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# Orogenic gold deposits: A proposed classification in the context of their crustal distribution and relationship to other gold deposit types

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## Abstract

The so-called ‘mesothermal’ gold deposits are associated with regionally metamorphosed terranes of all ages. Ores were formed during compressional to transpressional deformation processes at convergent plate margins in accretionary and collisional orogens. In both types of orogen, hydrated marine sedimentary and volcanic rocks have been added to continental margins during tens to some 100 million years of collision. Subduction-related thermal events, episodically raising geothermal gradients within the hydrated accretionary sequences, initiate and drive long-distance hydrothermal fluid migration. The resulting gold-bearing quartz veins are emplaced over a unique depth range for hydrothermal ore deposits, with gold deposition from 15–20 km to the near surface environment.

On the basis of this broad depth range of formation, the term ‘mesothermal’ is not applicable to this deposit type as a whole. Instead, the unique temporal and spatial association of this deposit type with orogeny means that the vein systems are best termed *orogenic gold deposits*. Most ores are post-orogenic with respect to tectonism of their immediate host rocks, but are simultaneously syn-orogenic with respect to ongoing deep-crustal, subduction-related thermal processes and the prefix *orogenic* satisfies both these conditions. On the basis of their depth of formation, the orogenic deposits are best subdivided into *epizonal* (< 6 km), *mesozonal* (6–12 km) and *hypozoneal* (> 12 km) classes. © 1998 Elsevier Science B.V. All rights reserved.

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## 1. Introduction

This thematic issue of *Ore Geology Reviews* includes a wide variety of papers on a single type of

quartz–carbonate lode-gold deposit. The deposit type in this issue alone is referred to as synorogenic, turbidite-hosted, mesothermal and Archaean lode-gold. This reflects the proliferation of such terms throughout the economic geology literature during the last ten years and a subsequent increase in confusion for the readers. For example, is a synorogenic

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Mother-lode type gold deposit different from an Archaean gold-only type or from a mesothermal greenstone–gold type? Many researchers working on such deposits would recognize these as essentially a variety of subtypes of a single deposit type, i.e. epigenetic, structurally-hosted lode-gold vein systems in metamorphic terranes (Kerrich, 1993). However, the consistent usage of a single and widely-accepted classification term for this deposit type as a whole is clearly warranted. ‘Mesothermal’ is such a term that has been widely adopted during the last ten years, but is a term that, as originally defined by Lindgren (1933) for deposits formed at about 1.2–3.6 km, is more applicable to sedimentary rock-hosted ‘Carlin-type’ deposits and the gold porphyry/skarn environment (Poulsen, 1996).

A principal aim of this introductory paper is to present and justify a unifying classification for these lode-gold deposits. An attempt is made to place these so-called ‘mesothermal’ deposits into a broader class that emphasizes their tectonic setting and time of formation relative to other gold deposit types. A second aim is to review briefly their more significant defining features in the light of current inconsistent terminology and the recognition that this deposit group may form over a wider range of crustal depths and temperatures than commonly recognized (Groves, 1993; Hagemann and Ridley, 1993; Gebre-Mariam et al., 1995). The term *orogenic* is introduced and justified as a term to replace ‘mesothermal’ and other descriptors for this deposit type. It is also suggested that the terms *epizonal*, *mesozonal* and *hypozoneal* be used to reflect crustal depth of gold deposition within the *orogenic* group of deposits.

## 2. Definition of so-called mesothermal gold deposits

The so-called ‘mesothermal’ gold deposits (Table 1) are a distinctive type of gold deposit which is typified by many consistent features in space and time. These have been summarized in a variety of comprehensive ore-deposit model descriptions that include Bohlke (1982), Colvine et al. (1984), Berger (1986), Groves and Foster (1991), Nesbitt (1991), Hodgson (1993) and Robert (1996). Kerrich (1993)

summarizes many of the steps that led to these evolving modern-day models. A unifying tectonic theme has recently been evaluated by workers such as Wyman and Kerrich (1988), Barley et al. (1989), Hodgson and Hamilton (1989), Kerrich and Wyman (1990), Kerrich and Cassidy (1994) and Goldfarb et al. (1998 - this issue).

### 2.1. Geological characteristics

#### 2.1.1. Geology of host terranes

Perhaps the single most consistent characteristic of the deposits is their consistent association with deformed metamorphic terranes of all ages. Observations from throughout the world’s preserved Archaean greenstone belts and most recently-active Phanerozoic metamorphic belts indicate a strong association of gold and greenschist facies rocks. However, some significant deposits occur in higher metamorphic grade Archaean terranes (e.g. McCuaig et al., 1993) or in lower metamorphic grade domains within the metamorphic belts of a variety of geological ages. In the Archaean of Western Australia, a number of synmetamorphic deposits extend into granulite facies rocks (Groves et al., 1992). Pre-metamorphic protoliths for the auriferous Archaean greenstone belts are predominantly volcano-plutonic terranes of oceanic back-arc basalt and felsic to mafic arc rocks. Clastic marine sedimentary rock-dominant terranes that were metamorphosed to graywacke, argillite, schist and phyllite host most younger ores, and are important in some Archaean terranes (e.g. Slave Province, Canada).

#### 2.1.2. Deposit mineralogy

These deposits are typified by quartz-dominant vein systems with  $\leq 3$ –5% sulfide minerals (mainly Fe-sulfides) and  $\leq 5$ –15% carbonate minerals. Albite, white mica or fuchsite, chlorite, scheelite and tourmaline are also common gangue phases in veins in greenschist-facies host rocks. Vein systems may be continuous along a vertical extent of 1–2 km with little change in mineralogy or gold grade; mineral zoning does occur, however, in some deposits. Gold:silver ratios range from 10 (normal) to 1 (less common), with ore in places being in the veins and elsewhere in sulfidized wallrocks. Gold grades are

relatively high, historically having been in the 5–30 g/t range; modern-day bulk mining methodology has led to exploration of lower grade targets. Sulfide mineralogy commonly reflects the lithogeochemistry of the host. Arsenopyrite is the most common sulfide mineral in metasedimentary country rocks, whereas pyrite or pyrrhotite are more typical in metamorphosed igneous rocks. In fact, the Salsigne gold deposit in Cambrian sedimentary rocks of the French Massif Central is the world's largest producer of arsenic (Guen et al., 1992). Gold-bearing veins exhibit variable enrichments in As, B, Bi, Hg, Sb, Te and W; Cu, Pb and Zn concentrations are generally only slightly elevated above regional backgrounds.

### 2.1.3. Hydrothermal alteration

Deposits exhibit strong lateral zonation of alteration phases from proximal to distal assemblages on scales of metres. Mineralogical assemblages within the alteration zones and the width of these zones generally vary with wallrock type and crustal level. Most commonly, carbonates include ankerite, dolomite or calcite; sulfides include pyrite, pyrrhotite or arsenopyrite; alkali metasomatism involves sericitization or, less commonly, formation of fuchsite, biotite or K-feldspar and albitization and mafic minerals are highly chloritized. Amphibole or diopside occur at progressively deeper crustal levels and carbonate minerals are less abundant. Sulfidization is extreme in BIF and Fe-rich mafic host rocks. Wallrock alteration in greenschist facies rocks involves the addition of significant amounts of  $\text{CO}_2$ , S, K,  $\text{H}_2\text{O}$ ,  $\text{SiO}_2 \pm \text{Na}$  and LILE.

### 2.1.4. Ore fluids

Ores were deposited from low-salinity, near-neutral,  $\text{H}_2\text{O}-\text{CO}_2 \pm \text{CH}_4$  fluids which transported gold as a reduced sulphur complex. Fluids associated with this gold deposit type are notable by their consistently elevated  $\text{CO}_2$  concentrations of  $\geq 5$  mol%. Typical  $\delta^{18}\text{O}$  values for hydrothermal fluids are about 5–8 per ml in the Archaean greenstone belts and about 2 per ml higher in the Phanerozoic gold lodes.

### 2.1.5. Structure

There is strong structural control of mineralization at a variety of scales. Deposits are normally sited in

second or third order structures, most commonly near large-scale (often transcrustal) compressional structures. Although the controlling structures are commonly ductile to brittle in nature, they are highly variable in type, ranging from: (a) brittle faults to ductile shear zones with low-angle to high-angle reverse motion to strike-slip or oblique-slip motion; (b) fracture arrays, stockwork networks or breccia zones in competent rocks; (c) foliated zones (pressure solution cleavage) or (d) fold hinges in ductile turbidite sequences. Mineralized structures have small syn- and post-mineralization displacements, but the gold deposits commonly have extensive down-plunge continuity (hundreds of metres to kilometres). Extreme pressure fluctuations leading to cyclic fault-valve behavior (Sibson et al., 1988) result in flat-lying extensional veins and mutually cross-cutting steep fault veins that characterize many deposits (e.g. Robert and Brown, 1986).

### 2.2. Tectonic setting and timing of 'mesothermal' vein emplacement

The so-called 'mesothermal' gold deposits (Table 1) occupy a consistent spatial/temporal position (Fig. 1), having formed during deformational processes at convergent plate margins (orogeny) irrespective of whether they are hosted in Archaean or Proterozoic greenstone belts or Proterozoic and Phanerozoic sedimentary rock sequences (e.g. Barley and Groves, 1992; Kerrich and Cassidy, 1994). The placing of these deposits in a plate tectonic setting was a logical outgrowth of the acceptance of plate tectonic theory in the early 1970's. Guild (1971) initially discussed the "orogen-associated endogenic mineral deposits of Mesozoic and Tertiary age on the sites of Cordilleran-type (continent/ocean) collisions". Sawkins (1972) noted, soon after, how both these Circum-Pacific gold ores and spatially associated felsic magmas were probable products of subduction-related tectonism. Just as significant was Sawkins (1972) observation that Archaean gold lodes in the Superior Province, Canada, may have some relationship to the southward younging of igneous ages, interpreted as being reflective of a seaward-migrating trench. It would be, however, another sixteen years (cf. Wyman and Kerrich, 1988) before workers would follow-up on this important concept

Table 1  
Timing of orogenic gold vein formation and significant tectonic relationships from some gold provinces in metamorphic rocks (partly modified from Kerrich and Cassidy, 1994; Goldfarb et al., 1998). Host terranes are mainly Archaean greenstone belts and younger oceanic sedimentary rock-dominant assemblages. Provinces are ordered, from top to bottom of the table, in increasing age of formation

