka Zolotaya, Sergeevsk and Balka Shiroka, formed during this same time because well-dated examples from throughout the world's Precambrian greenstone belts show coeval greenstone belt evolution and gold ore genesis. Alternatively, limited model lead ages suggest that the orogenic gold deposits may instead be of Late Archean age (Koval et al., 1997).

2.2. Late Archean (3.0–2.5 Ga)

The exposed Late Archean crust has been long-recognized as extremely favorable terrane for hosting orogenic gold deposits (Table 1). These cratonic blocks in Western Australia (Fig. 5b), India (Fig. 5b), southern and central Africa (Fig. 5a), northern South America (Fig. 5c), and north-central North America (Fig. 5c) contain a high percentage of world gold resources. Significant Archean orogenic gold deposits are not recognized from large areas of Archean crust that form the Siberian platform, East European platform, Wyoming craton, Chinese cratons, and Greenland shield (Fig. 1). This reflects both the relatively high percentage of Archean interior basement covered by younger sedimentary rock sequences within these platformal areas and the commonly high metamorphic grade of exposed rocks.

Late Archean gold ores are especially well-studied from the many world-class deposits of the Yilgarn craton in Western Australia and Superior province of central Canada. The Yilgarn craton (Fig. 5b), dominated by 3.0–2.6 Ga granitoid and greenstone lithologies, is characterized by a broad distribution of orogenic gold deposits. The ores mainly formed at about 2630 Ma (Groves, 1993; Kent et al., 1996), with a minority purported to have formed between 2670 and 2660 Ma (Yeats et al., 1999) and possibly at about 2600 Ma (Kent et al., 1996). The Yilgarn craton itself is now hypothesized by some workers as

composed of four superterrane made up of 11 distinct terranes, which, in turn, contain 40 distinct greenstone belts (Myers, 1997).

Gold veining in many of the greenstone belts occurred toward the end of a 50-m.y.-long period of deformation and magmatism. Although Barley et al. (1989) hypothesized that gold mineralization was associated with collisional processes that resemble those characterizing Cordilleran-type tectonics, there is little evidence from published age data for a major tectonothermal event at 2630 Ma, the time of major gold mineralization, in the ore-hosting granitoid–greenstone terranes. However, Qiu and Groves (1999) have shown that a major thermal event, possibly related to lithosphere delamination, occurred in adjacent areas at 2640–2630 Ma. This event, perhaps due to the earlier removal of voluminous magma, was at the end of collisional orogeny in the higher-grade gneiss terranes to the west of the granitoid–greenstone terranes and involved the widespread emplacement of felsic alkaline igneous rocks (Smithies and Champion, 1999). Post-collisional reactivation of earlier formed shear zones, including terrane and superterrane boundaries, may have been critical for migration of gold vein-forming fluids. Much of the fluid was focused into the area of the giant Kalgoorlie lode-gold system, which is the source for about half of the combined past production and recognized resource of > 130 Moz Au of the craton.

The 3.1–2.6 Ga Superior province (Fig. 5c), the main component of the Canadian shield, is second to the Kaapvaal craton (Witwatersrand) in terms of historic gold productivity. The older northern and central parts of the craton are dominated by continental sedimentary–volcanic rock sequences and, like many other rift-related and intracontinental basalt-dominated belts, they generally lack orogenic gold-vein deposits (Poulsen et al., 1992). The southern part of the province is dominated by approximately 35 distinct 2.77–2.70 Ga greenstone belts that contain most of Canada's largest gold deposits. More than 25% of this approximately 200 Moz Au is from the Timmins district. The 20 Moz Hemlo deposit remains controversial, with the replacement style of mineralization (Pan and Fleet, 1995) being either just another variant of orogenic gold deposit or, instead, representative of a distinct replacement gold deposit type (Poulsen, 1996).

Subprovinces within the southern Superior province are now commonly recognized as superterrane that grew between about 2.99 and 2.71 Ga (Stott, 1997; Polat and Kerrich, 1999). The progression of deformational and plutonic ages, younging southward, has been suggested to reflect the growth of a continental margin and migration of a subduction zone during the 2.71–2.66 Ga Kenoran orogen (Card, 1990; Hoffman, 1991; Jackson and Cruden, 1995). As in the Yilgarn craton, transpressional tectonics during crustal growth is hypothesized as critical to gold genesis (Kerrich and Wyman, 1990). Many of the gold deposits in the Superior province formed during orogenesis at about 2680 Ma, but it remains controversial as to whether other ores in the same greenstone belts formed as late as about 2600 Ma (Robert, 1990; Kerrich and Cassidy, 1994). Multiple veining episodes in a number of the significant gold districts, established by relative timing relationships between veins and various deformational and magmatic events, suggest that a variety of Late Archean absolute ages are feasible (Robert, 1996).

Gold ores of Late Archean age characterize the Kolar (> 27 Moz Au production), Hutti–Maski (17 Moz Au resource), Ramagiri–Penkacherla, and Gadag–Shimoga schist (or greenstone) belts in the eastern block of the Dharwar craton (Fig. 5b) of India (Radhakrishna and Curtis, 1999). The western half of the craton is dominated by the 3.3–2.9 Ga basement rocks of the Peninsular gneiss and 2.9–2.6 Ga schist of the Dharwar Supergroup; the eastern block comprises the massive ca. 2.75–2.51 Ga Dharwar batholith, which contains relatively thin slivers of auriferous, poorly dated schist belts (Chadwick et al., 2000). The most economically important deposits occur in the center of the Kolar schist belt. A post-kinematic granitoid that cuts ore in the Kolar goldfields is dated at 2.55 Ga (Hamilton and Hodgson, 1986), providing a minimum age on veining. It is uncertain as to whether cratonic growth accompanying Dharwar orogenesis, which likely continued until about 2.42 Ga, was characterized by Phanerozoic-type accretionary tectonics (Hanson et al., 1988; Krogstad et al., 1989; Zachariah et al., 1997). In support of this is the possibility that the 500-km-long by 10-km-wide, 2.6–2.5 Ga Closepet granitoid complex represents a magmatic arc oblique to subduction from what is now the east (Chadwick et al., 1996,

Table 1
Summary characteristics of Archean orogenic gold deposits

Gold province	Host area	Districts (deposits)	Associated structures	Production (Moz Au)
Barberton G.B.	Kaapvaal craton	(Sheba, New Consort, Fairview, Agnes)	Saddleback–Inyoka	> 10
Northern Pilbara craton	Pilbara craton	(Mount York, Bamboo Creek, Marble Bar, Blue Spec)		2.2
Pre-Dnieprovia block	Ukrainian shield	(Sergeevsk, Balka Zolotaya, Appolonovsk)	Sursk, Verkhovtsevsk	
Eastern Goldfields superterrane	Yilgarn craton	(Golden Mile, Norseman, Kambalda, Bronzewing, Sunrise Dam, Jundee)	Boulder–Lefroy, Boorara–Menzies	90
Southern Cross superterrane	Yilgarn craton	(Marvel Loch, Transvaal)		8
West Yilgarn superterrane	Yilgarn craton	(Big Bell, Hill 50)		18
Southern Superior Province (mainly Abitibi G.B.)	Canadian shield	(McIntyre–Hollinger, Sigma–Lamaque, Hemlo(?), Dome, Kerr–Addison)	Larder Lake–Cadillac, Destor–Porcupine	180
Slave Province	Canadian shield	Yellowknife (Con, Giant), Gordon Lake, Lupin(?)	Campbell–Giant	16
Greenstone belts of E. Dharwar block	Indian shield	Kolar (Champion, Mysore, Nandydroog, Oorgaum) Hutti, Ramagiri, Gadag		27.6
Midlands, Harare–Shamva, and Odzi–Mutare greenstone belts	Zimbabwe craton	Kwekwe (Globe/Phoenix), Kadoma (Cam/Motor), (Freda–Rebecca, Shamva, Rezende, Redwing)	Kadoma, Lilly, Munyati, Shamva	17
Limpopo belt	Between Kaapvaal and Zimbabwe cratons	(Renco)	Tuli Sabi	0.5
Lake Victoria goldfields	Tanzania craton	Geita (Bulyanhulu, Buhemba, Macalder)	Suguti shear zone	3
Rio das Velhas greenstone belt	S. Sao Francisco craton	Quadrilatero Ferrifero (Cuiaba, Morro Velho, Raposos, Sao Bento, Santana)		30
South Pass greenstone belt	Wyoming province	Sweetwater (Miners Delight, Carissa)		0.3
Karelian craton	Fennoscandian shield	Ilomantsi (Kelokorpi, Kuittila, Korvilansuo, Muurinsuo, Ramepuro), Kuhmo (Lokkiluoto)	Korvilansuo–Kauravaara shear zone, Pampalo	0

Resource estimates are combined from numerous sources to give the most reliable numbers as of the year 2000. The sited mineralization ages are from what are viewed as the most reliable published isotopic dates. Older conflicting K–Ar, Rb–Sr, etc., dates are not used where newer dates exist.

2000). This sill-like belt of granitoids was emplaced along a major crustal shear zone a few tens of

kilometers landward of the auriferous greenstone belts, parallels these belts, and appears coeval with

Resource (Moz Au)	Associated placer	Deformation age (Ma)	Granitoid ages (Ma)	Mineralization age (Ma)	Reference
0.8	present but unknown amount	3230–3080	3490–3450, 3230, 3105, 2690	3126–3084	Anhaeusser (1986), de Ronde et al. (1991), de Ronde and de Wit (1994)
		3340, 3200, 3000–2900	3520–3400, 3315–3270, 3100, 3000–2900	3430–3300, 3200, 3000–2900	Neumayr et al. (1998), Witt et al. (1998)
		3000, 2750	3500–3100, 2970, 2800–2600	Middle Archean? 2900–2500	Kushev and Kornilov (1997), Koval et al. (1997)
75		2660–2640	2900–2630	2670–2660, 2640–2620, 2600	Witt et al. (1998), Kent et al. (1996), Yeats et al. (1999)
8		2660–2650	2700–2620	2650–2620	same as above
20		2900, 2660–2640	2900–2630	2640–2620	same as above
200(?)		2710–2670	2720–2670	2720–2660, 2600	Robert (1990, 1996), Kerrich and Cassidy (1994), Polat and Kerrich (1999)
10		> 2800, 2700–2600	2800, 2700–2580	2670–2656, 2585	Abraham et al. (1994), King and Helmstaedt (1997)
17	> 30 Moz has been estimated	2630–2520	2750–2510	≥ 2550	Hamilton and Hodgson (1986), Balakrishnan et al. (1999), Radhakrishna and Curtis (1999), Chadwick et al. (2000)
5		2710–2620	2680–2580	2670–2650, 2618–2604, 2413(?)	Herrington (1995), Darbyshire et al. (1996), Vinyu et al. (1996), Schmidt-Mumm et al. (1994), Oberthur et al. (2000)
		2700–2600, 2550–2530	2720–2550, 2400	2570	Kisters et al. (1998), Kolb et al. (2000)
> 20		2750–2530	2680, 2580–2570, 2530, 1870	< 2644, 2568–2534	Borg (1994), Walraven et al. (1994), Pinna et al. (1999)
> 10	paleoplacers at Moeda	2780–2770, 2150–1800, ca. 600	2780–2770, 2720–2700, 2600	2710–2580, 1830, ca. 600	Chauvet et al. (1994), Olivo et al. (1996), Lobato et al. (2001)
	< 0.1 Moz Au from placers	2800, 2630–2550	2800, 2670, 2630, 2550	2800	Bayley et al. (1973), Wilks and Harper (1997)
0.2		2750–2720	2840, 2750–2690	2740–2690, 2607	Sorjonen-Ward et al. (1997), Stein et al. (1998), Eilu (1999)

gold veining. Also, U–Pb dating in the Dharwar craton suggests that a series of accretionary colli-

sions occurred between about 2.53 and 2.50 Ga (Balakrishnan et al., 1999), which seems inconsistent

with the 2.55 Ga absolute age. As an alternative to Phanerozoic-style tectonics, plume-related diapirism and subsequent transpression have also been suggested (Choukroune et al., 1997; Jayananda et al., 2000).

The tectonic amalgamation of the 3.5–2.6 Ga granitoid–gneiss terranes and more than 20 greenstone belts of the Zimbabwe craton (Fig. 5a) is also not well documented. Wilson (1990) hypothesized accretionary crustal growth between 3.5 and 3.3 Ga and 2.9 and 2.6 Ga, with final cratonization at about 2.6 Ga. The most significant Late Archean gold ores in Africa formed late during this latter event in at least three of the greenstone belts. The most productive of the three, hosting the Kwekwe and Kadoma districts, formed in the Midlands belt in the center of the craton, perhaps at about 2.67 Ga (Herrington, 1995; Darbyshire et al., 1996). Deposits in the Harare–Shamva belt to the northeast, and Odzi–Mutare belt to the east, may also have been formed at about 2.66–2.65 Ga (Schmidt-Mumm et al., 1994; Vinyu et al., 1996) or 2.62–2.60 Ga (Oberthur et al., 2000). However, there are some conflicting dates from the Kwekwe district (Darbyshire et al., 1996) and Harare–Shamva greenstone belt ores (Frei and Pettke, 1996; Oberthur et al., 2000) that could be used to argue for Paleoproterozoic mineralizing events. Such events in a stable cratonic setting are atypical of orogenic gold deposits, and internal granitoids dated at 2618 Ma within the Harare–Shamva belt are not mineralized (Pitfield and Campbell, 1994; Vinyu et al., 1996). At this stage, it is best to consider that orogenic gold-vein formation occurred in one or more events between 2.67 and 2.60 Ga, which is potentially a similar period to that in the Yilgarn craton.

Immediately south of the margin of the Zimbabwe craton, high-grade metamorphic rocks of the Limpopo belt were deformed at about 2.7–2.6 Ga during collision between the Zimbabwe and Kaapvaal cratons. Granitoids were also widely emplaced throughout the entire belt at this time (Kroner et al., 1999). Gold deposition at the Renco mine (Kisters et al., 1998), and throughout the southernmost part of the mobile belt (Gan and van Reenen, 1997), was broadly coeval with the deformation. Ore formation continued for about 100 km inland into the Middle Archean greenstone belts described above within the

northern Kaapvaal craton. The approximately north–south far-field stress responsible for ore-hosting structures in the Harare greenstone belt (e.g., Campbell and Pitfield, 1994) potentially implicates an association with this collision as well, again implying similarities to the Yilgarn craton (Qiu and Groves, 1999).

The Slave province in northwestern Canada (Fig. 5c) contains about seven 2.7–2.6 Ga greenstone belts within a Late Archean granitoid–turbidite–greenstone terrane. Major gold producers include the Con and Giant mines within metavolcanic units of the Yellowknife greenstone belt of the southwestern Slave province and the Lupin mine within banded iron formation (BIF) in the center of the province. The origin of the latter remains controversial, perhaps being an epigenetic orogenic gold deposit (Bullis et al., 1996), although many workers still consider a syngenetic origin for the Lupin ores (Kerswill et al., 1996). Less significant orogenic gold deposits occur within the Anialik River greenstone belt in the northwestern part of the province. Gold formation at 2670–2656 Ma in this latter belt, in contrast to formation at about 2585 Ma in the Yellowknife belt, suggests diachronous ore formation for at least 80 m.y. across the province (Abraham et al., 1994). Kusky (1989) suggested that this was a period of accretionary-style tectonics, whereas others still question such Archean plate tectonics in the Slave province (Hamilton, 1998).

The Quadrilatero Ferrifero deposits in the Rio das Velhas greenstone belt, southern Sao Francisco craton (Fig. 5c), Minas Gerais, eastern Brazil, most likely formed during the Late Archean (Lobato et al., 2001). Most of the gold ores occur along major E–W transcurrent faults in greenschist-facies, mafic volcanic, clastic, and chemical sedimentary rocks of the Middle to Late Archean Nova Lima Group of the Rio das Velhas Supergroup. These rocks underwent major deformation at ca. 2.78–2.77 Ga, with magmatic events occurring at that time, and then subsequently at 2.72–2.70 Ga and at ca. 2.6 Ga (Carneiro, 1992). Complex infolding of Paleoproterozoic platform sedimentary rocks during the 2.15–1.8 Ga Transamazonian collisional orogeny and the effects of late Neoproterozoic “Brasiliano” thin-skinned tectonism have, however, led to many complexities regarding the timing of gold formation. Lobato et al.

(2001) summarize a few absolute Pb–Pb and U–Pb dates on gold-related sulfide minerals and rutile from some Quadrilatero Ferrifero deposits, which vary between 2.71 and ≥ 2.58 Ga. However, a Transamazonian Paleoproterozoic age is also indicated to characterize some of the Quadrilatero Ferrifero ores hosted by both Late Archean and much less commonly Paleoproterozoic(?) volcano–sedimentary sequences and BIFs (Olivo et al., 1995), as an additional lead isotope date suggests an age of gold deposition of 1.83 Ga for the Caue deposit (Olivo et al., 1996). Finally, a latest Proterozoic Brasiliano hydrothermal event has been suggested for some Quadrilatero Ferrifero ore formation. Chauvet et al. (1994) indicate that Brasiliano age thrust faults contain some of the gold-bearing quartz veins in the Ouro Preto mine area.

A few other, economically less significant and/or less well-studied, Late Archean orogenic gold ores are scattered among other greenstone belts in Africa, North America, and the Baltic region. The Tanzania (Fig. 5a) and Kibalian (or NE Zaire) cratons surrounding Lake Victoria in eastern Africa contain a few auriferous greenstone belts, which were separated during post-Archean rifting between the cratons. In the former craton, the Sukumaland and other greenstone belts of the Lake Victoria goldfields region (northern Tanzania and southwestern Kenya) contain quartz veins and disseminated gold ores in mafic volcanic rocks, BIF, and overlying volcanoclastic units. Some gold lodes, such as the large Bulyanhulu deposit in Tanzania and the Macalder deposit in Kenya, appear to overprint syngenetic pyritic to base metal-rich volcanogenic massive sulfide (VMS) deposits or their related alteration systems. Recent estimates suggest resources of as much as 20 Moz Au within the combined larger deposits of the Lake Victoria goldfields (i.e., *Mining Journal*, Oct. 24, 1997). Unlike many significant orogenic gold provinces, those of the Lake Victoria goldfields have not been described as showing a spatial association with major crustal structures, although such structures are apparent in some parts of the goldfields (e.g., the Golden Ridge deposit lies adjacent to a > 100-km-long lineament). At the most important past producer and the site of a major new resource, the Geita deposit, ores cut a 2644 Ma dike and give model lead ages on galena of 2568 and 2534 Ma

(Borg, 1994; Walraven et al., 1994). Lode and placer gold deposits occur in the Moto and Kilo greenstone belts along the eastern edge of the Late Archean Upper Zaire granitoid massif (Lavreau, 1984). The ages of the deposits are equivocal, but they are probably Late Archean and perhaps part of the same broad event responsible for the Lake Victoria goldfields.

In the Rocky Mountains of the western United States, minor production has been recorded from gold-bearing quartz veins within metasedimentary rocks of the South Pass greenstone belt. These Late Archean rocks of the Wyoming craton (Fig. 5c) represent isolated blocks throughout Wyoming and southern Montana, which were uplifted during Late Cretaceous and early Tertiary Laramide orogeny. These blocks were originally deformed sometime before 2.55 Ga and gold veining may be about 2.8 Ga in age (Wilks and Harper, 1997). Recently discovered, small gold deposits are scattered throughout the Ilomantsi (e.g., Hattu schist belt occurrences), Kuhmo, Suomussalmi, and Kostamuksha greenstone belts of the poorly exposed, Late Archean Karelian craton in the Fennoscandian (or Baltic) shield of eastern Finland (Fig. 5a). The veins may have formed during continental growth and tectonism at about 2.74–2.69 Ga (Sorjonen-Ward et al., 1997) or about 100 m.y. later (Stein et al., 1998).

Orogenic gold deposits are possibly also present in other, but more poorly understood, areas of exposed Late Archean crust (Figs. 1 and 5a–c). In Eurasia, these may include the Aldan–Stanovik (Popov et al., 1999) and Anabar shields along the northern and southern edges of the Siberian platform, respectively; the Bug–Podolian block of the Ukrainian shield along the southwestern margin of the East European platform; and basement uplifts within the North China and Tarim cratons of northern China. Because of superimposed, post-Archean deformational events along the marginal areas of these Proterozoic–Paleozoic platforms, recognition of Late Archean ore-forming events is much more difficult than within the more stable Late Archean cratons. Extensive areas of Late Archean rocks characterize the Man and Requibat shields of western Africa, but most economic gold in this part of Africa was emplaced in adjacent Proterozoic rocks during the later 2.1 Ga Eburnean orogeny. These relatively

Table 2
Summary characteristics of Proterozoic orogenic gold deposits

Gold province	Host area	District (deposits)	Associated structures	Production (Moz Au)
Birimian greenstone belts	West Africa craton	Obuasi (Ashanti), Prestea, Bogosu, Konongo (Sadiola Hill, Damang)		50
Ubendian belt	SW Tanzanian craton	Mpanda, Lupa (Ntumbi Reef (New Saza))	Saza shear zone, Magamba	0.8 (much in placer)
Rio Itapicuru G.B.	NE Sao Francisco craton	Weber (Fazenda Brasileiro) (Fazenda Maria Preta, Ambrosio), Serra de Jacobina		2
Eteke G.B.	Congo craton	Eteke (Dondo–Mobi, Ovala, Dango)	Ogoulou–Offoue	minor
Guyana shield	N. Amazonian craton	(El Callao, Las Cristinas, Omal, Gross Rosebel, Camp Cayman, Paul Isnard, Villa Nova)	Makapa–Kuribrong, Issano–Appaparu	uncertain, but at least 4 Moz in Guyana
Tapajos–Parima orogenic belt	W. Amazonian craton	Alta Floresta, Tapajos, Parima		uncertain
Flin Flon G.B. (Manitoba–Saskatch. segment)	Trans-Hudson orogen	(Rio, Tartan Lake, Snow Lake)	Tartan Lake shear zone	1.25
Dakota segment	Trans–Hudson orogen	(Homestake)		> 40
Svecofennian province	Baltic shield	Tampere, Rantasalmi (Osikonmaki), Seinajoki (Kalliosalo), Haapavesi (Klimala), Skellefte	Raahe–Ladoga deformation zone	0.3
Ketilidian mobile belt	North Atlantic craton	(Nalunaq, Niaqomaarsuk, Igutsait, Ipatit, Kutseq)		none
Transvaal basin	Kaapvaal craton	Sable–Pilgrim’s Rest		6
Northern Territory Inliers	North Australian craton	Arunta (Callie, Granites, Tanami), (Tennant Creek), Pine Creek (Cosmo Howley)		9
Paterson province	Paterson orogen	(Telfer)	Telfer lineament	> 4
Arabian shield	African platform (Pan-African orogen)	(Sukhaybarat East), Al Wajh (Umm al Qurayyat)	Najd, Yanbu	0.5
Nubian shield	African platform (Pan-African orogen)	Luxor in Egypt to N. Sudan, SE Egypt to N. Ethiopia (Umm Rus, El Sid, Lega Dembi)		100(?) by ancients
Hoggar (or Tuareg) shield	African platform (Pan-African orogen)	(Amesmesa, Terek), Bin Yauri	East Ouzzal, Anka	minor
Brasilia fold belt	South American platform	(Luziania, Morro do Ouro, Bossoroca, Mina III)		0.5
Borborema province	South American platform	(Sao Francisco, Cachoeira de de Minas), Itapetim	Patos, Pemambuco	
Yenisei fold belt	Angara craton	(Olympiada, Sovetsk, Uderey), Gerfedskoye		0.6

Resource (Moz Au)	Associated placer	Deformation age (Ma)	Granitoid ages (Ma)	Mineralization age (Ma)	Reference
30	0.7 Moz Au Tarkwa paleoplacers; 15 Moz Au prior to 1900 much of the known production was from placers	2190–2080	2180–2145, 2110–2090, 2000	> 2132–2116, 2105–2080	Oberthur et al. (1998)
> 3		2100–2025, 1860, 1725, 750	2025, 1900–1800, 725	Paleoproterozoic(?)	Lenoir et al. (1994), Kuehn et al. (1990)
		2127, 2100–2070	2130, 2100–2070, 2025	2083–2031	Xavier and Foster (1999), Vasconcelos and Becker (1992), Teixeira et al. (2001), Neto (1994)
0.5	0.5 Moz Au mined from 1937 to 1959	> 2375, 2285–2050, 2040, 1915	2374, 2286, 2042, 1980–1915	2285–2050	Bouchot and Feybesse (1996)
> 20	some but unknown amount	2250–2000	2120–2090, 1790	ca. 2100–2000	Sidder and Mendoza (1995), Norcross et al. (2000), Santos (1999), Voicu et al. (1999)
	35 Moz Au	2100–1850	2030–1980, 1920–1890, 1870–1850	1850	Santos (1999), Santos et al. (2001)
5		1860–1790	1874–1834	1791, 1760	Ansdell and Kyser (1992), Fedorowich et al. (1991)
		1770–1715	1720–1715	< 1840, > 1720	Caddey et al. (1991), Dahl et al. (1999)
0.5		1850, 1820–1800	2000–1860	1840–1820	Eilu (1999), Billstrom and Weihed (1996)
2		1792–1785	1850–1770	1792–1785, 1780	Stendal and Frei (2000), Kaltoft et al. (2000)
9		2100–2050	2100, 2050 (Bushveld)	ca. 2050	Boer et al. (1995)
12		1880–1840	1835–1810	1835–1820	Cooper and Ding (1997), Campbell et al. (1998)
6		620–540	633–617	ca. 620	Myers et al. (1996), Rowins et al. (1997)
2.5	A large part of the 100 Moz production was probably alluvial	700–660, < 620	620–615, 585–565	700–660, ca. 620	LeAnderson et al. (1995), Albino et al. (1995)
		1000–600(?)	850–540	580–550	Sedillot (1972), Worku (1996), Berhe (1997)
6		650–613, 566–535	620	611–575, ca 500	Ferkous and Monie (1997), Garba (1996)
3		790–600	590–563, 503–492	500	Fortes et al. (1997), Valeriano et al. (1995)
		900–500	760–570, 510	≤ 750	Coutinho and Alderton (1998)
30	20 Moz estimated production	620–600	1050–900, 850–810	900–800, 660–600	Safonov (1997), Khiltova and Pleskach (1997), Konstantinov et al. (1999)

gold-poor Late Archean parts of Africa are dominated by gneissic and granitoid terranes, and typically lack extensive greenstone belts. Similarly, Late Archean rocks are exposed in the Guyana and Atlantic shields of the South American platform, but although they may contain small deposits of this age (e.g., Goias, Brazil), these lack large, recognized, Late Archean orogenic gold deposits.

2.3. Paleoproterozoic (2.5–1.6 Ga)

Significant growth of continental masses continued until 1.9–1.8 Ga, a time by which about 75–80% of the present-day stable continental crust was established (Goodwin, 1991; Condie, 1998). This growth involved the continued generation of Archean-type greenstone belts and an increased importance of supracrustal metasedimentary rocks. Resulting Paleoproterozoic sequences are now most widely exposed in cratonic regions of interior Australia (Fig. 5b), northwestern Africa (Fig. 5a) to northern South America (Fig. 5c), Svecofennia (Fig. 5a), Greenland (Fig. 5c) and the Canadian shield (Fig. 5c). Similar to relative timing of events in the Late Archean, gold ores developed throughout these new crustal blocks prior to their final cratonization (Table 2). Some of the resulting districts have been significant gold producers, including the Ashanti gold belt and the Homestake deposit, which rival the larger camps within the Late Archean Superior province and Yilgarn craton.

Important Paleoproterozoic orogenic gold ores formed in the West Africa and Amazonian cratons, perhaps in relatively adjacent crustal blocks, during the growth of Unrug's (1992) speculated Pangea X supercontinent. The blocks were deformed during the 2.1 Ga Eburnean/Transamazonian orogenies, and stabilized by 1.9 and 2.0 Ga, respectively. The Transamazonian orogen, where recognized along the northern part of the Amazonian craton, is dominated by greenstone belts that resemble many Late Archean greenstone belts in lithostratigraphy, style of deformation, and metamorphism (Gibbs, 1987). Perhaps the main distinction from Archean greenstone belts

is the fact that the Transamazonian greenstone belts have less voluminous ultramafic sequences (Bertoni et al., 1991), with komatiites recognized only in French Guyana (Gruau et al., 1985; Milesi et al., 1995) and Brazil (e.g., in Amapa state, McReath and Faraco, 1996).

The 2.2–2.0 Ga West Africa craton is dominated by the greywacke sequences of the Birimian “greenstone” belts (Fig. 5a), which like many other Precambrian belts are argued to have been generated by either collisional tectonics or mantle plume activity. The productive deposits of the Ashanti goldfields in Ghana formed in these rocks at about 2105–2080 Ma, during the Eburnean tectonism and magmatic episodes (Oberthur et al., 1998). These were the most important gold producers in the world from about the 14th through to the 18th centuries. The newly developed Sadiola Hill gold deposit, within a Birimian inlier in Mali, may be a similar type of orogenic gold system (Boshoff et al., 1998). In addition to Ghana and Mali, related smaller occurrences are known in parts of Senegal, Burkina Faso, Guinea and Ivory Coast. The 2132–2116 Ma Tarkwa placer goldfields of Ghana represent the erosion of lodes in Ghana that are slightly older than those in the Ashanti belt (Oberthur et al., 1998). Some Tarkwaian paleoplacers, however, are overprinted by orogenic gold systems of probable Eburnean age at the newly discovered Damang deposit (Pigois et al., 2000), which is located to the north of Tarkwa.

The Ubendian orogeny in east-central Africa (Fig. 5a), occurring simultaneously with the Eburnean events farther to the northwest, deformed Paleoproterozoic passive margin sedimentary rocks along the southwestern margin of the Tanzania craton. A series of little-studied orogenic gold deposits, including those of the Lupa and Mpanda districts in southwestern Tanzania, are mainly hosted in metabasalts and occur near Ubendian age granitoids (Sango, 1988; Kuehn et al., 1990). It is probable that these ores were emplaced during the ca. 2.1–2.0 Ga tectonism.

To the northeast of the Archean Quadrilatero Ferrifero region, the 2.2–1.9 Ga Rio Itapicuru green-

Notes to Table 2:

Resource estimates are combined from numerous sources to give the most reliable numbers as of the year 2000. The sited mineralization ages are from what are viewed as the most reliable published isotopic dates. Older conflicting K–Ar, Rb–Sr, etc., dates are not used where newer dates exist.

stone belt is the largest Paleoproterozoic granitoid–greenstone belt in the northeastern part of the Sao Francisco craton (Fig. 5c). It contains important Transamazonian gold ores, including the Fazenda Brasileiro and Maria Preta deposits. Ore formation was localized near the end of a period of widespread magmatism and major strike–slip tectonics that occurred between 2.12 and 2.07 Ga (Mello et al., 1996; Xavier and Foster, 1999). Transamazonian age veining may have occurred in the adjacent western side of the Congo craton at this same time. In that area, structural data constrain ore formation to about 2285–2050 Ma in Late Archean greenstone belts of the Eteke district in Gabon (Bouchot and Feybesse, 1996).

There are also hypothesized paleoplacer deposits to the west of the Rio Itapicuru greenstone belt, within the Serra de Jacobina region of Bahia. Minter et al. (1990) constrained the age of the sedimentary sequences to between 2.8 and 2.2 Ga, which would imply a relatively old Late Archean or a pre-Transamazonian age if these were, in fact, paleoplacers. The presence of fuchsite alteration in these rocks, however, suggests a similar alteration style to that of the orogenic lode-gold deposits, and there are more conventional lode-gold deposits in non-conglomeratic host rocks (Teixeira et al., 2001). Therefore, the origin of the gold in the paleoplacers needs to be carefully re-examined, particularly in light of uncertainties in the genesis of the Witwatersrand deposits with which they have been compared. Teixeira et al. (2001) report $^{40}\text{Ar}/^{39}\text{Ar}$ ages on hydrothermal micas from some of the Jacobina occurrences of between 1943 and 1912 Ma, near the center of a 170-m.y.-long period of peraluminous magmatism. These data further support the Transamazonian hydrothermal hypothesis for gold deposition.

Mainly on the northeastern side of the Amazon basin, rocks of the Guyana shield (Fig. 5c) in the northern part of the Archean–Paleoproterozoic Amazonian craton host significant gold resources related to 2.25–2.0 Ga Transamazonian tectonism (Santos, 1999). These include the El Callao and Las Cristinas (about 12 Moz Au) deposits of Venezuela (Sidder and Mendoza, 1995). To the east, and also within the Guyana shield, the epizonal 4.2 Moz Omai gold deposit in Guyana formed at about 2.00 Ga during the later stages of tectonism within the Barama–

Mazaruni greenstone belt (Voicu et al., 1999; Norcross et al., 2000). Similar ores in the shield, each also containing resources of > 1 Moz Au, include Gross Rosebel in Surinam, Camp Cayman and Paul Isnard in the northern part of French Guyana, and Vila Nova in the Amapa state of Brazil.

A large number of small gold deposits and associated placer fields are scattered throughout Paleoproterozoic greenstone belts and supracrustal rocks that are exposed along the western side of the Amazonian craton, both south (Alta Floresta and Tapajos gold provinces of the Central Brazil shield) and north (Parima gold province of the Guyana shield) of the Amazon basin (Santos, 1999; Santos et al., 2001). Termed the Tapajos–Parima orogenic belt (Fig. 5c) by Santos (1999), this gold-rich crustal block is the probable product of compressional tectonism along part of the craton margin between about 2.10 and 1.85 Ga. Orogenic lode-gold deposits were emplaced at about 1.85 Ga along the belt, and the resulting production, mainly from related placers, has been about 35 Moz Au since 1960 (Santos, 1999). The gold lodes along the Amazonian craton margins, within both the Tapajos–Parima and Transamazonian orogens, formed during the final stages of orogeny.

The Paleoproterozoic collision between Late Archean blocks to form Laurentia included development of the Trans-Hudson orogen between the Superior and Wyoming provinces. This collision, subsequent to broad-scale 2.2–1.9 Ga rifting between Archean blocks, deformed mainly newly generated, 1.9–1.8 Ga juvenile greenstone–granitoid crust along the edges of the blocks. In the Manitoba–Saskatchewan segment of the orogen (Fig. 5c), orogenic gold veins were deposited at approximately 1790–1760 Ma within the Flin Flon greenstone belt (Fedorowich et al., 1991; Ansdell and Kyser, 1992) and at about 1740–1720 Ma in the La Ronge greenstone belt (Ibrahim and Kyser, 1991; Hrdy and Kyser, 1995). As recorded in the Late Archean of the Yilgarn block and Superior province, and possibly the Zimbabwe craton, these gold ores post-date magmatism and metamorphism within the exposed parts of the host greenstone belt, but were generated during simultaneous high-grade metamorphism in adjacent gneissic belts and perhaps at depth. In the Dakota segment of the Trans-Hudson orogen (Fig.

5c), the largest known BIF-hosted gold deposit is hosted by the 1.97 Ga Homestake Formation (Redden et al., 1990). Gold mineralization apparently took place between the 1.84 Ga peak of regional deformation of the metasedimentary rock-dominant Paleoproterozoic sequence and 1.72 Ga post-tectonic magmatism (Caddey et al., 1991), perhaps during a ca. 1.78 Ga episode of arc accretion (Dahl et al., 1999).

Numerous small orogenic gold deposits are scattered throughout the Paleoproterozoic supracrustal and greenstone belts of the Svecofennian province (Fig. 5a), underlying southwestern Finland and Sweden. The belts were accreted on to the southwestern side of the Karelian craton between about 1.9 and 1.8 Ga. During this deformation, gold ore-forming processes were active in what is now Finland at about 1.89–1.86 Ga (Sorjonen-Ward and Nurmi, 1997) and in Sweden at 1.87–1.82 Ga (Billstrom and Weihed, 1996). This would include formation of many deposits in the Tampere schist belt in southernmost Finland (Luukkonen, 1994), in the Rantasalmi region of southeastern Finland (i.e., the Osikonmaki deposit), in the Seinajoki (i.e., the Kalliosalo occurrence) and Haapavesi (i.e., the Kimala deposit) areas of western Finland, and in the VMS-rich Skellefte district of northern Sweden. Additional small deposits of the same age are also described as being on the northeastern side of the Karelian craton (Pankka and Vanhanen, 1992) and in the Paleoproterozoic of the Ukrainian shield (Safonov, 1997; Fig. 5a).

