# AMPHIBOLITE-HOSTED GOLD: HYPOZONAL OR SKARN DEPOSITS?

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**Summary**

The genetic classification of gold deposits that are hosted in amphibolite facies terranes in the Yilgarn Craton of Western Australia is controversial. Several authors suggest that these are hypozonal gold deposits which form as part of a continuum of deposits, over an extended range of crustal depths in concert with P-T conditions that reflect the crustal level. Other authors argue that the occurrence of calc-silicate alteration (eg., diopside, garnet) in these deposits is indicative of skarn mineralization, and, even though no direct magmatic relationship can be established, they propose that gold mineralization was related to local granitoid-derived magmatic fluids. Recent detailed deposit-scale descriptions of calc-silicate alteration assemblages demonstrate clearly that calc-silicate alteration can be pre-syn- and/or post-orogenic, and, in most cases, is only a minor constituent of the main gold ores. In addition: (1) the high metamorphic grade of the host rocks, (2) deep (10 to 15 km) crustal depth, (3) distance from plutons, (4) lack of endoskarn, (5) low salinities of ore fluids, and (6) lack of a clearly-demonstrable contemporaneous pluton, are all significant differences to Phanerozoic gold skarns. Therefore, on the weight of evidence, these deposits are best classified as orogenic hypozonal lode-gold deposits.

**Introduction**

Archean lode-gold deposits in the Yilgarn Craton of Western Australia occur over an extended range of the crust from epizonal (< 6km) to hypozonal (10 to 15km) settings. Groves (1993) has presented a crustal continuum model in which all of the lode-gold deposits, including those at hypozonal crustal settings, are part of a continuum of gold deposits which Groves et al. (1998) have subsequently termed Archean orogenic lode-gold deposits.

Alternatively, Mueller (1988) and Mueller et al. (1991) have suggested that some high-temperature lode-gold deposits, particularly those in the Southern Cross Province of Western Australia, represent analogues to Phanerozoic gold-skarn deposits. Characteristic calc-silicate alteration assemblages, in conjunction with the proximity of syn-tectonic granitoids, led them to classify these deposits as Archean gold skarns.

This contribution highlights the occurrence of amphibolite-hosted lode-gold deposits in the Yilgarn Craton, constrains the timing of the ubiquitous calc-silicate alteration with respect to gold mineralization, and highlights the genetic and exploration significance of models for amphibolite-hosted lode-gold deposits.

**Hypozonal Lode-gold Deposits in the Yilgarn Craton**

Ridley et al. (1995) divided hypozonal Archean lode-gold deposits into three major classes based on alteration assemblages developed in mafic and ultramafic wallrocks: (1) Amphibole-class (470° to 540°C), corresponding to lower amphibolite facies with Ca-amphibole as the major and diopside as the minor alteration mineral, (2) Diopside-class (520° to 580° C), corresponding to middle-amphibolite facies with diopside as the common alteration mineral, and (3) diopside-K-feldspar-class (>570°), with diopside, K-feldspar and garnet common distinctive alteration minerals. Figure 1 shows the distribution of significant hypozonal deposits (generally deposits with > 5t contained gold) in the Yilgarn Craton, distinguishing amphibole-class deposits from diopside and diopside-K-feldspar classes. The two major areas of high-temperature deposits in the Yilgarn Craton are the Southern Cross greenstone belt (Fig. 2) and the western margin of the Norseman-Wiluna greenstone belt, between Coolgardie and Norseman. A number of other hypozonal deposits occur throughout the Yilgarn Craton, generally at the margins of major greenstone belts, where they are in contact with granitoids and/or gneisses.

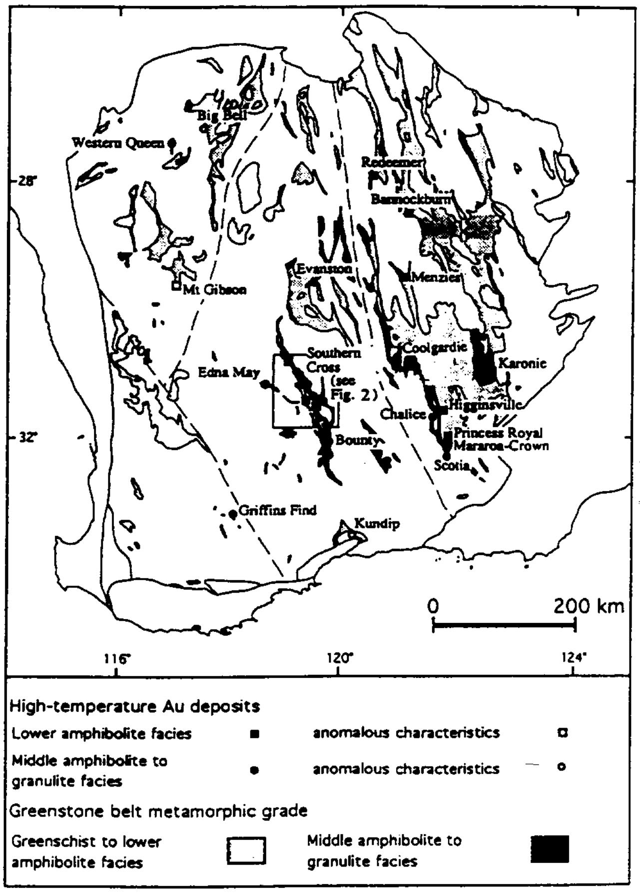


Figure 1. Major hypozonal lode-gold deposits of the Yilgarn Craton (modified after Ridley et al., 1995). Areas of greenstone belts that have been metamorphosed to amphibolite- or lower-granulite-facies are also shown.