Province	Age of veining (Ma)	Age of host terranes (Ma)	Spatially associated magmatism (Ma)	Metamorphic events (Ma)	Other important events	Geochron. Refs.
Mt. Rosa, upper nappes, W. Alps, Italy	≤ 33	Palaeozoic	310, 42–25 (most abundant at 33–29)	41.5, 90–60 (blueschist); 44–40	hypothesized slab delamination at 45 Ma	Curti (1987), Blanckenburg and Davies (1995)
Chugach accretionary prism, S. Alaska	57–49	L. Cretaceous	66–50	66–50	veining during subduction of spreading ridge beneath growing prism	Häussler et al. (1995)
Juneau gold belt, S. Alaska	57–53	Permian–mid-Cretaceous	mid-Cret, 70–60 (sill), 60–48 (batholith)	mid-Cret, 70–60	emplacement of sill during Barrovian metamorphism; change from orthogonal to oblique convergence during veining	Goldfarb et al. (1991b), Miller et al. (1994)
Willow Creek district, south-central Alaska	66	Late Paleozoic	74–66	Jurassic	veining during onset of oroclinal bending of Alaska; syn-veining accretion and subduction tens of km seaward	Madden-McGuire et al. (1989)
Bridge River, SW British Columbia	91–86	Late Paleozoic–early Mesozoic	270, 91–43	Jurassic	veining during seaward collision of Wrangellia terrane and early stages of Coast batholith formation	Leitch et al. (1991)
Fairbanks, east-central Alaska	92–87, 77	Early Paleozoic	95–90	Early–Middle Jurassic	120–110 Ma regional extension; syn-veining accretion and subduction tens of km seaward; veining continues into unmetamorphosed rocks of craton in Yukon	McCoy et al. (1997)
Nome, NW Alaska	109	Early Paleozoic	108–82	170–130 (blueschist), 108–82 (Barrovian)	veining during regional extension and slab rollback; veins 40–50 km from high- <i>T</i> magmatic/metamorphic front	Ford and Snee (1996)

Russian Far East	135–100	Late Paleozoic–middle Mesozoic	144–80	Late Jurassic–Early Cretaceous	veining during increased convergence rates between Eurasian and Izanagi plates	Nokleberg et al. (1996), Goldfarb et al. (1998)
Shandong Peninsula (E. China), NE China and Korea	Early Cretaceous	Archaean	190–170, 132–121	Archaean	veining during late stage of Yanshanian magmatism; hypothesized mantle plume during onset of post-collisional extension	Trumbull et al. (1996), Wang et al. (1996), Nie (1997)
Sierra foothills and Klamath Mts., California	144–108 (127–108 = Mother lode belt)	Middle Paleozoic–Jurassic	177–135 (north), 150–80 (south)	Jurassic–Early Cretaceous	150–140 Ma seaward stepping of trench; 120 Ma onset of rapid, orthogonal convergence and Sierra Nevada batholith emplacement	Bohlike and Kistler (1986), Landefeld (1988), Elder and Cashman (1992)
Otago, South Island, New Zealand	Jurassic–Early Cretaceous	Permian–Late Triassic	none	Early Jurassic–Early Cretaceous	veining likely throughout last period of collisional deformation along Gondwanan margin	McKeag and Craw (1989)
SW Yukon and Interior British Columbia	180–≥134	Early Paleozoic–Triassic	190–160	Late Triassic–Early Jurassic	younger dates on mineralization could be cooling ages; syn-veining accretion and subduction tens of km seaward	Rushton et al. (1993), Ash et al. (1996)
New England fold belt, E. Australia	Permian–Early Triassic	Carboniferous–Permian	306–280, 255–245, Early Triassic	Permian–Triassic	veining related to final period of accretion and subduction along eastern Australia	Ashley et al. (1994), Scheiber (1996)
Muruntau, Uzbekistan and adjacent central Asia deposits	Late Carboniferous–Early Permian	Cambrian–Ordovician	310, 271–261	Late Carboniferous–Early Permian	deposits near suture of Hercynian continent–continent collision	Berger et al. (1994), Drew et al. (1996)
Variscan-related, Europe	340–310 (Bohemia Massif); 300±20 (Massif Central)	Late Proterozoic–early Paleozoic	360–320	350–340	Late Devonian(?)–Permian subduction; Laurussia–Africa collision by 380–350 Ma	Bouchot et al. (1989), Cathelineau et al. (1990), Moravcek (1995), Stein et al. (1996)

Table 1 (continued)

Province	Age of veining (Ma)	Age of host terranes (Ma)	Spatially associated magmatism (Ma)	Metamorphic events (Ma)	Other important events	Geochron. Refs.
Southern Appalachians, USA	343–294	Paleozoic	Late Ordovician to Carboniferous	Carboniferous (main event); lower grade episodes in Late Ordovician and Devonian	veins emplaced at higher $P-T$ and deeper crustal levels than other Phanerozoic orogenic gold deposits in North America	Stowell et al. (1996)
Meguma, Nova Scotia	380–362	Cambrian–Ordovician	380–370, 316	415–377	host rocks obducted to continental margin between Late Silurian and Early Permian	Kontak et al. (1990), Keppie and Dallmeyer (1995)
Victoria, SE Australia	460(?), 415–360	Ordovician Early Devonian	415–390, 370–360	460–430 (Stawell–Ballarat–Bendigo), 410–400 (Melbourne)	subduction event?; thin-skinned tectonics; conflicting data on age of gold mineralization	Arne et al. (1996), Foster et al. (1996), Phillips and Hughes (1996)
Queensland, NE Australia	408 ± 30, Late Carboniferous	Silurian–Devonian	Middle Ordovician–Middle Carboniferous	Devonian	subduction event?; thin-skinned tectonics	Peters and Golding (1989), Solomon and Groves (1994)
Trans-Hudson orogen, central Canada	1807–1720	Early Proterozoic	1890–1834	1870–1770	perhaps a series of unrelated thermal and ore-forming events; regional transpression continued until 1690 Ma	Ansdell and Kyser (1992), Thomas and Heaman (1994), Fayek and Kyser (1995), Conners (1996)
Birimian belt of Ghana–eastern Cote d'Ivoire–Burkina Faso	about 2100	2185–2150 (volcanics); adjacent basins are slightly younger	2185–2150, 2116–2088		veining in basinal rocks during oblique thrusting (Eburnean deformation) of these over volcanic sequences	Hirdes et al. (1996)

Dharwar craton, S. India	about 2400(?)	2700–2530	2550	mineralization during collision and suturing of numerous terranes to form the Kolar schist belt, which is the site of the most important ores; age of mineralization poorly-constrained	Krogstad et al. (1989), Balakrishnan et al. (1990)
Yilgarn craton, W. Australia	2640–2620, 2602, 2565(?)	2750–2685	2690–2660, 2650–2630	youngest date on veining could be cooling age; metamorphism poorly-constrained	Kent and McDougall (1995), Kent et al. (1996), Kent and Hagemann (1996)
Slave craton, NWT, Canada	about 2670–2660	Middle and Late Archaean	2663, 2640– 2585	100-m.y.-long subduction regime initiated by 2712	Abraham and Spooner (1995), MacLachlan and Helmstaedt (1995)
Zimbabwe craton, Zimbabwe	2670, 2659, 2410(?)	Early and Late Archaean	2700–2600, 2460 (Great Dyke), 2428	poorly dated crustal evolution	Foster and Piper (1993), Darbyshire et al. (1996), Vinyu et al. (1996)
Superior Province, Canada	2720–2670, 2633–2404(?)	Middle and Late Archaean	2720–2673, 2645–2611	young period for mineralization might reflect thermal resetting of true ages	Kerrick (1994), Kerrich and Cassidy (1994), Jackson and Cruden (1995), Powell et al. (1995)
Kaapvaal craton, South Africa	3200–3064 (Barberton belt); > 2700 with perhaps some at 2850 (Murchison belt)	3600–3200 (in Barberton belt)	3437, 3106, 3000–2700, 2600–2500	in Barberton, mineralization at least 100 m.y. after thrusting and regional metamorphism of hosts; some of the mineralization may correlate with that of the Pilbara block, western Australia	deRonde et al. (1991), Foster and Piper (1993)

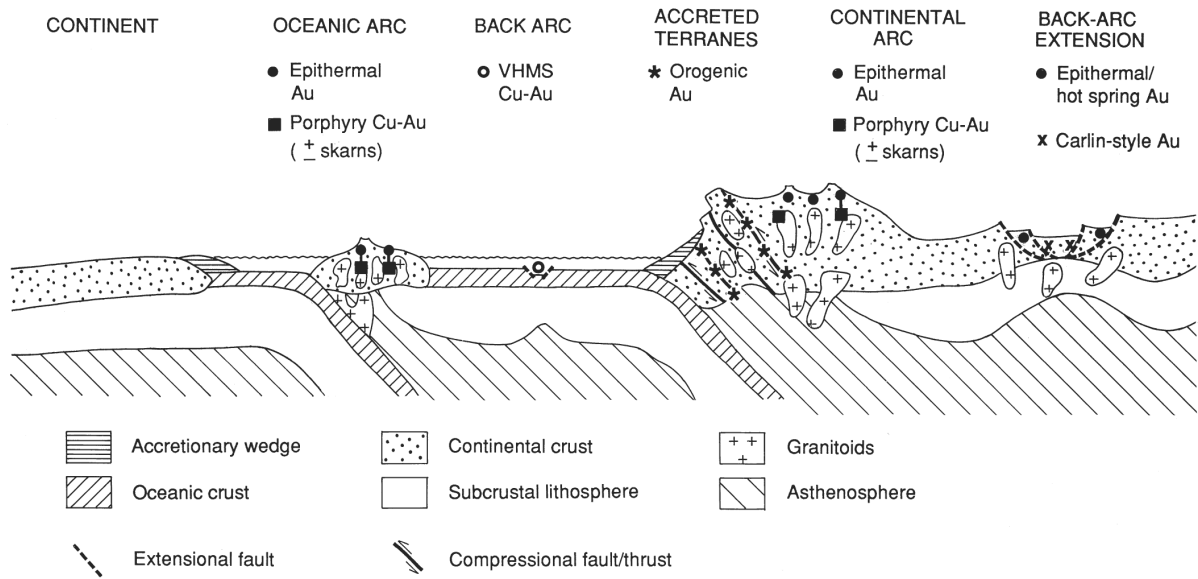


Fig. 1. Tectonic settings of gold-rich epigenetic mineral deposits. Epithermal veins and gold-rich porphyry and skarn deposits, form in the shallow ( $\leq 5$  km) parts of both island and continental arcs in compressional through extensional regimes. The epithermal veins, as well as the sedimentary rock-hosted type Carlin ores, also are emplaced in shallow regions of back-arc crustal thinning and extension. In contrast, the so-called 'mesothermal' gold ores (termed *orogenic gold* on this diagram) are emplaced during compressional to transpressional regimes and throughout much of the upper crust, in deformed accretionary belts adjacent to continental magmatic arcs. Note that both the lateral and vertical scale of the arcs and accreted terranes have been exaggerated to allow the gold deposits to be shown in terms of both spatial position and relative depth of formation.

and begin to widely look at Archaean gold as a product of continental-margin deformational events.