High-grade gneisses and granite–greenstone terranes define the Early to Late Archean North Atlantic craton that underlies much of Greenland (Nutman, 1997). The Ketalidian mobile belt, on the southern side of the craton, represents one of a number of surrounding Paleoproterozoic mobile belts and contains a number of significant orogenic gold occurrences (Fig. 5c). Stendal and Frei (2000) indicate that gold formation post-dates widespread 1850–1800 Ma magmatism, but overlaps regional deformation, metamorphism, and late tectonic magmatism, at ca. 1800–1780 Ma.

Formation of an intracratonic basin within the Kaapvaal craton between about 2.45 and 2.05 Ga concluded with intrusion of the famous Bushveld intrusive suite. Mainly dolomite-hosted gold systems

of the Sabie-Pilgrim's Rest goldfield, located along the eastern margin of the resulting Transvaal basin (Fig. 5a), were also formed at about 2.05 Ga and approximately 65 km east of the Bushveld complex (Boer et al., 1995). Unlike other Precambrian settings discussed above, these lode-gold deposits were not developed during any type of collisional orogenesis, although the deposits are hosted in flat thrust faults and anticlinal structures related to compressional tectonics (Harley and Charlesworth, 1992, 1996).

Gold-depositing fluids were widespread in the Proterozoic inliers of the Northern Territory of Australia, at about the time of final assembly of the North Australian craton, and broadly during the same time period characterized by the above-described ore formation in the Canadian shield and Svecofennia. Host rocks for ores are mainly 2000 to 1850 Ma, thinly bedded, basinal sedimentary sequences. Orogenic gold systems were generated in the Arunta (e.g., Callie, Granites, Tanami), Tennant Creek (e.g., Tennant Creek) and Pine Creek (e.g., Mt. Todd, Union Reefs, Cosmo Howley) inliers (Fig. 5b). Structural controls and styles of mineralization are commonly very similar to those in Phanerozoic "slate belts", with many deposits occurring as sheeted vein sets in anticlinal hinges of folded metasilstones. In other cases, however, ores occur as disseminations in BIF. Tectonism in the inliers, broadly referred to as the Barramundi orogen, is generally reported to be diachronous between about 1880 and 1840 Ma. The Tennant Creek gold deposits are well constrained to about 1825 Ma, and post-date local deformation and most magmatism by about 15–25 m.y. (Campbell et al., 1998). Gold deposits in the Pine Creek inlier likely formed more-or-less simultaneously with emplacement of the post-tectonic Cullen batholith at 1835–1820 Ma; they show a distinct spatial association, although all lodes are no closer than 3–5 km to the igneous rocks (Solomon and Groves, 1994). Deposits in the Arunta inlier are overprinted by the 1810 Ma Granites granite (Cooper and Ding, 1997), and, therefore, may be of similar age.

A potential difference between the above deposits in southern Africa and northern Australia and most other orogenic lode-gold deposits is the recognition of saline fluids in fluid inclusions from the former deposits (Zaw et al., 1994; Boer et al., 1995; Tyler

and Tyler, 1996). The former deposits are collectively hypothesized here to be related to introduction of hydrothermal fluids derived from host basinal sequences in these regions, rather than to magmatic fluids. As pointed out by Yardley (1998), metamorphic fluids derived from tectonized basinal or passive margin strata are characteristically moderately to highly saline, because initially salt-rich connate brines survive into deeper metamorphic environments. In such situations, chloride complexing may be unusually important in the hydrothermal systems, and this would explain atypically high base-metal contents reported for some orogenic gold ores (e.g., the high concentrations of copper at Tennant Creek and 10–20% sulfides, as well as the significant silver production, at Sabie-Pilgrim's Rest). As suggested by Campbell et al. (1998) for the Tennant Creek ores, the lack of magmatism temporally associated with veining suggests that salinities must have been derived from basinal salts, which were incorporated into metamorphic fluids. Also, before the origin of deposits in areas such as Sabie-Pilgrim's Rest, Pine Creek and Tennant Creek can be completely understood, it is important to better demonstrate whether the saline fluids are actually the ore fluids that deposited the gold. Alternatively, they may just be other fluids trapped in inclusions in the quartz veins sometime prior to or subsequent to precipitation of the ore. In one case, results from the Howley goldfield of the Pine Creek inlier suggest that the saline fluids are not related to the gold-forming event (e.g., S.E. Ho, oral communication, 1997) and that the ore fluids are of more typical $\text{H}_2\text{O}-\text{CO}_2 \pm \text{CH}_4$, low-salinity composition.

2.4. Mesoproterozoic and Neoproterozoic (1.6–0.57 Ga)

Subsequent to the widespread 1.9–1.8 global orogenesis, the preserved geological record indicates that the stabilized juvenile continental crust was subjected to long periods of extension during most of the next one billion years (Goodwin, 1991). This stage of global crustal development included repeated intracrustal rifting, basin formation, and anorogenic magmatism dominated by intrusion of large anorthosite masses and rapakivi granites. During late Neoproterozoic time, the gradual formation

of the Gondwana supercontinent indicates widespread continental collision. Similar activity also probably took place near the end of the Mesoproterozoic with the assembly of Rodinia (Rogers et al., 1995; Li et al., 1996; Fig. 6). However, in both the Mesoproterozoic and much of the Neoproterozoic, resulting orogens, especially their shallow and mid-crustal regions, are not well preserved in the geologic record. This latter half of the Proterozoic is consequently notable for its lack of economically significant orogenic gold lodes. Such deposits do not seem to become globally widespread again until the establishment of relatively better-preserved, latest Neoproterozoic collisional orogens.

There are only a few, poorly described examples of small Mesoproterozoic orogenic gold ores that developed during deformational events associated with the establishment of Rodinia (Fig. 6). A series of terranes were accreted to the western margin of the Amazonian craton (Fig. 1), and now comprise the ca. 1.3–0.95 Ga San Ignacio and Sunsas–Aguapei mobile belts. The gold deposits of the Pontes e Lacerda region in the Mato Grosso state of Brazil developed near the end of deformation in the latter mobile belt at ca. 960–920 Ma, although one K–Ar date suggests veining as young as 840 Ma (Geraldès and Figueiredo, 1997). North of Lake Ontario in the Grenville province of Canada (Fig. 1), a series of small gold lodes developed during orogenesis at about 1.1 Ga (Sangster et al., 1992). These reflected accretion of a 5000-km-long belt of Mesoproterozoic supracrustal sequences to the eastern and southern sides of older Precambrian North America. The Kibariides (Fig. 5a) represent a ca. 1400–900 Ma orogenic belt developed, in part, between the colliding Tanzania and Sao Francisco–Congo cratons. Small lode-gold deposits in Burundi and Rwanda appear to be related to a period of post-tectonic 1000–900 Ma magmatism within the belt. They have some characteristics typical of orogenic type ores, as reported by Pohl and Gunther (1991) and Pohl (1994), although their broad regional spatial association with tin-bearing ores is an atypical feature of such deposit types and more characteristic of the intrusion-related type of gold deposits as defined by Lang et al. (2000).

There are no well-documented lode-gold occurrences that developed during the early Neoproterozoic

Archean - Paleoproterozoic gold

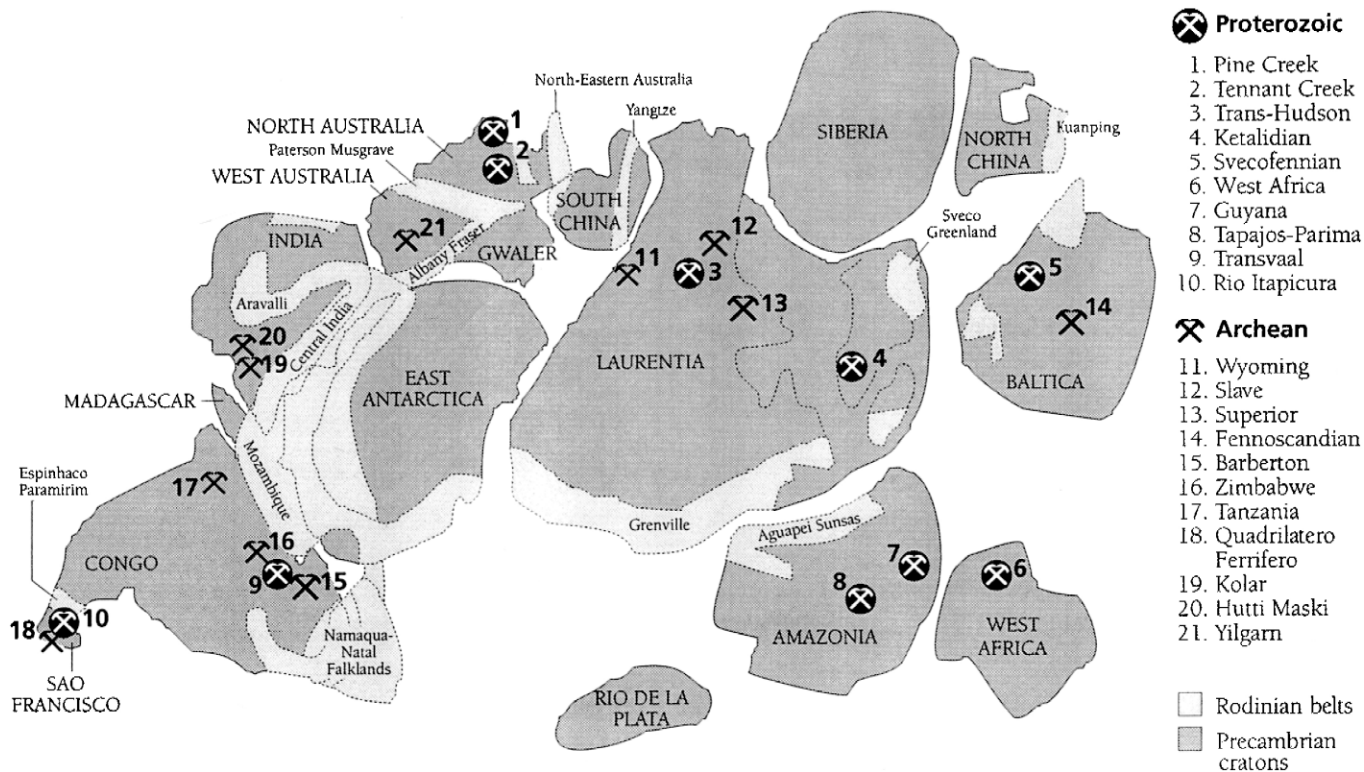


Fig. 6. The distribution of major Precambrian orogenic gold provinces as they likely appeared near the end of the Proterozoic. This reconstruction of Rodinia (after Unrug, 1996) represents the oldest reliable supercontinent reconstruction. This supercontinent configuration is interpreted to have formed through the latter Mesoproterozoic and to have begun its breakup in the latter Neoproterozoic. Also shown is the distribution of gold-poor Mesoproterozoic collisional belts associated with the formation of Rodinia ca. 1.3–1.0 Ga. These evolved as plate tectonic styles changed from episodic to a more continuous, modern-day style of continental growth. Resulting crust was added to continents as narrow belts along margins, rather than as the more massive cratonic blocks preserved from Archean and Paleoproterozoic growth events. Such narrow belts were more easily reworked during subsequent collisions and, therefore, are now characterized by deep crustal exposures that were below gold-favorable mid-crustal depths.

zoic breakup of Rodinia. However, the reconfiguration of crustal fragments to form Gondwana, during the latest Proterozoic and early Paleozoic, initiated a period of orogenic gold-forming events that has continued for the last 600 m.y. The most significant late Neoproterozoic ore-forming events occurred near transcrustal shear zones as part of the Pan-African thermotectonic activity adjacent to many of Africa's cratonic blocks, within the Brasiliano tectonic belt in eastern South America, and in deformed fold belts along the southern margin of the Siberian platform (Table 2). In all cases, the orogenic gold deposits are related to terranes in which new volcano-sedimentary sequences were formed, rather than in terranes in which only pre-existing crust was reworked.

The East African orogen reflects the closure of the Mozambique Ocean between Eastern and Western Gondwana and the eventual suturing of the blocks along the Mozambique belt (Shackleton, 1986; Stern, 1994). The orogen developed between about 800 and 550 Ma, and involved deformation of both reworked Mesoproterozoic and older crust and newly accreted Neoproterozoic crust undergoing oblique collision. The last 100 m.y. of orogeny were characterized by formation of extensive strike-slip regimes along the margin of eastern Africa. The orogen is dominated by accreted terranes of the Arabian-Nubian shield (Fig. 5a) to the north, but generally high metamorphic-grade, tectonically reworked earlier Precambrian units to the south. In the latter, gold occurrences are rare.

The northern part of the East African orogen typically exposes shallower crustal levels and a much wider zone of accreted crustal material. Consequently, gold ores are much more common here (Fig. 5a) than within the more southerly and deeply eroded parts of the orogen, and they occur in both accreted material and the deformed African craton. Orogenic gold deposits were emplaced throughout much of Saudi Arabia, especially along the numerous strands of the major Najd fault system (Agar, 1992), during ca. 700–600 Ma strike-slip events in the Arabian shield associated with the latter phases of accretionary tectonics (Albino et al., 1995; LeAnderson et al., 1995). Geological constraints on the timing of ore formation suggest a younging of ages towards the east.

To the west, in the African Nubian shield, numerous small gold deposits formed in latest Proterozoic and/or Cambrian time in the Eastern Desert of Egypt and Sudan (Almond et al., 1984; El-Bouseily et al., 1985; Harraz and El-Dahhar, 1993). Whereas modern-day gold production from orogenic deposits has been relatively minor from the Arabian-Nubian shield, Sedillot (1972) suggested that > 100 Moz Au were produced from this region in ancient times and the Middle Ages. It is uncertain as to how realistic such an estimate may be, but extensive alluvial and lode fields were worked by the Egyptians along the western side of the Red Sea from the central part of the Nile south into northern Sudan. Small, but numerous, placer and lode occurrences continue into southern Ethiopia, where mineralization apparently also formed during tectonically late strike-slip events (Worku, 1996), probably between 580 and 550 Ma (Aberra Mogessie, written communication, 1999).

Additional gold veining correlates with other Pan-African activity farther west in Africa as a part of the 750–500 Ma (e.g., Neoproterozoic, but continuous into the early Paleozoic) Trans-Saharan orogen (Fig. 5a). A number of 3 Moz, 611–575 Ma gold deposits are located along a short length of the 900-km-long by 1- to 3-km-wide East Ouzzal shear zone in the western Hoggar belt of the Tuareg shield in Algeria (Ferkous and Monie, 1997). The shear zone was originally a ca. 2.0 Ga suture between mainly buried, high metamorphic-grade Archean and Paleoproterozoic blocks. The veining was, however, simultaneous with Pan-African deformation along the shear zone, as well as final collision and thrusting of the shield over the passive margin of the West African craton, in an area today located less than 100 km to the west. To the south, near where the Benin Nigeria shield also collided with the West African craton, small sedimentary-rock hosted orogenic lode-gold deposits in western Nigeria developed in the shield during latest deformation in Cambro-Ordovician time (Woakes and Bafor, 1984; Garba, 1996). This group of deposits may have continued into what is now the Borborema province of the Atlantic shield of northeastern Brazil. In that region, a series of gold prospects throughout the state of Pernambuco cut both Mesoproterozoic schists and younger granitoids of Brasiliano age (Beurlen et al.,

1997; Coutinho and Alderton, 1998), and, therefore, are part of a broader Gondwana gold belt.

A few small gold systems have been recognized in the Pan-African Damara orogen (Fig. 5a), which separates the late Precambrian Congo and Kalahari cratons, and continues into South America as the Ribeira fold belt. To the southwest, small sedimentary-rock hosted orogenic lode-gold deposits were formed in the Early Ordovician in central Namibia (Moore et al., 1999). Another group of about 20 small gold deposits is recognized in relatively low-grade units of the tectonically complex Malawi province in the northwestern part of the orogen in eastern Zambia. The lodes were deposited at approximately the Precambrian/Cambrian boundary, during a Pan-African period of transcurrent motion along the transcrustal Mwembeshi shear zone and of synkinematic granitoid intrusion (Kamona, 1994). Ores in both locations are likely associated with movement along the 3000-km-long Trans-African shear zone, which is a series of deep-crustal, parallel shear zones that define the locus of major translation between the two large cratonic blocks (Daly, 1988).

In South America, significant gold vein formation is associated with development of the 1200-km-long Brasilia fold belt (Fig. 5c), which extends along much of the western edge of the Sao Francisco craton in Brazil (Thomson and Fyfe, 1990). This belt consists of a series of Mesoproterozoic and Neoproterozoic metasedimentary rocks that were deformed along the edge of the craton at about 790–600 Ma (Valeriano et al., 1995); the younger rocks contain important and undated gold vein deposits at Luziania and Morro do Ouro. The Brasiliano belt evolved during aggregation of western Gondwana and represents a semi-continuous deformational belt that extended into the auriferous Trans-Saharan orogen (Trompette, 1994), discussed above.

The gold deposits of the Quadrilatero Ferrifero, described above as also of controversial age, occur in the craton about 200 km east of the southeastern edge of the Brasilia fold belt. However, Brasiliano age tectonism extends into the 'craton' and, as shown by Chauvet et al. (1994), the resulting host structures for lodes in the Ouro Preto district of the Quadrilatero Ferrifero formed during this late Neoproterozoic thrusting. Immediately northwest of the Brasilia mobile belt, another series of gold deposits are lo-

cated in the Archean Crixas greenstone belt that is a part of the Goias Median Massif. Absolute dates for veining of 500 Ma at the Mina III mine (Fortes et al., 1997) define the final stages of Brasiliano deformation, which continued into the early Paleozoic. Importantly, these dates confirm gold ore formation during the Brasiliano event within an area that lacks any recognized coeval magmatism. Fluid inclusion studies of the Mina III deposit indicate high ore-fluid salinities that have been hypothesized as derived from metamorphism of basinal units in the Proterozoic sequence (Giuliani et al., 1991).

The Paterson orogeny in northwestern Australia (Fig. 5b) represents one of a series of latest Neoproterozoic events that occurred between the main Rodinian cratons. Compressional reactivation of the suture between the West Australian and North Australian Paleoproterozoic cratonic blocks was characterized by thrusting, folding, and subsequent strike-slip deformation at ca. 620–540 Ma (Myers et al., 1996). The early part of the deformation was accompanied by magmatism and gold veining within Neoproterozoic basinal rocks (Rowins et al., 1997). High salinity ore-forming fluids at deposits such as Telfer (> 10 Moz Au production and reserves) make correlation with the orogenic lode-gold group tenuous, although the structural controls are very similar to those orogenic deposits associated with sedimentary rock sequences. Perhaps the deposits that most closely resemble Telfer are the Paleoproterozoic deposits of the Sabie-Pilgrim's Rest goldfield in South Africa.

The most important gold-forming event often suggested as Neoproterozoic is that associated with the concentration of more than 100 Moz Au along the southern margin of the Siberian platform (Fig. 5b). Significant orogenic gold deposits are preserved in the Yenisei (Khiltova and Pleskach, 1997; Konstantinov et al., 1999) and East Sayan (Mironov and Zhmodik, 1999) fold belts to the southeast, and the Baikal fold belt to the southeast. These represent the mainly Riphean, first-accreted materials of the Altaid orogenic zone that developed in front of a gradually closing Paleo-Tethys Ocean. These belts are deformed shield margins that were characterized by an extensive period of rifting and then were the focus of subsequent re-collision of Precambrian continental fragments along the edges of the main Precambrian

block (Sengor and Natal'in, 1996a,b). In the Yenisei belt, deposits such as Olympiada, with about 24 Moz Au, and Sovetsk are believed to have formed during 850–810 Ma synorogenic magmatism (Safonov, 1997) or perhaps during younger tectonomagmatic events at about 600 Ma (Konstantinov et al., 1999). But, in contrast and also along the southwestern side of the Siberian craton, Neimark et al. (1995) used Pb isotope data to show that some gold formation was as young as 450 Ma in the Eastern Sayan fold belt. This is an age roughly similar to that of other “Caledonian” deposits (e.g., Vasil'kovsk, Zholybet, Bestyube, Sarala, Kommunar) in the main part of the Altaid fold belt to the south (see below). Descriptions of the ores from the 3 Moz Au Zun–Kholba deposit in the Eastern Sayan fold belt suggest local reworking of older VMS bodies along parts of the platform margin (Mironov and Zhmodik, 1999). The Caledonian timing of gold formation is also consistent with extensive Ordovician and Silurian magmatism in the Eastern Sayan fold belt (Vladimirov et al., 1999).

The > 30 Moz Sukhoi Log gold resource, the producing Irokindinskoe and Kedrovskoe deposits, and many other significant lode resources occur in a series of complexly deformed terranes within the Baikal fold belt. The majority of these commonly platinum-rich gold lodes are concentrated within the turbidites of the Bodaibo terrane, typically within a broad synclinorium in the northern part of the fold belt (Bulgatov and Gordienko, 1999). The anomalous platinum in the gold ores has led many Russian workers to suggest leaching of ores from the ophiolite complexes scattered throughout and below the turbidite units (Korobeinikov, 1993; Rundqvist, 1997). Erosion of some of the lodes in the terrane resulted in many very rich placer fields, which include those of the Lena River region. During the last 150 years, about 70 Moz Au have been recovered along an 80-km-stretch of the Bodaibi River (Bulgatov and Gordienko, 1999), a tributary to the Lena River itself.

Lode resources in the Baikal fold belt, such as at Sukhoi Log, are most commonly stated as having formed during the late Neoproterozoic Baikaside orogeny (Safonov, 1997). However, isotopic ages from gold ores in the Baikal fold belt are very poorly constrained, with published data from a variety of

isotopic systems ranging widely between 1050 and 175 Ma (Bulgatov and Gordienko, 1999). The more significant deposits from the Bodaibo terrane are characterized by model Pb, K–Ar, and Rb–Sr isochron ages mainly from the Paleozoic to Mesozoic part of the range, thus hinting that much of the southern Siberian platform gold resource could be post-Neoproterozoic. These include a 380–365 Ma Rb–Sr age range for Sukhoi Log (Bulgatov and Gordienko, 1999). In addition, Ar–Ar dating of white mica from Sukhoi Log yields a total gas release date of 336 Ma and a fairly well-developed plateau age at ca. 345 Ma (L. Miller and R. Goldfarb, unpublished data). Perhaps more significantly, deposits of the Baikal belt are spatially associated with the immense (140,000 km²) Angara–Vitim batholith and associated contact metamorphic zones, which have been well-dated by a variety of methods as Carboniferous through Early Permian (ca. 340–280 Ma), and not Neoproterozoic (Yarmolyuk et al., 1997). It is, therefore, quite likely that the ores of the Baikal fold belt are linked with regional Variscan tectonism along the Paleo-Tethyan Ocean. On a local scale, this might be due to the early stages of Mongolia–Okhotsk ocean closure.

The terranes of the Taimyr fold belt also collided with the Siberian platform (Fig. 1) in the late Neoproterozoic and now define the northwestern margin of the platform. Although syntectonic granitoids and 620–580 Ma medium-grade regional metamorphism characterize this belt of accreted arcs and sedimentary rock sequences (Bogdanov et al., 1998), major orogenic gold ores are not recognized. However, low relief and poor exposure may be responsible for the lack of orogenic gold resources in an otherwise quite favorable ore-forming environment along the margin of the platform.

2.5. Paleozoic (570–250 Ma)

Orogenic gold-forming events, which had once again become commonplace near the end of the Neoproterozoic, continued to be extremely widespread during Paleozoic time along the extensive margins of both Gondwana and the Paleo-Tethyan Ocean basin (Table 3). An active Gondwana margin existed throughout the Paleozoic, along which gold veins were deposited throughout what is now eastern

Table 3
Summary characteristics of Paleozoic orogenic gold deposits

Gold province	Host area	Districts (deposits)	Associated structures	Production (Moz Au)
Lachlan fold belt	Tasman orogen	Ballarat, Bendigo, Stawell, Hill End		34
Westland, South Island, NZ	Tasman orogen	Reefton (Blackwater, Globe-Progress)	Globe-Progress shear	2.1
Thomson fold belt	Tasman orogen	Charters Towers, Etheridge, Croyden		8
Hodgkinson–Broken River fold belt	Tasman orogen	Hodgkinson		0.15
Sierras Pampeanas	Paleozoic Andes	Sierra de Las Minas, Cruz del Eje, Rio Candelaria, San Ignacio	Guamanes shear zone	0.1
East Sayan fold belt	Angara craton	Urik–Kitoi (Zun–Kholba, Zun–Ospa, Taln, Vodorazdel'noe)	Okino–Kitoi, Kholbin	minor
Baikal fold belt	Angara craton	(Sukhoi Log, Irokindinskoe, Kedrovskoe, Vysochaishee)	Karakonsk, Tompudo–Nerpinsk, Tochersk	minor
Mongol–Zabaikal fold belt	North–Central Mongolia	Booroo–Zuunmod, Zaamar, Erun–Gol		minor
Kipchak arc (Kazakhstan and Irtysh–Zalsanskaya metal. provs.)	Kazakstania micro-continent (Caledonian orogen)	Vasil'kovsk, Zholymbet, Bestyube, Stepnyak, Bakyrchlk)		
Southern Tian Shan	Central Asia Variscan orogen	(Muruntau, Daugyztau, Charmitan, Jilau, Kumtor, Sawayaerdun)	Tian Shan suture zone, Sangruntau–Tamdytau shear zone	50
Meguma terrane	Northern Appalachian (Acadian event)	Goldenville, Caribou, Beaver Dam, Cochrane Hill, Forest Hill		1.4
Blue Ridge belt	Southern Appalachian (Alleghany event)	Goldville, Dahlonga belt, Hog Mountain		0.4
Eastern Cordillera	Paleozoic Andes	Pataz, La Rinconada, Yani	Maranon lineament	
Caledonides	United Kingdom (Caledonian orogen)	Dolgellau gold belt (Gwynfynydd, Clogua), (Dolaucothi), Tyndrum, Clontibret	Tyndrum fault, Orlock Bridge fault	0.2
Iberian Massaif	European Variscan	(Jales, Gralheira, Salave)		mostly alluvial
Massif Central	European Variscan	Saint Yrieix (Le Boumeix), (Salsigne), Brioude–Massiac, La Marche (Le Chatelet)	Marche–Combrailles shear zone	25 (mainly by Romans)
Bohemian Massif	European Variscan	(Celina–Mokrsko, Kasperske Hory, Jilove)		5
East–Central Ural Mountains	Uralian orogen	Berezovsk, Kochkar	Main Uralian fault	> 28

Resource (Moz Au)	Associated placer production (Moz Au)	Deformation age (Ma)	Granitoid ages (Ma)	Mineralization age (Ma)	Reference
	46	460–250	420–390, 370–360, 320	460–370, 357, 343	Arne et al. (1998), Bierlein et al. (1999), Lu et al. (1996)
> 12 (mainly placer)	8 (still very active)	420–260	380–370	500(?), 370(?)	Cooper and Tulloch (1992), Muir et al. (1996)
		490–250	490–407, 330–270	415–398, 320	Perkins and Kennedy (1998), Bain et al. (1998)
		490–250	330–270	300	Peters et al. (1990)
		535–390	535, 520, 490–470, 430–390	390–360	Skirrow et al. (2000), Rapela et al. (1998)
> 3		500–450	510–430	450	Mironov and Zhmodik (1999), Neimark et al. (1995), Vladimirov et al. (1999)
40	70	L. Pt–Pz	354, 330–290	380–365, 345, 280–250	Yarmolyuk et al. (1997), Bulgatov and Gordienko (1999), Larin et al. (1997), L. Miller and R. Goldfarb (unpublished)
10's	5(?)	Late Paleozoic	Early Paleozoic–Early Mesozoic–	Late Paleozoic	United Nations (1999)
> 30		E.–M. Paleozoic	455–440	L. Ordovician(?)	Sengor and Natal'in (1996a,b), Spiridonov (1996)
130		M.–L. Paleozoic	Permian–E. Triassic	Permian–Triassic	Shayakubov et al. (1999), Bortnikov et al. (1996), Drew and Berger (1996), Wilde et al. (2000)
		415–360	380–370	380–362	Kontak et al. (1990), Gibbons et al. (1998)
	0.4	M. Ordovician, E. Carboniferous	335–320	343–294	Stowell et al. (1996), West (1998)
	abundant, but poorly recorded	374–360	329	313	Fornari and Heraïl (1991), Haerberlin et al. (1999)
0.6	minor	520–480, 460–440, 420–400	425–390	410–380, 368(?), 345(?)	Ineson and Mitchell (1975), McArdle (1989), Curtis et al. (1993), Steed and Morris (1986)
3	Estimates vary between 7 and 65 Moz by the Romans	390–310	320–305, 290–280	347, < 292–286	Murphy and Roberts (1997), Quiring (1972), Noronha et al. (2000)
		440–280	360–290	320–285	Bouchot et al. (1989), Guen et al. (1992), Maignac and Cuney (1999), Foster (1997)
13	minor	440–280	360–290	349–342	Stein et al. (1998), Moravek (1996a,b)
significant	> 60 (estimate includes past production and resources)	370–250	360–320	L. Carboniferous to Permian	Bortnikov et al. (1997), Puchkov (1997), Kisters et al. (1999)

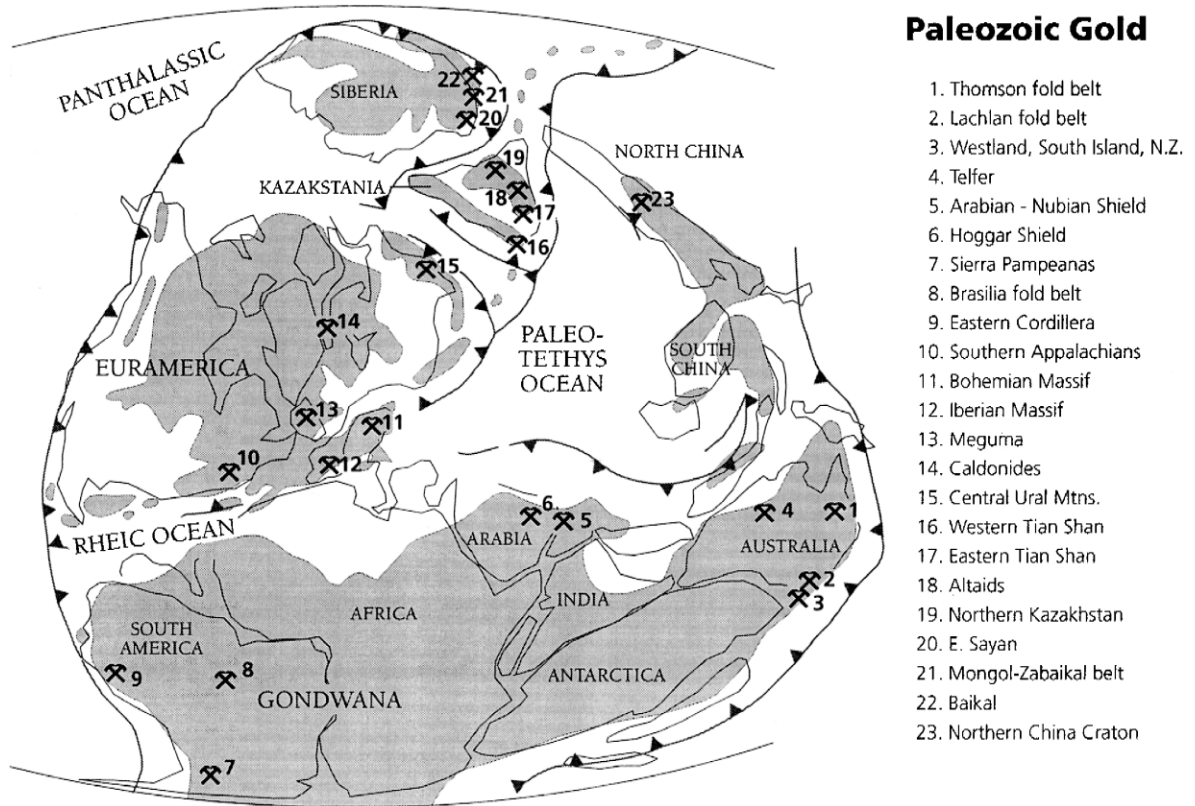


Fig. 7. The distribution of major Paleozoic gold provinces on the 356-Ma global reconstruction of Scotese (1997). By the middle Paleozoic, important gold ores that had formed at the start of the era in northern Africa (#5, 6), Brazil (#8), and northern Australia (#4) were isolated in stable cratonic areas. During Ordovician–Devonian time, gold ores probably formed along much of the length of the active Gondwana margin, from what is now Queensland, Australia (#1) to southern Argentina (#7). Terrane collisions in front of the closing Iapetus and then Rheic Oceans between Euramerica and Gondwana led to formation of a series of mid-Paleozoic Caledonian–Appalachian (#10, 13–14) and Variscan (#11–12) gold provinces. A complex series of subduction–collision events in the northern Paleotethys basin throughout the Paleozoic resulted in emplacement of orogenic gold lodes now recognized in the Ural Mountains (#15) and throughout present-day central Asia (#5–6, 16–23).

Australia, the South Island of New Zealand, Victoria Land in Antarctica, and the Eastern Cordillera of South America (Fig. 7). The belt of Gondwanan ores along a long-lived and extensive active continental margin is a feature very similar to that which has characterized the margin of western North America since Jurassic time (see next section). In the Late Ordovician, a series of collisions forming the Kazak-

stania microcontinent within the northern Paleotethys Ocean was associated with a major Caledonian gold-forming event in what is now mainly northern Kazakhstan. As the Iapetus Ocean gradually closed between Baltica, Laurentia (Baltica and Laurentia then combining to form Euramerica of Fig. 7), Avalonia, and eventually Gondwana to form the Pangea supercontinent, less extensive veining oc-

Notes to Table 3:

Resource estimates are combined from numerous sources to give the most reliable numbers as of the year 2000. The sited mineralization ages are from what are viewed as the most reliable published isotopic dates. Older conflicting K–Ar, Rb–Sr, etc., dates are not used where newer dates exist.

curred along some of the sutures during the Silurian to Early Carboniferous. In addition, during the Carboniferous and Permian, collisions along the northern and western margins of the Paleo-Tethys Ocean (between Euramerica and a series of Precambrian continental fragments) resulted in development of significant orogenic lode systems. These include the ores of the Uralide orogen, formed during accretionary events along the eastern edge of the East European platform in Euramerica. Most extensively, a diachronous 100-m.y.-long Variscan tectonothermal event is characterized by gold districts presently continuing from southern Europe, through central Asia, and across northern China (Fig. 7).

The Tasman orogenic belt has been historically one of the economically most productive Phanerozoic gold regions, with more than 80 Moz of lode and placer gold recovered from the Lachlan fold belt (Figs. 5b and 7), central Victoria, Australia. Lesser production in the orogenic belt has come from districts in Queensland and New South Wales, Australia, and South Island, New Zealand, with additional small occurrences continuing along the Gondwanan margin into Antarctica and South America. Mainly Ordovician, quartz-rich turbidite sequences were amalgamated and deformed throughout a 200-m.y.-long Paleozoic orogeny dominated by episodic contraction and strike-slip events.

In the early to middle Paleozoic, continental growth was characterized by development of the Lachlan, Thomson, and Hodgkinson–Broken River fold belts along the eastern side of the amalgamated North Australian and South Australian Precambrian cratons. The absolute timing of mid-Paleozoic gold-forming episodes across the productive Victorian part of the Lachlan fold belt is still poorly understood. Most data suggest some overlap of gold veining with Late Ordovician to Early Devonian diachronous deformation (Foster et al., 1999) and Early and Late Devonian periods of magmatism. The majority of the gold veining in the Lachlan belt appears to be coeval with the deformational events at about 460–440 Ma, although other veining events did occur episodically until 370 Ma (Arne et al., 1998; Foster et al., 1998; Bierlein et al., 1999). To the north in Queensland, the Charters Towers and Etheridge goldfields in the Thomson fold belt also formed during Late Silurian to Early Devonian de-

formation (Perkins and Kennedy, 1998; Bain et al., 1998). Gray (1997) has proposed a complex tectonic model involving a series of three active subduction zones beneath the Lachlan fold belt during the middle Paleozoic gold veining events. However, the nature and timing of many specific tectonic events in this lengthy period of subduction, collision, local extension, and voluminous S- and I-type magmatism are still very controversial.