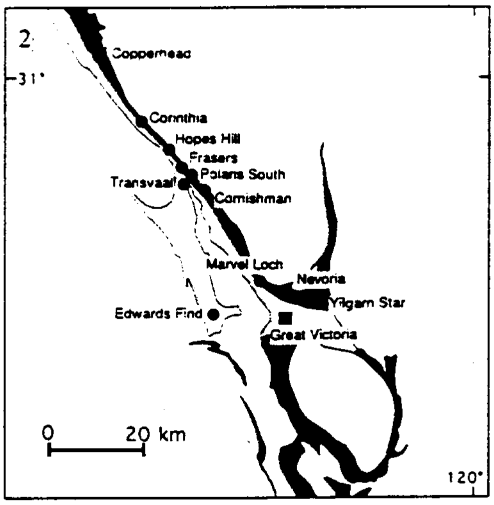


Figure 2. Major hypozonal lode-gold deposits in the central Southern Cross greenstone belt (modified after Ridley et al., 1995). For location and symbols, see Figure 1.

**Calc-Silicate Alteration and Skarn Deposits**

The crucial aspect of hypozonal lode-gold deposits, and also the source of much confusion with regards to their genesis, is the occurrence of calc-silicate alteration within the area of gold mineralization. Calc-silicate alteration is the product of metasomatic exchange, resulting in an enrichment of calcium, iron, aluminium, manganese and magnesium in metasomatised rocks. Calc-silicate alteration is recorded from widely different geologic environments, such as the seafloor, different crustal depths in buried metamorphic terranes, and proximity to plutons. The last environment is commonly accompanied by Fe, W, Cu, Pb, Zn, Mo, Ag, Au, U, REE, F, B or Sn mineralization. Economic accumulations of one or several of these metals are termed skarn deposits. Meinert (1992) emphasises that skarns occur in diverse environments, with respect to lithologies, and proximity to plutons, faults, and metamorphic terranes, that are linked by the distinct mineralogy, which includes a wide variety of calc-silicate and associated minerals, but is normally dominated by garnet and pyroxene. Einaudi et al. (1981) and Meinert (1992) suggest that skarn and skarn deposit be used as descriptive terms based upon their contained mineralogy, free of genetic implications.

Mueller (1988, 1997) has suggested that Archean lode-gold deposits in which calc-silicate alteration occurs within the area of gold mineralization be classified as gold skarns. He also implies or interprets the fluid source responsible for gold mineralization to be related to granitoids, or derived from them.

**Timing of Calc-Silicate Alteration (Skarn Mineralization) in the Yilgarn Craton**

An important aspect of calc-silicate alteration and gold mineralization in Archean terrains is their relative timing and spatial occurrence. Detailed deposit-scale studies in the Southern Cross Province have shown that calc-silicate alteration occurs pre-, syn-, and post-gold mineralization. Grainger (1998), in a detailed structural-hydrothermal investigation on the Copperhead gold deposit in the northern portion of the Southern Cross Province, demonstrated that calc-silicate alteration pre-dated gold mineralization. At Copperhead, gold-bearing ductile shear-zones and associated actinolite-tremolite-calcite-biotite-quartz-green hornblende alteration crosscut barren, banded actinolite-biotite schist (skarns) and a massive dolomite unit, which is interpreted as a product of seafloor alteration. Bodycoat (1999) has shown that, although gold mineralization at the Yilgarn Star gold deposit is associated with spatially restricted diopside- and amphibole-rich veins, it is not spatially associated with extensive calc-silicate metasomatic alteration. These studies, in addition to investigations at the world-class amphibolite-hosted Big Bell deposit (Platel, 1998) show convincingly that. even though calc-silicate alteration is an ubiquitous alteration assemblage in amphibolite facies terrains, it may relate to significantly different geological processes, such as seafloor alteration, regional metamorphism, plutonism, or metasomatism (that is related to gold mineralization), at different times in the history of the terrains.

**Genetic Models**

The majority of authors (Groves, 1993; Ridley et al., 1995; Witt et al., 1997) have interpreted calc-silicate alteration in Archean lode-gold deposits to be the higher temperature equivalent, in amphibolite facies host rocks, of the carbonate-sericite±chlorite alteration which typifies the lode- gold deposits in greenschist-facies host rocks. This carries the implication that the fluids are likely deeply sourced (possibilities include subducted oceanic crust, mid-crust, deep granitoids, or combinations of these), not derived from local granitoid sources as a specific style of gold deposit different from that at higher crustal levels. Groves (1993) and Witt et al. (1997) have presented a model in which all of the lode-gold deposits, including those with calc-silicate alteration, are part of a crustal continuum of gold mineralization, which Groves et al. (1998) have subsequently termed orogenic lode-gold deposits.