The concept of a general spatial association between the gold deposits and subduction-related thermal processes in *accretionary orogens* (oceanic-continental plate interactions) became commonplace in the mid-1980's. Fyfe and Kerrich (1985) presented a model at that time to explain the massive fluid volumes required for the numerous gold-bearing vein swarms adjacent to crustal-scale thrust zones of continental margins. They hypothesized that underplated hydrated rocks contained the required water and such water was released during thermal reequilibration as subduction ceased. Subsequent models for the Mesozoic and Cenozoic gold fields of westernmost North America relied heavily on correlating gold vein emplacement with subduction-driven processes (Bohlke and Kistler, 1986; Goldfarb et al., 1988). Landefeld (1988), expanding on the ideas in Fyfe and Kerrich (1985), detailed how the seaward stepping of subduction accompanying terrane accretion could have been

crucial for the formation of the Sierra foothills gold districts (including the Mother lode belt). With an abundance of new geochronological data from western North America, recent models of gold genesis in accretionary orogens have been able to look closely at specific processes (e.g. changing plate motions, changing collisional velocities, ridge subduction, etc.) occurring during accretion/subduction that tend to be most closely associated with veining (e.g. Goldfarb et al., 1991b; Elder and Cashman, 1992; Haeussler et al., 1995). Theoretically, as a subduction zone steps seaward, a series of gold systems and plutonic bodies should develop and young towards the trench-part of a so-called Turkic-type (Sengor and Okurogullari, 1991) orogen. This type of scenario crudely characterizes Alaska, USA, a part of the North American margin almost entirely composed of accreted oceanic rock sequences (Plafker and Berg, 1994).

*Collisional orogens* (continent–continent collision), including the Variscan, Appalachian and

Alpine, also are host environments for gold deposits. In fact, collisional (or internal) and accretionary (or peripheral) orogens may represent end-members of a continuous process. Any continent–continent collision will be preceded by closure of an ocean basin, and hence is nothing more than a final stage of a peripheral orogen. The gold systems that are associated with the Phanerozoic internal orogens are actually all spatially associated with marine rocks that have been caught up within the suture. In addition, within peripheral orogens, accretion of microcontinents such as Wrangellia along western North America (Plafker and Berg, 1994) or Avalonia along Laurentia (Keppie, 1993) may be viewed as a type of small-scale continent–continent collision. A key point in all examples is that hydrated marine sedimentary and volcanic rocks were added to continental margins and, at some time during this growth, the accreted rocks experienced relatively high geothermal gradients.

Oligocene veins in the western European Alps (Curti, 1987) are the youngest recognized, economic examples of this deposit type. They also serve to point out that more than simple plate subduction is required for vein formation. The closure of an ocean basin between Europe and Adria (perhaps a part of northern Africa) occurred during an 80-m.y.-long period of Early Cretaceous–early Tertiary oceanic crust subduction without any preserved evidence of gold veining or magmatism; blueschist metamorphic facies in the Alps now record the low thermal gradients. By the early Eocene, complete closure of the ocean had led to continent–continent collision and a partial subduction of the European continental margin between 55 and 45 Ma (Blanckenburg and Davies, 1995). It was not until almost 100 m.y. subsequent to the onset of convergence, perhaps due to slab delamination resulting in the cessation of subduction at 45–40 Ma (Blanckenburg and Davies, 1995), that magmatism and high temperature metamorphism impacted the obducted upper nappes of the western Alps near the collisional suture. Much of the Alpine gold veining occurred during the early Oligocene peak of magmatism (Curti, 1987).

The understanding of gold-forming processes and timing in older Phanerozoic orogens may be complicated by the hundreds of millions of years of additional geological time, but certainly such Palaeozoic

continental margins were favorable environments for veining. Geochronological study of the gold deposits in the Meguma terrane of Nova Scotia, Canada, indicates veining between 380 and 362 Ma (Kontak et al., 1990), during the late part of Acadian deformation of the Appalachian orogen. The Meguma was the final terrane accreted to the Atlantic margin during the poorly-understood late Palaeozoic Laurentia–Gondwanaland collision. Keppie and Dallmeyer (1995), noting that magmatism and high-temperature metamorphism were restricted to a narrow time range of about 380–370 Ma, rather than the prolonged 100 m.y. of Meguma collision, suggest a distinct episode of lower lithospheric delamination for the thermal perturbation. This brief thermal event, occurring at the same time as gold veining, is also likely to be important to the ore-forming process. Whereas little is certain about the subduction-related tectonics of the northern Appalachians, mesothermal-type gold ores such as the Hammer Down in northwestern Newfoundland (Gaboury et al., 1996) indicate that a broad belt of gold systems accompanied continental growth.

Palaeozoic gold veins of the Tasman orogenic system in eastern Australia make it clear that the ore-forming process need not require a ‘Cordilleran-style’ of terrane accretion. Unlike the collage of small terranes that formed the accreted margin of western North America, eastern Australia is mainly composed of a single lithotectonic assemblage (the Lachlan ‘terrane’) that represents a 2,000-km-wide Palaeozoic turbidite fan sequence developed adjacent to the Gondwanan craton (Coney, 1992). Such an environment lacks deep-crustal terrane-bounding faults located between accreted material and the active margin, which, where present in the North American Cordillera, expose a variety of crustal levels and often serve as the focus of hydrothermal fluid flow. Compression-related deformation is solely intraplate rather than concentrated along sutures between terranes. The fact that such a large percentage of gold has been concentrated in the Bendigo–Ballarat area of Victoria (Phillips and Hughes, 1996; Ramsay, 1998 - this issue) indicates some significant and still poorly-understood, local control on vein emplacement in the orogenic system. Nonetheless, similar to the North American Cordillera, the Tasman orogenic system is characterized by significant

growth of the eastern Australian margin (addition of the Lachlan ‘terrane’) and a subduction zone east of the Lachlan assemblage throughout much of the Palaeozoic (Solomon and Groves, 1994).

The abundance of geological similarities between the gold ores of the Phanerozoic orogens and those in Archaean greenstone belts began to be interpreted by the late 1980’s as evidence of a similar tectonic setting for ore formation. Wyman and Kerrich (1988) hypothesized that gold mineralization in the Superior Province of Canada was “related to convergent plate margin-style tectonics”. At roughly the same time, Barley et al. (1989) independently reached the same conclusion to explain the development of gold lodes in Western Australia. Subduction of oceanic rocks into the zone of partial melting appeared to be significant in the development of these gold ores within orogens of all ages (Hodgson and Hamilton, 1989). Major fault zones spatially associated with auriferous belts in the Archaean terranes were now recognized by several researchers as ancient terrane boundaries. Kerrich and Wyman (1990) pointed out that, as observed in present-day convergent margins, Archaean ore-forming fluids were products of deeper crustal thermotectonic events which occurred subsequent to magmatism and metamorphism in ore-hosting supracrustal rocks. Detailed geochronological studies now recognize such lower- to mid-crustal, late deformational regimes in Archaean terranes (Jackson and Cruden, 1995; Kent et al., 1996). Gold deposits in any given Archaean province may all be a part of the same supercontinent cycle (cf. Barley and Groves, 1992), but can show a wide variation in age (Table 1), reflecting a variety of thermal events during many tens of millions of years of accretion and subduction.

### 2.3. Crustal environment of ‘mesothermal’ gold deposition

The majority of deposits of this ore style are sited in ductile to brittle structures, have proximal alteration assemblages of Fe sulfide–carbonate–sericite  $\pm$  albite (in rocks of appropriate composition to stabilise the assemblage) and were deposited at  $300 \pm 50^\circ\text{C}$  and 1–3 kbar, as indicated by fluid inclusion and other geothermobarometric studies (Groves and Foster, 1991; Nesbitt, 1991). They are consistently

syn- to post-peak-metamorphic and were emplaced at temperatures generally within  $100^\circ\text{C}$  of peak metamorphic temperatures experienced by the surrounding host rocks. However, recent studies in mainly Archaean greenstone belts have extended the ranges of temperature and pressure, and hence extended the inferred crustal range of formation of the deposits into higher- and lower-grade metamorphic rocks (e.g. the crustal continuum model of Groves, 1993). The evidence for formation of these gold deposits over  $P$ – $T$  ranges of about  $180$ – $700^\circ\text{C}$  and  $< 1$ – $5$  kbar (Groves, 1993; Hagemann and Brown, 1996; Ridley et al., 1996) implies vertically extensive hydrothermal systems that contrast sharply with other continental-margin gold systems that are apparently restricted to the upper 5 km or so of crust (Fig. 2).

Studies in the early 1990’s, summarized in McCuaig et al. (1993), identified higher  $P$ – $T$  examples of these gold ores in amphibolite facies terranes of Western Australia, the Superior and Slave Provinces in Canada, India and Brazil. Most such mineralization occurred between  $450$ – $600^\circ\text{C}$  and 3–5 kbar. A few examples in granulite terranes formed at even higher  $P$ – $T$  regimes (Barnicoat et al., 1991; Lapointe and Chown, 1993). The gold ores were still precipitated from the same low salinity,  $\text{CO}_2$ - and  $^{18}\text{O}$ -rich fluids, but, because of the higher temperatures and different mineral stabilities, there is a scarcity of carbonate phases and an abundance of calc-silicate minerals characterizing alteration haloes (Mikucki and Ridley, 1993). Such assemblages are similar to those typifying skarn systems (Mueller and Groves, 1991).

It is somewhat problematic as to why a similar continuum of gold deposits has not been widely recognized in higher metamorphic-grade portions of Phanerozoic orogenic belts. Was there something inherently different between the tectonics of Archaean and Phanerozoic continental growth? Or do such gold deposits occur in high-grade terrains of the Phanerozoic and they have just been classified differently? Perhaps a re-evaluation of the classification of some of the gold-bearing ‘skarns’ or contact-metamorphosed deposits in younger orogenic belts might help to solve this problem. Ore fluid salinity might be a key discriminator in the case of the skarns, with relatively high ore-fluid salinities being