The Robertson Bay terrane of northern Victoria Land, Antarctica, and the Buller terrane of South Island, New Zealand, are the widely accepted southern parts of the formerly continuous Tasman orogenic belt. Subduction and arc magmatism, accompanying accretion of these terranes to the Eastern Gondwana margin (Fig. 7), subsequent to final amalgamation of the main Gondwanan continents, was initiated at about 530–500 Ma (Grunow et al., 1996) as a part of the Ross (or Delamerian) orogen. The Cambrian subduction zone may have continued across the closing Iapetus Ocean and along the southern tip of South America. Continental margin tectonism continued along this part of the Gondwana margin throughout the Paleozoic, thus overlapping with the subsequent Tasman orogen as defined in eastern Australia. Productive gold lodes of the Reefton district, and other eroded veins that contributed to the Westland placer fields (Fig. 5b), formed in the Buller terrane sometime between 500 and 370 Ma (Goldfarb et al., 1998) during Ross or Tasman orogeny. Although there has been no exploration for mineral resources in this remote region, reports of sulfide-bearing quartz veins in Victoria Land and elsewhere along the Gondwana margin of Antarctica (Rowley et al., 1991) support the presence of Paleozoic orogenic gold occurrences.

Small ca. 390–360 Ma orogenic gold deposits along transcrustal structures in the southern Sierra Pampeanas (Figs. 5c and 7), Argentina, including veins of the Sierra de Las Minas, Rio Candelaria, and San Ignacio districts (Skirrow et al., 2000), appear as products of additional tectonism (e.g., Achalian orogeny) along the supercontinent margin. These deposits apparently developed during oblique collision of the Precordillera terrane, rifted from eastern Laurentia, with the early Paleozoic rocks of the Sierras Pampeanas that stretched along the southwestern Gondwana foreland (Rapela et al., 1998). As

with some of the previously described Proterozoic orogenic gold deposits, relatively high salinity ore fluids and unusual base-metal enrichments in some of the Sierra Pampeanas deposits (Skirrow et al., 2000) may be products of prograde metamorphic thermal events within passive margin sequences. Much of the basement stratigraphy hosting the Devonian gold deposits in this region of the Andes was rifted from the passive margin of Laurentia (Rapela et al., 1998). Related gold-forming events continued into the Carboniferous along the supercontinent margin, with resultant ores recognized in Paleozoic sedimentary rock terranes now exposed in the Eastern Cordillera of the Central Andes (Haerberlin et al., 1999), accepting the Paleozoic reconstructions of Salda et al. (1998).

Less-voluminous orogenic gold veining characterized all three of Australia's Tasman fold belts in the Carboniferous. These included gold deposition in the Hill End district of the Lachlan fold belt, in the Croydon district of the Thomson fold belt, and in the Hodgkinson district of the Hodgkinson–Broken River fold belt (Fig. 5b; Perkins and Kennedy, 1998). The ore-forming events occurred during a part of the period of latest Devonian to Middle Triassic terrane accretion and subduction along the eastern margin of the Lachlan and Thomson fold belts (Schreiber, 1996). The resultant accreted terranes that formed the New England fold belt also host a number of other lode deposits in the Hillgrove and Gympie goldfields, with a number of less significant deposits of the Great Serpentine Belt located along a terrane suture. These deposits formed in the Early and Middle Triassic during a period of widespread subduction-related magmatism in the accretionary prism (Collins, 1996; Ashley, 1997).

The Kazakstania microcontinent (Fig. 7) originated in the Late Ordovician along the Kipchak arc of Sengor and Natal'in (1996a,b) via a series of arc collisions and accretions in the northern Paleo-Tethys Ocean. These collisions were associated with widespread synkinematic magmatism and hydrothermal fluid flow at about 445 Ma. Resultant orogenic gold systems, with perhaps a combined > 25–30 Moz Au, are now exposed in northern Kazakhstan (Fig. 5b) and extend eastward into the Altai Shan of northern Xinjiang province in China (Rui et al., 2002) and the northwestern corner of Mongolia

(United Nations, 1999). In the latter area, associated placers have been mined for more than 100 years (Jamsradorj and Diatchkov, 1996). Large lode deposits include Vasil'kovsk (> 13 Moz), Zholymbet, Bestyube, Stepnyak, Bakyrchik (8 Moz) and Aksu (Spiridonov, 1996; Safonov, 1997). Most of the ores and adjacent Caledonian plutons are hosted in Ordovician black shales that represent small basins, which closed during the early Paleozoic collisions. Approximately 100 m.y. after ore formation, during Early Carboniferous closure of the Khanty-Mansi Ocean, the Kazakstania microcontinent and its gold ores were accreted on to the Siberian craton (Sengor and Natal'in, 1996a,b). They now make up a large part of the Altaid orogenic zone, immediately outboard of older Neoproterozoic orogenic gold deposits in the East Sayan and Yenisei fold belts.

Closure of the Iapetus Ocean between Baltica, Avalonia, and Laurentia, formed the Euramerican supercontinent by about 400 Ma. The collision between these early Paleozoic continental blocks was accompanied by orogenic gold formation in what is now the North Atlantic Caledonide region. Neoproterozoic through early Paleozoic turbidite-dominated complexes, trapped between colliding continents in the North Iapetus Ocean, host many small Early and Middle Devonian "Caledonide" gold deposits (Figs. 5a and 7) that include those of the Dolgellau gold belt in northern Wales (Ineson and Mitchell, 1975), in eastern and western Ireland (McArdle, 1989), and in the Tyndrum area and elsewhere in the Western Highlands of Scotland (Curtis et al., 1993). The ores are coeval with Devonian plutonism, both overlapping and slightly post-dating the 425–400 Ma Baltica–Laurentia collision and peak of Caledonian orogeny. Closure of the South Iapetus Ocean between Laurentia and Avalonia at about the same time was immediately followed by accretion and obduction of the Meguma terrane, the most outboard of the northern Appalachian terranes now exposed in Nova Scotia, Canada. Whereas the Acadian deformational peak of the gold-hosting Cambro-Ordovician turbidites in the Meguma terrane (Figs. 5c and 7) was ca. 400 Ma, voluminous magmatism was concentrated at 380–370 Ma (Keppie and Dallmeyer, 1995), major transpression along the suture continued until 370–360 Ma (Gibbons et al., 1998), and extensive gold veining took place at ca. 380–362 Ma (Kontak

et al., 1990). It is possible that the thermal event driving magmatism and gold veining was ultimately a product of the final Gondwana–Laurentia collision, closing the Rheic Ocean behind the Meguma terrane and initiating subduction of the Gondwana margin beneath Laurentia during formation of Pangea.

The syngenetic vs. epigenetic origin of gold ores in the southern Appalachians (Figs. 5c and 7) has been a long-standing controversy. Recent Neoproterozoic Re–Os dates by Stein et al. (1997) of the deposits in the Carolina slate belt, the economically most important gold ores of this part of the Euramerican margin, indicate a latest Neoproterozoic, pre-accretionary formation during seafloor volcanism. The smaller, ca. 330 Ma lode deposits of the Blue Ridge in the southernmost Appalachians (Stowell et al., 1996) are, in contrast, clearly epigenetic and represent surprisingly the only well-recognized orogenic gold province along the eastern seaboard of the United States. Veining appears to be temporally associated with deformation accompanying the Allegheny orogeny, a possible consequence of the docking of the Tallahassee–Suwanee terrane to the Blue Ridge in Laurentia during final Pangea assembly.

Another late Paleozoic continental-margin gold belt is defined by a series of orogenic gold deposits clustered along the eastern side of the central Ural Mountains of Russia (Figs. 5a and 7), with a few additional ore systems mainly extending into the southern Ural Mountains of Russia and northwestern Kazakhstan. These mineral deposits are poorly documented in the Western literature, although some districts such as Berezovsk, which has been active for 250 years, and Kochkar have produced more than 11 and 15 Moz Au, respectively (Bortnikov et al., 1997; Safonov, 1997). Placer deposits scattered throughout the entire Ural fold belt are responsible for an additional 60 Moz of combined past production and present gold resources (Safonov, 1997).

The eastern half of the north–south-trending Ural fold belt is made up of a series of middle to upper Paleozoic marine sedimentary rocks and lower to middle Paleozoic arc complexes and ophiolites. These were accreted to the passive margin sequences along the eastern side of the Eastern European craton. Collision began in the Late Devonian and was most intense between middle Carboniferous and Late Per-

mian, also a period of extensive anatectic plutonism (Puchkov, 1997). Some of the mineralized veins appear to be localized in low metamorphic-grade Silurian volcano-sedimentary accreted sequences and serpentized ultramafic rocks along the main suture zone termed the Main Uralian fault. The larger orogenic gold systems, however, are sited in highly deformed, greenschist to amphibolite facies accreted terranes about 50–100 km east of the suture (Bortnikov et al., 1997; Kisters et al., 1999). The veining is mainly concentrated within, and adjacent to, relatively competent ca. 360–320 Ma granitoids. There are no isotopic dates for the veining, but it is most likely that ore formation overlapped with at least some of the final tectonothermal events at ca. 320–250 Ma (Kisters et al., 1999). It is suggested that ages of gold veining progressively decrease over this period away from the Main Uralian fault, that is from west to east, which would correlate with a 40- to 60-m.y.-long progressive younging of magmatism and deformation in the easterly building orogen (Montero et al., 2000). Although not commonly referred to as Variscan, the orogenic gold ores of the Ural Mountains are probably of a similar age to those of the extensive southern Europe–central Asia–northern China Variscan gold belt.

The Variscan orogenic gold deposits that formed along the active western edge of the Paleo-Tethys Ocean are those now exposed in southern Europe and central Asia (Figs. 5a,b and 7). The 3000-km-long Variscan belt of southern Europe formed as a number of small Precambrian blocks (sometimes referred to as the Armorica–Barrandia terrane), and were accreted to Euramerica along the southwestern margin of the Paleo-Tethys Ocean, subsequent to the collision with Gondwana. The event included high pressure metamorphism at the initial ca. 440–390 Ma collision; deformation and high temperature metamorphism during continued collision at ca. 390–330 Ma; and extension and uplift forming basement-cored migmatitic domes at ca. 330–280 Ma (Rey et al., 1997). Voluminous magmatism was continuous throughout the collisional to extensional transition, with most reported dates at 360–290 Ma. The main gold-forming events occurred over broadly the same period within uplifted basement blocks (Moravek, 1996a,b). Significant changes in far-field regional stress fields, such as from an extensional to

strike–slip regime in the French Massif Central, may have been critical for hydrothermal fluid flow (Charonnat et al., 1999). These Variscan gold ores are also notable by their consistent abundance of stibnite (Mossman et al., 1991). Gold production in the 20th century has been about 6 Moz, with perhaps another 10 Moz in remaining resources, mainly in the Bohemian Massif and at Jales, Portugal. In addition, historic production from the Iberian Massif was probably significant, with estimates varying over an order of magnitude, from about 7.4 Moz (Foster, 1997) to 65 Moz Au (Quiring, 1972). This production would have been mainly from Tertiary alluvial fields in the Tagus River Valley and its tributaries in northwestern Spain, and was carried out by the Romans between 50 B.C. and A.D. 500 (Rice, 1981).

Stein et al. (1998) indicate emplacement of gold lodes in the Proterozoic and lower Paleozoic high-grade metamorphic rocks of the Bohemian Massif of the Czech Republic at 349–342 Ma. In the French Massif Central, orogenic lodes were deposited sometime between 320 and 285 Ma (Bouchot et al., 1989; Guen et al., 1992). The older dates for veining correlate with a major period of transcurrent motion within the southern Massif Central (Cassard et al., 1993). Gold-bearing lodes of the Hesperian Massif, Spain and Portugal, are also estimated to have formed at both ca. 347 and < 292–286 Ma (Murphy and Roberts, 1997). Cross-cutting relationships from the lodes in northern Portugal indicate gold formation subsequent to emplacement of ca. 320–305 Ma granitoids and favor mineralization being coeval with post-tectonic 290–280 Ma granitoids (Noronha et al., 2000). The exact location of the suture between Euramerica and the Armorica–Barrandia terrane is unclear; hence, it is uncertain as to whether these ore-hosting massifs in southern Europe are part of the allochthons and/or the backstop to accretion. The geochemistry of Variscan granitoids suggests that the massifs developed within both areas (Schermaier et al., 1997).

Important Variscan gold ores also formed in central Asia, further north along the western Paleo-Tethys oceanic margin and between the Siberian and Eastern European cratons. In this area of Asia, subduction continued throughout the middle Paleozoic on the eastern side of Kazakstania (or the older Kipchak arc of Sengor and Natal'in, 1996a,b), al-

though likely separated from the Altaid orogenic zone within the microcontinent by the Junggar Sea (Carroll et al., 1995). These events included amalgamation of the flyschoid units of the Tian Shan, Tarim craton, and Yili microcontinent to form the Tian Shan mountain belt. The 3500-km-long belt is now located south of the Altai in western China and continues westward (through Tajikistan and Kyrgyzstan) until merging with the Sultan–Uvais Mountains in Uzbekistan. Tectonism in the Tian Shan is associated with formation of important gold ores in the Kyzylkum desert area of Uzbekistan (Muruntau—170 Moz, Amantaitau, Daugyztau, Charmitan—> 10 Moz). Orogenic lodes also continue eastward across the central and southern Tian Shan into Tajikistan (Jilau, Taror—each > 3 Moz), eastern Kyrgyzstan (Kumtor—13.6 Moz) and Xinjiang, China (Sawayaerdun—> 3 Moz, Kanggurtag, Wangfeng). Absolute dates for veining in these parts of the Tian Shan are very variable; most from Uzbekistan suggest vein and coeval granitoid emplacement in Permian to Triassic time (for example, see Kostitsyn, 1993; Novozhilov and Gavrilo, 1994; Bortnikov et al., 1996; Shayakubov et al., 1999; Wilde et al., 2000). If these dates are taken as correct, then ore formation is somehow correlated with final collision of the amalgamated Tarim microcontinent/central Tian Shan with the northern Tian Shan, closure of the Junggar sea between the Altai and the Tian Shan, and the onset of major strike–slip landward of the uplifting mountain range (Carroll et al., 1995; Allen and Vincent, 1997). Carboniferous dates on small orogenic gold deposits in the Chinese part of the Altai (e.g., Duolonasayi, Saidu), north of the Junggar basin, suggest that Variscan lodes were emplaced along the Kazakstania continental margin at slightly earlier times (Yuanchao et al., 1996; Rui et al., 2002).

Temporally overlapping gold formation in the Ural Mountains and the Tian Shan, between two late Paleozoic cratonic masses, was the formation of Variscan gold ores in north-central China and north-central Mongolia (Figs. 5b and 7), as deformation occurred on both sides of a closing ocean basin between the Precambrian Siberian and North China cratons. This seemingly reflects two opposite-facing subduction zones beneath the northernmost part of the Paleo-Tethys Ocean (e.g., Scotese, 1997), some-

what similar to the late Mesozoic pattern (see below) of the northern Pacific basin. Late Carboniferous subduction on what is now the southern side of the Siberian craton was associated with accretion of a number of terranes that compose much of north-central Mongolia (Zorin, 1998). These broadly reflect the continued seaward growth of the continental margin that initially led to Early Carboniferous(?) formation of the Lena River deposits (e.g., Sukhoi Log) north of Lake Baikal (see above Neoproterozoic discussion). The subsequent terrane collisions south of Lake Baikal appear to have generated an abundance of Variscan orogenic gold deposits (e.g., Boroo, Zaamar) in a vast region to the north and southwest of Ulaan-Baatar, Mongolia. Although poorly studied and little developed, gold resources in the lode and related placer deposits exceed 10 Moz (Jamsradorj and Diatchkov, 1996; United Nations, 1999).

Variscan orogenic gold deposits formed diachronously along the length of the northern margin of the North China craton, in the Inner Mongolia autonomous region and northern Hebei province, north-central China, during much of the latter Paleozoic. Significant deposits include those at Saiyinwusu and Wulashan in the Daqinshan gold province and Zhongshangou and Xiaoyinpan in the Yan-Liao gold province (Miller et al., 1998; Hart et al., 2002). Almost all the major Variscan gold deposits are located within the North China craton, inland of the suture with oceanic terranes that were accreted throughout the Permian and Early Triassic. Similar to the southern European part of the Variscan gold belt, orogenic gold ores and coeval granitoids in North China occur in Precambrian basement uplifts that are surrounded by younger cover rocks.

2.6. Mesozoic (250–65 Ma)

The Mesozoic breakup of Pangea was associated with development of the Pacific Ocean basin and formation of an immense system of subduction zones extending along the entire eastern margin of the ocean and continuing across the northern sector of the Pacific to eastern Asia. Andean arc formation along the Pacific margin of South America is not associated with emplacement of significant orogenic gold lodes, although productive epithermal ores are commonplace. This, in large part, reflects the erod-

ing continental margin, which is not characterized by a broad forearc region with a series of moderately to highly metamorphosed allochthonous terranes (Goldfarb et al., 1998). In contrast, Mesozoic growth of western North America, from California to Alaska, and of eastern Asia, from northern Russia to east-central China, is characterized by a remarkable episode of orogenic gold deposit formation (Fig. 8; Table 4). The continued growth of the Gondwana supercontinent along the southwestern margin of the Pacific basin in the Triassic and Jurassic led to additional gold veining seaward of the Tasman gold belts in what is now the Otago region of New Zealand (Fig. 8).

Kula–Farallon plate convergence initiated gold veining along western North America at ca. 180 Ma. Terrane collisions of the Cordilleran orogen, between allochthonous oceanic terranes and pericratonic continental margin assemblages, drove widespread Middle Jurassic ore-forming events along the length of easternmost central Alaska, central Yukon, and British Columbia (Figs. 5c and 8). From north to south, productive districts, which include the Middle Jurassic Seventymile, Klondike, Atlin, Cassiar, and Cariboo districts (Rushton et al., 1993; Ash et al., 1996; Craig Hart, oral communication), developed in many of the accreted terranes, now located between the craton and the subsequently emplaced Cretaceous magmatic arc. Orogenic gold deposits have weathered to placers throughout all these areas, including the Klondike where eroded lodes have been concentrated into more than 10 Moz of placer gold.

South of British Columbia, terrane accretion also occurred against the continental margin of central California from Triassic through Middle Jurassic during Farallon–North America plate convergence, and then stepped seaward about 200 km in the Late Jurassic (Burchfiel et al., 1992). This Late Jurassic event initiated intrusion of the 150–80 Ma Sierra Nevada magmatic arc into the earlier accreted terranes. Gold veins were emplaced at the same time, with absolute dates ranging between 144 and 110 Ma (Bohlke and Kistler, 1986), along the length of terranes on the seaward side of the arc (Landefeld, 1988). Approximately 100 Moz Au have been recovered from the Sierra foothills districts that include the famous Mother Lode belt, with about two-thirds of this total production being from placer fields.

Mesozoic - Tertiary Gold

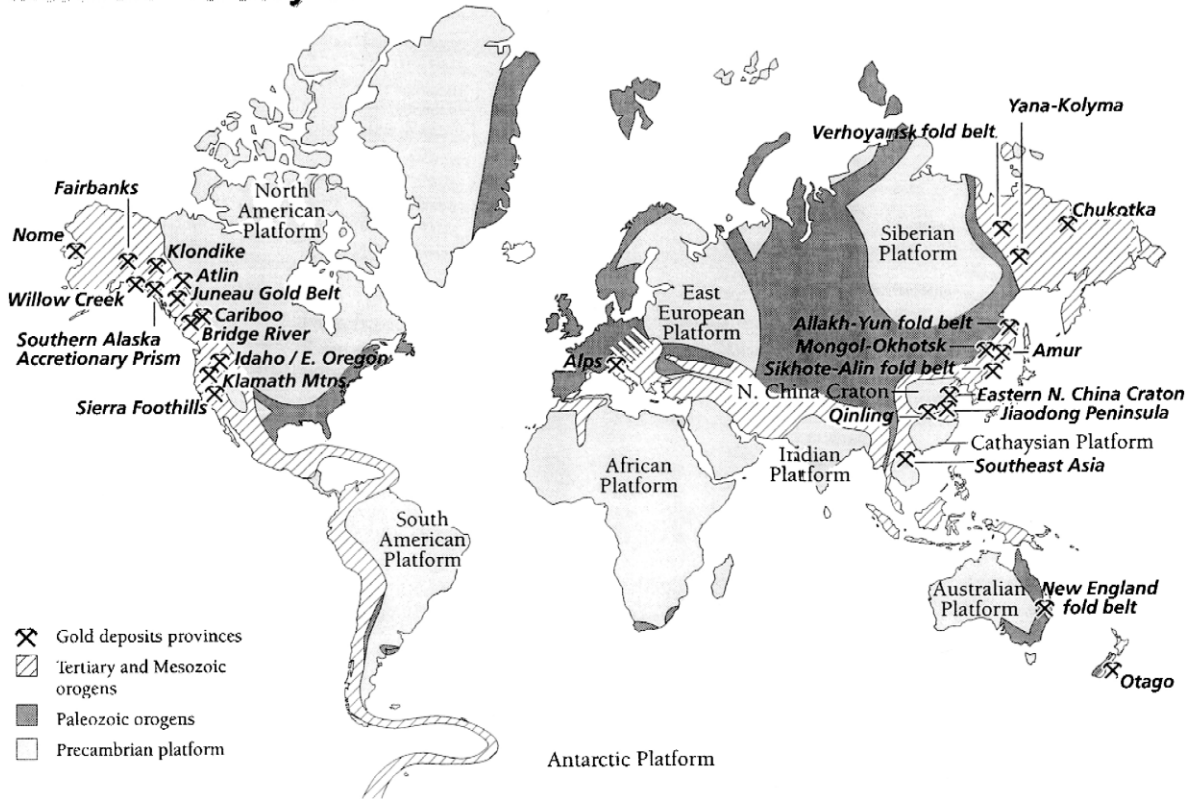


Fig. 8. The distribution of Mesozoic–Tertiary orogenic gold provinces is mainly restricted to Circum-Pacific accretionary orogens. Deposits extend across the entirety of the Cordilleran orogen of western North America, from the Sierra Foothills belt northwest to Nome, Alaska (#1). Deposits on the western side of the northern Pacific basin extend from eastern China to the northeastern corner of Russia. Final Gondwanan accretionary events are defined by gold lodes in the New England fold belt and the South Island of New Zealand. A few small lode systems are located in the Alpine orogen.

Coeval veining continued into northern California and southern Oregon, where similar mid-Mesozoic accretionary events are associated with the less productive goldfields of the Klamath Mountains. Elder and Cashman (1992) indicate that processes depositing orogenic gold ores in the Klamath Mountains were ultimately controlled by changes in relative Farallon–North America plate velocities and convergence angles. Small middle Cretaceous (ca. 110–80 Ma) orogenic deposits in northwestern Nevada (Cheong, 2000) likely reflect thermal events caused by the subsequent inland migration of the downgoing Farallon slab.

Orogenic deposits began to form in Alaska by the mid-Cretaceous, once opening of the Canada basin

rotated rocks of the Brooks Range to an east–west configuration that formed a backstop to terrane accretion for allochthonous material moving north within the Pacific basin. Small gold deposits developed at ca. 110 Ma near Nome on the Seward Peninsula (Ford and Snee, 1996), and these subsequently eroded to concentrate gold in the famous beach placers that yielded about 6 Moz Au. Vein emplacement and magmatism in this part of Alaska are temporally related with a period of slab rollback and extension (Rubin et al., 1995). This thermal event occurred about 20 m.y. subsequent to termination of collisional orogenesis and associated high-P–low-T metamorphism that characterizes much of northern Alaska.

Many hundreds of kilometers to the southeast of Nome, continued subduction and collision of the Wrangellia microcontinent with the growing North American continental margin at ca. 90 Ma triggered formation of the Tombstone belt of plutons and associated gold ores (Mortensen et al., 1996; McCoy et al., 1997; Goldfarb et al., 2000). In the part of the belt in east-central Alaska, past placers have yielded more than 11 Moz Au, the Fort Knox lode deposit in the Fairbanks district has a combined gold production and resource exceeding 7 Moz, and the recently discovered Pogo deposit exceeds 5 Moz Au. Where the Tombstone belt continues into Canada's Yukon Territory, granitoids and gold lodes are emplaced into, locally greenschist facies-metamorphosed, basinal rocks of the Precambrian craton margin of North America. High salinity fluids in some of the Tombstone gold systems in Yukon might be analogous to those from the Paleoproterozoic and Neoproterozoic, where metamorphism of basinal sequences favors an uncommonly saline mid-crustal fluid. However, until more data are available, it remains uncertain as to whether the style of sheeted veins and the spatial association with large granitoid bodies at Fort Knox and in the Yukon prospects reflect a series of intrusion-related gold deposits (Thompson et al., 1999) that are simply coeval with orogenic gold deposits (e.g., Pogo, Ryan Lode, Cleary Hill) in this part of the North American Cordillera.

In the southernmost part of southeastern Alaska (90 Ma in the Ketchikan area), and in adjacent parts of southwestern British Columbia (70 Ma in the Bridge River district), gold veins were emplaced adjacent to, and on opposite sides of, the Coast batholith during the Late Cretaceous. (Leitch et al., 1991; Goldfarb et al., 1998). These too may relate to tectonism associated with transpressional collision of the Wrangellia superterrane or, instead, the consequent outboard oblique collision of the Chugach terrane. Dextral slip along the evolving margin may not only have enhanced formation of these gold systems, but also subsequently displaced deposits such as the small Coquihalla district from the > 4 Moz Au Bridge River deposits.

A very similar style of accretionary tectonics characterized Farallon plate subduction beneath the eastern Siberian platform of the Eurasia plate throughout the late Mesozoic (Goryachev and Ed-

wards, 1999). Resulting orogenic lodes (Figs. 5b and 8) have been eroded to yield about 125 Moz Au in the placer fields of the Russian Far East; remaining lodes were recognized to have resources of > 45 Moz Au, 10% of which has already been mined (Goryachev, 1995). Early Cretaceous gold veining occurred in deformed post-Devonian continental shelf strata (Verhoyansk and Allakh–Yun fold belts), in Permian through Early Jurassic basinal shales to the east (Kular–Nera terrane), and in the further seaward Kolyma–Omolon accreted microcontinent. Final docking of the microcontinent and Kular–Nera accretionary wedge to the Siberian pericratonic units along the 40-km-wide Adycha–Taryn fault occurred near the end of the Jurassic (Parfenov, 1995). Some important orogenic gold deposits, such as Nezhdaninskoe (> 15 Moz Au) hosted in the late Paleozoic to Jurassic clastic sedimentary units of the Allakh–Yun fold belt, formed in the passive continental margin sequences. However, about 65% of the placer production, and most of the lode resource in the Russian Far East, are concentrated seaward of the suture in the 1000-km-long by 150- to 300-km-wide Yana–Kolyma gold belt (Nokleberg et al., 1993, 1994). Dates determined for syn- to post-tectonic granitoids intruding rocks of the Kular–Nera terrane, and the western side of the Kolyma–Omolon superterrane along this belt, cluster between about 140 and 100 Ma (Parfenov, 1995). The orogenic gold deposits in the same area, such as Natalka (14.5 Moz Au) and other lode systems of the Omchak district, Shkolnoye, and Svetloye, show a similar age range (Eremin et al., 1994), although it is likely that the younger part of the relatively broad ore-forming range is a consequence of partial resetting of isotopic systems. Gold vein emplacement also overlaps the Early Cretaceous onset of dextral strike–slip faulting, which developed along many of the northwest-trending sutures (Oksman, 1998; Abzalov, 1999).

Coeval with the Siberian/Kolyma–Omolon collision were additional tectonic events on the northeastern and southeastern sides of the Siberian block. To the southeast, the Mongol–Okhotsk fold belt (also called the Ural–Mongolian or Central Asian fold belt) developed during collision of the North China craton and other small blocks with the Siberia craton. Gold deposits in the northeastern tip of China and the adjacent parts of the Russian Far East (area

Table 4
Summary characteristics of Mesozoic–Tertiary orogenic gold deposits

Gold province	Host area	Districts (deposits)	Associated structures	Production (Moz Au)
Trans-Baikal belt	Mongol–Okhotsk orogenic belt	(Darasun), Mogochoa (Klyuchevsk), Selemdzha, Niman, Kerbi (Tokur, Malomyr, Unglichikan)	Mongolia–Okhotsk suture	2
Daqinshan/Yan-Liao	North China craton (Chinese Variscan)	Wulashan (Saiyinwusu, Zhongshangou, Xiaoyinpan)		< 5?
New England fold belt	Tasman orogen	Hillgrove, Gympie (Timbarra), Great Serpentine Belt	Peel fault system	4
Otago	Tasman orogen(?)	Macraes	Hyde-Macraes shear zone	0.5
Tombstone belt	Cordilleran orogen	Fairbanks (Ft. Knox, Ryan Lode, True North), Goodpastor (Pogo), (Brewery Creek, Scheelite Dome, Dublin Gulch, Clear Creek)	Tintina and Denali fault systems	1.5
Seward Peninsula	Cordilleran orogen	Nome (Rock Creek), Council (Big Hurrah)		< 0.1
Klondike	Cordilleran orogen	(Sheba, Mitchell, Hunker)		< 0.1
Interior British Columbia	Cordilleran orogen	Atlin, Casslar, Cariboo		> 1?
Chugach accretionary prism	Cordilleran orogen	Chichagof (Chichagof, Hirst–Chichagof), Port Valdez (Cliff), Port Wells, Girdwood, Hope–Sunrise, Moose Pass, Nuka Bay	Border Ranges	0.9
Juneau gold belt	Cordilleran orogen	(Alaska–Juneau, Treadwell, Kensington, Sumdum Chief)	Fanshaw, Sumdum	6.8
Talkeetna Mountains	Cordilleran orogen	Willow Creek (Independence)	Border Ranges	0.6
Bridge River	Cordilleran orogen	(Pioneer, Bralome)	Yalakom	4.3
Central Idaho	Cordilleran orogen	Buffalo Hump, Elk City, Yellow Pine, Boise Basin		7
Sierra Foothills	Cordilleran orogen	Alleghany, Grass Valley, Mother Lode	Melones, Bear Mountain	35
Klamath Mountains	Cordilleran orogen	French Gulch, Deadwood	Soap Creek–Siskiyou	3.5
Yana–Kolyma	Russian Far East	Omchak (Natalka, Shkolnoye, Utinka, Pavlik, Omchak, Svetloye), Tuostakh, Kular, Adycha–Taryn (Sarylakh, Sentachan)	Tenka fault	5
Verhojansk fold belt	Russian Far East	Djanda–Okhonosoy		uncertain
Allakh–Yun fold belt	Russian Far East	Yur–Duet (Nezdaninskoye)	Kiderikinsk deep fault, Tyrynsk fault	
Chukotka terrane	Russian Far East	(Kartalveem, Malskoe, Palyangai)		

Resource (Moz Au)	Associated placer production (Moz Au)	Deformation age (Ma)	Grantoid ages (Ma)	Mineralization age (Ma)	Reference
7	35	190–140	280–260, 164–145	L. Jurassic–E. Cretaceous	Zorin (1999), Yakubchuk and Edwards (1999), Krivolutskaya (1997), Stepanov (1998)
10?	minor	Permo-Triassic	325–245	ca. 300–220	Miller et al. (1998), Hart et al. (2002)
minor	0.25	320–230	310–300, 285, 270–240	E.–M. Triassic	Ashley (1997), Cranfield et al. (1997)
3	8	200–140	no granitoids	E. Jurassic–E. Cretaceous	McKeag and Craw (1989), Paterson (1986), Adams et al. (1998)
12	12	Jurassic	105–90	105, 92–87, 77(?)	McCoy et al. (1997), Goldfarb et al. (2000), Newberry (2000)
	7	170–130, 108–82	108–82	109	Ford and Snee (1996), Rubin et al. (1995)
	15	Jurassic	no granitoids	175	Rushton et al. (1993), C. Hart (unpublished)
1	1	Jurassic	E.–M. Jurassic	170–140	Ash et al. (1996)
	0.1	L. Cretaceous to Eocene	66–50	57–49	Goldfarb et al. (1986), Haeussler et al. (1995)
> 5	minor	mid-Cretaceous, 70–60	mid-Cretaceous, 70–48	57–53	Goldfarb et al. (1991), Miller et al. (1994)
	minor	Jurassic	74–66	66	Madden-McGuire et al. (1989)
0.6	minor	Jura-Cretaceous	270, 91–43	70	Leitch et al. (1991), Goldfarb et al. (2000)
	1	L. Cretaceous–Eocene	120–70, 64–47	78–67	Cookro (1996), Foster and Fanning (1997), Lund et al. (1986)
15	65	Jurassic–E. Cretaceous	150–80	144–141, 127–108	Bohlke and Kistler (1986), Landefeld (1988)
	3.5	Jurassic–E. Cretaceous	177–135	≥ 147, ≤ 136	Elder and Cashman (1992)
20	125	L. Jurassic–E. Cretaceous	170–110	147–131, 125–115, 105–95	Goryachev and Edwards (1999), Nokleberg et al. (1993), Parfenov (1995), Abzalov (1999)
uncertain		L. Jurassic–E. Cretaceous	140–70		Goryachev and Edwards (1999), Nokleberg et al. (1993), Parfenov (1995)
15		Cretaceous	154–94	170–130, 115–100	Goryachev and Edwards (1999), Bortnikov et al. (1998)
11		E. Cretaceous		124–110	Abzalov (1999), Nokleberg et al. (1996)

(continued on next page)

Table 4 (continued)

Gold province	Host area	Districts (deposits)	Associated structures	Production (Moz Au)
Jiaodong Peninsula	North China craton (Yanshanian orogen)	(Jiaojia, Xincheng, Linglong, Fushan, Taishang, Sanshandao)	Sanshandao–Canshan, Jiaojia–Xinchen	> 1–2(?)
Qinling	North China craton (Yanshanian orogen)	Xiaoqinling (Dongchuang, Wenyu, Dahu, Yangzhalyu, Tongyu)		minor
Yan-Liao/ Changbaishan	North China craton (Yanshanian orogen)	(Dongping, Jinchanggouliang, Jinchangyu, Jaipigou, Maoling)		minor
European Alps	Alpine–Carpathian orogen	W. Alps (Brusson, Vogogna, Gondo), Swiss Alps (Mont Chemin), E. Alps (Rotguldin)		1
Southeast Asia	Himalayan orogen	N. Vietnam (Bo Cu, Da Mai, Na Pac, Pac Lang, Lang Vai); Ailaoshan (Zhenyuan, Mojiang, Daping)	Ailao Shan–Red River shear zone	uncertain

Resource estimates are combined from numerous sources to give the most reliable numbers as of the year 2000. The sited mineralization ages are from what are viewed as the most reliable published isotopic dates. Older conflicting K–Ar, Rb–Sr, etc., dates are not used where newer dates exist.

presently east of Lake Baikal) are located within Mesozoic sedimentary rocks and older trapped blocks of the closed Mongol–Okhotsk Ocean. Ocean closure at about 140–120 Ma (Xu et al., 1997) apparently correlates with gold veining in the Amur region (Figs. 5b and 8) in the eastern side of the fold belt. Early Cretaceous orogenic gold deposits (Moiseenko et al., 1999) such as Malomyr, Tokur, and Sagur, associated with > 20 Moz placer gold in the Amur region, are restricted to late Paleozoic black shale units of the Selemdzha–Kerbi composite terrane. Other orogenic gold deposits continue into the central (e.g., Klyuchevsk; Krivolutskaya, 1997) and western (e.g., Darason) parts of the Mongol–Okhotsk fold belt, where ocean closure was slightly earlier in the Middle and Late Jurassic (Zorin, 1999). Regional strike–slip events along the east–west-trending Mongol–Okhotsk fault zone, with final movement constrained by Cretaceous igneous rocks (Yakubchuk and Edwards, 1999), may be associated with the gold deposition. These gold deposits clearly formed subsequent to the late Paleozoic orogenic gold deposits of north-central Mongolia and the Lake Baikal region (see above), which are located to the west and reflect earlier deformation along the Siberian margin.

To the northeast of the Siberian craton, opening of the Canada basin led to collision of the Chukotka terrane on to the seaward margin of the Kolyma–

Omolon superterrane along the South Anyui suture (Nokleberg et al., 1994, 1996). Middle Cretaceous magmatic arc formation and coeval hydrothermal events in the Anyui fold belt of the Chukotka terrane may be parts of the same regional extension that triggered gold veining near Nome, Alaska, across the Bering Straits (Goldfarb et al., 1998). In contrast to the placers of Nome, important lode resources have been discovered in the Paleozoic–early Mesozoic passive continental margin sedimentary rocks of the Chukotka terrane (e.g., 9.6 Moz Au at Maiskoe; Figs. 5b and 8; Abzalov, 1999).