In contrast, Mueller (1988, 1991, 1997) has termed several gold deposits in the Yilgarn Craton skarn deposits based on the occurrence of calc-silicate alteration (but not necessarily related to gold mineralization), and has interpreted the hydrothermal fluids and gold to be derived from a local granitic pluton. He further postulated that these deposits are Archean equivalents of Phanerozoic gold skarns.

There are several significant differences between Phanerozoic gold skarns and Archean hypozonal lode-gold deposits. These include: (1) metamorphic grade of the host rock; most Phanerozoic gold skarns are located in very low-grade metamorphic rocks, whereas Archean hyopzonal deposits are hosted by amphibolite facies rocks and, importantly, are broadly contemporaneous with peak-metamorphism.; (2) depth of emplacement; the characteristic depth of the majority of Phanerozoic skarns is between 2 and 5 km (Einaudi et al., 1981), whereas amphibolite-hosted gold deposits formed at mid-crustal levels between 10 and 15km (Hagemann and Brown, 1996); (3) distance from pluton and lack of endoskarns; most Phanerozoic gold skarns are located either within, or immediately adjacent to, the pluton; in all Archean lode-gold deposits where a skarn model has

been postulated, there is a distinct lack of a pluton in the immediate vicinity of the deposit. Importantly, except for Chalice (Fig. 1) near the Pioneer Dome, 180km south of Kalgoorlie, endoskarn mineralization has nowhere been documented. (4) temperature of host rock: most plutons that are related to skarn mineralization are intruded into "cold" host rocks (mostly unmetamorphosed calcareous sedimentary rocks); in contrast Archean gold mineralization is emplaced contemporaneous with amphibolite facies metamorphism into 400° to 600°C "hot" host rocks. Phanerozoic skarns are everywhere hotter than their host rock, whereas most Archean deposits are slightly retrograde (colder) with respect to their host rocks. (5) salinities; Phanerozoic skarns are characterized by highly saline (>10 eq. wt% NaCl) fluid inclusions; fluid inclusion data on Archean amphibolite-hosted gold deposits are scant, but, where inclusions have been measured, there is generally a lack of high salinity inclusions related to gold mineralization. (6) lack of contemporaneous plutons: for most Phanerozoic gold skarn systems, a contemporaneous proximal plutonic stock is identified; in Archean terrains, most granitoids that border amphibolite-hosted gold deposits are pre- or post-gold mineralization and are distal. (7) minor occurrence of calc-silicate alteration that is unubiquitously related to gold mineralization; as outlined above, many types of calc-silicate alteration are either pre- or post gold mineralization, and, even where calc-silicate alteration is synchronous with gold mineralization, it is normally only a minor host to gold (e.g., Bodycoat, 1999).
Given these geological constraints, gold deposits in amphibolite facies terrains are best classified as hypozonal lode-gold deposits within a crustal continuum of gold mineralization from epizonal to hypozonal crustal levels. However, there are several anomalous deposits hosted in amphibolite facies terrains in the Yilgarn Craton (e.g., Mt Gibson: Yeats and Groves, 1998) that show characteristics that do not conform with those outlined above, and hence are not simply included in this deposit class. In addition, recent research on the Chalice gold deposit (Bucci et al., 1999) has shown that gold occurs within a granite dike (the possible endoskarn) and in adjacent mafic amphibolites (exoskarns), making it the most likely Archean gold-skarn deposit, although many of the differences with Phanerozoic skarns outlined above still hold.

## Exploration Significance and Implications

The quality and applicability of genetic models are best tested by their predicability in mineral exploration. In the case of the proposition of a skarn model for the hypozonal end-member of Archean orogenic gold deposits the key evidence for such a model, the occurrence of calc-silicate alteration, cannot be used successfully as a vector towards gold mineralization, due to its pre-, syn- or post-gold mineralization timing. Nor can a specific granitoid body be identified. The continuum model, however, predicts that source is not the key parameter, but that, critical controls are structure, reactive hosts rocks of suitable rheology, and characteristic distal alteration assemblages. These can all be defined from a combination of geological maps, geophysical data and alteration mapping, and hence have predictive capability.

## Conclusions

Due to the variable timing of calc-silicate alteration, pre-, syn-, and/or post gold mineralization, this alteration type is not necessarily genetically related to gold mineralization in Archean amphibolite-facies gold deposits. Even where there is calc-silicate alteration which is syn-gold mineralization it is commonly only a minor host to gold. Therefore, a genetic link to skarn mineralization is a gross oversimplification. Specifically, many significant geological differences to Phanerozoic skarns, including lack of contemporaneous pluton and associated endoskarn, much greater depth of emplacement, similar temperatures of alteration and host rocks at the time of mineralization, lack of calcareous rocks, and low-salinity ore fluids, argue against a classification of amphibolite-hosted gold deposits as gold skarns. Instead, these deposits are best classified as Archean hypozonal orogenic lode-gold deposits, and viewed as the deep end-member of a crustal continuum of gold mineralization.

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