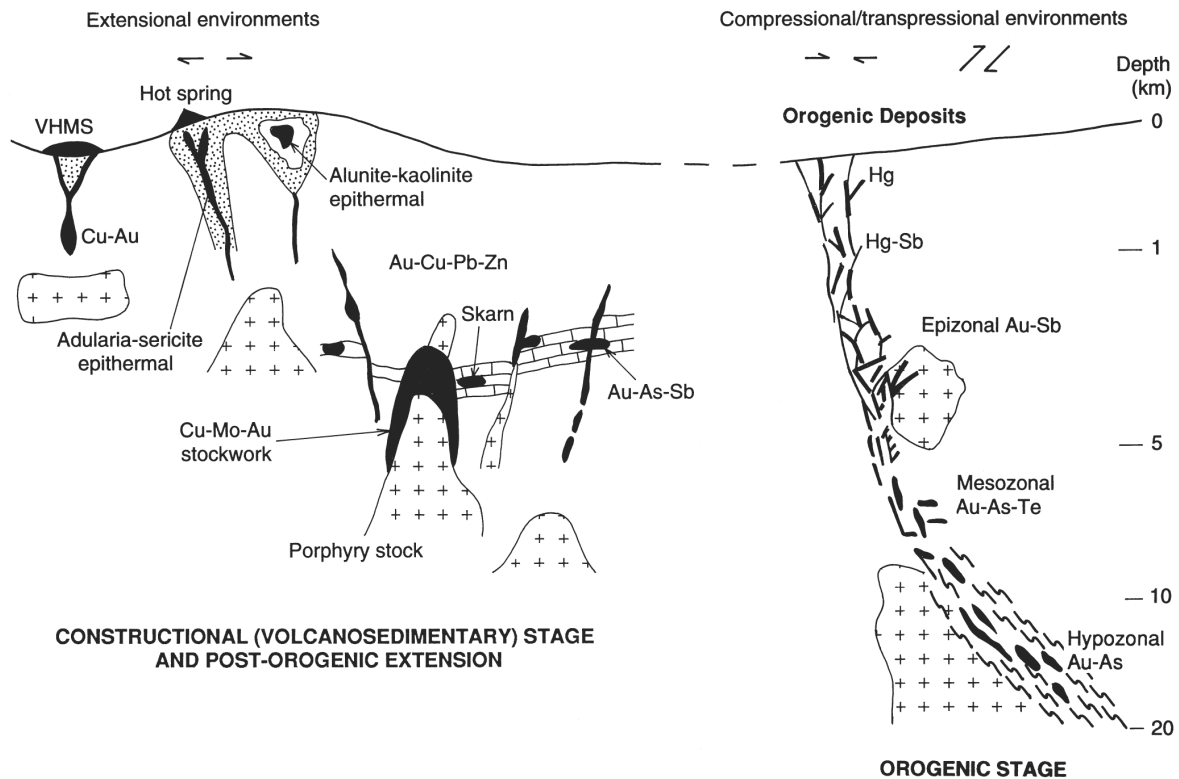


Fig. 2. Schematic representation of crustal environments of hydrothermal gold deposits in terms of depth of formation and structural setting within a convergent plate margin. This figure is by necessity stylised to show the deposit styles within a depth framework. There is no implication that all deposit types or depths of formation will be represented in a single ore system. Adapted from Groves (1993), Gebre-Mariam et al. (1995) and Poulsen (1996).

associated with typical gold skarn deposits that are more directly linked to intrusive sources (Meinert, 1993). The late Palaeozoic Muruntau deposit in Uzbekistan is apparently one example of a post-Archaeon, higher metamorphic grade 'mesothermal-type' deposit. The abundance of thin quartz layering, fluid inclusion data suggesting trapping temperatures in excess of 400°C (Berger et al., 1994) and a skarn-like, calc-silicate assemblage (Marakushev and Khokhlov, 1992) from deeper parts of the ore system all suggest that the deposit may represent a deeper part of the crustal continuum.

Ore formation at temperatures of 200–250°C and at crustal depths of only a few kilometers is not uncharacteristic of these ores where hydrothermal fluids have migrated to shallower crustal levels. However, a few anomalies from shallow gold systems in the Yilgarn block of Western Australia are

notable. Comb, cockade, crustiform and colloform textures at the Racetrack deposit, deposited from CO<sub>2</sub>-poor fluids in lower greenschist facies rocks at depths ≤ 2.5 km, are more like those developed in classic epithermal vein deposits (Gebre-Mariam et al., 1993). Similar textures at the Wiluna gold deposits in subgreenschist facies rocks, as well as  $\delta^{18}\text{O}_{\text{quartz}}$  measurements as light as 6–7 per ml, provide some of the strongest evidence of meteoric water involvement in some of the 'mesothermal' hydrothermal systems (Hagemann et al., 1992, 1994).

Gold solubility relationships at temperatures below 200–250°C best explain the observation that the continuum of this type of gold deposit does not continue into the uppermost few kilometres of the crust. The moderately-reducing and only moderately sulphur-rich conditions likely to characterize 'mesothermal' gold ore-fluids at low temperature

(Mikucki, 1998 - this issue), would favor low gold solubilities at these low temperatures (e.g. Shenberger and Barnes, 1989). However, hydrothermal fluids that have been depositing 'mesothermal' gold along crustal-scale fault zones at depth, must still advect along these faults to the surface. Such is probably the case in the westernmost part of North America where CO<sub>2</sub>-rich, isotopically-heavy fluids migrated to near-surface environments of very low *P–T* in the Cordilleran orogen. Cinnabar ± stibnite-bearing epithermal, silica–carbonate veins, which were deposited within the upper few kilometres of crust, define such flow (Nesbitt and Muehlenbachs, 1989). Examples include the Hg–Sb deposits of the Kuskokwim basin in SW Alaska, the Pinchi belt of British Columbia and the coast ranges of northern California. In fact, it has been recognized now for thirty years that many of the thermal springs within the accreted margin of western North America have a unique chemical character (White, 1967) and could be the surface expression of deeper 'mesothermal' gold deposits.  $\delta^{18}\text{O}_{\text{quartz}}$  values for Hg-rich veins emplaced in the near surface are as heavy as +30 per ml because of greater quartz–water fractionation, as temperatures of ore fluids cooled to as low 150°C. Such heavy oxygen values are very distinct from  $\delta^{18}\text{O}_{\text{quartz}}$  values of other types of vein systems deposited in classical epithermal environments, such as those of the Nevada Basin and Range (Goldfarb et al., 1990). The identification of this type of Hg–Sb epithermal system in a continental margin terrane with limited erosion may be a valuable guide to the down-dip existence of a so-called 'mesothermal' gold occurrence.

#### 2.4. Comparisons with other lode-gold deposit types

Most deposit types that contain ore-grade gold (Table 2), whether with gold as the principal metal or together with copper, are sited along convergent plate margins (Sawkins, 1990). There are notable exceptions, such as gold-rich volcanogenic massive sulfide deposits developed along spreading ocean ridges (e.g. Bousquet) and other deposit styles associated with possible anorogenic hot spots (e.g. Olympic Dam). However, as a rule, many of the Phanerozoic gold-bearing epithermal vein, Carlin-

type sedimentary rock-hosted and porphyry/skarn deposits developed within the same active continental margins as the so-called 'mesothermal' deposits (Fig. 1). Notable distinctions, however, can be made that relate to local changes in tectonism within a developing orogen and to crustal depth range (a reflection of regional geothermal gradient) of the auriferous hydrothermal systems.

As shown schematically in Fig. 1, a significant proportion of epithermal and porphyry deposits are distinct in that they form above subduction zones distal to continental margins or within continental margins, but during post-collisional extension. Many other gold-rich epithermal and porphyry systems develop in oceanic regimes within the top few kilometres of crust of volcano-plutonic island arcs located above intermediate- to steeply-dipping subduction zones (e.g. Sawkins, 1990; Sillitoe, 1991), with a vertical transition from porphyry-style to classic epithermal vein-style mineralization (e.g. White and Hedenquist, 1995). Other epithermal lodes, including some of the world-class deposits (Muller and Groves, 1997), are associated with alkalic, mantle-related rocks that reflect extensional episodes in a convergent orogen in either a near-arc region (e.g. Porgera: Richards et al., 1990) or far inland of the accretionary wedge (e.g. Cripple Creek: Kelley et al., 1996). Certainly, many of the well-studied Tertiary epithermal ores associated with volcanic rocks throughout Nevada are products of post-orogenic Basin and Range extension. Geochronological evidence is beginning to favour a similar temporal setting for Carlin-type mineralization (Hofstra, 1995; Emsboo et al., 1996).

The gold-bearing epithermal vein and porphyry systems that are, however, associated with collisional, subduction-related tectonics (Sillitoe, 1993) are typically located in different crustal regimes in the orogen than the so-called 'mesothermal' gold systems. Whether in an island arc, compressional orogen, or a zone of back-arc rifting, the porphyry-skarn-epithermal vein continuum normally is telescoped into the upper 2–5 km of crust (Figs. 1 and 2; Poulsen, 1996). Magmatism (generally I-type) and high temperatures impose a very steep geothermal gradient on the upper crust, often locally far in excess of 100°C/km. An abundance of subvolcanic to volcanic rocks necessitates that much of the gold

Table 2  
 Characteristics of epigenetic gold deposits. Summarized from Foster (1991), Robert et al. (1991), Kirkham et al. (1993), Hedenquist and Lowenstern (1994), Richards (1995) and Poulsen (1996)

Deposit type	Examples	Tectonic setting	Temp. of formation (°C)	Depth of emplacement (km)	Ore fluid composition	Au:Ag	Alteration types	Other key features
Orogenic	Kalgoorlie (Australia), Val d'Or (Canada), Ashanti (Ghana), Mother lode (USA)	continental margin; compressional to transpressional regime; veins typically in metamorphic rocks on seaward side of continental arc	200–700	2–20	3–10 eq. wt% NaCl, ≥ 5 mol% CO <sub>2</sub> ; traces of CH <sub>4</sub> and N <sub>2</sub>	1–10	carbonation, sericitization, sulfidation; skarn-like assemblages in higher temperature deposits	hosted in deformed metamorphic terranes; ≤ 3–5% sulfide minerals; individual deposits of ≥ 1–2 km vertical extent; spatial association with transcrustal fault zones and granitic magmatism
Epithermal (low and high sulfidation)	high sulf. = Goldfield (USA), Summitville (USA), Julcani (Peru), Lepanto (Philippines); low sulf. = Comstock Lode (USA), Fresnillo (Mexico), Golden Cross (New Zealand)	oceanic arc, continental arc, or back arc extension of continental crust; extensional environments normal, but commonly in compressional regimes	100–300	surface–2 km	< 1–20 eq. wt% NaCl; early acidic condensate (high sulf.)	0.02–1	adularia–sericite–quartz (low sulf.) versus quartz–alunite–kaolinite (high sulf.)	veins and replacements are similar age as ore-hosting or nearby volcanic rocks; ore zones generally 100–500 m in vertical extent; disseminated ore common in high sulf. systems
Epithermal (alkalic-related)	Cripple Creek (USA); Pongera (PNG); Emperor, Fiji	post-subduction, back arc extension; extension can be adjacent to magmatic arc or hundreds of km landward	generally ≤ 200	surface–2 km	≤ 10 eq. wt% NaCl; high CO <sub>2</sub> ; traces of CH <sub>4</sub> and N <sub>2</sub>	very variable	carbonation, K-metasomatism, propylitic assemblages	Te-rich deposits associated with alkalic igneous rocks; ores commonly in breccia pipes and as manto-type replacements
Sedimentary-rock hosted	Carlin (USA), Jerritt Canyon (USA), Guizhou (PR China)	back-arc extension and thinning of continental crust	200–300	2–3	≤ 7 eq. wt% NaCl;	0.1–10	intense silicification; some kaolinitization	very fine-grained gold in intensely silicified rock; dissolution of surrounding carbonate
Gold-rich porphyry	Bingham (USA), Grasberg (Indonesia), Lepanto-Far Southeast (Philippines), Kingking (Philippines)	oceanic or continental arc; subduction-related but often associated with extensional environments	300–700	2–5	some fluids > 35 eq. wt% NaCl; can mix with low salinity surface waters; often immiscible vapor	0.001–0.1	central biotite–KF zone surrounded by quartz–chlorite; common sericite–pyrite overprinting; distal propylitic alteration	disseminated sulfides and veinlets within and adjacent to porphyritic, silicite-to intermediate composition intrusions; low oxidation state of magmas may favor gold enrichments; generally I-type magmas; gold introduced with Cu-sulphides
Gold-rich skarn	Hedley (Canada), Fortitude (USA), Crown Jewel (USA)	oceanic or continental arc; subduction-related but often associated with extensional environments	300–600	1–5	10 to > 35 eq. wt% NaCl	≤ 1–10	garnet–pyroxene–epidote–chlorite–calcite	most occur as calcic exoskams; typically associated with mafic, low-silica, very reduced plutons
Submarine exhalative	Home (Canada), Bousquet (Canada), Greens Creek (USA), Boliden (Sweden)	back-arc rift basins (Kuruko-type) or mid-ocean seafloor spreading (Cyprus- and Besshi-type)	≤ 350	on or near seafloor	3.5–6.5 eq. wt% NaCl; much higher salinities where fluid interaction with brines	0.0001–0.1	quartz–talc–chlorite is most common with an outer zone of illite ± smectite; anhydrite or barite cap in places	laminated, banded, or massive fine-grained sulphides; commonly both exhalative and syndimentary replacement textures; gold relatively more important in back-arc regions

ore is hosted in lithologies of roughly equivalent age. The shallow level of the hydrothermal activity restricts much of the lode-gold emplacement to rocks that are unmetamorphosed to only slightly regionally metamorphosed.

