Orogenic gold deposits

This text is based on the review article of Groves et al. (1998) and on the text of Robert Moritz (University of Geneva, Switzerland), available in internet. Additional references are listed at the end of this chapter.

Definition. Orogenic gold deposits are associated with regionally metamorphosed terranes of all ages. They form at convergent plate margins and are built by gold-bearing quartz veins, often with very simple mineralogy. They are characteristic by a relatively high temperature and pressure of ore deposition (see below) which distinguishes them from a number of other types of gold deposits. Their fluids are also characteristic by increased CO_2 content. In general, however, there is no good single definition of these deposits. A lack of definition and the variability in some of the features of these deposits led in the past to a major confusion in their terminology, see in the next paragraph.

Terminology. Gold deposits discussed here have been called mesothermal gold, metamorphic gold, gold-only, lode gold, shear-zone hosted, structurally-controlled deposits, and also include the variety of greenstone-hosted and turbidite-hosted deposits. The term orogenic gold deposits has been proposed by Groves et al. (1998), since the earlier term mesothermal appears to be misused with respect to the original definition of Lindgren (1933). Why do we have this proliferation of nomenclature? It certainly reflects some confusion within the scientific community. Most certainly the confusion of the terminology does not stem from a lack of studies. Indeed, since around 1980, orogenic gold deposits have been studied in great detail. This research effort is reflected in a large number of scientific papers and reviews (e.g. Foster, 1991; Macdonald, 1986; Keays et al., 1989; Ramsay et al., 1998). The reason about the confusion probably resides in the inherent nature of these gold deposits hosted by metamorphosed and intensely altered rocks, that are generally highly deformed and display a complex geologic evolution.

Tectonic settings. The orogenic gold deposits occupy a consistent spatial and temporal position in their tectonic environment. They formed at convergent plate margins, during deformational processes of the ongoing orogenetic activities. Such activity may have been recorded in an accretionary orogen, that is, at the convergence and collision of an oceanic and a continental plate (Fyfe and Kerrich 1985). An attractive feature of this idea is that the subducting oceanic plate is able to deliver a large volume of fluids into the crustal volume and generate swarms of gold-bearing veins. Underplating of the crust with hydrated rocks would be an important mechanism that operated in such systems.

Another possibility are collisional orogens, where two continental plates collide. Such orogens include the Variscan, Appalachian, and Alpine systems. In fact, it seems that accretionary and collisional orogens represent end-members of a continuum because any continent-continent collision will be preceded by closure of an ocean basin. Also in the case of a continent-continent collision, hydrated marine sediments and volcanic rocks are added to the continental margins and aid in the formation of the gold veins.

Geographic and age distribution. Orogenic gold deposits have formed over more than 3 billion years of Earth's history, episodically during the Middle Archean to younger Precambrian, and continuously throughout the Phanerozoic. The Oligocene veins in the western Alps are the youngest recognized, economic example of these deposits. The oldest examples date back to Archean and are represented by Pilbara craton (Australia) and the Barberton greenstone belt (South Africa). Hence, the age of orogenic deposits varies from 3 Ga to very young.

Because orogenic gold deposits formed over this large time span in regions of orogenic activity, their modern geographic distribution shows little systematics, unless one considers the regional geology of the deposits. Of course, these deposits are constrained to the old to ancient orogens, wherever they evolved during the geological history of the Earth.

There are two particular periods in the history of Earth when no orogenic deposits seems to have formed. More than 50% of the exposed Precambrian crust formed between 1.8 and 0.6 Ga, yet these rocks contain few orogenic gold deposits. This fact is interesting because there is a number of older as well as younger deposits (see Goldfarb et al. 2001). Another gap in the orogenic gold deposit formation is the time between 2.1 and 2.5 Ga. These gaps are explained by the lack of orogenic activity in these times of the evolution of Earth.