Orogenic lode-gold deposits are well-recognized in eastern China. Such deposits in the Qinling Mountains on the southern side of the North China craton, on the Jiaodong Peninsula on the eastern side, and along much of the northern side (Figs. 5b and 8) all formed in the Early Cretaceous, but the ultimate tectonic controls on mineralization are uncertain. These represent the most important historical and presently active centers of gold mining in China. Gold districts along the northern and southern cratonic margins are typically located a few tens of kilometers inland of faults marking Paleozoic accretionary events. The ores in all three regions are concentrated in areas of uplifted Precambrian basement, show a spatial–temporal association with Early Cretaceous magmatism, are characterized by both

Resource (Moz Au)	Associated placer production (Moz Au)	Deformation age (Ma)	Grantoid ages (Ma)	Mineralization age (Ma)	Reference
> 28		Jurassic– E. Cretaceous	165–125	130–120	Qiu et al. (2001), Wang et al. (1998a,b)
13		Jurassic– E. Cretaceous	180–108	E. Cretaceous	Mao et al. (2001b), Jiang and Zhu (1999)
15?		Jurassic– E. Cretaceous	200–120	ca. 200–120	Miller et al. (1998), Hart et al. (2001)
		90–60, 44–19	43–20	32–10	Pettke et al. (1999), Marshall et al. (1998)
> 2	perhaps significant in Vietnam	33–17	35–22	49–29(?)	Yang (1996), Harrison et al. (1996), Wang et al. (1998a,b), Dzung (1995), Zhang and Scharer (1999)

quartz vein and disseminated styles of mineralization, and show extensive potassium metasomatism of wall rocks. In addition, these gold deposits along the edges of the North China craton are consistently characterized by ^{18}O - and CO_2 -rich ore fluids, which are common to orogenic types of lode-gold deposits (e.g., Groves et al., 1998).

The most significant gold mineralization in eastern China is associated with large-scale, 400-km-wide, NNE-trending intracratonic transcurrent faults that have been active since the Late Jurassic (Jiawei, 1993). The easternmost of these, the 5000-km-long Tan–Lu fault system, is spatially associated with the orogenic gold lodes of the Jiaodong Peninsula and eastern Liaoning Peninsula of China, and then continues into the Sikhote–Alin fold belt (or Selemdzhā–Dzhadi fold belt of Nokleberg et al., 1994) of the Russian Far East accretionary complex. The lodes of the Jiaodong Peninsula are generally hosted by 165–125 Ma plutons and the > 28 Moz Au resource represents the most significant gold district in China (Qiu et al., 2002). It is uncertain if the 130–120 Ma gold-forming thermal event (Wang et al., 1998a,b; Qiu et al., 2002) was ultimately due to ongoing oblique collision between the Izangi and Eurasia plates, occurring south of the Izanagi/Farallon plate boundary in the northwestern Pacific basin (Harbert et al., 1990). Wang et al. (1998a,b) suggest

that post-collisional strike–slip along the Tan–Lu fault system, coinciding with a hypothesized mantle plume event, might have initiated gold veining. Erosion of the lodes in the Early Cretaceous Sikhote–Alin fold belt yielded more than 30 Moz of placer gold (Ratkin, 1995). These lodes may have been products of the same period of tectonism along the eastern Eurasian transcurrent fault systems.

In the Qinling area on the southeastern side of the North China craton, orogenic gold lodes, such as those of the Xiaoqinling district (about 13 Moz Au), are widespread in rocks of the uplifted Precambrian basement (Mao et al., 2002b). These are located immediately north of island arc terranes accreted to the craton during the middle Paleozoic and of the rocks of the Qinling–Dabie orogen, which reflects the Late Permian to Middle Triassic collision of the Yangtze (or South China) craton (Nie and Rowley, 1994). The gold ores within the Qinling area, however, are probably Early Cretaceous in age and are spatially associated with, but not hosted within, 130–108 Ma granitoids (Jiang and Zhu, 1999). As was also seen on the Jiaodong Peninsula, the Cretaceous timing indicates that hydrothermal activity was coeval with Mesozoic circum-Pacific tectonism. In fact, the rocks of the easternmost part of the Qinling–Dabie Shan orogen were displaced 500 km to the north during the Late Jurassic and/or Early Creta-

ceous along the Tan–Lu fault system (Li, 1994), suggesting that the gold ores of the Jiaodong Peninsula and Qinling region may have originally been part of a single, large circum-Pacific gold province. Less productive gold deposits (e.g., Baguanmiao, Shuangwang) farther to the west, and hosted in accreted Devonian rocks of the Qinling–Dabie Shan orogen, formed earlier during the final stages of Triassic suturing of the two large cratonic blocks (Mao et al., 2002a).

Mesozoic gold ores along the northern edge of the North China craton have a complex and poorly understood temporal distribution across the eastern Inner Mongolia region, and northern Hebei, Liaoning, and southern Jilin provinces. They are clustered within the informally termed Yan Liao (e.g., Dongping, Jinchangyu deposits) and Changbaishan (e.g., Jiapigou, Maoling, Baiyan deposits) gold provinces of Miller et al. (1998). In the former province, the ores spatially overlap with older Variscan orogenic gold deposits, as described above (e.g., Zhongshangou, Xiaoyinpan). Again, the gold deposits show a spatial association with uplifted Precambrian blocks inland of collisional sutures. Recent argon (Hart et al., 2002) and lead (Yumin Qiu, oral communication, 1999) isotope geochronology indicates that hydrothermal events were concentrated between ca. 200 and 120 Ma, but with little pattern as to the age distribution. Most likely, because of the observed spatial relationships, fluid flow was correlated with a scattering of basement uplift events in relatively localized parts of the northeastern part of the craton.

It is possible that the ores throughout the eastern side of the North China craton were products of Cretaceous circum-Pacific events because of the overlap in time. As early as 200 Ma, orthogonal subduction of the Farallon and Izanagi plates occurred beneath the southern (Pacific) margin of the Yangtze craton. During this subduction, the accretionary complexes of the Japan Islands formed seaward of the amalgamated Yangtze and North China cratons. In the Early Cretaceous, there was a major change in circum-Pacific plate trajectories, with Izanagi–Eurasia plate convergence shifting to highly oblique and transform faulting dominating eastern Asia (Maruyama et al., 1997). It is possible that the Tan–Lu fault zone, discussed above, is a product of such tectonism.

In strong contrast to the other circum-Pacific Mesozoic gold provinces, it is uncertain as to exactly how feasible a direct correlation between gold and Mesozoic circum-Pacific tectonism really can be in eastern China. Early Cretaceous magmatism is widespread for more than 1000 km into the North China craton. The gold events in the Qinling Mountains, Jiaodong Peninsula, and along the northern cratonic margin are also all of roughly the same age. It is unlikely that a northerly migrating transform margin fault-system would effect all areas of the eastern side of the craton at the same time and would lead to magmatism so far inland over such a broad region.

It would seem most likely that the gold ores of the North China craton are ultimately related to the thermal event caused by a deep-seated heterogeneity in the upper mantle. Griffin et al. (1998) note a north–south gravity lineament that cuts the entire craton near the longitude of Beijing, traversing along the length of the Taihang Mountains. The lineament marks a major change in the subcontinental lithosphere. During the Jurassic and Cretaceous, 80–140 km of Archean lithosphere was removed from beneath the craton to the east of the lineament, resulting in asthenosphere upwelling to depths of as shallow as 50 km and generating high crustal temperatures at shallow depths (Griffin et al., 1998). This is a possible cause of the widespread “Yanshanian” magmatism and coeval gold veining in the North China craton. Where tectonic processes have uplifted deeper parts of the thermally upgraded crust, gold ores are common. Such uplifts certainly appear to localize ore-forming fluids in eastern China, as well as in other tectonically reworked orogenic belts (e.g., the Variscan of southern Europe). It is possible that such basement zones are crustal exposures that carry up previously formed examples of this style of lode-gold deposit from depths of perhaps 5 or 10 km. Alternatively, during the time of uplift itself, these blocks perhaps represent loci for large fluxes of deep crustal fluids, either due to increasing pressure gradients or structural competency contrasts. All such possibilities obviously require future investigation. The ultimate cause of the proposed lithosphere erosion is also uncertain; it could reflect some type of slab delamination subsequent to Qinling–Dabie Shan orogeny or, as sug-

gested by Griffin et al. (1998), extremely high-temperature events associated with circum-Pacific tectonism.

Subsequent to the break-up of Pangea, subduction and terrane accretion continued along the Gondwanan margin into the Early Cretaceous. The final terranes accreted to the Australasian margin of the supercontinent were the predominantly turbiditic rocks of the Permian to Late Triassic Torlesse and Caples terranes, which are now present over much of the subsequently rifted South Island of New Zealand. Gold veining within the Otago region of these terranes (Figs. 5b and 8) occurred sometime during Early Jurassic to Early Cretaceous deformation and greenschist-facies metamorphism, which formed the Haast schists, accompanying terrane accretion (McKeag and Craw, 1989).

As with ores of the Brasiliano fold belt, the veins and related placers in this part of New Zealand show no spatial association to any igneous rocks at the present erosion level. A possible temporal overlap between ore formation and emplacement of the 158–132 Ma Median batholith has been pointed out to help support a magmatic origin for the gold-forming fluids (De Ronde et al., 2000), but given the distance of more than 200 km between the two, such a link is quite tenuous. Another concern with such a link is the above-mentioned possible Early Jurassic initiation of gold formation.

Detrital zircon age patterns suggest that the sedimentary rocks hosting the deposits formed near northeastern Australia, far north of present-day New Zealand (Adams et al., 1998). They are hypothesized to have subsequently been continuously deformed, metamorphosed and uplifted during 200–140 Ma tectonism along the northern New England orogen prior to rapid, southerly terrane translation in the mid-Cretaceous. Therefore, the orogenic gold lodes of southeastern New Zealand are most likely products of final collisional events along the seaward margin of a ca. 280–140 New England orogen.

Whereas most Mesozoic orogenic gold deposits are associated with circum-Pacific tectonism, terrane accretion along the northeastern Meso-Tethys Ocean (Metcalf, 1996), in front of the eventual Indian–Asian collision, also led to formation of a series of small orogenic gold deposits. On the seaward side of the Yangtze craton, orogenic gold deposits of proba-

ble early Mesozoic age, some with > 20 t Au (e.g., Zhenyuan, Jinchang, Gala), are associated with serpentized ultramafic rocks along sutures in melange of the Chinese Sanjiang fold belt (Zhou et al., 2002). Younger Late Cretaceous gold deposits formed in what is now Myanmar, as the Eurasian margin grew seaward. Lode and placer deposits in a series of slate belts, and spatially associated with Late Cretaceous granitoids, include those of the Wuntho, Mabein, and Phayaung Tang–Kyaikto districts (Mitchell et al., 1999).

2.7. Tertiary (< 65 Ma)

Widespread gold veining in southern Alaska (Figs. 5c and 8; Table 4) correlates with periods of early Tertiary collision and translation along the North American continental margin. The 200-km-long Juneau gold belt in southeastern Alaska is situated a few hundred kilometers inland from the Pacific Ocean and within accreted terranes immediately seaward of the Coast Mountains continental batholith. Auriferous vein systems are located on both sides of a pair of steeply dipping thrust faults that originally formed as boundaries between accreted terranes. Veining occurred at 56–53 Ma during calc-alkaline magmatism, regional uplift, and a change in regional stress fields from orthogonal compression to a more oblique regime (Goldfarb et al., 1991; Miller et al., 1994). Where the continental-margin magmatic arc continues into south-central Alaska, veins of the Willow Creek district were emplaced mainly into the Talkeetna Mountains batholith at the start of the Tertiary. Vein formation occurred about 10 m.y. after granitoid crystallization, and may ultimately have been a product of Kula plate subduction and/or the oroclinal bending of Alaska (Goldfarb et al., 1998).

The 2000-km-long accretionary prism of southern Alaska is dominated by turbidites of the Chugach terrane, which were accreted to the continental margin in the Late Cretaceous. Early Tertiary granitoids and 57–49 Ma gold-bearing quartz veins extend along the entire length of the prism that rims the northern Gulf of Alaska. The plutons and veins are characterized by a consistent younging trend from west to east. Haeussler et al. (1995) attribute this pattern to a slab window along the subducting

Kula–Farallon ridge. As a result, the typically cool base to the accretionary prism is systematically heated to form magmas and hydrothermal fluids.

The globally youngest-dated orogenic gold lodes are the small and very widespread vein systems of the Alpine–Carpathian orogen (Figs. 5a and 8; Table 4), which record final Europe–Adria/Africa collision in the Paleogene by closure of the Penninic Ocean (the western side of the Tethyan Ocean). Much of this region underwent nappe thrusting and high temperature metamorphism in the latest Eocene, followed by Oligocene vein formation. The best-studied gold deposits in the central Alps include those of the Monte Rosa province in northwestern Italy. Veins were emplaced into pre-Mesozoic basement schists and gneisses, metamorphosed Variscan granitoids, and Mesozoic ophiolites between about 33 and 10 Ma (Diamond and Wiedenbeck, 1986; Curti, 1987; Pettke et al., 1999). This was simultaneous with a change to wide-scale strike–slip faulting, rapid exhumation of the orogen, and melting of the lower lithosphere, which have been attributed to slab breakoff beneath the orogen. Pettke et al. (1999) indicate a northeast-trending diachronous younging of vein emplacement across the gold province. Formation of Oligocene gold veins continued eastward into the Austrian Alps (Prochaska et al., 1995) and additional Late Miocene veining occurred in the Swiss Alps at about 10 Ma (Marshall et al., 1998). In contrast to the orogenic gold deposits of the Alps, many of the more poorly documented ore systems of the Carpathians and other mountain chains in Slovakia, Romania, Greece, etc., appear to be volcanic rock-related epithermal systems (Mitchell, 1996).

Additional mid-Tertiary orogenic gold lodes, although little described in the western literature, appear to extend along the more than 2000-km-long Red River fault zone in southeast Asia (Figs. 5b and 8; Table 4). This major crustal shear zone separates the South China and Indochina blocks, which were likely amalgamated in the middle Paleozoic or Late Triassic (Metcalf, 1996). The most significant gold resources in Vietnam are situated near the eastern margin of the fault zone and, to the west, these continue through south-central China. Yang (1996) indicates that initial dates on gold veins from the Ailaoshan area range from about 50 to 30 Ma, thus indicating veining during the onset of Indo-Asian

collision and resulting strike–slip extrusion along the older Red River suture. Recent U–Pb geochronology along the China side of the fault zone indicates that much of the tectonism and magmatism is post-Eocene (Zhang and Scharer, 1999), suggesting that the reported dates of gold formation older than about 35 Ma are problematic.

2.8. Present and future

Absolute dating of orogenic gold-vein formation from many of the above Tertiary and older mineral deposits clearly indicates hydrothermal fluids formed along active continental margins during collisional orogenesis, and subsequent associated fluid migration typically occurred during strike–slip events that reactivated earlier-formed structures within the orogen. Veins with economic amounts of gold were emplaced in epizonal to hypozonal environments indicative of depths of anywhere between about 3 and 20 km. But what about areas of the globe where these 3- to 20-km-deep host rocks have yet to reach the surface? What shallower surface features can possibly be indicative of deeper, unexposed orogenic gold veins? And where are these hydrothermal systems active within the present-day crust?

Major translational fault zones along present-day plate boundaries are characterized by spring discharges that may include a large component of deep crustal fluids. These fluids may have deposited gold at deeper levels of their flow path, but, in the cooler, near-surface environment, gold solubilities are reduced. Mercury and antimony are much more likely to be soluble as bisulfide complexes at relatively low temperatures and, therefore, cinnabar and stibnite are commonly encountered in the most shallowly emplaced veins along collisional margins (Goldfarb et al., 1993).

The Alpine fault defines the boundary between the Australian and Pacific plates on the South Island of New Zealand. A shift from strike–slip to oblique convergence since the late Miocene has resulted in rapid uplift of the Southern Alps along the east side of the fault. Gold-bearing quartz veins have been identified in extensional fractures within greenschist facies rocks of the New Zealand Alps. The veins are interpreted to have formed within the uplifting rocks sometime during the last 7 m.y. as geotherms were

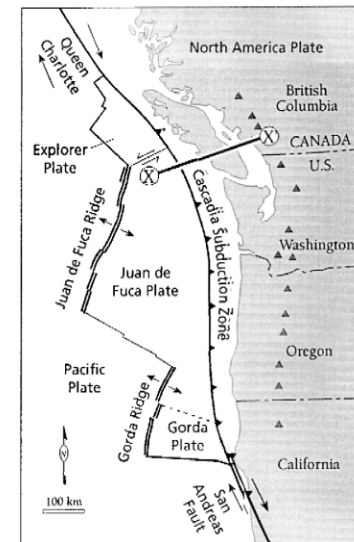
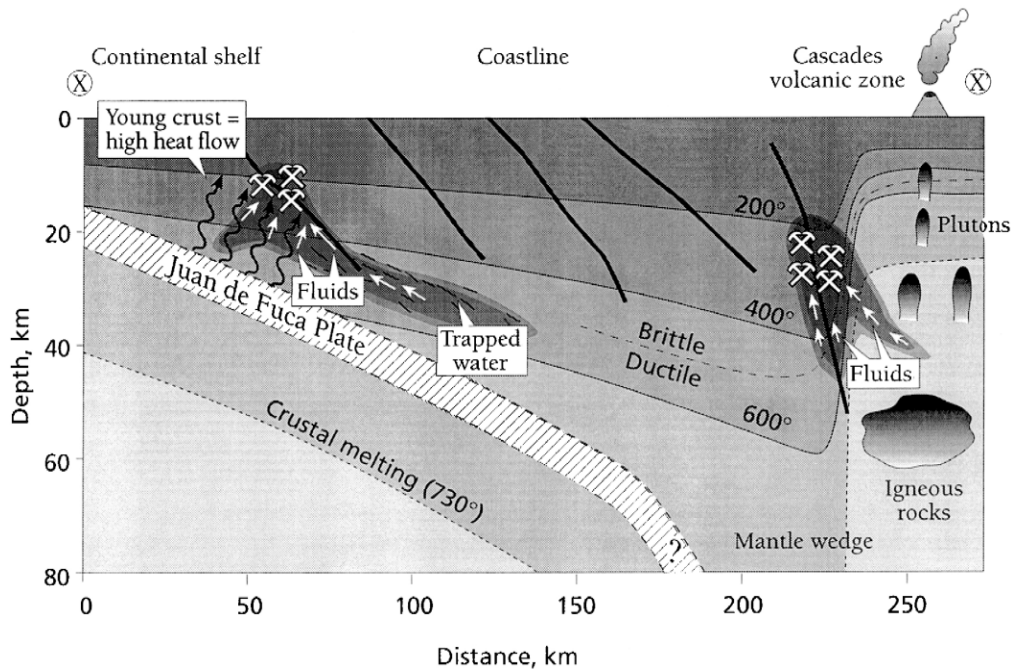


Fig. 9. Present-day subduction of the Juan de Fuca plate beneath the North America plate, and associated crustal thermal data, after Lewis (1991) and Hyndman (1995). High electrical conductivity at about 450°C indicated by seismic reflectivity data may be indicative of layers of high fluid porosity, reflecting devolatilization beneath the continental shelf and driven by hot, young oceanic crust spreading from the Juan de Fuca ridge. Measured heat flow data also indicate very high thermal gradients extending for about 20 km west of the active Cascadia magmatic arc. Such conditions would favor production of a very large mid-crustal to deep crustal fluid reservoir. At both locations, focusing of fluids into major terrane-bounding faults could lead to the present-day formation of orogenic gold deposits that will be exposed at the surface some tens of millions of years into the future.

elevated in the thickened core of the Kaikouran orogen (Craw and Koons, 1989; Koons and Craw, 1991). At lower elevations to the west of the Southern Alps, and along the main valley of the Alpine fault, hot springs may represent discharge of some of the deep-crustal gold-transporting fluids that have mixed with shallower surface waters (Craw et al., 1997). A similar situation exists where the San Andreas transform fault system separates the North American and Pacific plates along the California coast. The lack of a dominant compressional component, such as is active along the Alpine fault, prevents rapid exposure of any orogenic gold vein systems from alongside the deep levels of the San Andreas fault system. However, an abundance of hot springs and mercury vein systems along the San Andreas fault system provides evidence of large volumes of deep crustal fluids migrating to the surface. The unique isotopically heavy character and gas-rich nature of many of the mercury-depositing springs have long suggested that much of the discharge was tapping deep-crustal fluid sources (White, 1967).

North of the San Andreas fault system, subduction of the Juan de Fuca plate beneath the North American plate has formed the Cascadia arc that extends from northern California to southern British Columbia. Relatively orthogonal convergence has characterized this part of the continental margin throughout much of the Cenozoic (Engelbreton et al., 1985). Active volcanoes in the overriding North American plate track the extent of underthrusting. In contrast to the Australian/Pacific plate boundary in New Zealand, only very shallow levels of the evolving orogen are exposed. Studies of the deep structure along the North American plate boundary suggest significant fluid volumes at depth above the downgoing Juan de Fuca plate (Hyndman, 1995), and these could be reservoirs for forming lode-gold deposits at higher crustal levels during future uplift and exposure of deeper parts of the orogen. Crustal heat flow data indicate a major rise in geotherms about 200 km inland from the seaward edge of the accretionary prism and about 20 km seaward of the Cascadia arc (Lewis, 1991; Fig. 9). Such a location is consistent with many major forearc settings for orogenic gold, including the Sierra foothills of central California and the Juneau gold belt in southeastern Alaska. It is

not unrealistic to consider that orogenic gold lodes are forming at present, or will form in the future, at depth along this part of the North American continental margin.

3. Observations on the distribution of orogenic gold through geological time

Orogenic gold veins have formed in the crust for at least the last 3 b.y. The consistent geological characteristics of these ores suggest mobilization of a crustal fluid with a distinct chemistry during the main episodes of orogenesis (Groves et al., 1998). The temporal distribution of the most important Precambrian (Fig. 3) and Phanerozoic (Fig. 4) gold deposits, excluding the still controversial Witwatersrand ores, indicates most exposed and not eroded veins formed at about 3.1, 2.7–2.5, 2.1–1.8, and 0.6–0.05 Ga. Exclusive of these periods, the only other recognized orogenic gold deposits that have yielded more than about 1 Moz Au are lodes rimming the southern Siberian platform with some reported dates as old as 0.83 Ga; however, in terms of the history of their host terrane, many of these Russian ores are potentially much younger. Is there something special about these now well-defined time periods in Earth history that favored the concentration of gold described above? Conversely, can this pattern, which we have attempted to refine above, be used to help resolve plate tectonic evolution?

The pattern of ages of Precambrian vein formation is, in part, remarkably similar to that of the episodic growth of juvenile continental crust. Condie (1998) suggests that 75% of the juvenile continental crust on Earth developed in two “super-events”, which formed supercontinents at 3.0–2.5 and 2.15–1.65 Ga. These may be periods of major mantle overturning (Davies, 1995), when whatever style of tectonics was active at that time was driven by rapid replacement of the upper mantle and extreme heating of the base of the lithosphere. Much of the world lode-gold resource was deposited in new and adjacent reworked crust during related tectonism. An additional super-event, however, characterized the growth of Rodinia between 1.3 and 1.0 Ga, but without significant gold veining. The remainder of the world’s gold formed in younger Phanerozoic

orogenic belts, which included the development of small fragments of juvenile crust throughout the last 600 m.y.

3.1. Archean / Early Proterozoic vs. Phanerozoic orogenic gold: products of the same process?

The geological similarities of the Middle Archean, Late Archean and Paleoproterozoic orogenic gold deposits with the Phanerozoic deposits require some significant degree of consistency in the ore-forming process. These similarities have led many workers to conclude that both groups of deposits are related to the same type of convergent plate margin-style tectonics (Wyman and Kerrich, 1988; Barley et al., 1989; Hodgson and Hamilton, 1989). Most models for Phanerozoic orogenic gold deposits stress some type of association between hydrothermal activity and subduction-related events along a continental margin (e.g., Goldfarb et al., 1988; Landefeld, 1988; Haeussler et al., 1995); in fact, a relationship to subduction-related tectonics is the unifying characteristic of the Phanerozoic deposits. Are the same type of tectonic events likely to have occurred episodically between 3.1 and 1.8 Ga? Such a question essentially requires a decision as to whether or not present-day plate tectonics were operative as far back as 3.1 Ga and, if not, identifying other options that are feasible to ultimately cause formation of the Precambrian ores.

The question of whether the Phanerozoic style of plate tectonics continues far back into the Precambrian, a time of significantly more heat loss by the Earth, remains extremely controversial (e.g., Hamilton, 1998). Many workers today favor the validity of such a model. The rifted margins of many Archean cratons have often prevented comprehensive study of Precambrian tectonics much farther back in time than about 1.0 Ga, but, in a few cratons (e.g., Superior province of Canada), there is strong evidence for Archean plate tectonic processes (e.g., de Wit, 1998). It has been suggested by de Wit (1998) that a major transition in global tectonic regimes took place at about 3.0 Ga, perhaps correlating with formation of the first supercontinent (the Ur supercontinent of Rogers, 1996). Such a model favors a change from “overstacking” of oceanic allochthons and development of cratonic keels, to present-day,

subduction-style plate tectonics. Resulting subduction-related thermal regimes and dehydration reactions would have initiated significant hydrothermal fluid flow that was capable of dissolving gold from mafic rock residue, which dominated in abundance the lower parts of the keels. This initiation of recycling of the hydrated oceanic lithosphere also would temporally correlate with the oldest-recognized major crustal gold-forming events in areas such as the Kaapvaal craton.

Orogenic gold occurrences appear throughout many Archean/Paleoproterozoic cratons (Fig. 6), despite a variety of crustal responses to Precambrian tectonic regimes. For example, the gold-rich Yilgarn craton is dominated by a granodiorite–granite–monzogranite series of plutons that is typical of calc-alkaline magmatism derived by relatively shallow fractional crystallization. Alternatively, the gold-rich Superior province is dominated by the tonalite–trondhjemite–granodiorite (TTG) series of sodic igneous bodies that is more consistent with deep partial melting of mafic material in the cratonic keels. Despite the different Late Archean magmatic processes that probably broadly operated in the two cratonic blocks, both blocks were similarly characterized by voluminous, gold-depositing fluid generation and flow events.

Within some Precambrian cratons dominated by TTG suites, ovoid-shaped granitoids have commonly been suggested to represent diapiric structures formed through vertical displacement during local mantle-plume episodes (e.g., Choukroune et al., 1997). If such a tectonic process really was active in some of the Late Archean cratons, then it can be concluded that the occurrence of major syntectonic gold systems in these (i.e., Dharwar and Zimbabwe cratons) indicates that ore-forming events were also associated with this second style of Archean crustal growth. This suggests that a variety of processes capable of transferring heat into the lower and middle crust, during relatively rapid 3.0–2.5 Ga continental growth, were likely ultimate causes of gold genesis; subduction-related tectonics need not be a requirement for orogenic gold-vein formation. Barley et al. (1998) take the further step to suggest that a coupling of both subduction-related tectonics and the tapping of hot mantle was required for generation of the major provinces of Late Archean, Paleoproterozoic

zoic, and Phanerozoic orogenic gold lodes. Whether or not subduction-related plate tectonics did occur in the Precambrian, the episodic nature of continental growth in the Precambrian relative to a continuous 600-m.y.-long history of tectonism throughout the Phanerozoic suggests that some, still poorly understood, basic difference in global tectonics must have characterized these times.

3.2. *Preservation of orogenic lodes*

Perhaps the most obvious explanation for some aspects of the nature of the global distribution of orogenic gold is that of preservation. The Archean has been typically viewed as the premier period for orogenic gold-vein formation (e.g., Hodgson, 1993), but (exclusive of Witwatersrand) presently recognized Phanerozoic gold resources are about twice as great as those from the Archean (Figs. 3 and 4). In recent years, increased accessibility to production/resource data for Phanerozoic gold provinces, including those of the central Asian republics, the Ural Mountains of Russia, and deposits in eastern China, have led to improved estimates of global gold distribution. The great circum-Pacific placer fields of California, eastern Russia, and the Tasman orogenic system also must be considered when estimating gold concentrations from Phanerozoic orogenic belts. Finally, if the early production by the Romans in Iberia and Egyptians in the Arabian–Nubian shield is included, slightly more than 1000 Moz Au were sited in discovered economic orogenic gold-deposits that formed during the last 600 m.y.

It could be argued that more of these gold-favorable environments occur as parts of Phanerozoic orogenic belts simply because more of such young crust is exposed over the Earth's surface. Based on global crustal distributions described by Goodwin (1991), about 50% of the Earth's continental crust is older than 600 Ma. However, 71% of this Precambrian crust is buried by younger rock sequences (Goodwin, 1991), and younger Phanerozoic orogens are less likely to be similarly buried. If the same gold-forming processes were continuous throughout geologic time, and assuming little significant change in gold content of source rocks, then a greater resource of orogenic gold from Phanerozoic time is expected.

The great Phanerozoic gold resource, therefore, superficially, is consistent with more voluminous exposure of younger rocks.

The above argument, however, fails when the Proterozoic is compared with the Late Archean. The exposed Precambrian crust consists of 22–23% each of Archean, Paleoproterozoic, and Mesoproterozoic rocks, with 33% Neoproterozoic rocks (Goodwin, 1991). However, the relatively small surface area of Archean crust hosts a very high proportion of the Precambrian gold resource. More than 400 Moz Au have come from Late Archean concentrations (e.g., Yilgarn craton, Superior province, Kolar greenstone belt), which is about double the resource from the Paleoproterozoic (e.g., western Africa, Homestake). More significantly, with the exception of perhaps 100 Moz Au from the mobile belts surrounding the Siberian craton, where absolute dates are still problematical, and the ores of the Arabian–Nubian shield from the very latest Proterozoic, there are no important gold concentrations within the period of 1.8–0.6 Ma. This is despite about 55% of the exposed, preserved Precambrian crust having formed during this time. This inequity within the Precambrian would be significantly further skewed to the Archean if the Witwatersrand gold ores have some association with the orogenic lode-gold deposits, either directly or indirectly as sources for giant placer deposits.

The Archean gold ores are mainly restricted to the Late Archean. The 10 Moz Au from the Barberton greenstone belt is the only significant gold concentration from the Early and Middle Archean despite extensive continental growth at 3.8–3.5 and 3.2–3.0 Ga. Preserved granitoid–greenstone sequences older than 3.0 Ga comprise about 7% of the recognized Archean sequences. They contain, however, no more than about 2% of the Archean orogenic gold lodes. Again, questions regarding a possible Middle Archean lode source for the Witwatersrand ores, assuming a paleoplacer origin, make meaningful generalizations difficult. In addition, the very widespread, but limited in volume, outcrops of older Archean crust support extensive recycling of such material into the mantle during increased convection rates on a much hotter early Earth (Condie, 1997). It is, therefore, unlikely that the importance of orogenic gold vein formation during the first billion years of Earth history, including the 3.8–3.5 Ga period of

rapid continental growth, can ever be fully determined.

In summary, the large gold resource in Late Archean rocks, and, to a lesser extent, in Paleoproterozoic rocks, is certainly due to the preservation of this crust in platforms and inliers of early Precambrian crust. However, preserved crust from the later Precambrian (1.8–0.6 Ga) is widespread in many Precambrian platforms (Fig. 5a–c). It thus follows that other reasons, in addition to simple preservation of terranes formed by equivalent geological processes, are required to explain the temporal distribution of orogenic gold.

3.3. Proterozoic gaps in gold veining: what was different?

It is widely recognized that, during the almost 2000 m.y. of Proterozoic history, significant orogenic gold-deposit formation was concentrated at 2.15–1.8 Ga (Fig. 3). This is the only time during the Proterozoic when supracrustal sequences are dominated by greywackes, turbidites, and ocean-floor volcanic rocks, which include komatiites. The remainder of the preserved Proterozoic is noted for an abundance of lithologies indicative of intracratonic basins, stable continental margins, continental rifts and shallow platforms, with associated giant stratiform base-metal deposits and iron-rich intracratonic ores (Condie, 1982; Tittley, 1993a,b).

Not only is there a significant apparent gap in gold ore deposition between 1.8 and 0.6 Ga, but there is also no significant gold veining recognized at the start of the eon between 2.5 and 2.15 Ga. This earliest Proterozoic gap and the period from ca. 1.65–1.3 Ga are especially noted for a lack of syntectonic granitoids, and greenstone and/or slate-greywacke belts (Condie, 1997). These are periods of the Proterozoic with the least juvenile crustal growth (Condie, 1998) and, subsequently, few well-developed orogens that would have provided favorable environments for orogenic gold formation. Instead, most of the exposed continental crust of these ages is reworked material, which was eroded from and covers older ca. 3.0–2.5 and 2.15–1.65 Ga juvenile basement rocks, and was not widely tectonized. Nevertheless, the lack of major goldfields in younger Rodinian orogens (for example, the gold-poor, 1.2–0.9 Ga Grenville province of the southern

and eastern United States, eastern Canada, and Scandinavia) indicates that factors in addition to continental growth must be considered in evaluating ultimate controls on ore genesis. Most likely, it is the lack of large orogens that developed between 2.5 and 2.15 Ga and between 1.65 and 1.3 Ga, and the limited preservation of gold-bearing, mid-crustal parts of orogens formed between 1.3 and 0.6 Ga, which are jointly responsible for limited gold-veining during certain periods of Earth history. Such possibilities are evaluated in more detail below.

3.3.1. 2.5–2.1 Ga

Geological features of earliest Proterozoic strata from all Precambrian platforms indicate that these environments are unfavorable for the formation of lode-gold deposits. Thick wedges of stable-shelf sedimentary rocks that have accumulated upon the margins of Archean continental crust are most abundant. This apparently was a time of continental breakup of some Archean blocks, as shown by intracratonic rifts, grabens, and troughs containing 2.5–2.1 Ga sedimentary sequences (Goodwin, 1991). No major orogenies are so far known during this interval (Rogers, 1993), perhaps reflecting the episodic nature of global tectonism during Archean–Paleoproterozoic Earth history (Davies, 1992, 1995). Final collision of the Kolar terranes, which established the Indian platform, perhaps extending to a time as young as 2.4 Ga, is one of the very few recognized collisional events between about 2.5 and 2.25 Ga. The initiation of a subsequent worldwide period of subduction-related, collisional tectonics is first marked by relatively minor, ca. 2.25 Ga deformational events in northern China (Wutaian orogen) and northeastern Brazil (Maroni–Itacainus mobile belt). Within another 100 m.y., parts of many Precambrian platforms were impacted by orogeny and potentially a 250-m.y.-long period of widespread gold vein formation began.

These Paleoproterozoic platform–shelf–slope sequences are not targets for gold deposits formed between 2.5 and 2.1 Ga. Where such sequences remain preserved within cratonic blocks, they will not contain orogenic gold deposits. But where these strata have been tectonically reworked as parts of later active continental margins, a potential for gold resources can exist. The 1.88–1.85 Ga Barramundi

orogen in northern Australia, and the Variscan ores along the margins of the North China craton, provide examples where tectonically reworked earliest Proterozoic rocks become important gold hosts during later collisional episodes. Therefore, it appears that older miogeoclinal sequences developed along a passive margin certainly must be considered permissive regions for orogenic lode-gold deposits, if these sequences are later impacted by an evolving orogenic belt and not simply preserved in stable cratonic areas. This also indicates that, if the common hypothesis that the ore-forming fluid and the associated metals in the orogenic gold systems evolved within the lower to middle crust is correct, the lack of gold formed between 2.5 and 2.1 Ga is not simply due to inherently low metals or sulfur deeper within the epicratonic sedimentary facies. Rather, it indicates the absence of the necessary ore-forming hydrothermal processes themselves at that time of limited crustal growth.

The period between ca. 2.5 and 1.9 Ga is also well-recognized as a time of increasing oxygen abundance in the atmosphere, significant paleoplacer formation, and deposition of most Superior-type BIFs. The exceptional concentrations of orogenic gold within the crust, both just prior to 2.5 Ga and just subsequent to 2.1 Ga, indicate that the major change in oxidation state of the atmosphere had no direct impact on the ore-forming process. Cratonization of many auriferous Archean provinces by 2.5 Ga, followed by extensive earliest-Proterozoic basin formation, formed potentially favorable environments for placer gold accumulations (e.g., Tarkwa, Ghana). This is possibly a similar cycle to that of the earlier Precambrian, when cratonization of the Kaapvaal block at about 3.0 Ga was followed by hypothesized placer gold accumulation during subsequent intracratonic Witwatersrand-basin formation. The Superior-type BIFs formed in the stable platform environments described above and, in contrast to the Algoma-type BIF deposits that are more closely associated with oceanic volcanic activity, show no association with gold ores (see Section 3.5 below for discussion of Algoma-type BIFs).