In contrast, the so-called ‘mesothermal’ ore deposit type is deposited over a very broad range of the upper crust (Groves, 1993; Poulsen, 1996). Rather than bringing a concentrated heat source to the near surface, the fluids, granitic magmas and heat are carried to higher crustal levels along major fault zones that may have been suture zones between accreted terranes. Crustal geotherms of perhaps  $\geq 30^\circ\text{C}/\text{km}$  are elevated, but not to the levels of the more telescoped group of ore deposit types. Where hydrothermal fluids reach the near-surface environment, their relatively low temperature hinders significant gold transport; however, bisulphide complexes still may carry significant Sb and Hg into the upper few kilometres of crust (Fig. 2). Where such fluids migrate into the realm of the typical porphyry-skarn-epithermal continuum, complex overlapping of deposit styles may develop. Such a situation may characterize southwestern Alaska, where epithermal Hg–Sb ores that suggest so-called ‘mesothermal’ gold deposits at depth (Gray et al., 1997) are spatially associated with volcano-plutonic-related gold deposits (Bundtzen and Miller, 1997), or northern California where the McLaughlin gold deposit sits among a series of Hg-rich hot springs (Sherlock and Logan, 1995).

### 3. Problem of nomenclature

Prior to 1980, the so called ‘mesothermal’ group of Archaean through Tertiary deposits was not widely recognized as a single special type of gold ore. Most classifications scattered the deposits among the mesothermal and hypothermal regimes of Lindgren (1933). Others, such as Bateman (1950), divided these deposits into groups within a very broad ‘cavity filling’ type of epigenetic ore deposit. Hence, many Archaean lodes were classified as fissure filling type deposits, Otago was a shear zone deposit type, Bendigo was a saddle reef deposit type, Treadwell, Alaska was a stockwork type deposit, etc. The relatively low price of gold correlated with a limited

research interest in gold genesis studies. In fact, in the 75th Anniversary Volume of Economic Geology (1981), there is notably no chapter that is devoted to this economically important ore deposit type. Economic geologists had begun to notice the basic association of the Phanerozoic deposits with subduction zones and convergent margins during the growth of plate tectonic theories. However, books on tectonics and ore deposits barely mentioned these gold systems (e.g. Mitchell and Garson, 1981).

As the price of gold increased dramatically in the late 1970’s, so did interest in the understanding of these gold deposits. ‘Mesothermal’ lode-gold deposits began to receive extensive study by ore geologists, and were subsequently described by a variety of terms during the last fifteen years as workers began recognizing them as a single mineral deposit type. The abundance of terms that define these ores reflects both the great expansion of knowledge about these systems accumulated during the 1980’s (e.g. Robert et al., 1991) and the efforts by various groups to establish ore deposit model volumes that classify deposits by type (e.g. Cox and Singer, 1986). One consequence of so many terms for the same deposits is the resulting confusion for those not extremely familiar with the gold literature. Certainly, a single deposit type title would be helpful for all workers.

The paper by Nesbitt et al. (1986) on lode-gold deposits of the Canadian Cordillera seemed to initiate popularity of the phrase mesothermal. They define a group of Canadian ‘mesothermal’ gold deposits that formed between  $200\text{--}350^\circ\text{C}$  within a series of accreted terranes. Prior to this paper, the broad class of ‘mesothermal’ gold deposits did not exist. Major gold volumes such as ‘Gold ’82’ (Foster, 1984), ‘Turbidite-hosted Gold Deposits’ (Keppie et al., 1986) and ‘Gold ’86’ (Macdonald, 1986) lacked any mention of such a deposit type. However, since the Nesbitt et al. (1986) paper, the ‘mesothermal’ terminology has become well-entrenched in the literature. This may be a response, in part, to the need to easily contrast this group of gold deposits with the generally more shallowly-deposited types of gold ores that had already been classified as ‘epithermal’ for many years previous. Because of this widespread acceptance of the mesothermal label, subsequent comprehensive descriptions of these gold deposits have tended to group them under such a

‘mesothermal heading’ (Groves et al., 1989; Kerrich, 1991; Hodgson, 1993).

Whereas ‘mesothermal’ has become the most common term used in referring to this type of deposit during the last ten years, Poulsen (1996) has recently shown how it is very inconsistent with the meaning originally proposed by Lindgren (1907, 1933). Lindgren’s description of such a deposit type is for that which formed at depths of about 1,200–3,600 m and at temperatures of 200–300°C. Because of the restrictive temperature range, high-temperature alteration phases, including tourmaline, biotite, hornblende, pyroxene and garnet, were stated as being absent in and surrounding mesothermal type ores. Gold districts such as those of the California foothills belt, the Meguma domain of Nova Scotia, central Victoria, and Charters Tower in Queensland were classified by Lindgren (1933) as mesothermal.

Many other gold districts, however, that are routinely classified as ‘mesothermal’ today were actually termed ‘hypothermal’ by Lindgren (1933). These deposits were described as having formed at 300–500°C, thus exhibiting higher temperature alteration assemblages, and at depths below 3,600 m. Most of the world’s Archaean gold deposits were clearly stated as being hypothermal deposits. In addition, some Phanerozoic lodes, including those of the Bohemian Massif and Juneau, Alaska, were included in the class. The groupings into the mesothermal and hypothermal temperature ranges by Lindgren are remarkably accurate in light of many modern fluid inclusion studies. But the key point is that many of the deposits that are now termed ‘mesothermal’ did not fit in the mesothermal category in the early 20th century and still do not fit in the category today.

If one such Lindgren-type term was used to define the broad observed range for  $P$ – $T$  conditions of these deposits, it probably is ‘xenothermal’. The term, coined by Buddington (1935), covers the  $P$ – $T$  conditions from lepothermal (a vague  $P$ – $T$  regime between epithermal and mesothermal) to hypothermal. As such, it would include the broad range of ore forming pressures and temperatures that is well-documented in the Yilgarn block of Western Australia, as summarised by Groves (1993). However, other factors, such as structural control, wall rock type and fluid chemistry play a major role in the localization of a gold deposit and definition of a gold

deposit type solely on  $P$ – $T$  environment is not advisable (Bateman, 1950).

The contrasting tectonic setting between the sites of most ‘epithermal’ gold deposits and the sites of all so-called ‘mesothermal’ deposits presents another basic problem with usage of the Lindgren model. As envisioned by Lindgren (1907, 1933), the epithermal, mesothermal and hypothermal terms were intended to define a continuum among deposits. However, as implied in Fig. 2, the term ‘epithermal’ is now entrenched in the literature as a specific mineral-deposit type that most commonly describes high-level veining and alteration broadly associated with volcanism or subvolcanic magmatism (e.g. Berger and Bethke, 1985). As discussed above, such epithermal gold deposits may form in oceanic arcs long before continental margin orogenesis or, as in the Basin and Range of the USA, during post-orogenic extension, as shown schematically in Fig. 1. Hence, there are typically neither consistent spatial nor temporal relations between the two gold deposit types.

Many other terms relating to host rocks, vein mineralogy or ore-fluid chemistry are equally unacceptable in the overall description of these deposits. Commonly used terms, such as ‘greenstone gold’, ‘slate belt gold’, or ‘turbidite-hosted gold’, disguise the fact that the deposits have many similarities despite their different hosting sequences (the theme of this special *Ore Geology Reviews* issue) and should be used, if at all, to describe subgroups of the major deposit type, and not the deposit type itself. The use of ‘Archaean’ or ‘Mother lode-type’ gold deposits is also unacceptable, clearly reflecting a specific temporal or spatial preference, respectively. ‘Metamorphic gold’ implies an understanding of the ore-forming process which is, however, still strongly under debate. The fact that these deposits contain only a few percent sulfide minerals, in most cases, has led to classifications referring to them as ‘low sulfide’ (Berger, 1986), and the fact that gold is enriched by orders of magnitudes over base metals and Au:Ag ratios are generally  $> 1$  has led to their classification as ‘gold only’ (Hodgson and MacGeehan, 1982; Phillips and Powell, 1993) deposits. However, many other types of gold deposits, including the sedimentary rock-hosted ores at Carlin and elsewhere in Nevada, show the same low sulfide

content. Similarly, ‘lode-gold’ (McCuaig and Kerrich, 1994) may be interpreted to contain a variety of gold deposit types.

A critical feature of all these deposits seems to be their common tectonic setting, as described in detail above. These deposits were classified as ‘pre-orogenic’ by Bache (1980, 1987), who recognized their association with the world’s orogenic belts. However, at the same time, the classification assumed a syngenetic exhalative origin for the auriferous lodes, an assumption clearly in conflict with modern geochronological data. Goldfarb et al. (1991a, 1998 - this issue) have often preferred the term ‘synorogenic’, given the clear overlap of gold-forming events in the North American Cordillera with a broad, 120-m.y.-long period of continental margin growth. The term ‘post-orogenic’ has been used by other workers (Gebre-Mariam et al., 1993; Groves, 1996) who emphasize that deformation and metamorphism of ore host rocks commonly predate hydrothermal vein emplacement (Groves et al., 1984; Colvine, 1989; Hodgson and Hamilton, 1989).