3.3.2. 1.8–1.3 Ga

The late Paleoproterozoic through middle Mesoproterozoic is another period in the crustal evolution

of Earth characterized by little orogenic gold formation. In addition, subsequent to about 1.65 Ma, there was little new juvenile crust preserved in continental masses and limited amounts of continental growth (Condie, 1998). Stable cratonic amalgamations were characterized again by widespread epicratonic sedimentary rock sequences (Windley, 1995). However, in contrast to the previous gold-poor, 2.5 to 2.1 Ga period of Earth history, the time from 1.8 to 1.3 Ga was characterized by extensive felsic magmatism. Worldwide extensional tectonism, perhaps correlated with the break-up of a pre-Rodinia supercontinent, included extensive melting of the lower crust forming anorogenic rapakivi granites and emplacement of associated, mantle-derived anorthosites. Although generally not considered a time of important continental growth, major accretionary orogens along the North and South American margins, and collisional orogens between the Paleoproterozoic Australian blocks, developed near the Paleoproterozoic to Mesoproterozoic transition. These theoretically would be expected to represent favorable terranes for orogenic gold deposits, but they lack known resources.

The present Australian continent is composed of three major cratonic blocks that amalgamated as part of Rodinia at about 1.3 Ga (Fig. 1; Myers et al., 1996). The so-called North, South, and West Australia cratons were sutured at this time by the Albany–Fraser and Musgravian orogens. The continental-scale collisional zones were partly characterized by deformation and metamorphism of old basement rocks, although Myers et al. (1996) also suggest a possible initial accretionary orogen similar to that of the Mesozoic–Cenozoic North American Cordillera. In either case, the lack of gold resources is notable. During other times elsewhere in the world, certainly both reworked basement in collisional orogens (i.e., the European Variscan) and allochthonous terranes of many accretionary orogens provide abundant favorable sites for gold ores. Furthermore, in a very similar scenario, the Proterozoic sequence of the Trans-Hudson orogen, which sutured the Archean Wyoming and Superior provinces of central North America into the Hudsonian craton by about 1.8 Ga (Sims et al., 1993), hosts the important orogenic gold veins of the Homestake deposit. However, in the slightly younger, yet tectonically similar, Albany–

Fraser and Musgravian orogens, there are no lode-gold deposits. Possible reasons for this include: (1) the relatively deep crustal exposures of much of the orogens that show rocks from depths below those typically most favorable for orogenic gold, (2) the lack of a major syncollisional thermal event as supported by restricted distributions of granitoids, and, somewhat related, (3) the probable lack of significant accretion/subduction, as shown by high-grade gneisses that are suggestive of reworked Archean thrust fragments from colliding cratonic blocks.

Significant growth of North America occurred between 1.8 and 1.5 Ga along the southern side of the Hudsonian craton (Hoffman, 1989). Accreted seafloor volcanic rocks and turbidites form the resulting Transcontinental Proterozoic provinces (Van Schmus et al., 1993), which now extend from eastern California to Labrador in a belt locally as much as 1000-km-wide. These sedimentary and volcanic rock successions probably reflect many individual amalgamated and accreted crustal fragments from a variety of sources. The syncollisional inner Yavapai and outer Mazatzal orogens formed within the accreted juvenile crust at about 1.78–1.69 and 1.68–1.61 Ga, respectively, and were affected soon after, at 1.5–1.4 Ga, by voluminous anorogenic magmatism.

The lack of Proterozoic gold deposition during this growth of southern Laurentia is problematic and could relate to any of a number of possibilities. Much of the hypothesized tectonic evolution of this margin is interpreted similarly to that which is characteristic of the gold-rich, Phanerozoic Cordilleran orogen. However, unlike the > 100-m.y.-long Cordilleran orogeny, stabilization of both the inner and outer accreted belts in the Transcontinental provinces occurred within about 10 m.y. of collision and deformation (Van Schmus et al., 1993). This may, in part, reflect the lack of typical crustal thickening and regional uplift during these periods of orogenesis characterized by isostatically stable crust. Perhaps processes of uplift, coupled with decreasing lithostatic loads (e.g., Norris and Henley, 1976; Groves et al., 1987), are critical for establishing the crustal fluid dynamics needed to form orogenic gold lodes. An additional structural constraint may be the fact that the Cordilleran orogen is dominated by extensive transcurrent structures, whereas the generally unfragmented Yavapai/Mazatzal orogens were

mainly developed through orthogonal collisional events (Condie and Chomiak, 1996). As with the need for regional uplift, a lack of more oblique movement between accreted blocks may hinder crustal-scale hydrothermal fluid flow events (e.g., Goldfarb et al., 1991).

Condie and Chomiak (1996) attempt to define major differences between the Cordilleran and Yavapai/Mazatzal orogens. Lithologically, the Cordilleran terranes are characterized by a higher percentage of carbonates, non-turbiditic pelites, non-komatiitic ultramafic rocks, and other units that are typical of relatively immature oceanic terranes. The terranes of the southwestern United States are alternatively composed of more mature sedimentary rocks derived from a continental margin arc, with few remnants of oceanic crust. The most significant difference in the bulk chemistries of the two areas is the 11.6% LOI content of the Cordilleran rocks relative to the 1.5% LOI of the Yavapai/Mazatzal rocks. Condie and Chomiak (1996) attribute much of this difference to the relatively extensive carbonate platform sequences within the Cordillera. However, if water and sulfur were also significantly lower in the more mature sequences, this could hinder formation of important orogenic gold lodes (assuming a genetic model where ore fluids are produced during devolatilization events in the crust). Typically, water concentrations in rocks within oceanic terranes are about 5% (Fyfe et al., 1978) and, if shales are abundant, sulfur may also be present at the percent level (Govett, 1983), suggesting that the Yavapai/Mazatzal rocks are relatively depleted in all volatile species.

The absolute gold content of these rocks is also probably relatively low. The average gold content of Cordilleran-type accreted terranes is perhaps about 2.2 ppb, whereas the continental arc that was eroded to form the southwestern US terranes likely averaged < 1 ppb Au (e.g., Crocket, 1991). These latter terranes would, therefore, not have been very good source rocks for leaching of gold, if this is an important factor in ore genesis.

Another possible explanation for the lack of orogenic gold within the Yavapai and Mazatzal orogens is simply a lack of exposure, rather than problems with the regional hydrology or source rock chemistry. It is possible for ores to have formed between 1.8 and 1.6 Ga, and then simply been eroded away

or remain buried. In support of the former possibility, much of the exposed Mesoproterozoic section is at amphibolite facies. The more typically gold vein-bearing, greenschist-grade rocks were likely eroded during a 1.45–1.20 Ga period of regional uplift that accompanied collision of the Grenville terranes on to southern Laurentia. However, if gold veins did occur here prior to deep erosion, then some important paleoplacers would be expected in the southwestern United States and none are recognized. Alternatively, if gold deposits were formed and remain in unweathered greenschist facies rocks, perhaps they are simply not exposed. Less than about 5% of the rocks of the Transcontinental Proterozoic provinces are exposed, with the vast majority buried beneath the Paleoproterozoic and Phanerozoic cover rocks.

A vast and long-lived accretionary orogen also characterized what is the present-day southwestern margin of the Amazonian craton. Resulting, mainly gold-poor mobile belts evolved throughout the final stages of the Paleoproterozoic and much of the Mesoproterozoic (Goodwin, 1991). The more northerly Rio Negro belt formed along the western edge of the Guyana shield at about 1.75–1.5 Ga. Although lacking recognized orogenic gold lodes, recently discovered and still poorly understood paleoplacer gold occurrences (e.g., Caranacoa, Maimachi, Traira and Caparro) suggest that some auriferous lodes may have formed in the belt and been eroded during unroofing (Orestes Santos, written communication, 1999). Subsequently, at ca. 1.3–1.0 Ga, the even more extensive Rondonian Complex belt was added to the growing continental margin, with the end of the orogeny defined by 1.0–0.95 Ga anorogenic granitoids (Goodwin, 1991). Various collisional events in the gold-poor complex are apparently represented by the Juruena, San Ignacio, Sunsas, and Aguapei belts or provinces. Much of the collision was between metamorphosed basement rocks, rifted during 1.5–1.4 Ga supercontinent breakup and accreted to the Amazonian craton prior to final closure of the Grenville Sea at about 1.0 Ga (Sadowski and Bettencourt, 1996). As with the Transcontinental Provinces along Laurentia, exposures of these mobile belts along the South American platform margin are dominated by high-grade schists and gneisses. Again, it is conceivable that the lack of economic gold reflects crustal exposures beneath those that typically

would be most favorable for orogenic lode formation.

3.3.3. 1.3–0.6 Ga

This 700-m.y.-long period represents the formation (1.3–1.0 Ga), stabilization (1.0–0.75 Ga), and eventual break-up (0.75–0.6 Ga) of Rodinia. Significant accretionary and collisional orogens characterized initial supercontinent growth, although many specifics of reconstruction remain contentious. The Grenville orogen is commonly shown to have extended from Baltica, along Amazonia (San Ignacio and Sunsas–Aguapei belts), to the present-day south of the Laurentian Transcontinental Provinces. If the SWEAT (Southwestern U.S.–Eastern Antarctica connection) hypothesis of Moores (1991) is accepted, some of the Grenville rocks in North America may have been connected to those impacted by Musgravian events in eastern Australia (see above section). Other extensive late Mesoproterozoic–middle Neoproterozoic orogens were initiated along the present-day southern margin of the Kaapvaal craton (Namaqua–Natal–Falklands mobile belt); eastern margin of the Tanzania craton (Mozambique belt); between the amalgamated Tanzania, Zimbabwe, and Congo cratons (Kibaran–Irumide belts); between Eastern Antarctica and India (Eastern Ghats–central India belt); between India and Western Australia (Pinjarra orogen) and on the margins of the Siberian Platform. Among these, significant ca. 1.3–0.6 Ga gold ores were potentially only produced at about 0.85–0.81 Ga in the latter Russian example, and even the dates there are very suspect. Many of the Russian lodes might also be Paleozoic in age (see discussion above on the Balkides).

Many of the same possibilities as described above, for the period from 1.8–1.3 Ga, are also potential causes for limited gold deposit formation between 1.3 and 0.6 Ga. For example, the predominantly deep crustal levels (20–30 km) of the Grenville orogen that are now exposed across North America, from the southwestern USA to Labrador, may have been beneath suggested greenschist/amphibolite zones of auriferous fluid production (e.g., Goldfarb et al., 1997) and resulting shallower orogenic lodes. High-grade gneisses and schists also characterize many of the other orogenic belts, including the Namaqua–Natal–Falklands belt and much of the Mozambique

belt. The central African Kibaran–Irumide belts, however, are dominated by mid-crustal greenschist facies, suggesting that other factors, including limited uplift, limited transcurrent motion, or unfavorable source rocks, characterized accretion and collision of the central African blocks. The abundance of early Neoproterozoic gold ores around the southern margin of the Siberian platform indicates that, in some of the growing Rodinian margins, orogenic lodes did develop.

3.4. *Gold-poor Phanerozoic orogens*

Examination of Phanerozoic active margins that lack orogenic gold deposits can provide important clues in understanding the ore genesis process and may help explain why certain Precambrian orogens are gold-poor. The Andean orogenic belt along the western margin of South America is an extensive part of the active Pacific Rim margin lacking significant exposed orogenic-gold systems (Fig. 5c). Guilbert (1992) noted the variability in metallogeny between types of convergent continental margins. Mesozoic–Cenozoic margins of western North America and eastern Asia, as well as the Paleozoic Gondwanan margin of Australia and New Zealand, are regions of extensive continental growth via accretion of new allochthonous terranes. In contrast, the Pacific side of South America is a non-collisional “consuming margin”, which is characterized by “subduction–erosion” of what would normally be the forearc region and accretionary prism (Scholl et al., 1980). Paleozoic accreted terranes, which collided with the South American Gondwana margin, have been eroded during Mesozoic–Cenozoic subduction of the Nazca plate beneath the westwardly migrating South America plate. Most of the continental margin is dominated by the high elevations of the rising Andean arc, exposing shallow crustal levels that are typical hosts for porphyry and epithermal mineral deposits, but not more deeply emplaced orogenic gold lodes. Apparently, an active margin lacking extensive forearc development may contain important gold-bearing mineral deposits, but is not a favorable environment for orogenic gold deposits.

The Japanese Islands provide another Pacific-Rim situation where orogeny is characterized by subduction of an oceanic plate (often referred to as an

Andean or Cordilleran-type orogeny) without collision of buoyant terranes or other continents. Accretionary prisms have nevertheless been built along the Pacific margin of the islands, and, unlike the Andean margin, at least those in southwest Japan have not been destroyed by tectonic erosion. Examination of the geology of Japan suggests that the 1000-km-long and 40- to 70-km-wide Ryoke belt in the southwest would make a favorable target for orogenic gold lodes. Deeper metamorphic zones are exposed over much of the belt relative to the Andes. Rocks presently at the surface are part of a high-temperature inverted Barrovian sequence that regionally extends through greenschist facies and reaches upper amphibolite facies, and is widely intruded by Cretaceous–early Tertiary arc plutons. However, these rocks do not host any significant orogenic gold lodes. Establishment of a convergent margin and subduction began along the margins of the Pacific basin beneath southeastern Australia, California and Japan all at about the same time (about 150 m.y. after the 600 Ma initial opening of the Pacific Ocean; Maruyama, 1997; Maruyama et al., 1997). It is unclear why the resulting orogens in the former two localities contain tens of millions of ounces of orogenic gold, whereas only a few thousand ounces have been recognized in the latter. Nakajima (1997), in fact, compares the tectonic setting of the Ryoke belt and the more seaward Sanbagawa blueschist belt, to the auriferous Sierra foothills belt and outboard Franciscan rocks of central California.

What is different in southwest Japan relative to other circum-Pacific gold-rich orogens? It is not a lack of heat; high metamorphic temperatures and the granitoids record high-temperature conditions. It is not the lack of new continental crust that could provide a fluid and/or metal sources; despite a lack of terrane collisions, accretionary complexes were still built outward during offscraping from a subducting slab. Voluminous fluid production is recorded by the widespread regional metamorphism, and these fluids may, in part, have been responsible for the extensive melting. A lack of leachable gold or sulfur required to form a stable complex with gold in the ore fluids is possible, but unlikely. The accreted rocks of the Ryoke metamorphic belt include pelitic metasedimentary rocks and oceanic volcanic rocks similar to those in many continental margins with an

abundance of gold-bearing veins. Their gold or sulfur contents should not be exceptionally different. The most likely difference in the Japan example could be crustal hydrology. The Japanese Islands are generally defined as a series of mainly subhorizontal nappes of various accretionary complexes (Nakajima, 1997). The lack of well-defined subvertical fault zones, capable of upwardly focusing deep crustal fluids, may be a critical missing ingredient for the formation of orogenic gold ores here. Perhaps the Japanese Islands have not yet reached the stage where nappe/thrust structures are rotated to the near-vertical by continuing compression to be reactivated by transpressional motion subsequently with the release of auriferous fluids (Goldfarb et al., 1991), and/or where slab delamination has occurred.

Other examples of gold-poor Phanerozoic orogens from North America highlight the need for elevated geotherms. Orogenesis in both the Brooks Range of northern Alaska and the Taconic event of the Appalachians of eastern North America is dominated by obduction onto the continental margin. In northern Alaska, oceanic crust was overthrust passive-margin sedimentary rocks between 170 and 130 Ma during the main Brookian convergence. The underlying rocks, now exposed for about 1000 km, and composing the southern half of the Brooks Range, underwent blueschist- and then retrograde greenschist-facies metamorphism (Dusel-Bacon et al., 1989). Orogeny is notable for the lack of syntectonic magmatism along the entire length of the Brooks Range. This is indicative that crustal temperatures throughout the orogen never reached high enough levels for melt formation; in fact, the lack of high-grade metamorphic rocks is consistent with temperatures never exceeding about 450–500°C in any exposed levels of the orogen. This would suggest that regionally extensive blocks of crust at temperatures between greenschist facies conditions and crustal melting are required for formation of orogenic gold deposits. This is supported by the fact that the Otago gold deposits of South Island, New Zealand, are the only clear example of orogenic gold deposits lacking a spatial-temporal association with magmatism; they may represent a case where deep parts of an orogen devolatilized through amphibolite facies conditions (releasing fluids and sulfur), but did not reach temperatures required for melt formation. As stated

above, there is some syn-gold magmatism on the South Island, but it is only recognized > 200 km from the Otago goldfields.

The early Paleozoic part of the Appalachian orogen was also characterized by obduction of oceanic crust, as well as of allochthonous terranes, on to the North American passive margin. During the Middle Ordovician to Silurian Taconic event, a series of terranes were thrust on to the eastern margin of North America. This was a low temperature event with limited magmatism. It was followed by closure of the Iapetus Ocean, collision of the older accreted terranes with the Avalonia microcontinent, and a switch in polarity of subduction such that the Rheic Ocean basin was subducted beneath Avalonia in front of advancing Africa (Hatcher, 1989). It was only during this later Devonian to Early Carboniferous Acadian event that crustal temperature gradients were relatively high and magmatism was widespread. Additionally, at this time, gold ores were formed in probably what were parts of Avalonia, and these areas now make up the Carolina slate belt in the southeastern United States (with the more significant earlier gold-bearing VMS deposits discussed above) and Meguma terrane of Nova Scotia.

A similar scenario characterizes the Alpine orogen of Europe. Penninic oceanic crust and the trailing Adriatic microcontinent were thrust over the European passive continental margin between 130 and 90 Ma. This was a high-P, low-T tectonic event that lacked magmatism and gold vein formation. Orogenic gold formation in the Alps did not occur until much later during orogeny (about 100 m.y.) in the presently continuing transpressional collision between Europe and Africa. Fluid formation and migration probably were ultimately initiated by slab delamination that also caused widespread lithospheric melting of the uplifting nappe pile (Sinclair, 1997).

Based on these observations from gold-poor orogens, orogenic gold formation may require a series of events that are usually diachronous within a growing continental margin. First, convergent orogens characterized by lithospheric subduction below a growing forearc provide a very favorable thermal regime for orogenic gold formation along a continental margin. Thermal modeling experiments show that accretion of a wide zone of relatively radiogenic crustal material during subduction and collision

is the most effective method for generation of widespread increases in crustal temperatures (Jamieson et al., 1998; Fig. 10A). Such rising temperatures may be critical for initiation of hydrothermal fluid-flow events. The presence of both hydrous and sulfur-bearing marine minerals in the accreted pieces of ocean floor, and/or in the overlying sedimentary rocks, is critical for developing large fluid reservoirs in the crust of the continental margin, which are then capable of significant gold transport. If a spreading ridge is also subducted (Fig. 10D), that too may add heat into the growing margin (e.g., Haeussler et al., 1995).

Second, orogenic collapse due to detachment of a thickened and gravitationally unstable lithospheric root (Fig. 10E) or to detachment of cold subducting slab (Fig. 10F) can also trigger hydrothermal activity. In fact, rollback of a subducting slab (Fig. 10C) alone would produce the same type of heat conduction within the lithosphere. Not only will all such processes conduct heat, from the underlying convective mantle to relatively shallow levels in the core of an orogen, but also these will induce uplift and extension in the above part of the orogenic belt that may enhance fluid migration. In both cases, additional heat flow may be convectively transported by magma and fluid migration causing an even more concentrated and voluminous fluid flow event. Given these favorable fluid-generating and thermal conditions, the reactivation of earlier-formed, oversteepened thrust complexes and/or lock-up folds during a change in far-field stress, normally due to changing plate convergence, appears to be significant.

3.5. Other gold-bearing deposit types in space and time

The pattern for VMS deposits through geologic time (for example, see Titley, 1993a,b) is remarkably similar to that of the orogenic gold deposits. The VMS deposits are as old as 3.5 Ga in the Pilbara craton, and many important Precambrian examples formed during the Late Archean and Paleoproterozoic broadly simultaneously with the generation of the major orogenic gold ores. However, in more detail, the syngenetic VMS deposits pre-date orogenic gold vein formation where they occur together in a given gold province within a specific terrane

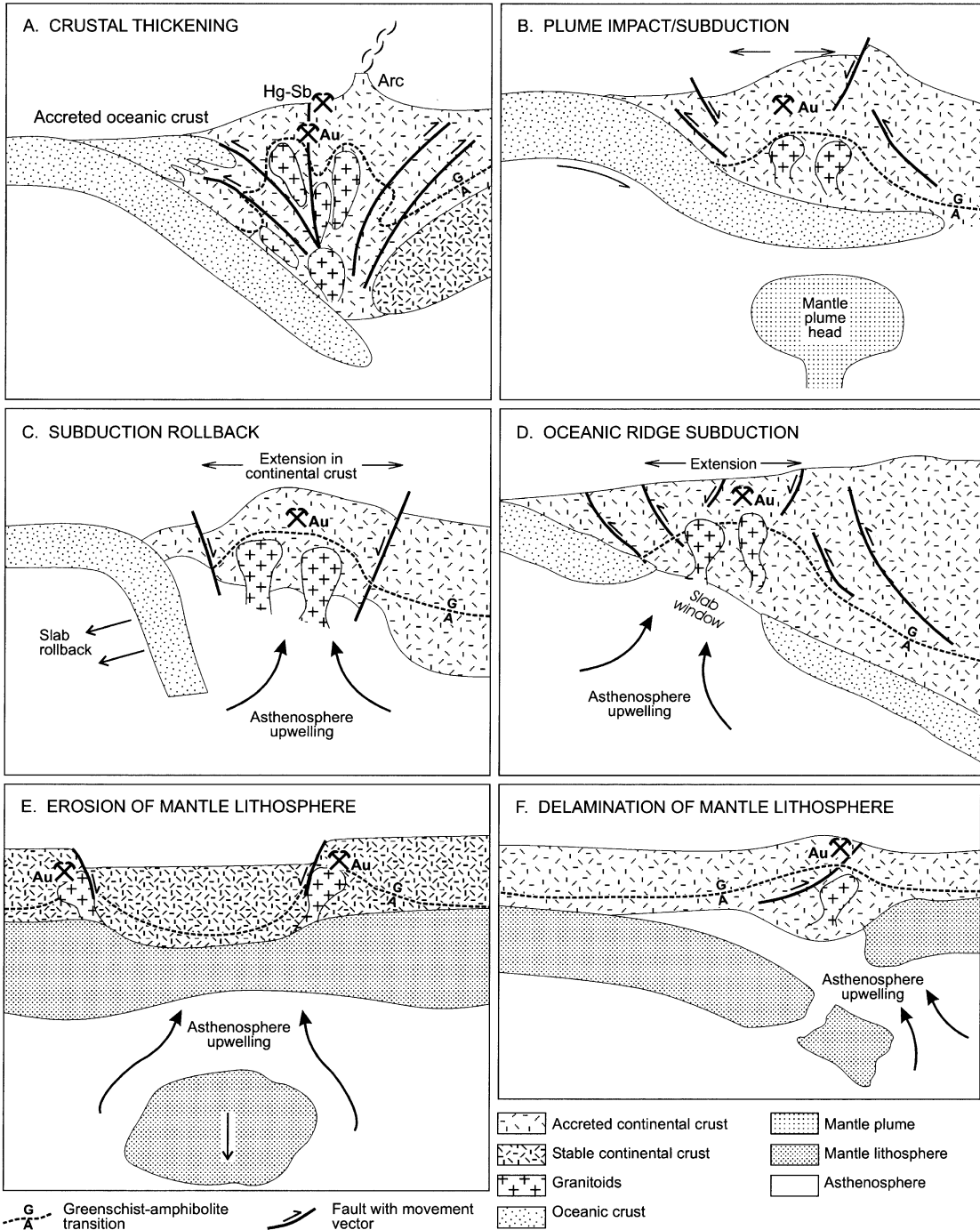
(e.g., Spooner and Barrie, 1993.) Subsequent to about 1.8 Ga, few important VMS deposits were formed until the last 600 m.y. Titley (1993a,b) notes a concentration of VMS ores that formed in the early Paleozoic and the late Mesozoic. Many recent discoveries, however, especially from the northern Cordillera of western North America, indicate that important VMS deposits formed continuously since latest Neoproterozoic time. In fact, unlike orogenic gold deposits that take many tens of millions of years to reach the surface subsequent to formation, ongoing processes of VMS deposition are widely recognized on present-day seafloor spreading ridges such as the East Pacific Rise.

The overall dynamics of plate motions are responsible for the spatial and approximate temporal association between the orogenic gold and VMS deposit types. Slab sinking, whether during possible super-events in the Precambrian or continuously during the Phanerozoic, obviously is critical to the growth of continents via collisional orogenesis. This slab motion is typically coupled with the spreading of new crust in zones of thermal upwelling in the ocean basins and backarc areas. Therefore, gold ores are being developed in the former collisional environment, while the VMS deposits are generated in the latter extensional zones. When a metalliferous block of the new oceanic crust reaches the continental margin, it may be incorporated into the growing margin. Any continuing tectonism may result in formation of new orogenic gold deposits subsequent to emplacement of the VMS deposits. As shown, for example, by the age relationships within the younger terranes of coastal Alaska (e.g., Goldfarb, 1997), formation of orogenic gold deposits will post-date VMS deposit formation within a given terrane. However, other orogenic gold deposits may be older than nearby VMS deposits, where the gold lodes formed inboard of, and prior to, the suturing of new VMS-bearing oceanic crustal blocks.

Hutchinson (1987) discussed the clustering of orogenic gold deposits in the Late Archean, Paleoproterozoic, and Phanerozoic, and attributed such to initial seafloor hydrothermal exhalative processes. Whereas it is not suggested that formation of orogenic gold systems is dependent on a metal source from older VMS deposits, it is agreed that sea floor processes are likely to add much of the water and

sulfur into the sea floor crust and overlying sediments before these are accreted to a convergent

continental margin. Later devolatilization of marine sulfide and hydrated silicate minerals, within a de-



veloping and mainly collisional orogen, is likely critical for the formation of a large-scale, gold-transporting fluid phase. Although the source of gold is still poorly understood, it too may be concentrated in widely disseminated mineral phases (e.g., pyrite, magnetite) that formed on the ocean floor. This high degree of metal and solute “inheritance” (e.g., Tittley, 1987, 1993a,b; Hutchinson, 1993) in greenstones and oceanic metasedimentary rocks, therefore, may be critical for forming important orogenic gold deposits.

The general lack of VMS deposits throughout much of the Mesoproterozoic and Neoproterozoic is problematic. Some minor VMS systems have been recognized from this time period in recent years, but there remains a strong under-representation of such deposits in the geological record from ca. 1.7 to 0.8 Ga (e.g., Fig. 5 of Barrie and Hannington, 1999). It is likely that, as with the lack of orogenic gold deposits, the similar lack of VMS deposits relates to the common exposure of the deeper parts to orogens formed during this period. There is a strong tendency for oceanic lithosphere to become isolated at high structural levels as the relatively buoyant oceanic crust is obducted into ophiolite sequences in growing accretionary wedges (Helmstaedt and Scott, 1992). Such volcanic units and surrounding sedimentary rocks are obvious hosts for most VMS systems and also are preferentially eroded during the reworking of orogens. In addition, extensive metamorphism and structural reworking of the accreted oceanic rocks, which accompany the gradual exposure of the oro-

gen core, would also hinder preservation of economic concentrations of massive sulfide.

There is a distinct spatial association between many Late Archean and Paleoproterozoic Algoma-type BIF's and a few of the important deposits classified here as orogenic. Many workers have attempted to relate these BIF-hosted gold ores (e.g., Quadrilatero Ferrifero province, Ladeira, 1991; Homestake deposit, Rye and Shelton, 1983) to syngenetic processes associated with BIF deposition. It is most likely, however, that during the Late Archean and Early Proterozoic global episodes of orogenesis, significant volumes of BIF were located along deforming cratonic margins, and these formed favorable chemical traps for orogenic gold formation within the complex volcano-sedimentary terranes. Iron-rich rocks in the deforming continental margins provide preferential zones for replacement style mineralization.

Epithermal gold and sediment-hosted micron-gold deposits are generally restricted to arc environments of relatively young age. The epithermal ores typically will evolve just above magmatic arcs on the landward side of many orogenic gold deposits or above oceanic island arcs (Fig. 2; White and Hedenquist, 1995). Therefore, at least in the former environment, there may be a temporal overlap and a slight two-dimensional spatial offsetting between orogenic and epithermal gold deposits within growing continental margins. The shallow nature ($\leq 1-2$ km), however, of lode emplacement for epithermal ores hinders their preservation within the geologic

Fig. 10. Series of simplified cartoons showing potential scenarios for generating lithosphere-scale thermal anomalies to drive orogen-scale hydrothermal systems that may result in the formation of orogenic lode-gold deposits. (A) Characteristic plate subduction leading to crustal thickening, increased geotherms, and formation of a magmatic arc. Associated fluids form orogenic lode-gold deposits over most crustal depths, with upward convecting fluids depositing Hg–Sb-rich lodes within the top few kilometers of the overthickened crust. (B) Plume subduction (or impact) as suggested for Late Archean orogenic gold deposits by Barley et al. (1998). Dalziel et al. (1999) and Keppie and Krogh (1999) also discuss the thermal consequences of the impact of plumes along subduction zones. (C) Subduction rollback, as suggested by Goldfarb et al. (1997) for the Farallon plate at ca. 110 Ma in Arctic Alaska. Seaward-stepping of subduction zones was also suggested by Landefeld (1988) as the trigger for generation of the Jurassic Mother Lode gold belt in California, USA. (D) Subduction of an oceanic ridge, as shown by Haeussler et al. (1995), for the Kula–Farallon plate window migrating beneath the southern margin of Alaska during the early Tertiary. (E) Erosion of mantle lithosphere (e.g., Griffin et al., 1998), perhaps by convective removal, allowing upwelling of asthenosphere and melting at the base of the crust. This may explain the distribution of gold systems surrounding the North China craton. (F) Delamination of mantle lithosphere, as suggested by Qiu and Groves (1999) for Late Archean orogenic gold deposits in the Yilgarn craton and by Gray (1997) for the Paleozoic Lachlan fold belt deposits.

record. Most important economic examples are of Cenozoic age, with a few of these as old as middle Mesozoic (e.g., Early Jurassic arc-related epithermal veins of British Columbia). Sediment-hosted micron gold or Carlin-like deposits are generally restricted to carbonate facies rocks of continental shelves on the landward side of any accreted terranes. They too seem fairly well-restricted to Phanerozoic times, with mid-Tertiary deposits being dominant in Nevada and similar deposits of Triassic age within the West Qinling belt area of China. It is uncertain as to whether Precambrian passive-margin carbonate sequences are also permissive for this type of gold deposit and, if permissive, whether these also would be too shallow for significant preservation.

The link between the orogenic gold deposits and the intrusion-related gold deposit class (e.g., Sillitoe, 1991; Sillitoe and Thompson, 1998; Thompson et al., 1999; Lang et al., 2000) is still unclear. Certainly, there are many gold deposits described from this latter class where ore-forming fluids are direct products of magmatic exsolution. The diatremes at Kidstone (northeastern Australia), the auriferous miarolitic cavities and disseminated gold at Timbarra (southeastern Australia), the near-surface emplacement of gold ores at Kori Kolla (Bolivia), the Fe oxide and copper-dominant ores at Mantos de Punitaqui (Chile), the base metal zoning at Snip (western Canada), and the relatively minor CO₂ in ore fluids at Parcoy-Pataz (Peru) are not characteristic of orogenic gold deposits. It is likely that most, if not all, of these systems were direct products of an evolving magma system. The lack of moderate metamorphic-grade host rocks to many of these gold systems is suggestive also of a shallower crustal environment than is common for most orogenic gold deposits. In addition, the young, ca. 16 Ma age of Kori Kolla (Thompson et al., 1999) appears to be uncharacteristic of orogenic gold ores. There are some small middle Tertiary orogenic gold deposits now being exposed in the European Alps and along the Red River fault zone (northern Vietnam and southeastern China). However, as a group, no discovered > 1 Moz Au orogenic ore systems younger than about 50 Ma have been yet uplifted and totally exposed over the entire Earth.

Other gold deposits, however, classified by the above workers as “intrusion-related” would appear

to equally fit the orogenic gold-deposit model of Groves et al. (1998). Deposits such as Ryan Lode and Pogo (Alaska, USA), Vasilkovskoe (Kazakhstan), and Mokrsko (Czech Republic), which are classified by some workers as intrusion-related (Sillitoe, 1991; McCoy et al., 1997; Sillitoe and Thompson, 1998; Thompson et al., 1999; Smith et al., 1999), appear similar to orogenic gold deposits. These specific deposits all occur in metallogenic provinces where there are less equivocal examples of coeval metasedimentary rock-hosted gold vein deposits that are clearly orogenic gold deposits. It also is well established that small pre- to syn-tectonic, competent granitoid stocks are good hosts for orogenic gold deposits (Groves et al., 2000), and such granitoids are common throughout orogenic belts, globally. The main criterion that leads some workers to classify some deposits as intrusion-related is exsolution of ore fluids from a local magmatic source (e.g., Spooner, 1993). This contrasts with the more typical metamorphic (or distal magmatic) source favored by many workers for orogenic gold deposits (e.g., Fyfe and Henley, 1973; Kerrich and Fyfe, 1981; Phillips and Groves, 1983; Goldfarb et al., 1988).

Deposits defined as hypozonal orogenic gold deposits in the Yilgarn craton (Groves, 1993; Groves et al., 1998) have also been recently reclassified as both gold skarns and intrusion-related gold deposits (Mueller and McNaughton, 2000). A major point argued against an orogenic deposit classification appears to be the 150-m.y.-long gap between metamorphism in the host rocks and ore formation. However, as pointed out by Qiu and Groves (1999), large scale melting of the lower crust was coeval with the gold-forming events and, therefore, gold mineralization in upper crust rocks at some time after their metamorphism is expected.

3.6. Toward a comprehensive model of gold through time

The distinctive temporal distribution of the ages of orogenic gold-deposit formation is clearly not a random pattern; rather, given the repetitive tectonic association of the deposits, it must ultimately be a product of processes that controlled the overall differentiation and evolution of Earth. Conversely, the age distribution of these deposits obviously provides

information regarding the evolution of the planet. A model that explains this distribution must attempt to define why gold clusters in two broad Precambrian time intervals (2.7–2.5 and 2.1–1.8 Ga) prior to the Mesoproterozoic. It must then examine also why gold is essentially concentrated within solely the final 600 b.y. of the remaining 1.8-m.y.-long period of geological time.

Approximately 75% of the juvenile crust on Earth was developed in the Precambrian during two periods that essentially overlap those of orogenic gold formation. Both the end of the Archean and the end of the Paleoproterozoic are marked by exceptionally sudden and rapid episodes of crustal growth (Stein and Hoffmann, 1994; Condie, 1995). These periods of crustal growth must reflect major changes in the Earth's overall heat budget, now commonly thought to be due to overturns from a layered mantle to one with a transient, whole-mantle convection (e.g., Davies, 1992, 1995). Resulting mantle plumes during the convection could have generated vast amounts of new crust due to decompression melting at the base of the lithosphere. These two "super-events" may have been initiated by sudden slab failure and rapid sinking of oceanic lithosphere to depths below the 660-km discontinuity (Condie, 1998). The slabs themselves may have been trapped above the discontinuity until total lithospheric load and gradually cooling mantle temperatures, perhaps aided by mantle overturning. Resulting amalgamation of the developing greenstone blocks led to growth of the first two supercontinents.