#### 4. Proposed classification

These gold deposits, throughout the world’s collisional orogenic belts, can actually be viewed as both syn- and post-orogenic in origin. Whereas host rocks for ore may already be undergoing uplift and cooling (thus ‘post-orogenic’), the ore-forming fluids may be generated or set in motion by simultaneous thermal processes at depth (thus ‘syn-orogenic’) as described by Stuwe et al. (1993). For example, Kent et al. (1996) show that the main episode of gold mineralization in the Yilgarn craton postdates thermal events in the ore-hosting upper crust, but temporally correlates with melting and magmatism of lower-middle Archaean crust. Because of this, it is suggested that the gold ores simply be classified as ‘*orogenic*’ lode types, as was originally suggested by Bohlke (1982).

A remaining problem is whether to classify many ‘intrusion-related gold deposits’ within this group of orogenic gold deposits. Sillitoe (1991) places deposits such as Muruntau and Charters Tower in such an intrusion-related deposit type. McCoy et al. (1997) distinguish ‘plutonic-related mesothermal gold deposits’ of interior Alaska, such as Fort Knox, as

those where ore fluids are derived from evolving magmas. The Proterozoic gold lodes of northern Australia and the Mesozoic deposits of the north China craton and Korea are also commonly suggested to be genetically associated with igneous processes. Are such deposits, with ore fluid chemistries essentially identical to those of typical orogenic gold deposits, a different deposit type? Sillitoe (1991) indicated that the intrusion-related gold deposits also form in Phanerozoic convergent plate margins above zones of active subduction, although regional extension is stressed as an important characteristic and thus indicates some difference from the orogenic class defined here. Sillitoe (1991) does stress that the apparent overlap between orogenic and intrusion-related gold systems requires further attention. We would certainly agree.

A convenient terminology that both retains the prefixes ‘epi’, ‘meso’, and ‘hypo’ used by Lindgren (1907, 1933), and subdivides the orogenic gold deposit type, is introduced by Hagemann and Ridley (1993) and then further modified by Gebre-Mariam et al. (1995). Its continued usage is recommended. In such a scenario, *epizonal* deposits form within 6 km of the surface at temperatures of 150–300°C, *mesozonal* deposits form at depths of 6–12 km and at temperatures of 300–475°C and *hypozonal* deposits form below 12 km and at temperatures exceeding 475°C. It is critical to note that this terminology has been defined solely as a subdivision for orogenic gold deposits based on many modern geothermobarometric studies. Because of this, the depth zones for these orogenic subclasses do not correspond to those in Lindgren’s epithermal, mesothermal, and hypothermal regimes.

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## References

- Abraham, A.P.G., Spooner, E.T.C., 1995. Late Archean regional deformation and structural controls on gold–quartz vein mineralization in the northwestern Slave province, N.W.T., Canada. *Can. J. Earth Sci.* 32, 1132–1154.
- Ansdell, K.M., Kyser, T.K., 1992. Mesothermal gold mineralization in a Proterozoic greenstone belt, Western Flin Flon domain, Saskatchewan, Canada. *Econ. Geol.* 87, 1496–1524.
- Arne, D.C., Bierlein, F.P., McNaughton, N.J., Wilson, C.J.L., Morard, V.J., Ramsay, W.R.H., 1996. Timing of felsic magmatism in Victoria and its relationship to gold mineralization. In: Hughes, M.J., Ho, S.E., Hughes, C.E. (Eds.), *Recent Developments in Victorian Geology and Mineralisation*. Aust. Inst. Geosci. Bull. 20, 43–48.
- 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*. B.C. Geol. Surv., Cordilleran Roundup Short Course, pp. O1–O32.
- Ashley, P.M., Cook, N.D.J., Hill, R.L., Kent, A.J.R., 1994. Shoshonitic lamprophyre dykes and their relation to mesothermal Au–Sb veins at Hillgrove, New South Wales, Australia. *Lithos* 32, 249–272.
- Bache, J.J., 1980. Essai de typologie quantitative des gisements mondiaux d'or. BRGM Note SGN/GMX/GIT, No. 622. 9 pp.
- Bache, J.J., 1987. *World Gold Deposits: A Quantitative Classification*. North Oxford Academic, London, 179 pp.
- Balakrishnan, S., Hanson, G.N., Rajamani, V., 1990. Pb and Nd isotope constraints on the origin of high Mg and tholeiitic amphibolites, Kolar Schist Belt, South India. *Contrib. Mineral. Petrol.* 107, 279–292.
- Barley, M.E., Groves, D.I., 1992. Supercontinent cycles and the distribution of metal deposits through time. *Geology* 20, 291–294.
- 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.
- Barnicot, A.C., Fare, R.J., Groves, D.I., McNaughton, N.J., 1991. Synmetamorphic lode–gold deposits in high–grade Archean settings. *Geology* 19, 921–924.
- Bateman, A.M., 1950. *Economic Mineral Deposits*, 2nd ed. Wiley, New York, 916 pp.
- Berger, B.R., 1986. Descriptive model of low–sulphide Au–quartz veins. In: Cox, D.P., Singer, D.A. (Eds.), *Mineral Deposit Models*. U.S. Geol. Surv. Bull. 1693, 183–186.
- Berger, B.R., Bethke, P.M. (Eds.), 1985. *Geology and geochemistry of epithermal deposits*. *Rev. Econ. Geol.* 2, 298 pp.
- Berger, B.R., Drew, L.D., Goldfarb, R.J., Snee, L.W., 1994. An epoch of gold riches: The Late Paleozoic in Uzbekistan, central Asia. *Soc. Econ. Geol. Newslett.* 16 (1), 7–11.
- Von Blanckenburg, F., Davies, J.H., 1995. Slab breakoff: A model for syncollisional magmatism and tectonics in the Alps. *Tectonics* 14, 120–131.
- 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.
- 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.
- Buddington, A.F., 1935. High temperature mineral associations at shallow to moderate depths. *Econ. Geol.* 30, 205–222.
- Bundtzen, T.K., Miller, M.L., 1997. Precious metals associated with Late Cretaceous–Early Tertiary igneous rocks of southwestern Alaska. In: Goldfarb, R.J., Miller, L.D. (Eds.), *Mineral Deposits of Alaska*. Econ. Geol. Monogr. 9, 242–286.
- Cathelineau, M., Boiron, M.C., Hollinger, P., Poty, B., 1990. Metallogenesis of the French part of the Variscan orogen. Part II: Time–space relationships between U, Au and Sn–W ore deposition and geodynamic events. *Mineralogical and U–Pb data*. *Tectonophysics* 177, 59–79.
- Colvine, A.C., 1989. An empirical model for the formation of Archean gold deposits. Products of final cratonization of the Superior Province, Canada. In: Keays, R.R., Ramsay, W.R.H., Groves, D.I. (Eds.), *The Geology of Gold Deposits: The Perspective in 1988*. *Econ. Geol. Monogr.* 6, 37–53.
- Colvine, A.C., Andrews, A.J., Cherry, M.E., Durocher, M.E., Fyon, J.A., Lavigne, M.J., Macdonald, A.J., Marmont, S., Poulsen, K.H., Springer, J.S., Troop, D.G., 1984. An integrated model for the origin of Archean lode–gold deposits. *Ont. Geol. Surv. Open–File Rep.* 5524, 98 pp.
- Coney, P.J., 1992. The Lachlan belt of eastern Australia and Circum–Pacific tectonic evolution. *Tectonophysics* 214, 1–25.
- Connors, K.A., 1996. Unraveling the boundary between turbidites of the Kiseynew belt and volcano–plutonic rocks of the Flin Flon belt, Trans–Hudson Orogen, Canada. *Can. J. Earth Sci.* 33, 811–829.
- Cox, D.P., Singer, D.A. (Eds.), 1986. *Mineral Deposit Models*. U.S. Geol. Surv. Bull. 1693, 379 pp.
- Curti, E., 1987. Lead and oxygen isotope evidence for the origin of the Monte Rosa gold lode deposits (Western Alps, Italy): A comparison with Archean lode deposits. *Econ. Geol.* 82, 2115–2140.
- 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.
- deRonde, C.E.J., Hall, C.M., York, D., Spooner, E.T.C., 1991.

- Laser step heating  $^{40}\text{Ar}/^{39}\text{Ar}$  age spectra from early Archean Barberton greenstone belt sediments: A technique for detecting cryptic tectono-thermal events. *Geochim. Cosmochim. Acta* 55, 1933–1951.
- Drew, L.J., Berger, B.R., Kurbanov, N.K., 1996. Geology and structural evolution of the Muruntau gold deposit, Kyzylkum desert, Uzbekistan. *Ore Geol. Rev.* 11, 175–196.
- Economic Geology, 1981. 75th Anniversary Volume. Econ. Geol. Publ. Co., Littleton, CO, 964 pp.
- Elder, D., Cashman, S.M., 1992. Tectonic control and fluid evolution in the Quartz Hill, California, lode-gold deposits. *Econ. Geol.* 87, 1795–1812.
- Emsboo, P., Hofstra, A.H., Park, D., Zimmerman, J.M., Snee, L., 1996. A mid-Tertiary age constraint on alteration and mineralization in igneous dikes on the Goldstrike property, Carlin Trend, Nevada. *Geol. Soc. Am. Abstr. Prog.* 28 (7), 476.
- Fayek, M., Kyser, T.K., 1995. Characteristics of auriferous and barren fluids associated with the Proterozoic Contact Lake lode-gold deposit, Saskatchewan, Canada. *Econ. Geol.* 90, 385–406.
- 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.
- Foster, D.A., Kwak, T.A.P., Gray, D.R., 1996. Timing of gold mineralisation and relationship to metamorphism, thrusting, and plutonism in Victoria. In: Hughes, M.J., Ho, S.E., Hughes, C.E. (Eds.), *Recent Developments in Victorian Geology and Mineralisation*. Aust. Inst. Geosci. Bull. 20, 49–53.
- Foster, R.P. (Ed.), 1984. *Gold '82: The Geology, Geochemistry and Genesis of Gold Deposits*. A.A. Balkema, Rotterdam, 753 pp.
- Foster, R.P. (Ed.), 1991. *Gold Metallogeny and Exploration*. Blackie and Son, Glasgow, 432 pp.
- Foster, R.P., Piper, D.P., 1993. Archean lode-gold deposits in Africa: Crustal setting, metallogenesis and cratonization. *Ore Geol. Rev.* 8, 303–347.
- Fyfe, W.S., Kerrich, R., 1985. Fluids and thrusting. *Chem. Geol.* 49, 353–362.
- Gaboury, D., Dube, B., Lafleche, M.R., Lauziere, K., 1996. Geology of the Hammer Down mesothermal gold deposit, Newfoundland Appalachians, Canada. *Can. J. Earth Sci.* 33, 335–350.
- Gebre-Mariam, M., Groves, D.I., McNaughton, N.J., Mikucki, E.J., Vearncombe, J.R., 1993. Archean Au–Ag mineralisation at Racetrack, near Kalgoorlie, Western Australia: A high crustal-level expression of the Archean composite lode-gold system. *Miner. Deposita* 28, 375–387.
- Gebre-Mariam, M., Hagemann, S.G., Groves, D.I., 1995. A classification scheme for epigenetic Archean lode-gold deposits. *Miner. Deposita* 30, 408–410.
- 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.
- Goldfarb, R.J., Gray, J.E., Pickthorn, W.J., Gent, C.A., Ciutat, B.A., 1990. Stable isotope systematics of epithermal mercury–antimony mineralization, southwestern Alaska. In: Goldfarb, R.J., Nash, J.T., Stoesser, J.W. (Eds.), *Geochemical Studies in Alaska* by the U.S. Geological Survey, 1989. U.S. Geol. Surv. Bull., 1950, pp. E1–E9.
- Goldfarb, R.J., Leach, D.L., Pickthorn, W.J., 1991a. Source of synorogenic fluids of the northern Cordillera: Evidence from the Juneau Gold Belt, Alaska. In: Robert, F., Sheahan, P.A., Green, S.B. (Eds.), *Greenstone Gold and Crustal Evolution*. Geol. Assoc. Can., Mineral Deposits Div. Publ., pp. 160–161.
- Goldfarb, R.J., Snee, L.W., Miller, L.D., Newberry, R.J., 1991b. Rapid dewatering of the crust deduced from ages of mesothermal gold deposits. *Nature* 354, 296–298.
- 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 (this issue).
- Gray, J.D., Gent, C.A., Snee, L.W., Wilson, F.H., 1997. Epithermal mercury–antimony and gold-bearing vein lodes of southwestern Alaska. In: Goldfarb, R.J., Miller, L.D. (Eds.), *Mineral Deposits of Alaska*. Econ. Geol. Monogr. 9, 287–305.
- Groves, D.I., 1993. The crustal continuum model for late-Archean lode-gold deposits of the Yilgarn Block, Western Australia. *Miner. Deposita* 28, 366–374.
- Groves, D.I., 1996. Geological concepts in the exploration for large to giant late-orogenic (mesothermal) gold deposits: The Archean greenstone experience. In: *Mesothermal Gold Deposits: A Global Overview*. Geol. Dept. (Key Centre) Univ. Ext., Univ. West. Aust. Publ. 27, 114–117.
- Groves, D.I., Foster, R.P., 1991. Archean lode-gold deposits. In: Foster, R.P. (Ed.), *Gold Metallogeny and Exploration*. Blackie and Son, Glasgow, pp. 63–103.
- Groves, D.I., Phillips, G.N., Ho, S.E., Henderson, C.A., Clark, M.E., Woad, G.M., 1984. Controls on distribution of Archean hydrothermal gold deposits in Western Australia. In: Foster, R.P. (Ed.), *Gold '82: The Geology, Geochemistry and Genesis of Gold Deposits*. A.A. Balkema, Rotterdam, pp. 689–712.
- Groves, D.I., Barley, M.E., Ho, S., 1989. Nature, genesis and tectonic setting of mesothermal gold mineralization in the Yilgarn Block, Western Australia. In: Keays, R.R., Ramsay, W.R.H., Groves, D.I. (Eds.), *The Geology of Gold Deposits: The Perspective in 1988*. Econ. Geol. Monogr., 6, 71–85.
- Groves, D.I., Barley, M.E., Barnicoat, A.C., Cassidy, K.F., Fare, R.J., Hagemann, S.G., Ho, S.E., Hronsky, J.M.A., Mikucki, E.J., Mueller, A.G., McNaughton, N.J., Perring, C.S., Ridley, J.R., Vearncombe, J.R., 1992. Sub-greenschist to granulite-hosted Archean lode-gold deposits of the Yilgarn Craton: A depositional continuum from deep sourced hydrothermal fluids in crustal-scale plumbing systems. *Geol. Dept. (Key Centre) Univ. Ext., Univ. West. Aust. Publ.* 22, 325–338.
- Le Guen, M., 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.
- Guild, P.W., 1971. Metallogeny: A key to exploration. *Mining Eng.* 23 (1), 69–72.
- Haussler, P.J., Bradley, D., Goldfarb, R., Snee, L., Taylor, C., 1995. Link between ridge subduction and gold mineralization in southern Alaska. *Geology* 23, 995–998.

- Hagemann, S.G., Brown, P.E., 1996. Geobarometry in Archean lode-gold deposits. *Eur. J. Mineral.* 8, 937–960.
- Hagemann, S.G., Ridley, J.R., 1993. Hydrothermal fluids in epi- and katazonal crustal levels in the Archean—Implications for  $P$ - $T$ - $X$ - $t$  evolution of lode-gold mineralisation. In: Williams, P.R., Haldane, J.A. (Eds.), *An international conference on crustal evolution, metallogeny and exploration of the Eastern Goldfields*. Extended Abstr. Aust. Geol. Surv. Org., Record 54, pp. 123–130.
- Hagemann, S.G., Groves, D.I., Ridley, J.R., Vearncome, J.R., 1992. The Archean lode-gold deposits at Wiluna, Western Australia. High level brittle-style mineralisation in a strike-slip regime. *Econ. Geol.* 87, 1022–1053.
- Hagemann, S.G., Gebre-Mariam, M., Groves, D.L., 1994. Surface-water influx in shallow-level Archean lode-gold deposits in Western Australia. *Geology* 22, 1067–1070.
- Hedenquist, J.W., Lowenstern, J.B., 1994. The role of magmas in the formation of hydrothermal ore deposits. *Nature* 370, 519–527.
- Hirdes, W., Davis, D.W., Ludtke, G., Konan, G., 1996. Two generations of Birimian (Paleoproterozoic) volcanic belts in northeastern Cote d'Ivoire (West Africa): Consequences for the 'Birimian controversy'. *Precambrian Res.* 80, 173–191.
- Hodgson, C.J., 1993. Mesothermal lode-gold deposits. In: Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., Duke, J.M. (Eds.), *Mineral Deposit Modeling*. Geol. Assoc. Can., Spec. Pap., 40, 635–678.
- Hodgson, C.J., Hamilton, J.V., 1989. Gold mineralization in the Abitibi greenstone belt: End stage result of Archean collisional tectonics? In: Keays, R.R., Ramsay, W.R.H., Groves, D.I. (Eds.), *The Geology of Gold Deposits: The Perspective in 1988*. *Econ. Geol. Monogr.*, 6, 86–100.
- Hodgson, C.J., MacGeehan, P.J., 1982. A review of the geological characteristics of 'Gold Only' deposits in the Superior Province of the Canadian Shield. In: Hodder, R.W., Petruks, W. (Eds.), *Geology of Canadian Gold Deposits*. Can. Inst. Min. Metall., Spec. Vol. 24, 211–229.
- Hofstra, A.H., 1995. Timing and duration of Carlin-type gold mineralization in Nevada and Utah: Relation to back-arc extension and magmatism. *Geol. Soc. Am. Abstr. Progr.* 27 (6), 329.
- Jackson, S.L., Cruden, A.R., 1995. Formation of the Abitibi greenstone belt by arc-trench migration. *Geology* 23, 471–474.
- Kelley, K.D., Romberger, S.B., Beaty, D.W., Snee, L.W., Stein, H.J., Thompson, R.B., 1996. Genetic model for the Cripple Creek district: Constraints from  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology, major and trace element geochemistry and stable and radiogenic isotope data. In: Thompson, T.B. (Ed.), *Diamonds to Gold*. I. State Line Kimberlite district, Colorado. II. Cresson mine, Cripple Creek district, Colorado. *Soc. Econ. Geol., Guidebook Ser.* 26, 65–83.
- Kent, A.J.R., Hagemann, S.G., 1996. Constraints on the timing of lode-gold mineralisation in the Wiluna greenstone belt, Yilgarn Craton, Western Australia. *Aus. J. Earth Sci.* 43, 573–588.
- Kent, A.J.R., McDougall, I., 1995. Constraints on the timing of gold mineralization in the Kalgoorlie goldfield, Western Australia, from  $^{40}\text{Ar}/^{39}\text{Ar}$  and U–Pb dating: Evidence for multiple mineralization episodes. *Econ. Geol.* 90, 845–859.
- 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., 1993. Synthesis of Palaeozoic deformation events and terrane accretion in the Canadian Appalachians. *Geol. Rundsch.* 82, 381–431.
- 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., Boyle, R.W., Haynes, S.J. (Eds.), 1986. *Turbidite-Hosted Gold Deposits*. Geol. Assoc. Can., Spec. Pap. 32, 186 pp.
- Kerrick, R., 1991. Mesothermal gold deposits - A critique of genetic hypotheses. In: Robert, F., Sheahan, P.A., Green, S.B. (Eds.), *Greenstone Gold and Crustal Evolution*. Geol. Assoc. Can., Mineral Deposits Div. Publ., pp. 13–31.
- Kerrick, R., 1993. Perspectives on genetic models for lode-gold deposits. *Miner. Deposita* 28, 362–365.
- Kerrick, R., 1994. Dating Archean auriferous quartz vein deposits in the Abitibi greenstone belt, Canada:  $^{40}\text{Ar}/^{39}\text{Ar}$  evidence for a 70–100 m.y.-time gap between plutonism–metamorphism and mineralisation. A discussion. *Econ. Geol.* 89, 679–686.
- 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., Wyman, D.A., 1990. The geodynamic setting of mesothermal gold deposits: An association with accretionary tectonic regimes. *Geology* 18, 882–885.
- Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., Duke, J.M. (Eds.), 1993. *Mineral Deposit Modeling*. Geol. Assoc. Can., Spec. Pap. 40, 798 pp.
- Kontak, D.J., Smith, P.F., 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.
- 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.
- Landefeld, L.A., 1988. The geology of the Mother Lode-gold belt, Sierra Nevada Foothills metamorphic belt, California. In: *Bicentennial Gold 88*, Extended Abstracts, Oral Programme. Geol. Soc. Aust. Abstr. 22, pp. 167–172.
- Lapointe, B., Chown, E.H., 1993. Gold-bearing iron-formation in a granulite terrane of the Canadian Shield: A possible deep-level expression of an Archean gold-mineralizing system. *Miner. Deposita* 28, 191–197.
- Leitch, C.H.B., Van der Hayden, P., Godwin, 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.
- Lindgren, W., 1907. The relation of ore deposition to physical conditions. *Econ. Geol.* 2, 105–127.
- Lindgren, W., 1933. *Mineral Deposits*, 4th ed. McGraw Hill, New York and London, 930 pp.
- Macdonald, A.J. (Ed.), 1986. *Proceedings of Gold '86*. An Inter-