Condie (1998) argues that slight perturbations in crustal growth patterns suggest three sub-events during evolution at ca. 3.0, 2.7, and 2.6–2.5 Ga of the so-called Archean Ur (Rogers, 1996) or Vaalbara supercontinent (Zegers et al., 1998). This fits well with the slight periodicity in orogenic lode-gold formation, with Middle Archean deposits in the Barberton greenstone belt and eroded from Witwatersrand source lodes (if the paleoplacer model is favored); ca. 2.7–2.63 Ga ores in areas such as the Yilgarn craton, Superior province, and Zimbabwe craton; and latest Late Archean ores in the Dharwar craton. Similarly, Condie (1998) proposes four sub-events for crustal growth at ca. 2.1, 1.9, 1.8, and 1.7 Ga for subsequent supercontinent evolution. Age data for formation of Paleoproterozoic orogenic gold deposits

are too scarce and too uncertain to be able to determine confidently whether ore formation was spread over intervals spaced about 100 m.y. apart. However, clearly, orogenic gold deposits in western Africa, northern South America and the Transvaal of South Africa formed early during supercontinent growth, whereas other ores, such as those in the Trans-Hudson orogen of North America, in southern Greenland and in northern Australia, formed a few hundred million years later. What is most significant, however, is the broad and undeniable correlation between crustal growth and orogenic gold formation.

A different style of crustal growth after the Paleoproterozoic is indicated if one examines the map that shows the distribution of juvenile continental crust by age (Fig. 6). Archean and Paleoproterozoic blocks comprise large, relatively equi-dimensional continental masses, whereas younger juvenile crust appears as long, narrower microcontinents or accretionary collages, such as those that characterize present-day western North America. Even though the early Precambrian blocks are remnants of further break-ups, their widths, perpendicular to the elongations of supracrustal belts, are clearly anomalous. This suggests some change in the overall process of crustal growth during the last ca. 1.7 b.y. A probable cause is the gradual shift from strongly plume-influenced plate tectonics in the hotter, earlier Earth to a less-episodic style of plate tectonics as the Earth cooled. This may have been facilitated by a more homogeneous mantle, allowing slabs to readily penetrate below the 660-km discontinuity on a consistent basis (Davies, 1995). Instead of very broad masses of rapidly formed, buoyant blocks of new crust amalgamating into cratonic masses, the present-day tectonic style made for a continuation of collisions and orogeny along the margins of the Archean–Paleoproterozoic cratons. Through time, these orogens were often reworked, and thus older supracrustal rock sequences are typically eroded down to high metamorphic-grade, deep crustal levels.

The pattern of gold formation subsequent to about 1.7 Ga is interpreted, in this model, to reflect the decreasing influence of episodic plume activity on plate tectonics and increasing impact of modern-style plate tectonics on crustal evolution and, obviously, on associated orogenic gold formation. The only post-1.7 Ga time probably characterized by

a plume-related, abnormally productive period of crustal growth was about 1.3–1.1 Ga (Condie, 1995), which correlates with the assembly of Rodinia. About one-half of the remaining 25% of juvenile continental crust was formed in this brief episode, perhaps during a final period of massive slab failure and widespread sinking into the lower mantle (Condie, 1998). However, the resulting thermal event would have been less intense than similar earlier Precambrian events (Davies, 1995), and a relatively much smaller volume of new crust was generated at this time. More importantly, this crust appears as thin belts defining the internal and external orogens of Rodinia, rather than as broader blocks with well-protected interior regions. The more fragmented nature of the Rodinian crust is very compatible with Cordilleran (Plafker and Berg, 1994) and Turkeic (Sengor and Natal'in, 1996b) styles of continental growth that are well-documented in the Phanerozoic. Under such conditions, orogenic gold ores certainly would have formed, but these older orogens, especially because of their narrow widths, were totally reworked during post-Rodinian outboard terrane collisions. During such reworking to expose mainly deep-crustal belts of rock, any evidence of mid-crustal gold lodes was likely eroded away.

Exclusive of the 1.3–1.1 Ga event discussed above, a relatively consistent rate of crustal growth reflects the predominance of modern-style plate tectonics since the Mesoproterozoic. However, significant orogenic and placer gold deposits are essentially restricted in age to the last 600 m.y. of geologic time. Until detailed geochronology is available for the gold lodes surrounding the Siberian craton, it remains uncertain as to whether or not these are really remaining ores from Precambrian collisional events. The spatially associated Paleozoic granitoids makes such a scenario highly unlikely for many of the southern Siberian systems. Therefore, it appears that any significant gold concentrations older than about 600 Ma that did develop around the margins of ca. 1.8 Ga cratons have been eroded. Mid-crustal levels from younger orogens remain better preserved, particularly for times of continuous continental collisions younger than about 450 Ma.

The northern part of the East African orogen, with significant associated events extending west into the

Trans-Sahara area, includes the definitively oldest orogenic gold lodes preserved from post-Paleoproterozoic collisions. Much of this part of Africa has been relatively isolated from significant tectonism subsequent to the latest Proterozoic collision between the main Gondwana blocks. Continued growth of the Gondwana margin was associated with formation of the ores of the Lachlan fold belt and Paleozoic gold provinces. Simultaneously, perhaps the single most-important gold-forming epoch occurred with the closing of the Paleo-Tethys Ocean as Pangea was eventually formed. Formation of relatively small middle-Paleozoic Caledonian gold provinces was followed by ca. 350–280 Ma major ore events in uplifting massifs of southern Europe, in the Ural Mountains, in the central Asian republics, and perhaps within the mobile belts peripheral to the Siberian craton. As Pangea began its breakup during the Mesozoic, large gold provinces evolved on the active Pacific margins along western North America (e.g., Sierra Nevada foothills belt, Klondike, Alaskan provinces), eastern Asia (e.g., Russian Far East, eastern China), and Australasia (e.g., Haast schists probably along present-day Queensland).

A number of specific parameters characterize these orogenic gold deposits that formed throughout the Phanerozoic. The late Mesozoic–Cenozoic placer fields of the Sierra Foothills belt, Klondike, Fairbanks, Seward Peninsula, Yana–Kolyma belt, Amur, and Otago areas indicate the relatively short time required before major orogenic gold provinces are partly to completely lost to erosion (e.g., Henley and Adams, 1979). Unless protected in craton-like blocks, these continental-margin goldfields are typically lost to erosion within only 100 m.y. of formation. Therefore, it is no coincidence that significant in situ gold concentrations are not consistently preserved over the last 1.8 b.y. In fact, exclusive of central Asia, reflecting the abnormally high tonnage at Muruntau, all other Phanerozoic gold provinces with > 50 Moz Au are characterized by placer accumulations as a significant amount of the resource. A lack of such large gold resources in provinces developed post-Early Cretaceous suggests that at least about 100 m.y. is required to unroof such a gold-rich region, exposing larger lodes and concentrating additional gold in secondary environments.

4. Conclusions

The pattern of orogenic gold ages through geologic time is not random; rather it broadly correlates with that of thermal events associated with the growth of new continental crust. Large-scale fluid migration along major, deep-seated structures is inherent to most orogenies as moderate to high (e.g., ≥ 400 – 500°C) crustal temperatures are reached. If there are syngenetic sulfide minerals disseminated in this new crust, such as is common in greenstones and marine sedimentary sequences, then sulfur will be partly released into the hydrothermal fluid perhaps via prograde desulfidization reactions during crustal heating. If such sulfur-bearing hydrothermal fluids migrate through a complex pattern of fracture networks as they approach major fault zones, then they are capable of transporting a significant amount of the leachable gold along the flow path. This gold is eventually deposited in secondary and tertiary fault systems, adjacent to the main fault at shallower crustal levels of the uplifting orogen. If temperatures exceed about 700°C in and below fluid source areas, both fluids and melts will migrate upward simultaneously; hence, the ubiquitous spatial and temporal association between gold and granitoids in orogenic belts.

Areas of the Earth with the oldest continental crust are dominated by Late Archean and Paleoproterozoic cratonic blocks. Where rocks of this age are well-exposed in the near-surface in these cratons, they almost everywhere contain clusters of significant orogenic gold deposits (e.g., western Australia, north-central Australia, India, southern Africa, central Africa, western Africa, northern South America, and north-central North America). Where cratons of these ages are widely covered by younger sequences, they likely contain similar gold concentrations, but these are simply not exposed (e.g., Siberia, eastern Europe, Wyoming, China cratons, Greenland). Whether cratons are dominated by greenstone terranes (e.g., Yilgarn, Superior) or clastic metasedimentary rock sequences (e.g., Birimian, Northern Territory of Australia) appears irrelevant. Gold concentration was an inherent part of continental growth at 2.8–2.55 and 2.1–1.8 Ga regardless of immediate host lithology. Recent geochronology indicates that, within a given craton, gold formation may be quite

diachronous, as in many Phanerozoic orogenic belts, rather than occurring in a single craton-wide episode.

Phanerozoic orogens that developed around the margins of Gondwana and the Paleo-Tethys Ocean prior to final amalgamation of Pangea, and that surrounded much of the Pacific rim subsequent to the break up of Pangea, are the source for most of the Earth's other economic orogenic gold concentrations. However, where orogenesis was a low-T–high-P event, such as in formation of the Brooks Range in Alaska, the early Alps, and much of the Appalachians, gold veining was not an important part of orogenesis. Where high-T events do occur, but deep-seated structures are lacking, such as in relatively thin accretionary prisms on orogen margins, gold ores may still be relatively minor (e.g., Japanese Islands, Chugach terrane of Alaska). The lack of large gold provinces younger than ca. 50 Ma provides a threshold for approximating the minimum time required to unroof a major orogenic gold system. The fact that many of the Phanerozoic gold systems older than ca. 100 Ma are associated with large placer fields indicates the short-lived nature of this type of gold deposit, unless preserved for billions of years by the early Precambrian cratonization processes.

The style of plate tectonics need not be critical to the formation of orogenic gold deposits. Any thermal event within hydrous and sulfur-bearing juvenile crust, whether it be initiated by Precambrian plume-like events, or younger, more-typical subduction/collision type processes, can form the same type of gold deposit. The lack of significant gold ores between ca. 1.8 and 0.6 Ga appears to be a function of changing patterns of continental growth, eventually linked to a shift in styles of plate dynamics on a cooling Earth. Beginning in the Mesoproterozoic, mantle plumes formed fewer, large, regularly shaped masses of juvenile crust with a high potential for cratonization and preservation of gold lodes. A more modern-day style of plate tectonics, which was associated with the growth of Rodinia, led to juvenile crust being added as irregular fragments around the margins of the older cratonic blocks for at least the last 1.5 b.y. Such long, thin blocks of new crust were particularly susceptible to reworking and erosion by subsequent orogenesis. Most exposures of Mesoproterozoic and Neoproterozoic mobile belts, therefore,

are characterized by deep crustal orogenic root-zones that were below gold-favorable parts of the crust.

In conclusion, the following points best summarize present understanding of the distribution of orogenic gold through time:

(1) The oldest economically significant orogenic gold deposits are those of the Middle Archean Barberton greenstone belt. If a paleoplacer origin is correct for the Witwatersrand ores, then they are only the remnants of Middle Archean lode-gold systems.

(2) A large part of the global gold resource was formed between 2.8 and 2.55 Ga, including world class gold provinces in the Yilgarn craton, Superior province, Kolar schist belt, Zimbabwe craton, Slave craton, Sao Francisco craton and Tanzania craton.

(3) A third Precambrian episode of orogenic gold formation was concentrated between 2.1 and 1.8 Ga, and included deposition of the important ores in the West Africa craton, Amazonian craton and Trans-Hudson orogen. Less significant resources were formed at the same time in the Rio Itapicuru greenstone belt/western Congo craton, Flin Flon greenstone belt, Svevofennian province, Ketalidian mobile belt, Transvaal basin and North Australian craton.

(4) Few significant gold resources are recorded in the geological record for the period 1.8–0.6 Ga. Some of the orogenic gold deposits in the fold belts along the southern margin of the Siberian craton may be as old as 850 Ma, but many of these may be hundreds of millions of years younger. In addition, some of the older Pan-African gold deposits, including those developed by the ancient Egyptians, formed in the latest Neoproterozoic.

(5) Orogenic gold deposits formed along active continental margins throughout the Phanerozoic and concentrated at least 1000 Moz Au. They evolved along the southern Gondwana margin and the northern side of the Paleo-Tethys Ocean during the Paleozoic, and within the circum-Pacific accreted terranes in the Mesozoic–Tertiary. Phanerozoic orogenic gold systems of middle Cretaceous and older ages are typically partly eroded and reconcentrated in economically significant placers.

(6) There are no exposed, economically significant provinces of orogenic gold deposits younger than about 50 Ma. Such Cenozoic systems, typically having formed at mid-crustal regions, are still being

gradually unroofed within areas of ongoing tectonism.

(7) Archean and Paleoproterozoic gold-forming events correlate with episodic growth of juvenile continental crust. Resulting ores have been protected for billions of years within large, relatively equidimensional stable continental masses.

(8) Post-Paleoproterozoic gold deposits formed in long, narrow strips of juvenile crust added to the margins of the older cratonic blocks. The older of these mobile belts, including those of the Rodinian supercontinent, have been reworked to expose deep crustal levels, which are below gold-favorable zones. Mobile belts of Phanerozoic age, however, typically contain important gold deposits in greenschist, and slightly lower and higher grade, metamorphic facies rocks.

(9) The approximate 1.2-b.y.-long gold gap in the geological record will likely widen with time as oldest Phanerozoic gold ores are eroded and new gold systems are unroofed in evolving orogens.

(10) The similar distribution pattern of orogenic gold ores through time with that of VMS deposits suggests favorable fluid and metal reservoirs occur within first-generation continental crust. Inherited water-, sulfur-, and gold-bearing mineral phases in oceanic sedimentary rocks and greenstones added to cratonic masses have likely been recycled in regional crustal-scale flow events, which are driven by pressure gradients along major shear zones and thrust faults, to form orogenic gold deposits.

Acknowledgements

Many ideas developed in this paper grew out of a couple of invited presentations that were put together for the Society of Economic Geologists symposium on “Ore Deposits through Time” at the 1997 Geological Society of America Annual Meeting. Discussions with Pasi Eilu, Lance Miller, Dwight Bradley, Dave Leach, Yumin Qiu, Orestos Santos, Taihe Zhou, Jingwen Mao and Tanya Bounaeva have been invaluable in helping with our understanding of the geology and resources of areas generally lacking extensive information in the Western literature. Input and stimulation from Neil Phillips, Rob Kerrich and from the Centre for Global Metallogeny staff at

UWA, especially Derek Wyman and Mark Barley, is appreciated. David Groves acknowledges support of Normandy Exploration to his project at UWA to help investigate the global distribution of mineral resources. Critical reviews by Ed Spooner, Howard Poulsen, Barney Berger and Poul H. Emsbo are appreciated.

References

- Abraham, A.P.G., Davis, D.W., Kamo, S.L., Spooner, E.T.C., 1994. Geochronological constraints on late Archean magmatism, deformation and gold-quartz vein mineralization in the northwestern Anialik River greenstone belt and igneous complex, Slave Province, N.W.T. *Can. J. Earth Sci.* 31, 1365–1383.
- Abzalov, M.Z., 1999. Gold deposits of the Russian North East (The Northern Circum Pacific): Metallogenic overview. PACRIM '99. The Australasian Institute of Mining and Metallurgy, Carlton, Victoria, Australia, pp. 701–714.
- Adams, C.J., Barley, M.E., Fletcher, I.R., Pickard, A.L., 1998. Evidence from U–Pb zircon and $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite detrital mineral ages in metasediments for movement of Torlesse suspect terrane around the eastern margin of Gondwanaland. *Terra Nova* 10, 183–189.
- Agar, R.A., 1992. The tectono-metallogenic evolution of the Arabian Shield. *Precambrian Res.* 58, 169–194.
- Albino, G.V., Jahal, S., Christensen, K., 1995. Neoproterozoic mesothermal gold mineralization at Sukhaybarat East mine, Saudi Arabia. *Trans. Inst. Min. Metall.* 104, B157–B210.
- Allen, M.B., Vincent, S.J., 1997. Fault reactivation in the Junggar region, northwest China: the role of basement structures during Mesozoic–Cenozoic compression. *J. Geol. Soc. (London)* 154, 151–155.
- Almond, D.C., Ahmed, F., Shaddad, M.Z., 1984. Setting of gold mineralization in the northern Red Sea Hills of Sudan. *Econ. Geol.* 79, 389–392.
- Ansdell, K.M., Kyser, T.K., 1992. Mesothermal gold mineralization in a Proterozoic greenstone belt: Western Glin Flon domain, Saskatchewan, Canada. *Econ. Geol.* 87, 1496–1524.
- Arne, D.C., Bierlein, F.P., McNaughton, N., Wilson, C.J.L., Morand, V.J., 1998. Timing of gold mineralization in western and central Victoria, Australia—new constraints from SHRIMP II analysis of zircon grains from felsic intrusive rocks. *Ore Geol. Rev.* 13, 251–274.
- Ash, C.H., Reynolds, P.H., MacDonald, R.W.J., 1996. Mesothermal gold-quartz vein deposits in British Columbia oceanic terranes, New Mineral Deposit Models of the Cordillera. British Columbia Ministry of Employment and Investment, Energy and Minerals Division, Geological Survey Branch, Short Course Notes, Vancouver. pp. O1–O32.
- Ashley, P.M., 1997. Silica-carbonate alteration zones and gold mineralisation in the Great Serpentine Belt, New England orogen, New South Wales. In: Ashley, P.M., Flood, P.G. (Eds.), *Tectonics and Metallogensis of the New England Orogen*. *Geol. Soc. Aust., Spec. Publ.* 19, pp. 212–225.
- Bain, J.H.C., Withnall, I.W., Black, L.P., Etminan, H., Golding, S.D., Sun, S.-S., 1998. Towards an understanding of the age and origin of mesothermal gold mineralisation in the Etheridge Goldfield, Georgetown region, north Queensland. *Aust. J. Earth Sci.* 45, 247–263.
- Balakrishnan, S., Rajamani, V., Hanson, G.N., 1999. U–Pb ages for zircon and titanite from the Ramagiri area, southern India: evidence for accretionary origin of the eastern Dharwar craton during the Late Archean. *J. Geol.* 107, 69–86.
- Barley, M.E., Eisenlohr, B.N., Groves, D.I., Perring, C.S., Vearncombe, J.R., 1989. Late Archean convergent margin tectonics and gold mineralization—a new look at the Norseman-Wiluna belt, western Australia. *Geology* 17, 826–829.
- Barley, M.E., Krapez, B., Groves, D.I., Kerrich, R., 1998. The Late Archean bonanza: metallogenic and environmental consequences of the interaction between mantle plumes, lithospheric tectonics and global cyclicity. *Precambrian Res.* 91, 65–90.
- Barnicoat, A.C., Henderson, I.H.C., Knipe, R.J., Yardley, B.W.D., Napier, R.W., Fox, N.P.C. et al., 1997. Hydrothermal gold mineralization in the Witwatersrand basin. *Nature* 386, 820–824.
- Barrie, C.T., Hannington, M.D., 1999. Classification of volcanic-associated massive sulfide deposits based on host-rock composition. In: Barrie, C.T., Hannington, M.D. (Eds.), *Volcanic-Associated Massive Sulfide Deposits: Processes and Examples in Modern and Ancient Settings*. Society of Economic Geologists, Reviews in Economic Geology, vol. 8, pp. 1–11, Littleton, CO, USA.
- Bayley, R.W., Proctor, P.D., Condie, K.C., 1973. Geology of the South Pass area, Fremont County, Wyoming. *U.S. Geol. Surv. Prof. Pap.* 793, 39 pp.
- Berhe, S.M., 1997. The Arabian–Nubian shield. In: de Wit, M., Ashwal, L.D. (Eds.), *Greenstone Belts*. Clarendon Press, Oxford, pp. 761–771.
- Bertoni, C.H., Shaw, R.P., Singh, R., Minamoto, J., Richards, J.M., Belzile, E., 1991. Geology and gold mineralisation of the Omai property, Guyana. In: Ladeira, E.A. (Ed.), *Brazil Gold '91*. Balkema, Rotterdam, pp. 767–773.
- Beurlen, H., Da Silva, M.R.R., Dos Santos, R.B., 1997. Auriferous quartz veins from northeastern Brazil: a fluid-inclusion study. *Int. Geol. Rev.* 39, 578–588.
- Bierlein, F.P., Foster, D.A., McKnight, S., Arne, D.C., 1999. Timing of gold mineralisation in the Ballarat goldfields, central Victoria: constraints from $^{40}\text{Ar}/^{39}\text{Ar}$ results. *Aust. J. Earth Sci.* 46, 301–309.
- Billstrom, K., Weihed, P., 1996. Age and provenance of host rocks and ores in the Paleoproterozoic Skellefte district, northern Sweden. *Econ. Geol.* 91, 1054–1072.
- Boer, R.H., Meyer, F.M., Robb, L.J., Graney, J.R., Vennemann, T.W., Kesler, S.E., 1995. Mesothermal-type mineralization in the Sabie-Pilgrim's Rest gold field, South Africa. *Econ. Geol.* 90, 860–876.
- Bogdanov, N.A., Khain, V.E., Vernikovskiy, V.A., Drachev, S.S., Kostyuchenko, S.L., 1998. Continental accretion in the Taymyr part of the Eurasian basin margin. [abs] *International Conference on Arctic Margins III*. pp. 32–33.

- Bohlke, J.K., 1982. Orogenic (metamorphic-hosted) gold-quartz veins. U. S. Geol. Surv. Open-File Rep. 795, 70–76.
- Bohlke, J.K., 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. *Econ. Geol.* 81, 296–322.
- Borg, G., 1994. The Geita gold deposit in NW Tanzania—Geology, ore petrology, geochemistry and timing of events, Metallogensis of Selected Gold Deposits in Africa. *Geologisches Jahrbuch Reihe D, Heft 100, Hannover*. pp. 545–595.
- Bortnikov, N.S., Prokof'ev, V.Y., Razdolina, N.V., 1996. Origin of the Charmitan gold-quartz deposit (Uzbekistan). *Geol. Ore Deposits* 38 (3), 208–226.
- Bortnikov, N.S., Vikentyev, I.V., Safonov, Y.G., Zvyagina, O.V., Sazonov, V.N., Murzin, V.V., Naumov, V.B., Mironova, O.V., 1997. The Berezovsk giant gold quartz deposit, Urals, Russia: fluid inclusion and stable isotope studies. In: Papunen, H. (Ed.), *Mineral Deposits: Research and Exploration—Where Do They Meet?* Balkema, Rotterdam, pp. 157–160.
- Bortnikov, N.S., Gamyarin, G.N., Alpatov, V.A., Naumov, V.B., Nosik, L.P., Mironova, O.F., 1998. Mineralogy, geochemistry and origin of the Nezdansinsk gold deposit (Sakha-Yakutia, Russia). *Geol. Ore Deposits* 40 (2), 121–138.
- Boshoff, F., Hanssen, E., Hill, J.V., Jones, D., Kaisin, J., Traore, S., Voet, H.W., 1998. The Sadiola Hill mine: a lower Proterozoic gold deposit in the Kenieba window—Mali, West Africa. In: Walton, G., Jambor, J. (Eds.), *Pathways '98, Extended Abstracts Volume*. British Columbia and Yukon Chamber of Mines, Vancouver, pp. 83–86.
- Bouchot, V., Feybesse, J.-L., 1996. Palaeoproterozoic gold mineralization of the Eteke Archaean greenstone belt (Gabon): its relation to the Eburnean orogeny. *Precambrian Res.* 77, 143–159.
- Bouchot, V., Gros, Y., Bonnemaïson, M., 1989. Structural controls on the auriferous shear zones of the Saint Yrieix district, Massif Central, France—evidence from the Le Bourneix and Laurieras gold deposits. *Econ. Geol.* 84, 1315–1327.
- Brandl, G., de Wit, M.J., 1997. The Kaapvaal Craton. In: de Wit, M., Ashwal, L.D. (Eds.), *Greenstone Belts*. Clarendon Press, Oxford, pp. 581–607.
- Bulgatov, A.N., Gordienko, I.V., 1999. Terrains of the Baikal mountain range and the location of gold deposits. *Geol. Ore Deposits* 41 (3), 204–213.
- Bullis, H.R., Hureau, R.A., Penner, B.D., 1996. Distribution of gold and sulfides at Lupin, Northwest Territories—a reply. *Econ. Geol.* 91, 964–966.
- Burchfiel, B.C., Cowan, D.S., Davis, G.A., 1992. Tectonic overview of the Cordilleran orogen in the western United States. In: Lipman, P.W., Zoback, M.L. (Eds.), *The Cordilleran Orogen—Conterminous U.S.* Geological Society of America. The Geology of North America, Boulder, CO, pp. 407–479.
- Caddey, S.W., Bachman, R.L., Campbell, T.J., Reid, R.R., Otto, R.P., 1991. The Homestake gold mine, an Early Proterozoic iron-formation-hosted gold deposit, Lawrence County, South Dakota. *U.S. Geol. Surv. Bull.* 1857-J, 67 pp.
- Campbell, S.D.G., Pitfield, P.E.J., 1994. Structural controls of gold mineralization in the Zimbabwe craton—exploration guidelines. *Zimbabwe Geol. Surv., Bull.* 101, 253 pp.
- Campbell, I.H., Compston, D.M., Richards, J.P., Johnson, J.P., Kent, A.J.R., 1998. Review of the application of isotopic studies to the genesis of Cu–Au mineralisation at Olympic Dam and Au mineralisation at Porgera, the Tennant Creek district and Yilgarn Craton. *Aust. J. Earth Sci.* 45, 201–218.
- Card, K.D., 1990. A review of the Superior Province of the Canadian Shield, a product of Archean accretion. *Precambrian Res.* 48, 99–156.
- Carneiro, M.A., 1992. O Complexo Metamorfico Bonfim Setentrional (Quadrilátero Ferrífero, Minas Gerais): Litoestratigrafia e Evolução Geológica de um Segmento de Crosta Continental Arqueana. PhD Thesis, University Sao Paulo, 233 pp.
- Carroll, A.R., Graham, S.A., Henrix, M.S., Ying, D., Zhou, D., 1995. Late Paleozoic tectonic amalgamation of northwestern China: sedimentary record of the northern Tarim, northwestern Turpan and southern Junggar basins. *Geol. Soc. Am. Bull.* 107 (5), 571–594.
- Cassard, D., Feybesse, J.-L., Lescuyer, J.-L., 1993. Variscan crustal thickening, extension and late overstacking during the Namurian–Westphalian in the western Montagne Noire (France). *Tectonophysics* 222, 33–53.
- Chadwick, B., Vasudev, V.N., Ahmed, N., 1996. The Sandur schist belt and adjacent plutonic rocks: implications for Late Archean crustal evolution in Karnataka. *J. Geol. Soc. India* 47, 37–57.
- Chadwick, B., Vasudev, V.N., Hegde, G.V., 2000. The Dharwar craton, southern India, interpreted as the result of Late Archaean oblique convergence. *Precambrian Res.* 99, 91–111.
- Charonnat, X., Chauvet, A., Faure, M., 1999. Structural control of the Late-Hercynian Cevennes gold mineralization, French Massif Central. In: Stanley, C.J. (Ed.), *Mineral Deposits: Processes to Processing*. Balkema, Rotterdam, pp. 1311–1314.
- Chauvet, A., Faure, M., Dossin, I., Charvet, J., 1994. A three-stage structural evolution of the Quadrilátero Ferrífero: consequences for the Neoproterozoic age and the formation of gold concentrations of the Ouro Preto area, Minas Gerais, Brazil. *Precambrian Res.* 68, 139–167.
- Cheong, S., 2000. General characteristics and structural evolution of metamorphic gold-quartz veins in northwestern Nevada, USA. *Geosci. J.* 4 (2), 135–152.
- Choukroune, P., Ludden, J.N., Chardon, D., Calvert, A.J., Bouhalier, H., 1997. Archaean crustal growth and tectonic processes: a comparison of the Superior Province, Canada and the Dharwar Craton, India. In: Burg, J.-P., Ford, M. (Eds.), *Orogeny Through Time*. Geol. Soc. London Spec. Publ., vol. 121, pp. 63–98, London, Bath, UK.
- Collins, W.J., 1996. Tectonic setting of gold deposits in eastern Australia. *Mesothermal Gold Deposits: a Global Overview*. Geology Dept. (Key Centre) and UWA Extension, University of Western Australia Pub., Nedlands, WA, Australia, pp. 18–21.
- Colvine, A.C., Andrews, A.J., Cherry, M.E., Durocher, M.E., Fyon, J.A., Lavigne, M.J., MacDonald, A.J., Marmont, S. et al., 1984. An integrated model for the origin of Archean lode gold deposits. *Ont. Geol. Surv. Open-File Rep.* 5524, 98 pp.

- Condie, K.C., 1982. Early and Middle Proterozoic supracrustal successions and their tectonic settings. *Am. J. Sci.* 282, 341–357.
- Condie, K.C., 1995. Episodic ages of greenstones: a key to mantle dynamics. *Geophys. Res. Lett.* 22, 2215–2218.
- Condie, K.C., 1997. *Plate Tectonics and Crustal Evolution*. Butterworth-Heinemann, Oxford, 282 pp.
- Condie, K.C., 1998. Episodic continental growth and supercontinents: a mantle avalanche connection? *Earth Planet. Sci. Lett.* 163, 97–108.
- Condie, K.C., Chomiak, B., 1996. Continental accretion: contrasting Mesozoic and Early Proterozoic tectonic regimes in North America. *Tectonophysics* 265, 101–126.
- Cookro, T.M., 1996. Late Cretaceous ore deposits in the southern lobe of the Idaho batholith, central Idaho. In: Coyner, A.R., Fahey, P.L. (Eds.), *Geology and Ore Deposits of the American Cordillera*, vol. 2. Geological Society of Nevada, Reno, pp. 1035–1046.
- Cooper, J.A., Ding, P.Q., 1997. Zircon ages constrain the timing of deformation events in The Granites–Tanami region, north-west Australia. *Aust. J. Earth Sci.* 44, 777–788.
- Cooper, R.A., Tulloch, A.J., 1992. Early Palaeozoic terranes in New Zealand and their relationship to the Lachlan fold belt. *Tectonophysics* 214, 129–144.
- Coutinho, M.G.N., Alderton, D.H.M., 1998. Character and genesis of Proterozoic shear zone-hosted gold deposits in Borborema Province, northeast Brazil. *Trans. Inst. Min. Metall.* 107, B109–B119.
- Cranfield, L.C., Shorten, G., Scott, M., Barker, R.M., 1997. Geology and mineralisation of the Gympie Province. In: Ashley, P.M., Flood, P.G. (Eds.), *Tectonics and Metallogensis of the New England Orogen*. *Geol. Soc. Aust., Spec. Publ.*, vol. 19, pp. 128–147, Springwood, NSW, Australia.
- Craw, D., Koons, P.O., 1989. Tectonically induced hydrothermal activity and gold mineralization adjacent to major fault zones. In: Keays, R., Ramsay, R., Groves, D.I. (Eds.), *The Geology of Gold Deposits*. *Economic Geology Monograph*, vol. 6, pp. 463–470.
- Craw, D., Koons, P.O., Cox, S.C., Norris, R.J., 1997. Mesothermal gold mineralisation in the tectonically active Southern Alps: analogues for the Otago Schist? 1997 New Zealand Minerals and Mining Conference Proceedings. pp. 77–84, Littleton, CO, USA.
- Crocket, J.H., 1991. Distribution of gold in the Earth's crust. In: Foster, R.P. (Ed.), *Gold Metallogeny and Exploration*. Blackie, Glasgow, pp. 1–36.
- 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. *Econ. Geol.* 82, 2115–2140.
- Curtis, S.F., Patrick, R.A.D., Jenkin, G.R.T., Fallick, A.E., Boyce, A.J., Treagus, J.E., 1993. Fluid inclusion and stable isotope study of fault-related mineralization in Tyndrum area, Scotland. *Trans. Inst. Min. Metall.* 102, B39–B47.
- Dahl, P.S., Holm, D.K., Gardner, E.T., Hubacher, F.A., Folland, K.A., 1999. New constraints on the timing of Early Proterozoic tectonism in the Black Hills (South Dakota), with implications for docking of the Wyoming province with Laurentia. *Geol. Soc. Am. Bull.* 111, 1335–1349.
- Daly, M.C., 1988. Crustal shear zones in central Africa: a kinematic approach to Proterozoic tectonics. *Episodes* 11, 5–11.
- Dalziel, I.W.D., Lawver, L.A., Murphy, J.B., 1999. Plumes, orogenesis, and supercontinental fragmentation. [abs] *Geological Society of America Abstracts with Programs*. pp. A429–A430.
- Darbyshire, D.P.F., Pitfield, P.E.J., Campbell, S.D.G., 1996. Late Archean and Early Proterozoic gold–tungsten mineralization in the Zimbabwe Archean craton—Rb–Sr and Sm–Nd isotope constraints. *Geology* 24, 19–22.
- Davies, G.F., 1992. On the emergence of plate tectonics. *Geology* 20, 963–966.
- Davies, G.F., 1995. Penetration of plates and plumes through the mantle transition zone. *Earth Planet. Sci. Lett.* 133, 507–516.
- de Ronde, C.E.J., de Wit, M.J., 1994. The tectonothermal evolution of the Barberton Greenstone Belt, South Africa: 490 million years of crustal evolution. *Tectonics* 13, 983–1005.
- de Ronde, C.E.J., Kamo, S.L., Davis, D.W., de Wit, M.J., Spooner, E.T.C., 1991. Field, geochemical, and U–Pb isotopic constraints from hypabyssal felsic intrusion within the Barberton greenstone belt, South Africa: implications for tectonics and the timing of gold mineralization. *Precambrian Res.* 49, 261–280.
- De Ronde, C.E.J., Faure, K., Bray, C.J., Whitford, D.J., 2000. Round Hill shear zone-hosted gold deposit, Macraes Flat, Otago, New Zealand: evidence of a magmatic ore fluid. *Econ. Geol.* 95, 1025–1048.
- de Wit, M.J., 1998. On Archean granites, greenstones, cratons and tectonics: does the evidence demand a verdict? *Precambrian Res.* 91, 181–226.
- Diamond, L.W., Wiedenbeck, M., 1986. K–Ar radiometric ages of the gold-quartz veins at Brusson, Val d'Ayas, NW Italy: evidence of mid-Oligocene hydrothermal activity in the north-western Alps. *Schweiz. Mineral. Petrogr. Mitt.* 66, 385–393.
- Drew, L.J., Berger, B.R., 1996. Geology and structural evolution of the Muruntau gold deposit, Kyzylkum desert, Uzbekistan. *Ore Geol. Rev.* 11, 175–196.
- Dusel-Bacon, C., Brosge, W.P., Till, A.B., Doyle, E.O., Mayfield, C.F., Reiser, H.N., Miller, T.P., 1989. Distribution, facies, ages, and proposed tectonic associations of regionally metamorphosed rocks in northern Alaska. *U.S. Geol. Surv. Prof. Pap.* 1497-A, 44 pp.
- Dzung, D.H., 1995. Characteristics of hydrothermal and epithermal gold mineralization in Vietnam. *Proceedings of the I.G.C.P. Symposium on Geology of SE Asia*, Hanoi. pp. 354–364.
- Eilu, P., 1999. FINGOLD—a public database on gold deposits in Finland. *Geol. Surv. Finl., Rep. Invest.* 146, 224 pp.
- El-Bouseily, A.M., El-Dahhar, M.A., Arslan, A.I., 1985. Ore-microscopic and geochemical characteristics of gold-bearing sulfide minerals, El Sid gold mine, Eastern desert, Egypt. *Miner. Deposita* 20, 194–200.
- Elder, D., Cashman, S.M., 1992. Tectonic control and fluid evolution in the Quartz Hill, California, lode gold deposits. *Econ. Geol.* 87, 1795–1812.
- Engelbreton, D.C., Cox, A., Gordon, R.G., 1985. Relative mo-