- national Symposium on the Geology of Gold Deposits. Toronto, 517 pp.
- MacLachlan, K., Helmstaedt, H., 1995. Geology and geochemistry of an Archean mafic dike complex in the Chan Formation: Basis for a revised plate-tectonic model of the Yellowknife greenstone belt. *Can. J. Earth Sci.* 32, 614–630.
- 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. Monogr.* 6, 242–251.
- Marakushev, A.A., Khokhlov, V.A., 1992. A petrological model for the genesis of the Muruntau gold deposit. *Int. Geol. Rev.* 34 (1), 59–76.
- McCoy, D., Newberry, R.J., Layer, 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*. *Econ. Geol. Monogr.* 9, 191–241.
- McCuaig, T.C., Kerrich, R., 1994. *P–T–t*-deformation-fluid characteristics of lode-gold deposits: Evidence from alteration systematics. In: Lentz, D.R. (Ed.), *Alteration and Alteration Processes Associated with Ore-forming Systems*. *Geol. Assoc. Can., Short Course Notes*, 11, 339–379.
- McCuaig, T.C., Kerrich, R., Groves, D.I., Archer, N., 1993. The nature and dimensions of regional and local gold-related hydrothermal alteration in tholeiitic metabasalts in the Norseman goldfields: The missing link in a crustal continuum of gold deposits?. *Miner. Deposita* 28, 420–435.
- McKeag, S.A., Craw, D., 1989. Contrasting fluids in gold-bearing quartz vein systems formed progressively in a rising metamorphic belt: Otago Schist, New Zealand. *Econ. Geol.* 84, 22–33.
- Meinert, L.D., 1993. Igneous petrogenesis and skarn deposits. In: Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., Duke, J.M. (Eds.), *Mineral Deposit Modeling*. *Geol. Assoc. Can., Spec. Pap.* 40, 569–583.
- Mikucki, E.J., 1998. Hydrothermal transport and depositional processes in Archean lode-gold systems: A review. *Ore Geol. Rev.* 13, 307–321.
- Mikucki, E.J., Ridley, J.R., 1993. The hydrothermal fluid of Archean lode-gold deposits: Constraints on its composition inferred from ore and wallrock alteration assemblages over a spectrum of metamorphic grades. *Miner. Deposita* 28, 469–481.
- Miller, L.D., Goldfarb, R.J., Gehrels, G.E., Snee, 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.
- Mitchell, A.H.G., Garson, M.S., 1981. *Mineral Deposits and Global Tectonic Settings*. Academic Press, London, 405 pp.
- Moravek, P. (Ed.), 1995. Gold deposits of the central and SW part of the Bohemian Massif. In: *Excursion Guide, Third Biennial SGA Meeting*. Mineral deposits: From their origin to their environmental impacts. Prague, August 28–31, 104 pp.
- Mueller, A.G., Groves, D.I., 1991. The classification of Western Australian greenstone-hosted gold deposits according to wall-rock-alteration assemblages. *Ore Geol. Rev.* 6, 291–332.
- Muller, A.G., Groves, D.I., 1997. *Potassic Igneous Rocks and Associated Gold–Copper Mineralization*, 2nd ed. Springer-Verlag, Berlin, 238 pp.
- Nesbitt, B.E., 1991. Phanerozoic gold deposits in tectonically active continental margins. In: Foster, R.P. (Ed.), *Gold Metallogeny and Exploration*. Blackie and Son, Glasgow, pp. 104–132.
- Nesbitt, B.E., Muehlenbachs, K., 1989. Geology, geochemistry and genesis of mesothermal gold deposits of the Canadian Cordillera: Evidence for ore formation from evolved meteoric water. In: Keays, R.R., Ramsay, W.R.H., Groves, D.I. (Eds.), *The Geology of Gold Deposits: The Perspective in 1988*. *Econ. Geol. Monogr.* 6, 553–563.
- Nesbitt, B.E., Murowchick, J.B., Muehlenbachs, K., 1986. Dual origin of lode-gold deposits in the Canadian Cordillera. *Geology* 14, 506–509.
- Nie, F., 1997. An overview of gold resources in China. *Int. Geol. Rev.* In press.
- Nokleberg, W.J., Bundtzen, T.K., Dawson, K.M., Eremin, R.A., Goryachev, N.A., Koch, R.D., Ratkin, V.V., Rozenblum, I.S., Shpikerman, V.I., Frolov, Y.F., Gorodinsky, M.E., Khanchuck, A.I., Kovbas, L.I., Melnikov, V.D., Nekrasov, I.Ya., Ognyanov, N.V., Petrachenko, E.D., Petrachenko, R.I., Pozdeev, A.I., Ross, K.V., Sidorov, A.A., Wood, D.H., Grybeck, D., 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.* 513-A, 385 pp.
- Peters, S.G., Golding, S.D., 1989. Geologic, fluid inclusion, and stable isotope studies of granitoid-hosted gold-bearing quartz veins, Charters Towers, northeastern Australia. *Econ. Geol. Monogr.* 6, 260–273.
- Phillips, G.N., Hughes, M.J., 1996. The geology and gold deposits of the Victorian gold province. *Ore Geol. Rev.* 11, 255–302.
- Phillips, G.N., Powell, R., 1993. Link between gold provinces. *Econ. Geol.* 88, 1084–1098.
- 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*, vol. G-1. *Geol. Soc. Am.*, pp. 989–1021.
- Poulsen, K.H., 1996. Lode-gold. In: Eckstrand, O.R., Sinclair, W.D., Thorpe, R.I. (Eds.), *Geology of Canadian Mineral Deposit Types. The Geology of North America*, vol. P-1. *Geol. Soc. Am.*, pp. 323–328.
- Powell, W.G., Carmichael, D.M., Hodgson, C.J., 1995. Conditions and timing of metamorphism in the southern Abitibi greenstone belt, Quebec. *Can. J. Earth Sci.* 32, 787–805.
- Ramsay, W.R.H., 1998. A review of Victorian mesothermal gold, regional setting, styles, and genetic constraints. In: Keays, R.R., Ramsay, W.R.H., Groves, D.I. (Eds.), *The Geology of Gold Deposits: The perspective in 1988*.
- Richards, J.P., 1995. Alkalic-type epithermal gold deposits: A review. Turbidite-hosted gold deposits of Central Victoria, Australia: their regional setting, mineralisation styles and some genetic constraints. *Ore Geol. Rev.* 13, 131–151 (this issue) In: Thompson, J.F.H. (Ed.), *Magma, Fluids and Ore Deposits*. *Min. Assoc. Can., Short Course Ser.*, 23, 367–400.
- Richards, J.P., Chappel, B.W., McCulloch, M.T., 1990.

- Intraplate-type magmatism in a continent–island-arc collision zone–Porgera intrusive complex, Papua New Guinea. *Geology* 18, 958–961.
- Ridley, J., Mikucki, E.J., Groves, D.I., 1996. Archean lode-gold deposits: Fluid flow and chemical evolution in vertically extensive hydrothermal systems. *Ore Geol. Rev.* 10, 279–293.
- 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*, vol. P-1. *Geol. Soc. Am.*, pp. 350–366.
- Robert, F., Brown, A.C., 1986. Archean gold-bearing quartz veins at the Sigma mine, Abitibi greenstone belt, Quebec. Part I. Geologic relations and formation of the vein systems. *Econ. Geol.* 81, 578–592.
- Robert, F., Sheahan, P.A., Green, S.B. (Eds.), 1991. *Greenstone Gold and Crustal Evolution*. *Geol. Assoc. Can., Mineral Deposits Div. Publ.*, 252 pp.
- 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.
- Sawkins, F.J., 1972. Sulfide ore deposits in relation to plate tectonics. *J. Geol.* 80, 377–397.
- Sawkins, F.J., 1990. *Metal Deposits in Relation to Plate Tectonics*, 2nd ed. Springer-Verlag, Berlin, 451 pp.
- Scheiber, E., 1996. *Geology of New South Wales: Synthesis*. *Geol. Surv. N.S.W. Mem. Geol.* 13 (1), 295 pp.
- Sengor, A.M.C., Okurogullari, A.H., 1991. The role of accretionary wedges in the growth of continents - Asiatic examples from Argand to plate tectonics. *Eclogae Geol. Helv.* 84 (3), 535–597.
- Shenberger, D.M., Barnes, H.L., 1989. Solubility of gold in aqueous sulfide solutions from 150 to 350°C. *Geochim. Cosmochim. Acta* 53, 269–278.
- Sherlock, R.L., Logan, M.A.V., 1995. Silica–carbonate alteration of serpentinite: Implications for the association of mercury and gold mineralization in northern California. *Explor. Mining Geol.* 4 (4), 395–409.
- Sibson, R.H., Robert, F., Poulsen, K.H., 1988. High-angle reverse faults, fluid pressure cycling, and mesothermal gold–quartz deposits. *Geology* 16, 551–555.
- 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., 1993. Gold-rich porphyry copper deposits: Geological model and exploration implications. In: Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., Duke, J.M. (Eds.), *Mineral Deposit Modeling*. *Geol. Assoc. Can., Spec. Pap.* 40, 465–478.
- Solomon, M., Groves, D.I., 1994. *The Geology and Origin of Australia's Mineral Deposits*. *Oxford Monogr. Geol. Geophys.* 24, 951 pp.
- Stein, H.J., Markey, R.J., Morgan, J.W., Zak, K., Zachariad, J., Sundblad, K., 1996. Re–Os dating of Au deposits in shear zones using accessory molybdenite: Bohemian Massif, Carolina slate belt, and Fennoscandian Shield examples. *Geol. Soc. Am. Abstr. Progr.* 28 (7), 474.
- Stowell, H.H., Leshner, C.M., Green, N.L., Sha, P., Guthrie, G.M., Sinha, A.K., 1996. Metamorphism and gold mineralization in the Blue Ridge, southernmost Appalachians. *Econ. Geol.* 91, 1115–1144.
- Stuwe, K., Will, T.M., Zhou, S., 1993. On the timing relationship between fluid production and metamorphism in metamorphic piles: Some implications for the origin of post-metamorphic gold mineralization. *Earth Planet. Sci. Lett.* 114, 417–430.
- Thomas, D.J., Heaman, L.M., 1994. Geologic setting of the Jolu gold mine, Saskatchewan: U–Pb age constraints on plutonism, deformation, mineralization and metamorphism. *Econ. Geol.* 89, 1017–1030.
- Trumbull, R.B., Hua, L., Lehrberger, G., Satir, M., Wimbauer, T., Morteani, G., 1996. Granitoid-hosted gold deposits in the Anjiayingzi District of Inner Mongolia, People's Republic of China. *Econ. Geol.* 91, 875–895.
- 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.
- Wang, L.G., Luo, Z.K., McNaughton, N.J., Groves, D.I., Huang, J.Z., Miao, L.C., Guan, K., Liu, Y.K., 1996. SHRIMP U–Pb in zircon studies of plutonic rocks from the Jiaodong Peninsular, Shangdong Province, China: Constraints on crustal and tectonic evolution and gold metallogeny. In: *Mesothermal Gold Deposits: A Global Overview*. *Geol. Dept. (Key Centre) Univ. Ext., Univ. West. Aust. Publ.* 27, 34–38.
- 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. Newslett.* 23 (1), 9–13.
- Wyman, D., Kerrich, R., 1988. Alkaline magmatism, major structures, and gold deposits: Implications for greenstone belt gold metallogeny. *Econ. Geol.* 83, 451–458.