- tions between oceanic and continental plates in the Pacific basin. *Geol. Soc. Am. Spec. Pap.* 206, Boulder, CO, 64 pp.
- Eremin, R.A., Voroshin, S.V., Sidorov, V.A., Shakhtyrov, V.G., Pristavko, V.A., 1994. Geology and genesis of the Natalka gold deposit, Northeast Russia. *Int. Geol. Rev.* 36, 1113–1138.
- Fedorowich, J., Stauffer, M., Kerrich, R., 1991. Structural setting and fluid characteristics of the Proterozoic Tartan Lake gold deposit, Trans-Hudson orogen, northern Manitoba. *Econ. Geol.* 86, 1434–1467.
- Ferkous, K., Monie, P., 1997. Petrostructural data and $^{40}\text{Ar}/^{39}\text{Ar}$ laser probe dating of the Pan-African shearing and related gold-mineralization in the East In Ouzzal district (Western Hoggar, Algeria). In: Papunen, H. (Ed.), *Research and Exploration—Where Do They Meet?* Balkema, Rotterdam, pp. 185–189.
- Ford, R.C., Snee, L.W., 1996. $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology of white mica from the Nome district, Alaska—the first ages of lode sources to placer gold deposits in the Seward Peninsula. *Econ. Geol.* 91, 213–220.
- Fornari, M., Herail, G., 1991. Lower Paleozoic gold occurrences in the 'Eastern Cordillera' of southern Peru and northern Bolivia: a genetic model. In: Ladeira, E.A. (Ed.), *Brazil Gold '91*. Balkema, Rotterdam, pp. 135–142.
- Fortes, P.T.F.O., Cheilletz, A., Giuliani, G., Feraud, G., 1997. A Brasiliano age (500 ± 5 Ma) for the Mina III gold deposit, Crixas greenstone belt, central Brazil. *Int. Geol. Rev.* 39, 449–460.
- Foster, R.P., 1997. Gold mineralization in Europe—characteristics and tectonic setting. *Miner. Ind.* 24–31.
- Foster, D.A., Fanning, C.M., 1997. Geochronology of the northern Idaho batholith and the Bitterroot metamorphic core complex: magmatism preceding and contemporaneous with extension. *GSA Bull.* 109, 379–394.
- Foster, R.P., Piper, D.P., 1993. Archaean lode gold deposits in Africa—crustal setting, metallogensis and cratonization. *Ore Geol. Rev.* 8, 303–347.
- Foster, D.A., Gray, D.R., Kwak, T.A.P., Bucher, M., 1998. Chronology and tectonic framework of turbidite-hosted gold deposits in the Western Lachlan Fold Belt, Victoria— $^{40}\text{Ar}-^{39}\text{Ar}$ results. *Ore Geol. Rev.* 13, 229–250.
- Foster, D.A., Gray, D.R., Bucher, M., 1999. Chronology of deformation within the turbidite-dominated, Lachlan orogen: implications for the tectonic evolution of eastern Australia and Gondwana. *Tectonics* 18, 452–485.
- Frei, R., Pettke, T., 1996. Mono-sampling Pb–Pb dating of pyrrhotite and tourmaline: proterozoic vs. Archean intracratonic gold mineralization in Zimbabwe. *Geology* 24, 823–826.
- Frimmel, H.E., Hallbauer, D.K., Gartz, V.H., 1999. Gold mobilizing fluids in the Witwatersrand Basin: composition and possible sources. *Mineral. Petrol.* 66, 55–81.
- Fyfe, W.S., Henley, R.W., 1973. Some thoughts on chemical transport processes with particular reference to gold. *Miner. Sci. Eng.* 5, 295–303.
- Fyfe, W.S., Kerrich, R., 1984. Gold: natural concentration processes. In: Foster, R.P. (Ed.), *Gold '82*. Balkema, Rotterdam, pp. 99–127.
- Fyfe, W.S., Price, N.J., Thompson, A.B., 1978. Fluids in the Earth's Crust, *Developments in Geochemistry*, vol. 1. Elsevier, Amsterdam, 383 pp.
- Gan, S., van Reenen, D.D., 1997. Geology of gold deposits in the southern marginal zone of the Limpopo belt and adjacent Sutherland greenstone belt, South Africa: Klein Letaba. *S. Afr. J. Geol.* 100 (1), 73–83.
- Garba, I., 1996. Tourmalinization related to Late Proterozoic–Early Paleozoic lode gold mineralization in the Bin Yauri area, Nigeria. *Miner. Deposita* 31, 201–209.
- Geraldes, M.C., Figueiredo, B.R., 1997. Middle Proterozoic vein-hosted gold deposits in Pontes e Lacerda region, southwestern Amazonian craton, Brazil. *Int. Geol. Rev.* 39, 438–448.
- Gibbons, W., Doig, R., Gordon, T., Murphy, B., Reynolds, P., White, J.C., 1998. Mylonite to megabreccia: tracking fault events within a transcurrent boundary in Nova Scotia, Canada. *Geology* 24 (5), 411–414.
- Gibbs, A.K., 1987. Proterozoic volcanic rocks of the northern Guyana Shield, South America. In: Pharaoh, T.C., Beckinsale, R.D., Rickard, D. (Eds.), *Geochemistry and Mineralisation of Proterozoic Volcanic Suites*. *Geol. Soc. London Spec. Publ.* vol. 33. Blackwell, Oxford, pp. 275–288.
- Giuliani, G., Fortes, P.T.F.O., Nilson, A.A., Olivo, G.R., Ronchi, L.H., Santos, M.M., Marini, O.J., 1991. Contrasting Archean–Proterozoic-hosted gold deposit types and associated gold bearing fluids. In: Pagel, Leroy (Eds.), *Source, Transport, and Deposition of Metals*. Balkema, Rotterdam, pp. 665–668.
- Goldfarb, R.J., 1997. Metallogenic evolution of Alaska. In: Goldfarb, R.J., Miller, L.D. (Eds.), *Mineral Deposits of Alaska*. *Economic Geology Monograph*, vol. 9, pp. 4–34.
- Goldfarb, R.J., Leach, D.L., Miller, M.L., Pickthorn, W.J., 1986. Geology, metamorphic setting, and genetic constraints of epigenetic lode-gold mineralization within the Cretaceous Valdez Group, south-central Alaska. In: Keppie, J.D., Boyle, R.W., Haynes, S.J. (Eds.), *Turbidite-Hosted Gold Deposits*. *Geological Association of Canada Special Paper*, vol. 32, pp. 87–105, St. John's, New Foundland, Canada.
- Goldfarb, R.J., Leach, D.L., Pickthorn, W.J., Paterson, C.J., 1988. Origin of lode gold deposits of the Juneau gold belt, southeastern Alaska. *Geology* 16, 440–443, Littleton, CO, USA.
- Goldfarb, R.J., Snee, L.W., Miller, L.D., Newberry, R.J., 1991. Rapid dewatering of the crust deduced from ages of mesothermal gold deposits. *Nature* 354, 296–298.
- Goldfarb, R.J., Snee, L.W., Pickthorn, W.J., 1993. Orogenesis, high-T thermal events, and gold vein formation within metamorphic rocks of the Alaskan Cordillera. *Mineral. Mag.* 57, 375–394.
- Goldfarb, R.J., Miller, L.D., Leach, D.L., Snee, L.W., 1997. Gold deposits in metamorphic rocks in Alaska. In: Goldfarb, R.J., Miller, L.D. (Eds.), *Mineral Deposits of Alaska*. *Economic Geology Monograph*, vol. 9, pp. 151–190.
- Goldfarb, R.J., Phillips, G.N., Nokleberg, W.J., 1998. Tectonic setting of synorogenic gold deposits of the Pacific Rim. *Ore Geol. Rev.* 13, 185–218.
- Goldfarb, R.J., Hart, C., Miller, M., Miller, L., Farmer, G.L., Groves, D.I., 2000. The Tintina Gold Belt—a global perspec-

- tive. The Tintina Gold Belt: Concepts, Exploration, and Discoveries. British Columbia and Yukon Chamber of Mines, Vancouver, pp. 5–34.
- Goodwin, A.M., 1991. Precambrian Geology: The Dynamic Evolution of the Continental Crust. Academic Press, London, 666 pp.
- Goryachev, N.A., 1995. Mesothermal lode gold deposits of the Russian Far East. In: Bundtzen, T.K., Fonseca, A.L., Mann, R. (Eds.), The Geology and Mineral Deposits of the Russian Far East. Alaska Miners Association, Anchorage, AK, pp. 141–152.
- Goryachev, N.A., Edwards, A.C., 1999. Gold metallogeny of North-East Asia. PACRIM '99. The Australasian Institute of Mining and Metallurgy, Carlton, Victoria, Australia, pp. 287–302.
- Govett, G.J.S., 1983. Rock geochemistry in mineral exploration, Handbook of Exploration Geochemistry vol. 3. Elsevier, Amsterdam, 461 pp.
- Gray, D.R., 1997. Tectonics of the southeastern Australia Lachlan fold belt—structural and thermal aspects. In: Burg, J.P., Ford, M. (Eds.), Orogeny Through Time. Geol. Soc. London Spec. Publ. vol. 121, pp. 149–177, Littleton, CO, USA.
- Griffin, W.L., Zhang, A., O'Reilly, S.Y., Ryan, C.G., 1998. Phanerozoic evolution of the lithosphere beneath the Sino-Korean craton. In: Flower, M.F.J., Chung, S.-L., Lo, C.-H., Lee, T.-Y. (Eds.), Mantle Dynamics and Plate Interactions in East Asia. Geodynamics Series. American Geophysical Union, Washington, DC, pp. 107–126.
- Groves, D.I., 1993. The crustal continuum model for late-Archaean lode-gold deposits of the Yilgarn Block, Western Australia. Miner. Deposita 28, 366–374.
- Groves, D.I., Phillips, G.N., Ho, S.E., Houstoun, S.M., Standing, C.A., 1987. Craton-scale distribution of Archaean greenstone gold deposits: predictive capacity of the metamorphic model. Econ. Geol. 82, 2045–2058.
- Groves, D.I., Ridley, J.R., Bloem, E.M.J., Gebre-Mariam, M., Hagemann, S.G., Hronsky, J.M.A. et al., 1995. Lode-gold deposits of the Yilgarn block: products of Late Archaean crustal-scale overpressured hydrothermal systems. In: Coward, M.P., Ries, A.C. (Eds.), Early Precambrian Processes. Geol. Soc. London Spec. Publ., vol. 95, pp. 155–172, London, Bath, UK.
- Groves, D.I., Goldfarb, R.J., Gebre-Mariam, H., Hagemann, S.G., Robert, F., 1998. Orogenic gold deposits—a proposed classification in the context of their crustal distribution and relationship to other gold deposit type. Ore Geol. Rev. 13, 7–27.
- Groves, D.I., Goldfarb, R.J., Knox-Robinson, C.M., Ojala, J., Gardoll, S., Yun, G., Holyland, P., 2000. Late-kinematic timing of orogenic gold deposits and significance for computer-based exploration techniques with emphasis on the Yilgarn block, Western Australia. Ore Geol. Rev. 17, 1–38.
- Gruau, G., Martin, H., Leveque, B., Capdevila, R., Marot, A., 1985. Rb–Sr and Sm–Nd geochronology of lower Proterozoic granite–greenstone terrains in French Guiana, South America. Precambrian Res. 30, 63–80.
- Grunow, A., Hanson, R., Wilson, T., 1996. Were aspects of Pan-African deformation linked to Iapetus opening? Geology 21, 37–40.
- Guen, M.L., Lescuyer, J.L., Marcoux, E., 1992. Lead-isotope evidence for a Hercynian origin of the Salsigne gold deposit (Southern Massif Central, France). Miner. Deposita 27, 129–136.
- Guilbert, J.M., 1992. Metallogeny at Precambrian and Mesozoic continental margins. In: Bartholomew, M.J., Hyndman, D.W., Mogk, D.W., Mason, R. (Eds.), Basement Tectonics 8: Characterization and Comparison of Ancient and Mesozoic Continental Margins. Proceedings of the 8th International Conference of Basement Tectonics Kluwer Academic Publishing, Dordrecht, The Netherlands, pp. 129–141.
- Haeberlin, Y., Moritz, R., Fontbote, L., Cosca, M., 1999. The Pataz gold province, Peru, within the frame of a mesothermal gold and antimony belt of the Eastern Andean Cordillera. In: Stanley, C.J. (Ed.), Mineral Deposits: Processes to Processing. Balkema, Rotterdam, pp. 1323–1326.
- Haeussler, P.J., Bradley, D., Goldfarb, R.J., Snee, L.W., Taylor, C.D., 1995. Link between ridge subduction and gold mineralization in southern Alaska. Geology 23, 995–998.
- Hamilton, W.B., 1998. Archean magmatism and deformation were not products of plate tectonics. Precambrian Res. 91, 143–179.
- Hamilton, J.V., Hodgson, C.J., 1986. Mineralization and structure of the Kolar gold field, India. In: Macdonald, A.J. (Ed.), Gold '86: An International Symposium on the Geology of Gold Deposits, Toronto, pp. 270–283.
- Hanson, G.N., Krogstad, E.J., Rajamani, V., 1988. Tectonic setting of the Kolar schist belt, Karnataka, India. J. Geol. Soc. India 31, 40–42.
- Harbert, W., Frei, L., Jarrad, R., Halgedahl, S., Engebretson, D., 1990. Paleomagnetic and plate-tectonic constraints on the evolution of the Alaskan–eastern Siberian Arctic. In: Grantz, L., Johnson, L., Sweeny, J.F. (Eds.), The Arctic Ocean Region. The Geology of North America Geological Society of America, Boulder, CO, pp. 567–592.
- Harley, M., Charlesworth, E.G., 1992. Thrust-controlled gold mineralisation at the Elandshoogte mine, Sabie-Pilgrim's Rest goldfield, South Africa. Miner. Deposita 27, 122–128.
- Harley, M., Charlesworth, E.G., 1996. The role of fluid pressure in the formation of bedding-parallel thrust-hosted gold deposits, Sabie-Pilgrim's Rest goldfield, eastern Transvaal. Precambrian Res. 79, 125–140.
- Harraz, H.Z., El-Dahhar, M.A., 1993. Nature and composition of gold-forming fluids at Umm Rus area, Eastern Desert, Egypt: evidence from fluid inclusions in vein materials. J. Afr. Earth Sci. 16, 341–353.
- Harris, P.D., Robb, L.J., Tomkinson, M.J., 1993. The nature and structural setting of rare-element pegmatites along the northern flank of the Barberton greenstone belt, South Africa. Inf. Circ. 261, Econ. Geol. Res. Unit, Univ. of the Witwatersrand, 28 pp.
- Harrison, T.M., LeLoup, P.H., Ryerson, F.J., Tapponnier, P., Lacassin, R., Chen, W., 1996. Diachronous initiation of transtension along the Ailao Shan–Red River shear zone, Yunnan and Vietnam. In: Yin, A., Harrison, T.M. (Eds.), The

- Tectonic Evolution of Asia. Cambridge Univ. Press, Cambridge, pp. 208–226.
- Hart, C., Goldfarb, R.J., Qiu, Y., Snee, L.W., Miller, L.D., Miller, M.L., Nie, F.-J., 2002. Gold deposits of the northern margin of the North China craton. *Miner. Deposita* 36, in press.
- Hatcher, R.D.J., 1989. Tectonic synthesis of the U.S. Appalachians. In: Hatcher, R.D.J., Thomas, W.A., Viele, G.W. (Eds.), *The Appalachian–Ouachita Orogen in the United States*. The Geological Society of America The Geology of North America, Boulder, CO, pp. 511–535.
- Helmstaedt, H.H., Scott, D.J., 1992. The Proterozoic ophiolite problem. In: Condie, K.C. (Ed.), *Proterozoic Crustal Evolution*. Elsevier, Amsterdam, pp. 55–95.
- Henley, R.W., Adams, J., 1979. On the evolution of giant gold placers. *Trans. Inst. Min. Metall.* 88, B41–B50.
- Herrington, R.J., 1995. Late Archaean structure and gold mineralization in the Kadoma region of the Midlands greenstone belt, Zimbabwe. In: Coward, M.P., Reis, A.C. (Eds.), *Early Precambrian Processes*. *Geol. Soc. London Spec. Publ.*, vol. 95, pp. 173–191, London, Bath, UK.
- Hodgson, 1993. Mesothermal lode-gold deposits. In: Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., Duke, J.M. (Eds.), *Mineral Deposit Modeling*. Geological Association of Canada Special Paper, vol. 40, pp. 635–678, St. John's, New Foundland, Canada.
- Hodgson, C.J., Hamilton, J.V., 1989. Gold mineralization in the Abitibi greenstone belt—end stage result of Archaean collisional tectonics? In: Keays, R.R., Ramsay, W.R.H., Groves, D.I. (Eds.), *The Geology of Gold Deposits—The Perspective in 1988*. *Economic Geology Monograph*, vol. 6, pp. 86–100, Littleton, CO, USA.
- Hoffman, 1989. Precambrian geology and tectonic history of North America. In: Bally, A.W., Palmer, A.R. (Eds.), *The Geology of North America—An overview*. The Geology of North America Geological Society of America, Boulder, CO, pp. 447–512.
- Hoffman, P.F., 1991. On accretion of granite–greenstone terranes. In: Robert, F., Sheahan, P.A., Green, S.B. (Eds.), *NUNA Conference on Greenstone Gold and Crustal Evolution*. Geological Association of Canada, Mineral Deposits Division, St. John's, New Foundland, Canada, pp. 32–45.
- Hrdy, F., Kyser, T.K., 1995. Origin, timing, and fluid characteristics of an auriferous event: the Proterozoic Jasper Lake lode gold deposit, Saskatchewan, Canada. *Econ. Geol.* 90, 1918–1933.
- Hutchinson, R.W., 1987. Metallogeny of Precambrian gold deposits: space and time relationships. *Econ. Geol.* 82, 1993–2007.
- Hutchinson, R.W., 1993. Some broad processes and affects of evolutionary metallogeny. *Resour. Geol. Spec. Issue* 15, 45–54.
- Hutchison, R.W., Viljoen, R.P., 1988. Re-evaluation of gold source in Witwatersrand ores. *S. Afr. J. Geol.* 91, 157–173.
- Hyndman, R.D., 1995. The Lithoprobe corridor across the Vancouver Island continental margin: the structural and tectonic consequences of subduction. *Can. J. Earth Sci.* 32, 1777–1802.
- Ibrahim, M.S., Kyser, T.K., 1991. Fluid inclusion and isotope systematics of the high-temperature Proterozoic Star Lake lode gold deposit, northern Saskatchewan, Canada. *Econ. Geol.* 86, 1468–1490.
- Ineson, P.R., Mitchell, J.G., 1975. K–Ar isotopic age determinations from some Welsh mineral localities. *Trans. Inst. Min. Metall.* 84, B7–B16.
- Jackson, S.L., Cruden, A.R., 1995. Formation of the Abitibi greenstone belt by arc-trench migration. *Geology* 23, 471–474.
- Jamieson, R.A., Beaumont, C., Fullsack, P., Lee, B., 1998. Barrovia regional metamorphism: where's the heat? In: Treloar, P.J., O'Brien, P.J. (Eds.), *What Drives Metamorphism and Metamorphic Reactions?* *Geol. Soc. London Spec. Publ.*, vol. 138, pp. 23–51.
- Jamsradorj, G., Diatchkov, S.A., 1996. Placer deposits of Mongolia. *Soc. Econ. Geol. Newsl.* 24 (1), 10–13.
- Jayananda, M., Moyen, J.F., Martin, H., Peucat, J.J., Auvray, B., Mahabaleswar, B., 2000. Late Archaean (2550–2520 Ma) juvenile magmatism in the Eastern Dharwar craton, southern India—constraints from geochronology, Nd–Sr isotopes and whole rock geochemistry. *Precambrian Res.* 99, 225–254.
- Jiang, N., Zhu, Y., 1999. Geology and genesis of orogenic gold deposits, Xiaqingling district, southeastern China. *Int. Geol. Rev.* 41, 816–826.
- Jiawei, X. (Ed.) 1993. *The Tanchung–Jujiang Wrench Fault System*. Wiley, Chichester, England, 279 pp.
- Kaltoft, K., Schlatter, D.M., Kludt, L., 2000. Gold occurrences and lead isotopes in Ketilidian mobile belt, south Greenland. *Trans. Inst. Min. Metall.* 109, B23–B33.
- Kamona, A.F., 1994. Mineralization types in the Mozambique belt of eastern Zambia. *J. Afr. Earth Sci.* 19, 237–243.
- Kent, A.J.R., Cassidy, K.F., Fanning, C.M., 1996. Archean gold mineralization synchronous with the final stages of cratonization, Yilgarn Craton, Western Australia. *Geology* 24, 879–882.
- Keppie, J.D., Dallmeyer, R.D., 1995. Late Paleozoic collision, delamination, short-lived magmatism, and rapid denudation in the Meguma terrane (Nova Scotia, Canada): constraints from $^{40}\text{Ar}/^{39}\text{Ar}$ isotopic data. *Can. J. Earth Sci.* 32, 644–659.
- Keppie, J.D., Krogh, T.E., 1999. U–Pb geochronology of Devonian granites in the Meguma terrane of Nova Scotia, Canada: evidence for hotspot melting of a Neoproterozoic source. *J. Geol.* 107, 555–568.
- Kerrick, R., Cassidy, K.F., 1994. Temporal relationships of lode gold mineralization to accretion, magmatism, metamorphism and deformation—Archean to present—a review. *Ore Geol. Rev.* 9, 263–310.
- Kerrick, R., Fyfe, W.S., 1981. The gold carbonate association: Source of CO_2 fixation reactions in Archean lode deposits. *Chem. Geol.* 33, 265–294.
- Kerrick, R., Wyman, D.A., 1990. The geodynamic setting of mesothermal gold deposits—an association with accretionary tectonic regimes. *Geology* 18, 882–885.
- Kerswill, J.A., Henderson, J.R., Henderson, M.N., 1996. Distribution of gold and sulfides at Lupin, Northwest Territories—a discussion. *Econ. Geol.* 91, 957–964.
- Khiltova, V.Y., Pleskach, G.P., 1997. Yenisey fold belt. In:

- Rundqvist, D.V., Gillen, C. (Eds.), *Precambrian Ore Deposits of the East European and Siberian Cratons*. Elsevier, Amsterdam, pp. 289–316.
- King, J., Helmstaedt, H., 1997. The Slave Province, North–West Territories, Canada. In: de Wit, M., Ashwal, L.D. (Eds.), *Greenstone Belts*. Clarendon Press, Oxford, pp. 459–479.
- Kirk, J., Ruiz, J., Chesley, J., Titley, S., Walshe, J., 2001. Detrital model for the origin of gold and sulfides in the Witwatersrand basin based on Re–Os isotopes. [abs.] *Geol. Soc. Am. Abstr. Programs* 32 (7), A-79.
- Kirk, J., Ruiz, J., Chesley, J., Titley, S., Walshe, J., 2001. A detrital model for the origin of gold and sulfides in the Witwatersrand basin based on Re–Os isotopes. *Geochim. Cosmochim. Acta* (in press).
- Kisters, A.F.M., Kolb, J., Meyer, F.M., 1998. Gold mineralization in high-grade metamorphic shear zones of the Renco mine, southern Zimbabwe. *Econ. Geol.* 93, 598–601.
- Kisters, A.F.M., Meyer, F.M., Seravkin, I.B., Znamensky, S.E., Kosarev, A.M., Ertl, R.G.W., 1999. The geologic setting of lode-gold deposits in the central southern Urals: a review. *Geol. Rundsch.* 87, 603–616.
- Kolb, J., Kisters, A.M.F., Hoernes, S., 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. *Miner. Deposita* 35, 109–125.
- Konstantinov, M., Dankovtsev, R., Simkin, G., Cherkasov, S., 1999. Deep structure of the north Enisei gold district (Russia) and setting of ore deposits. *Geol. Ore Deposits* 41 (5), 425–436.
- Kontak, D.J., Smith, P.K., Reynolds, P., Taylor, K., 1990. Geological and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronological constraints on the timing of quartz vein formation in Meguma Group lode-gold deposits, Nova Scotia. *Atl. Geol.* 26, 201–227.
- Koons, P.O., Craw, D., 1991. Gold mineralization as a consequence of continental collision: an example from the Southern Alps of New Zealand. *Earth Planet. Sci. Lett.* 103, 1–9.
- Korobeinikov, A.F., 1993. Prognostic-exploration criteria of gold-platinum mineralization in black shales of ophiolite belts. *Otechestvennaya Geol.* 4, 19–25.
- Kostitsyn, Y.A., 1993. Rb–Sr isotope studies in the Murantau deposit: dating of ore veins by the isochron technique. *Geokhimiya* 9, 1308–1318 [in Russian].
- Koval, V.B., Koptuyukh, M.A., Yaroschchuk, M.A., Fomin, Y.A., Lapusta, V.F., 1997. Gold deposits of the Ukrainian Shield (Ukraine). *Geol. Ore Deposits* 39 (3), 194–208.
- Krivolutskaya, N.A., 1997. Paragenetic associations of minerals and formation conditions of the Klyuchevsk gold deposit (East Transbaikalian region) Russia. *Geol. Ore Deposits* 39 (4), 294–310.
- Krogstad, E.J., Balakrishnan, S., Mukhopadhyay, D.K., Rajamani, V., Hanson, G.N., 1989. Plate tectonics 2.5 billion years ago—evidence at Kolar, south India. *Science* 243, 1337–1340.
- Kroner, A., Jaekel, P., Brandl, G., Nemchin, A.A., Pidgeon, R.T., 1999. Single zircon ages for granitoid gneisses in the Central Zone of the Limpopo belt, Southern Africa, and geodynamic significance. *Precambrian Res.* 93, 299–337.
- Kuehn, S., Ogola, J., Sango, P., 1990. Regional setting and nature of gold mineralization in Tanzania and southwest Kenya. *Precambrian Res.* 46, 71–82.
- Kushev, V.G., Kornilov, M.F., 1997. The Ukrainian Shield. In: de Wit, M., Ashwal, L.D. (Eds.), *Greenstone Belts*. Clarendon Press, Oxford, pp. 726–729.
- Kusky, T.M., 1989. Accretion of the Archaean Slave Province. *Geology* 17, 63–67.
- Ladeira, E.A., 1991. Genesis of gold in Quadrilátero Ferrífero: a remarkable case of permanency, recycling and inheritance—a tribute to Djalma Guimarães, Pierre Routhier, and Hans Ramberg. In: Ladeira, E.A. (Ed.), *Brazil Gold '91*. Balkema, Rotterdam, pp. 11–30.
- Landefeld, L.A., 1988. The geology of the Mother Lode gold belt, Sierra Nevada Foothills metamorphic belt, California. *Bicentennial Gold 88, Extended Abstracts, Oral Programme*. Geological Society of Australia, Melbourne, pp. 167–172.
- Lang, J.R., Baker, T., Hart, C.J.R., Mortensen, J.K., 2000. An exploration model for intrusion-related gold systems. *SEG Newsl.* 40 (1), 6–15.
- Larin, A.M., Rytsk, Y.Y., Sokolov, Y.M., 1997. Baikal–Patom fold belt. In: Rundqvist, D.V., Gillen, C. (Eds.), *Precambrian Ore Deposits of the East European and Siberian Cratons*. Elsevier, Amsterdam, pp. 317–362.
- Lavreau, J.J., 1984. Vein and stratabound gold deposits of northern Zaire. *Miner. Deposita* 19, 158–165.
- LeAnderson, P.J., Yoldash, M., Johnson, P.R., Offield, T.W., 1995. Structure, vein paragenesis, and alteration of Al Wajh gold district, Saudi Arabia. *Econ. Geol.* 90, 2262–2273.
- Leitch, C.H.B., Van der Hayden, P., Goodwin, C.I., Armstrong, R.L., Harakal, J.E., 1991. Geochronometry of the Bridge River camp, southwestern British Columbia. *Can. J. Earth Sci.* 28, 195–208.
- Lenoir, J.L., Liegeois, J.P., Theunissen, K., Klerkx, J., 1994. The Paleoproterozoic Ubendian shear belt in Tanzania: geochronology and structure. *J. Afr. Earth Sci.* 19 (3), 169–184.
- Lewis, T.J., 1991. Heat flux in the Canadian Cordillera. In: Sleammons, D.B., Engdahl, E.R., Zoback, M.D., Blackwell, D. (Eds.), *Neotectonics of North America*. Geological Society of America, Boulder, CO, pp. 445–456.
- Li, Z.X., 1994. Collision between the North and South China blocks: a crustal detachment model for suturing in the region east of the Tan–Lu fault. *Geology* 22, 739–742.
- Li, Z., Zhang, L., Powell, C.M., 1996. Positions of the East Asian cratons in the Neoproterozoic supercontinent Rodinia. *Aust. J. Earth Sci.* 43, 593–604.
- Lindgren, W., 1909. Metallogenetic epochs. *Econ. Geol.* 4, 409–420.
- Lobato, L.M., Noce, C.M., Ribeiro-Rodrigues, L.C., Zucchetti, M., Baltazar, O.F., da Silva, L.C., Pinto, C.P., 2001. The Archaean Rio das Velhas greenstone belt in the Quadrilátero Ferrífero region, Minas Gerais, Brazil: Part II. Description of selected gold deposits. *Miner. Deposita* 36, in press.
- Loucks, R.R., Mavrogenes, J.A., 1999. Gold solubility in supercritical hydrothermal brines measured in synthetic fluid inclusions. *Science* 284, 2159–2163.
- Lu, J., Seccombe, P.K., Foster, D., Andrew, A.S., 1996. Timing of mineralization and source of fluids in a slate-belt auriferous

- vein system, Hill End goldfield, NSW, Australia—evidence from $^{40}\text{Ar}/^{39}\text{Ar}$ dating and O- and H-isotopes. *Lithos* 38, 147–165.
- Lund, K., Sneek, L.W., Evans, K.V., 1986. Age and genesis of precious metal deposits, Buffalo Hump district, central Idaho: implications for depth of emplacement of quartz veins. *Econ. Geol.* 81, 990–996.
- Luukkonen, A., 1994. Main geological features, metallogeny, and hydrothermal alteration phenomena of certain gold and gold–tin–tungsten prospects in southern Finland. *Geol. Surv. Finl., Bull.* 377, 153 pp.
- Madden-McGuire, D.J., Silberman, M.L., Church, S.E., 1989. Geologic relationships, K–Ar ages and isotopic data from the Willow Creek gold mining district, southern Alaska. In: Keays, R.R., Ramsay, W.R.H., Groves, D.I. (Eds.), *The Geology of Gold Deposits: The Perspective in 1988*. *Econ. Geol. Monograph*, vol. 6, pp. 242–251, Littleton, CO, USA.
- Mao, J., Qiu, Y., Goldfarb, R., Zhang, Z., Garwin, S., Ren, F., 2002a. Geology and distribution of gold deposits in the western Qinling belt, central China. *Miner. Deposita* 36, in press.
- Mao, J., Qiu, Y., Goldfarb, R.J., Zhang, Z., Xu, W., Deng, J., 2002b. Gold deposits in the Xiaoqinling–Xiong’ershan region, Qinling Mountains, central China. *Miner. Deposita* 36, in press.
- Marignac, C., Cuney, M., 1999. Ore deposits of the French Massif Central: insight into the metallogenesis of the Variscan collision belt. *Miner. Deposita* 34, 472–504.
- Marshall, D., Meisser, N., Taylor, R.P., 1998. Fluid inclusion, stable isotope, and Ar–Ar evidence for the age and origin of gold-bearing quartz veins at Mont Chemin, Switzerland. *Mineral. Petrol.* 62, 147–165.
- Maruyama, S., 1997. Pacific-type orogeny revisited: Miyashiro-type orogeny proposed. *Isl. Arc* 6, 91–120.
- Maruyama, S., Isozaki, Y., Kimura, G., Terabayashi, M., 1997. Paleogeographic maps of the Japanese Islands: plate tectonic synthesis from 750 Ma to the present. *Isl. Arc* 6, 121–142.
- McArdle, P., 1989. Geological setting of gold mineralization in the Republic of Ireland. *Trans. Inst. Min. Metall.* 98, B7–B12.
- McCoy, D., Newberry, R.J., Lauer, P., DiMarchi, J.J., Bakke, A., Masterman, J.S., Minehand, D.L., 1997. Plutonic-related gold deposits of interior Alaska. In: Goldfarb, R.J., Miller, L.D. (Eds.), *Mineral Deposits of Alaska*. *Economic Geology Monograph*, vol. 9, pp. 191–241, Littleton, CO, USA.
- McKeag, S.A., Craw, D., 1989. Contrasting fluids in gold-bearing quartz vein systems formed progressively in a rising metamorphic belt—Ottago Schist, New Zealand. *Econ. Geol.* 84, 22–33.
- McReath, I., Faraco, M.T.L., 1996. The deposition age and evolution of the Vila Nova Metamorphic Suite and the connection between the Guyana Shield and the West African craton. *Anais 39th Congr. Bras. Geol., Salvador, Soc. Bras. Geol., Nucleo Bahia/Sergipe*. pp. 74–76.
- Mello, E.F., Xavier, R.P., Tassinari, C.C.G., 1996. A review on the geochronology of the Rio Itapicuru greenstone belt, NE Bahia (Brazil), and the timing of the lode-gold deposits. *XXXIX Congresso Brasileiro de Geologia, Salvador, Bahia*. pp. 273–277.
- Metcalf, I., 1996. Gondwanaland dispersion, Asian accretion and evolution of eastern Tethys. *Aust. J. Earth Sci.* 43, 605–623.
- Meyer, C., 1981. Ore-forming processes in geologic history. *Econ. Geol.* 6–41, 75th Anniversary Volume.
- Milesi, J.P., Egal, E., Ledru, P., Vernhet, Y., Thieblemont, D., Cocherie, A., Tegvey, M., Martel-Santin, B. et al., 1995. Les mineralisations du Nord de la Guyane française dans leur cadre géologique. *Chron. Rech. Min.* 518, 5–58.
- Miller, L.D., Goldfarb, R.J., Gehrels, G.E., Sneek, L.W., 1994. Genetic links among fluid cycling, vein formation, regional deformation, and plutonism in the Juneau gold belt, southeastern Alaska. *Geology* 22, 203–206.
- Miller, L.D., Goldfarb, R.J., Hart, C.J.R., Nie, F.J., Miller, M.L., Yang, Y., Liu, Y., 1998. North China gold—a product of multiple orogens. *Soc. Econ. Geol. Newsl.* 33 (1), 6–12.
- Minter, W.E.L., Renger, F.E., Siegers, A., 1990. Early Proterozoic gold placers of the Moeda Formation within the Gandarela syncline, Minas Gerais, Brazil. *Econ. Geol.* 85, 943–951.
- Minter, W.E.L., Goedhart, M., Knight, J., Frimmel, H.E., 1993. Morphology of Witwatersrand gold grains from the Basal Reef: evidence for their detrital origin. *Econ. Geol.* 88, 237–248.
- Mironov, G., Zhmodik, S.M., 1999. Gold deposits of the Urik–Kitoi metallogenic zone (Eastern Sayan, Russia). *Geol. Ore Deposits* 41 (1), 46–60.
- Mitchell, A.H.G., 1996. Distribution and genesis of some epizonal Zn–Pb and Au provinces in the Carpathian–Balkan region. *Trans. Inst. Min. Metall.* 105, B127–B138.
- Mitchell, A.H.G., Htay, N., Ausa, C., Deiparine, L., Khine, A., Po, S., 1999. Geological setting of gold deposits in Myanmar. *PACRIM ’99. The Australasian Institute of Mining and Metallurgy, Carlton, Victoria, Australia*, pp. 303–309.
- Moiseenko, V.G., Stepanov, V.A., Shergina, Y.P., 1999. Age of the Kirov gold deposit, Amur region. *Dokl. Earth Sci.* 369A (9), 1217–1219.
- Montero, P., Bea, F., Gerdes, A., Fershtater, G., Zin’kova, E., Borodina, N., Osipova, T., Smirnov, V., 2000. Single-zircon evaporation ages and Rb–Sr dating of four major Variscan batholiths of the Urals—a perspective on the timing of deformation and granite generation. *Tectonophysics* 317, 93–108.
- Moore, J.M., Jacob, R.E., Harris, C., Armstrong, R., 1999. The Navachab gold deposit, Namibia: a mesothermal sheeted-vein/skarn system related to the Pan-African Damaran orogen. *J. Afr. Earth Sci.* 28 (4A), 50–51.
- Moores, E.M., 1991. Southwest U.S.–East Antarctic (SWEAT) connection: a hypothesis. *Geology* 19, 425–428.
- Moravek, P., 1996a. Gold in metallogeny of the Central and Western European units of the Peri-Alpine Variscan belt. *Global Tecton. Metallog.* 5 (3–4), 145–163.
- Moravek, P., 1996b. Gold Deposits in Bohemia. *Czech Geological Survey, Prague*, 96 pp.
- Mortensen, J.K., Murphy, D.C., Poulsen, K.H., Bremner, T., 1996. Intrusion-related gold and base metal mineralization associated with the early Cretaceous Tombstone plutonic suite, Yukon and east-central Alaska, New Mineral Deposit Models of the Cordillera. *British Columbia Ministry of Employment*

- and Investment, Energy and Minerals Division, Geological Survey Branch, Short Course Notes, Vancouver. pp. L1–L13.
- Mossman, D.J., Leblanc, M.L., Burzynski, J.F., 1991. Antimony-gold deposits of North Atlantic Acadian–Hercynian domain. *Trans. Inst. Min. Metall.* 100, B227–233.
- Mueller, A.G., McNaughton, N.J., 2000. U–Pb ages constraining batholith emplacement, contact metamorphism, and the formation of gold and W–Mo skarns in the Southern Cross area, Yilgarn craton, Western Australia. *Econ. Geol.* 95, 1231–1257.
- Muir, R.J., Ireland, T.R., Weaver, S.D., Bradshaw, J.D., 1996. Ion microprobe dating of Paleozoic granitoids: devonian magmatism in New Zealand and correlations with Australia and Antarctica. *Chem. Geol.* 127, 191–210 (Isotope Geoscience Section).
- Murphy, P.J., Roberts, S., 1997. Evolution of a metamorphic fluid and its role in lode gold mineralisation in the Central Iberian Zone. *Miner. Deposita* 32, 459–474.
- Myers, J.S., 1997. Preface: regional overview of Archaean granite–greenstone geology of the Eastern Goldfields, Yilgarn Craton. *Precambrian Res.* 83, 1–10.
- Myers, J.S., Shaw, R.D., Tyler, I.M., 1996. Tectonic evolution of Proterozoic Australia. *Tectonics* 15 (6), 1431–1446.
- Nakajima, T., 1997. Regional metamorphic belts of the Japanese Islands. *Isl. Arc* 6, 69–90.
- Neimark, L.A., Rytisk, E.Y., Ovchinnikova, G.V., Sergeeva, N.A., Gorokhovskii, B.M., Skopintsev, V.G., 1995. Lead isotopes in gold deposits of the Eastern Sayan (Russia). *Geol. Ore Deposits* 37 (3), 201–212.
- Neto, M.B. da R., 1994. Geologia e recursos minerais do Greenstone Belt do Rio Itapicuru, Bahia. Ser. Arquivos Abertos, Companhia Naiana de Pesquisa Mineral 4, 30 pp. (in Portuguese with English abstract).
- Neumayr, P., Ridley, J.R., McNaughton, N.J., Kinny, P., Barley, M.E., Groves, D.I., 1998. Timing of gold mineralisation in the Mount York district, Pilgangoora greenstone belt, and implications for the tectonic and metamorphic evolution of an area linking the western and eastern Pilbara craton. *Precambrian Res.* 88, 249–265.
- Newberry, R.J., 2000. Mineral deposits and associated Mesozoic and Tertiary igneous rocks within interior Alaska and adjacent Yukon portions of the ‘Tintina Gold Belt’: a progress report. The Tintina Gold Belt: Concepts, Exploration, and Discoveries. British Columbia and Yukon Chamber of Mines, Vancouver. pp. 59–88.
- Nie, S., Rowley, D.B., 1994. Comment on “Paleomagnetic constraints on the geodynamic history of the major blocks of China from the Permian to the Present”. *J. Geophys. Res.* 99 (B9), 18035–18042.
- Nokleberg, W.J., Bundtzen, T.K., Grybeck, D., Koch, R.D., Eremin, R.A., Rozenblum, I.S., Sidorov, A.A. et al., 1993. Metallogeny of mainland Alaska and the Russian Northeast: Mineral deposit maps, models, and tables, metallogenic belt maps and interpretation, and references cited. U. S. Geol. Surv. Open-File Rep. 93-339, 222 pp.
- Nokleberg, W.J., Parfenov, L.M., Monger, J.W.H., 1994. Circum-North Pacific tectono-stratigraphic terrane map. U. S. Geol. Surv. Open-File Rep. 94-714, 221 pp., 2 sheets.
- Nokleberg, W.J., Bundtzen, T.K., Dawson, K.M., Eremin, R.A., Goryachev, N.A., Koch, R.D., Ratkin, V.V. et al., 1996. Significant metalliferous lode deposits and placer districts for the Russian Far East, Alaska, and the Canadian Cordillera. U. S. Geol. Surv. Open-File Rep. 96-513-A, 385 pp.
- Norcross, C.E., Davis, D.W., Spooner, E.T.C., Rust, A., 2000. U–Pb and Pb–Pb age constraints on Paleoproterozoic magmatism, deformation and gold mineralization in the Omai area, Guyana Shield. *Precambrian Res.* 102, 69–86.
- Noronha, F., Cathelineau, M., Boiron, M.-C., Banks, D.A., Doira, A., Ribeiro, M.A., Norgueira, P., Guedes, A., 2000. A three stage fluid flow model for Variscan gold metallogenesis in northern Portugal. *J. Geochem. Explor.* 71, 209–224.
- Norris, R.J., Henley, R.W., 1976. Dewatering of a metamorphic pile. *Geology* 8, 333–336.
- Novozhilov, Y.I., Gavrilov, A.M., 1994. Evolution and dynamics of gold-ore associations in miogeosynclinal foldbelts. *Dokl. Akad. Ross. Nauk* 338 (1), 74–77.
- Nutmam, A., 1997. The Greenland sector of the North Atlantic craton. In: de Wit, M., Ashwal, L.D. (Eds.), *Greenstone Belts*. Clarendon Press, Oxford, pp. 665–674.
- Oberthur, T., Vetter, U., Davis, D.W., Amanor, J.A., 1998. Age constraints on gold mineralization and Paleoproterozoic crustal evolution in the Ashanti belt of southern Ghana. *Precambrian Res.* 89, 129–143.
- Oberthur, T., Blenkinsop, T.G., Hein, U.F., Hoppner, M., Hohndorf, A., Weiser, T.W., 2000. Gold mineralization in the Mazowe area, Harare–Bindura–Shamva greenstone belt, Zimbabwe–Genetic relationships deduced from mineralogical, fluid inclusion and stable isotope studies, and the Sm–Nd isotopic composition of scheelites. *Miner. Deposita* 35, 138–156.
- Oksman, V.S., 1998. Geodynamic evolution of the collisional belt of the Chersky mountain system (northeast Asia). *Geotectonics* 32, 47–59.
- Olivo, G.R., Gauthier, M., Bardoux, M., de Sa, E.L., Fonseca, J.T.F., Santana, F.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. *Econ. Geol.* 90, 118–134.
- Olivo, G.R., Gauthier, M., Garipey, C., Carignan, J., 1996. Transamazonian tectonism and Au–Pd mineralization at the Caue mine, Itabira district, Brazil: Pb isotopic evidence. *J. S. Am. Earth Sci.* 9, 273–279.
- Pan, Y., Fleet, M.E., 1995. The late Archean Hemlo gold deposit, Ontario, Canada: a review and synthesis. *Ore Geol. Rev.* 9, 455–488.
- Pankka, H.S., Vanhanen, E.J., 1992. Early Proterozoic Au–Co–U mineralization in the Kuusamo district, northeastern Finland. *Precambrian Res.* 58, 387–400.
- Parfenov, L.M., 1995. Tectonics and regional metallogeny of the Verkhoyansk–Kolyma region. In: Bundtzen, T.K., Fonseca, A.L., Mann, R. (Eds.), *The Geology and Mineral Deposits of the Russian Far East*. Alaska Miners Association, Anchorage, AK, pp. 61–84.
- Paterson, C.J., 1986. Controls on gold and tungsten mineralization in metamorphic–hydrothermal systems, Otago, New Zealand. In: Keppie, J.D., Boyle, R.W., Haynes, S.J. (Eds.), *Turbidite-*

- Hosted Gold Deposits. Geological Association of Canada Special Paper, vol. 32, pp. 25–39, St. John's, New Foundland, Canada.
- Perkins, C., Kennedy, A.K., 1998. Permo-Carboniferous gold epoch of northeast Queensland. *Aust. J. Earth Sci.* 45, 185–200.
- Peters, S.G., Golding, S.Z., Dowling, K., 1990. Melange- and sediment-hosted gold-bearing quartz veins, Hodgkinson gold field, Queensland, Australia. *Econ. Geol.* 85, 312–327.
- Pettke, T., Diamond, L.W., Villa, I.M., 1999. Mesothermal gold veins and metamorphic devolatilization in the northwestern Alps: the temporal link. *Geology* 27, 641–644.
- Phillips, G.N., Groves, D.I., 1983. The nature of Archaean gold-bearing fluids as deduced from gold deposits of Western Australia. *Geol. Soc. Aust. J.* 30, 25–39.
- Phillips, G.N., Myers, R.E., 1989. The Witwatersrand goldfields: Part II. An origin for Witwatersrand gold during metamorphism and associated alteration. *Econ. Geol. Monogr.* 6, 598–608.
- Phillips, G.N., Powell, R., 1993. Link between gold provinces. *Econ. Geol.* 88, 1084–1098.
- Pigois, J.-P., Groves, D.I., McNaughton, N.J., Marston, R.J., Tunks, A.J., McKevitt, M., 2000. Resolution of the age of orogenic and palaeoplacer gold deposits in the Ashanti belt, Ghana, from Shrimp-II U-Pb dating of xenotime from Damang and Tarkwa [abs.]. *Geol. Soc. Amer. Annu. Meet.* 32, A–424.
- Pinna, P., Cocherie, A., Thieblemont, D., Jezequell, P., Kayogoma, E., 1999. The Archean evolution of the Tanzanian craton (2.03–2.53 Ga). *J. Afr. Earth Sci.* 28 (4A), 62–63.
- Pitfield, P.E.J., Campbell, S.D.G., 1994. Structural controls of gold mineralisation and regional structure in the Harare–Shamva and Norton greenstone belts. Phase 2 Midlands Goldfield Project Final Report, 1, 50–60.
- Plafker, G., Berg, H.C., 1994. Overview of the geology and tectonic evolution of Alaska. In: Plafker, G., Berg, H.C. (Eds.), *The Geology of Alaska. The Geology of North America* Geological Society of America, Boulder, CO, pp. 989–1021.
- Pohl, W., 1994. Metallogeny of the northeastern Kibara belt, central Africa—recent perspectives. *Ore Geol. Rev.* 9, 105–130.
- Pohl, W., Gunther, M.A., 1991. The origin of Kibaran (late Mid-Proterozoic) tin, tungsten, and gold quartz vein deposits in Central Africa: a fluid inclusion study. *Miner. Deposita* 26, 51–59.
- Polat, A., Kerrich, R., 1999. Formation of an Archean tectonic melange in the Schreiber–Hemlo greenstone belt, Superior Province, Canada: implications for Archean subduction–accretion process. *Tectonics* 18, 733–755.
- Popov, N.V., Shaporina, M.N., Amuzinskii, V.A., Smelov, A.P., Zedgenizov, A.N., 1999. Gold metallogeny in the Aldan province. *Russ. Geol. Geophys.* 40 (5), 700–711.
- Poulsen, K.H., 1996. Lode gold. In: Eckstrand, O.R., Sinclair, W.D., Thorpe, R.I. (Eds.), *Geology of Canadian Mineral Deposit Types. Geological Survey of Canada, Geology of Canada*, vol. 8, pp. 323–328, Ottawa, Canada.
- Poulsen, K.H., Card, K.D., Franklin, J.M., 1992. Archean tectonic and metallogenic evolution of the Superior Province of the Canadian Shield. *Precambrian Res.* 58, 25–54.
- Prochaska, W., Hafellner, M., Banks, D.A., Yardley, B.W.D., 1995. Relation between metamorphism and mineralization in the Eastern Alps of Austria. In: Pasava, Kribek, B., Zak, K. (Eds.), *Mineral Deposits: From Their Origin to Their Environmental Impacts*. Balkema, Rotterdam, pp. 901–904.
- Puchkov, V.N., 1997. Tectonics of the Urals—modern concepts. *Geotectonics* 31 (4), 294–312.
- Qiu, Y., Groves, D.I., 1999. Late Archean collision and delamination in the southwest Yilgarn craton: the driving force for Archean orogenic lode gold mineralization. *Econ. Geol.* 94, 115–122.
- Qiu, Y., Groves, D.I., McNaughton, N.J., Wang, L., Zhou, T., 2002. Nature, age, and tectonic setting of orogenic lode-gold mineralization in the Jiaodong Peninsula of the North China Craton. *Miner. Deposita* 36, in press.
- Quiring, H., 1972. *Geschichte des Goldes*. In: Sedillot, R. (Ed.), *Histoire de l'Or*. Fayard, Paris.
- Radhakrishna, B.P., Curtis, L.C., 1999. *Gold in India*. Geological Society of India, Bangalore, India, 307 pp.
- Rapela, C.W., Pankhurst, R.J., Casquet, C., Baldo, E., Saavedra, J., Galindo, C., 1998. Early evolution of the Proto-Andean margin of South America. *Geology* 26, 707–710.
- Ratkin, V., 1995. Pre- and post-accretionary metallogeny of the southern Russia Far East. *Resour. Geol. Spec. Issue* 18, 127–133.
- Redden, J.A., Peterman, Z.E., Zartman, R.E., DeWitt, E., 1990. Early Proterozoic Trans-Hudson orogen of North America. *Geol. Surv. Can. Spec. Pap.* 37, 229–251.
- Rey, P., Burg, J.-P., Casey, M., 1997. The Scandinavian Caledonides and the relationship to the Variscan belt. In: Burg, J.-P., Ford, M. (Eds.), *Orogeny through Time*. Geological Society Special Publication. *Geol. Soc. London Spec. Publ.* vol. 121, pp. 179–200. London, Bath, UK.
- Rice, R., 1981. Gold: report of the fifth annual commodity meeting: gold exploration—past and future. *Trans. Inst. Min. Metall.* 90, A124–A129.
- Robb, L.J., Meyer, F.M., 1995. The Witwatersrand basin, South Africa: geological framework and mineralization processes. *Ore Geol. Rev.* 10, 67–94.
- Robert, F., 1990. Dating old gold deposits. *Nature* 346, 792–793.
- Robert, F., 1996. Quartz–carbonate vein gold. In: Eckstrand, O.R., Sinclair, W.D., Thorpe, R.I. (Eds.), *Geology of Canadian Mineral Deposit Types. The Geology of North America* Geological Society of America, Boulder, CO, pp. 350–366.
- Rogers, J.J.W., 1993. Contrast between an old and a young Gondwana shield. *J. Geodyn.* 16 (4), 211–214.
- Rogers, J.J.W., 1996. A history of continents in the past three billion years. *J. Geol.* 104, 91–107.
- Rogers, J.J.W., Unrug, R., Sultan, M., 1995. Tectonic assembly of Gondwana. *J. Geodyn.* 19 (1), 1–34.
- Rowins, S.M., Groves, D.I., McNaughton, N.J., Palmer, M.R., Eldridge, C.S., 1997. A reinterpretation of the role of granitoids in the genesis of Neoproterozoic gold mineralization in the Telfer dome, Western Australia. *Econ. Geol.* 92, 133–160.
- Rowley, P.D., William, P.L., Pride, D.E., 1991. Metallic and

- non-metallic mineral resources of Antarctica. In: Tingey, R.J. (Ed.), *The Geology of Antarctica*. Clarendon Press, Oxford, pp. 617–651.
- Rubin, C.M., Miller, E.L., Toro, J., 1995. Deformation of the northern circum-Pacific margin—variations in tectonic style and plate-tectonic implications. *Geology* 23, 897–900.
- Rui, Z., Goldfarb, R.J., Qiu, Y., Zhou, T., Chen, R., Pirjano, F., 2002. Variscan gold deposits of the Xinjiang Autonomous Region, northwestern China. *Miner. Deposita* 36, in press.
- Rundqvist, D.V., 1997. Time factor in the formation of hydrothermal deposits: periods, epochs, megastages, and stages of ore formation. *Geol. Rudn. Mestorozhd.* 38 (1), 11–24.
- Rushton, R.W., Nesbitt, B.E., Muehlenbachs, K., Mortensen, J.K., 1993. A fluid inclusion and stable isotope study of Au quartz veins in the Klondike district, Yukon Territory, Canada—a section through a mesothermal vein system. *Econ. Geol.* 88, 647–678.
- Rye, D.M., Shelton, K.L., 1983. A stable isotope study of the Homestake gold mine: an example of a lower Proterozoic submarine hydrothermal vent system. [abs] *Geol. Assoc. Can. Annu. Meet.* 8, A60.
- Sadowski, G.R., Bettencourt, J.S., 1996. Mesoproterozoic tectonic correlations between eastern Laurentia and the western border of the Amazon Craton. *Precambrian Res.* 76, 213–227.
- Safonov, Y.G., 1997. Hydrothermal gold deposits—distribution, geological/genetic types, and productivity of ore-forming systems. *Geol. Ore Deposits* 39 (1), 20–32.
- Salda, L.H.D., de Luchi, M.G.L., Cingolani, C.A., Varela, R., 1998. Laurentia–Gondwana collision: the origin of the Famatian–Appalachian orogenic belt (a review). In: Pankhurst, R.J., Rapela, C.W. (Eds.), *The Proto-Andean Margin of Gondwana*. *Geol. Soc. London Spec. Publ.*, vol. 142, pp. 219–234.
- Sango, P.M., 1988. Structural and lithological controls of gold mineralization in the Lupa goldfield, Tanzania. In: Ho, S.E., Groves, D.I. (Eds.), *Advances in Understanding Precambrian Gold Deposits*, vol. 12. The Geology Dept. and University Extension, The University of Western Australia, Nedlands, WA, Australia, pp. 99–109.
- Sangster, A.L., Gauthier, M., Gower, C.F., 1992. Metallogeny of structural zones, Grenville Province, northeastern North America. *Precambrian Res.* 58, 401–426.
- Santos, J.O.S., 1999. New understanding of the Amazon craton gold provinces, New Developments in Economic Geology. Centre for Teaching and Research in Strategic Mineral Deposits, University of Western Australia, Nedlands, Western Australia.
- Santos, J.O.S., Groves, D.I., Hartmann, L.A., Moura, M.A., McNaughton, N.J., 2001. Gold deposits of the Tapajos and Alta Floresta domains, Tapajos–Parima orogenic belt, Amazon craton, Brazil. *Miner. Deposita* 36, in press.
- Schermaier, A., Haunschmid, B., Finger, F., 1997. Distribution of Variscan I- and S-type granites in the Eastern Alps—a possible clue to unravel pre-Alpine basement structures. *Tectonophysics* 272, 315–333.
- Schmidt-Mumm, A., Oberthur, T., Blenkinsop, T.G.e.a., 1994. The Redwing gold mine, Mutare greenstone belt, Zimbabwe: a fluid-dynamic metallogenetic model. [abs] In: Schmidt-Mumm, A. (Ed.), *Abstracts Volume, Conference on Metallogenesis of Gold in Africa*, Hannover, Germany, pp. 71–72.
- Scholl, D.W., von Huene, R., Vallier, T.L., Howell, D.G., 1980. Sedimentary masses and concepts about tectonic processes at underthrust ocean margins. *Geology* 8, 564–568.
- Schreiber, E., 1996. *Geology of New South Wales—synthesis*. *Mem. Geol.* 13 (1), 295 pp.
- Scotese, C.R., 1997. *Paleogeographic Atlas. PALEOMAP project*, Arlington, TX.
- Sedillot, R., 1972. *Histoire de l’Or*. Fayard, Paris.
- Senor, A.M.C., Natal’in, B.A., 1996a. Paleotectonics of Asia—fragments of a synthesis. In: Yin, A., Harrison, T.M. (Eds.), *The Tectonic Evolution of Asia*. Cambridge Univ. Press, Cambridge, pp. 486–640.
- Senor, A.M.C., Natal’in, B.A., 1996b. Turkic-type orogeny and its role in the making of the continental crust. *Annu. Rev. Earth Planet. Sci.* 24, 263–337.
- Shackleton, R.M., 1986. Precambrian collision tectonics in Africa. In: Coward, M.P., Ries, A.C. (Eds.), *Collision Tectonics*. *Geol. Soc. London Spec. Publ.*, vol. 19, pp. 329–349.
- Shayakubov, T., Kremenetsky, A., Minzer, E., Obratsov, A., Graupner, T., 1999. The Muruntau ore field. In: Shayakubov, T., Islamov, F., Kremenetsky, A., Seltmann, R. (Eds.), *Ag, Au, and Cu Deposits of Uzbekistan. International Field Conference of IGCP-373, Excursion Guidebook SGA-IAGOD*, Potsdam, Germany, pp. 37–74.
- Sidder, G.B., Mendoza, S.V., 1995. Geology of the Venezuelan Guayana Shield and its relation to the geology of the entire Guyana Shield. In: Sidder, G.B., Garcia, A.E., Stoeser, J.W. (Eds.), *Geology and Mineral Deposits of the Venezuelan Guayana Shield*. *U.S. Geol. Surv. Bull.*, vol. 2124, pp. B1–B41, Reston, VA, USA.
- Sillitoe, R.H., 1991. Intrusion-related gold deposits. In: Foster, R.P. (Ed.), *Gold Metallogeny and Exploration*. Blackie and Son, Glasgow, pp. 165–209.
- Sillitoe, R.H., Thompson, J.F.H., 1998. Intrusion-related vein gold deposits: types, tectono-magmatic settings and difficulties of distinction from orogenic gold deposits. *Resour. Geol.* 48, 237–250.
- Sims, P.K., Anderson, J.L., Bauer, R.L., Chandler, V.W., Hanson, G.N., Kalliokoski, J., Morey, J.B., 1993. The Lake Superior region and Trans-Hudson orogen, Precambrian: conterminous U.S. The Geology of North America. The Geological Society of America, Boulder, CO, pp. 11–122.
- Sinclair, H.D., 1997. Flysch to molasse transition in peripheral foreland basins: the role of the passive margin versus slab breakoff. *Geology* 25, 1123–1126.
- Skirrow, R.G., Camacho, A., Lyons, P., Pieters, P.E., Sims, J.P., Stuart-Smith, P.G., Miro, R., 2000. Metallogeny of the southern Sierras Pampeanas, Argentina: geological, ^{40}Ar – ^{39}Ar dating and stable isotope evidence for Devonian Au, Ag–Pb–Zn and W ore formation. *Ore Geol. Rev.* 17, 39–81.
- Smith, M., Thompson, J.F.H., Bressler, J., Layer, P., Mortensen, J.K., Abe, I., Takaoka, H., 1999. Geology of the Liese Zone, Pogo property, east-central Alaska. *Soc. Econ. Geol. Newsl.* 1 (38), 12–21.
- Smithies, R.H., Champion, D.C., 1999. Late Archaean felsic

- alkaline igneous rocks in the Eastern Goldfields, Yilgarn Craton, Western Australia: a result of lower crustal delamination? *J. Geol. Soc. (London)* 156, 561–576.
- Solomon, M., Groves, D.I., 1994. The Geology and Origin of Australia's Mineral Deposits. Oxford Monogr. Geol. Geophys. vol. 24. Clarendon Press, Oxford, 951 pp.
- Sorjonen-Ward, P., Nurmi, P.A., 1997. An overview of the tectonic setting and characteristics of gold mineralization in Finland. In: Papunen, H. (Ed.), *Research and Exploration—Where do They Meet? Proceedings of the Fourth Biennial SGA Meeting Balkema, Rotterdam*, pp. 309–312.
- Sorjonen-Ward, P., Nironen, M., Luukkonen, E., 1997. Greenstone associations in Finland. In: de Wit, M., Ashwal, L.D. (Eds.), *Greenstone Belts*. Clarendon Press, Oxford, pp. 677–698.
- Spiridonov, E.M., 1996. Granitic rocks and gold mineralization of North Kazakhstan. In: Shatov, V. (Ed.), *Granite-Related Ore Deposits of Central Kazakhstan and Adjacent Areas*. Glagol Publishing House, St. Petersburg, pp. 197–217.
- Spooner, E.T.C. et al., 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 Geol. Rev.* 7, 359–379.
- Spooner, E.T.C., Barrie, C.T., 1993. A special issue devoted to Abitibi ore deposits in a modern context—preface. *Econ. Geol.* 88, 1307–1322.
- Steed, G.M., Morris, J.H., 1986. Gold mineralization in Ordovician greywackes at Clontibret, Ireland. In: Keppie, J.D., Boyle, R.W., Haynes, S.J. (Eds.), *Turbidite-Hosted Gold Deposits*. Geological Association of Canada Special Paper, vol. 32, pp. 67–86, St John's, Newfoundland, Canada.
- Stein, M., Hoffmann, A.W., 1994. Mantle plumes and episodic crustal growth. *Nature* 372, 63–68.
- Stein, H.J., Markey, R.J., Morgan, J.W., Hannah, J.L., Zak, K., 1997. Re–Os dating of shear-hosted Au deposits using molybdenite. In: Papunen, H. (Ed.), *Mineral Deposits: Research and Exploration—Where Do They Meet?* Balkema, Rotterdam, pp. 313–317.
- Stein, H.J., Morgan, J.W., Markey, R.J., Hannah, J.L., 1998. An introduction to Re–Os—what's in it for the mineral industry. *Soc. Econ. Geol. Newsl.* 32 (1), 8–15.
- Stendal, H., Frei, R., 2000. Gold occurrences and lead isotopes in Ketildian mobile belt, south Greenland. *Trans. Inst. Min. Metall.* 109, B6–B13.
- Stepanov, V.A., 1998. Gold and mercury of the Amur metallogenic province. *Dokl. Earth Sci.* 359 (2), 190–192.
- Stern, R.J., 1994. Arc assembly and continental collision in the Neoproterozoic East African orogen: implications for the consolidation of Gondwanaland. *Annu. Rev. Earth Planet. Sci.* 22, 319–351.
- Stott, G.M., 1997. The Superior Province, Canada. In: de Wit, M., Ashwal, L.D. (Eds.), *Greenstone Belts*. Clarendon Press, Oxford, pp. 480–507.
- Stowell, H.H., Leshner, C.M., Green, N.L., Sha, P., Sinha, K., 1996. Metamorphism and gold mineralization in the Blue Ridge, southernmost Appalachians. *Econ. Geol.* 91, 1115–1144.
- Teixeira, J.B.G., de Souza, J.A.B., da Silva, M. da G., Leite, C.M.M., Barbosa, J.S.F., Coelho, C.E.S., Abram, M.B., Filho, V.M.C., 2001. Gold mineralization in the Serra de Jacobina area, Bahia, Brazil: tectonic framework, deposit classification, and ore genesis. *Miner. Deposita* 36, in press.
- Thompson, J.H.F., Sillitoe, R.H., Baker, T., Lang, J.R., Mortensen, J.K., 1999. Intrusion-related gold deposits associated with tungsten–tin provinces. *Miner. Deposita* 34, 323–334.
- Thomson, M.L., Fyfe, W.S., 1990. Crixas gold deposit, Brazil: thrust-related, post-peak metamorphic gold mineralization of possible Brasiliano cycle age. *Econ. Geol.* 85, 928–942.
- Titley, S.R., 1987. The crustal heritage of silver and gold ratios in Arizona ores. *Geol. Soc. Am. Bull.* 99, 814–826.
- Titley, S.R., 1993a. Correspondence of ores of silver and gold with basement terranes in the American southwest. *Miner. Deposita* 26, 66–71.
- Titley, S.R., 1993b. Relationship of stratabound ores with tectonic cycles of the Phanerozoic and Proterozoic. *Precambrian Res.* 61, 295–322.
- Trompette, R., 1994. Geology of Western Gondwana (2000–500 Ma): Pan African–Brasiliano Aggregation of South America and Africa. Balkema, Rotterdam, 350 pp.
- Turneure, F.S., 1955. Metallogenic provinces and epochs. *Econ. Geol.* 38–98, Fiftieth Anniversary.
- Tyler, R., Tyler, N., 1996. Stratigraphic and structural controls on gold mineralization in the Pilgram's Rest goldfield, eastern Transvaal, South Africa. *Precambrian Res.* 79, 141–169.
- United Nations, 1999. Geology and mineral resources of Mongolia. Atlas of Mineral Resources of the ESCAP Region vol. 14. Economic and Social Commission for Asia and the Pacific, New York, NY, USA.
- Unrug, R., 1992. The supercontinent cycle and Gondwanaland assembly: component cratons and the timing of suturing events. *J. Geodyn.* 16 (4), 215–240.
- Unrug, R., 1996. Geodynamic map of Gondwana supercontinent assembly. Bureau de Recherches Géologiques et Minières, Orleans, France.
- Valeriano, C.M., de Almeida, J.C.H., Simoes, L.S.A., Duarte, B.P., Roig, H.L., Heilbron, M., 1995. Structural evolution of the Brasilia belt external domain in the southwestern Minas Gerais: records of Pre-Brasiliano age tectonics. *Rev. Bras. Geocienc.* 25, 221–234.
- Van Schmus, W.R., Bickford, M.E., Anderson, J.L., Bender, E.E., Anderson, R.R., Bauer, P.W., Robertson, J.M. et al., 1993. Transcontinental Proterozoic provinces, Precambrian: continuous U.S. The Geology of North America. The Geological Society of America, Boulder, CO, pp. 171–334.
- Vasconcelos, P., Becker, T., 1992. A idade da mineralização aurífera no depósito de Fazenda Brasileiro, Bahia, Brazil. Workshop em Metalogenese, Pesquisas atuais e novas tendências, UNICAMP, Boletim de Resumos: 29.
- Vinyu, M.L., Frei, R., Jelsma, H.A., 1996. Timing between granitoid emplacement and associated gold mineralization—examples from the ca. 2.7 Ga Harare–Shamva greenstone belt, northern Zimbabwe. *Can. J. Earth Sci.* 33, 981–992.
- Vladimirov, A.G., Gibsher, A.S., Izokh, A.E., Rudnev, S.N., 1999. Early Paleozoic granitoid batholiths of central Asia: abundances, sources, and geodynamic formation conditions. *Dokl. Earth Sci.* 369A (9), 1268–1271.

- Voicu, G., Bardoux, M., Jebrak, M., Crepeau, R., 1999. Structural, mineralogical, and geochemical studies of the Paleoproterozoic Omai gold deposit, Guyana. *Econ. Geol.* 94, 1277–1304.
- Walraven, F., Pape, J., Borg, G., 1994. Implications of Pb-isotopic compositions at the Geita gold deposit, Sukumaland greenstone belt, Tanzania. *J. Afr. Earth Sci.* 18 (2), 111–121.
- Wang, L.G., Qiu, Y.M., McNaughton, N.J., Groves, D.I., Luo, Z.K., Huang, J.Z., Miao, L.C., Liu, Y.K., 1998a. Constraints on crustal evolution and gold metallogeny in the Northwestern Jiaodong Peninsula, China, from SHRIMP U–Pb zircon studies of granitoids. *Ore Geol. Rev.* 13, 275–292.
- Wang, P.-L., Lo, C.-H., Lee, T.-Y., Chung, S.-L., Lan, C.-Y., Yem, N.T., 1998b. Thermochronological evidence for the movement of the Ailao Shan–Red River shear zone: a perspective from Vietnam. *Geology* 26, 887–890.
- West, T.E.J., 1998. Structural analysis of the Carolina–Inner Piedmont terrane boundary: implications for the age and kinematics of the central Piedmont suture, a terrane boundary that records Paleozoic Laurentia–Gondwana interactions. *Tectonics* 17, 379–394.
- 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*. Holt, Rinehart, and Winston, New York, pp. 575–631.
- White, N.C., Hedenquist, J.W., 1995. Epithermal gold deposits—styles, characteristics and exploration. *Soc. Econ. Geol. Newsl.* 23 (1), 9–13.
- Wilde, A.R., Layer, P., Mernagh, T., Foster, J., 2000. The giant Muruntau gold deposit: Why is it so large? [abs] *Geol. Soc. Aust.*, Abstr. 59, 539.
- Wilks, M.E., Harper, G.D., 1997. Wind River Range, Wyoming Craton. In: de Wit, M., Ashwal, L.D. (Eds.), *Greenstone Belts*. Clarendon Press, Oxford, pp. 508–516.
- Wilson, J.F., 1990. A craton and its cracks: Some of the behaviour of the Zimbabwe block from the Late Archaean to the Mesozoic in response to horizontal movements, and the significance of some of its mafic dyke fracture patterns. *J. Afr. Earth Sci.* 10, 483–501.
- Windley, B.F., 1995. *The Evolving Continents*. Wiley, New York, 526 pp.
- Witt, W.K., Hickman, A.H., Townsend, D., Preston, W.A., 1998. Mineral potential of the Archaean Pilbara and Yilgarn cratons, Australia. *AGSO J. Aust. Geol. Geophys.* 17 (3), 201–221.
- Woakes, M., Bafor, B.E., 1984. Primary gold mineralization in Nigeria. In: Foster, R.P. (Ed.), *Gold '82*. Balkema, Rotterdam, pp. 661–671.
- Worku, H., 1996. Structural control and metamorphic setting of shear zone-related Au vein mineralization of the Adola Belt (southern Ethiopia) and its tectono genetic development. *J. Afr. Earth Sci.* 23, 383–409.
- Wyman, D., Kerrich, R., 1988. Alkaline magmatism, major structures, and gold deposits—implications for greenstone belt gold metallogeny. *Econ. Geol.* 83, 451–458.
- Xavier, R.P., Foster, R.P., 1999. Fluid evolution and chemical controls in the Fazenda Maria Preta (FMP) gold deposit, Rio Itapicuru greenstone belt, Bahia, Brazil. *Chem. Geol.* 154, 133–154.
- Xu, X., Harbert, W., Dril, S., Kravchinsky, V., 1997. New paleomagnetic data from the Mongol–Okhotsk collision zone, Chita region, south-central Russia: implications for Paleozoic paleogeography of the Mongol–Okhotsk Ocean. *Tectonophysics* 269, 113–129.
- Yakubchuk, A.S., Edwards, A.C., 1999. Auriferous Paleozoic accretionary terranes within the Mongol–Okhotsk suture zone, Russian Far East. *PACRIM '99*. The Australasian Institute of Mining and Metallurgy, Carlton Victoria, Australia, pp. 347–358.
- Yang, K., 1996. Gold deposits in China: main types and potential. *Int. Geol. Rev.* 38, 1006–1019.
- Yardley, B.W.D., 1998. The evolution of fluids through the metamorphic cycle. In: Jamtveit, B., Yardley, B.W.D. (Eds.), *Fluid Flow and Transport in Rocks*. Chapman & Hall, London, pp. 99–121.
- Yarmolyuk, V.V., Kovalenko, V.I., Kotov, A.B., Sal'nikova, E.B., 1997. The Angara–Vitim batholith: on the problem of batholith geodynamics in the Central Asia foldbelt. *Geotectonics* 31 (5), 359–373.
- Yeats, C.J., McNaughton, N.J., Ruettger, D., Bateman, R., Groves, D.I., Harris, J.L., Kohler, E., 1999. Evidence for diachronous Archean lode gold mineralization in the Yilgarn craton, Western Australia: a SHRIMP U–Pb study of intrusive rocks. *Econ. Geol.* 94, 1259–1276.
- Yuanchao, S., Chengwei, J., Zhenyue, X., Hongtao, L., Hongyuan, X., 1996. The characteristics of the Altay–Junggar gold mineralization belt. In: Chengwei, J. (Ed.), *Geology of main gold metallogenic belts in northern part of China*. Seismological Press, Beijing, pp. 7–31.
- Zachariah, J.K., Rajamani, V., Hanson, G.N., 1997. Petrogenesis and source characteristics of metatholeiites from the Archaean Ramagiri schist belt, eastern part of the Dharwar craton, India. *Contrib. Mineral. Petrol.* 129, 87–104.
- Zaw, K., Huston, D.L., Large, R.R., Mernagh, T., Hoffman, C.F., 1994. Microthermometry and geochemistry of fluid inclusions from the Tennant Creek gold–copper deposits: implications for ore deposition and exploration. *Miner. Deposita* 29, 288–300.
- Zegers, T.E., de Wit, M.J., Dann, J., White, S.H., 1998. Vaalbara, Earth's oldest assembled continent? A combined structural, geochronologic, and paleomagnetic test. *Terra Nova* 10, 250–259.
- Zhang, L.-S., Scharer, U., 1999. Age and origin of magmatism along the Cenozoic Red River shear belt, China. *Contrib. Mineral. Petrol.* 134, 67–85.
- Zhou, T., Goldfarb, R., Phillips, G.N., 2002. Tectonics and distribution of gold deposits in China—an overview. *Miner. Deposita* 37, in press.
- Zorin, Y.A., 1998. Terranes of east Mongolia and central Transbaikalia and evolution of the Okhotsk–Mongolian fold belt. *Russ. Geol. Geophys.* 39 (1), 8–21.
- Zorin, Y.A., 1999. Geodynamics of the western part of the Mongolia–Okhotsk collisional belt, Trans-Baikal region (Russia) and Mongolia. *Tectonophysics* 306, 33–56.