Geometry. The structures hosting the gold deposits (shear zones, faults, extensional veins, breccia) are typically discordant with respect to the stratigraphic layering of the host rocks, but in some cases they can be parallel to bedding planes and fold hinges or intrusive contacts. This reflects the epigenetic nature of the gold deposits and the influence of strength anisotropy on their development. The mineralized structures display syn- to post-mineralization displacements, such as striated slip surfaces with hydrothermal slickenlines, and folding and boudinage. This indicates that the gold deposits are syn-tectonic. Veins and structures in the wallrocks typically record reverse-oblique movements along the associated shear zones and faults. A combination of dynamic stress changes and fluid pressure variations is generally invoked to explain the geometry of the vein systems.

In metamorphic greenschist grade settings, hydrothermal alteration assemblages are typically superimposed on the regional metamorphic mineralogy of the host rocks. Therefore, the gold deposits are interpreted as post-peak metamorphic. However, the relationship is more ambiguous in higher metamorphic grade environments where hydrothermal alteration is reported as syn-metamorphic, and in other cases as overprinted by deformation and regional metamorphism.

Mineralogy. Mineralogy of the orogenic gold deposits is usually very or rather simple, although complex mineral assemblages may develop if sulfosalts are present. Veins in the orogenic gold deposits are dominated by quartz with subsidiary carbonate and sulfide minerals, and less abundantly, albite, chlorite, white mica (fuchsite in ultramafic host rocks), tourmaline, and scheelite. Carbonate minerals consist of calcite, dolomite and ankerite. Gold occurs in the veins and in adjacent wallrocks. Gold is usually intimately associated with sulfide minerals, including pyrite, pyrrhotite chalcopyrite, galena, sphalerite, and arsenopyrite. In volcano-plutonic settings, pyrite and pyrrhotite are the most common sulfide minerals in greenschist and amphibolite grade host rocks, respectively, while arsenopyrite is the predominant sulfide mineral in ores hosted by sedimentary rocks. Tellurides can be significant ore minerals in some deposits. Gold to silver ratios typically range between 10:1 and 5:1, less commonly 1:1. Although the vein systems can be continuous for over 1 to 2 km vertical extent, there is generally little change in ore grade, and ore and gangue mineralogy with depth.

Size and grade. Gold grade in these deposits 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 ores. Apart of gold, other elements may be extracted. For example, the Salsigne gold deposits in France was the globally largest arsenic producer at the beginning of 1990's. These deposits may contain elevated concentrations of Bi, Hg, Sb, Te, and W. On the other hand, Cu, Pb, and Zn concentrations are also slightly elevated above the regional background.

The estimated resources for Archean and Phanerozoic orogenic gold deposits usually vary between 0-30 Moz (million ounces) of gold, converting to 0-850 tons of gold. The resources of the largest deposits of this type may reach unbelievable 200 Moz (5700 t) of gold. It is interesting to note that, because of their high grades, these deposits were mined already at the dawn of the civilization. The ancient Egyptians recovered perhaps as much as 100 Moz (2800 t) of gold from the orogenic gold deposits in the Nubian shield.

Hydrothermal alteration. Hydrothermal wallrock alteration in orogenic gold deposits is developed in a zoned pattern with a progression from proximal to distal assemblages. The alteration intensity decreases with distance with respect to the orebodies. Scale, intensity and mineralogy of the alteration is a function of wallrock composition and crustal level. Alteration is most intensely developed in intermediate to ultramafic igneous wallrocks. In clastic sedimentary rocks, alteration is restricted to narrow zones around the orebodies. The main alteration products of the wallrocks include (1) carbonate minerals (calcite, dolomite, ankerite, in some cases siderite and magnesite), (2) sulfide minerals (generally pyrite, pyrrhotite or arsenopyrite), (3) alkali-rich silicate minerals (sericite, fuchsite, albite, and less commonly, K-feldspar, biotite, paragonite), (4) chlorite and (5) quartz. Carbonatization, sulfidation and alkali-metasomatism of the wallrocks reflect the addition of variable amounts of CO_2, S, K, Na, H_2O, and LILE during mineralization. Amphibole, diopside, plagioclase and garnet are recognized at deeper crustal levels under amphibolite and granulite metamorphic grades, where carbonate minerals become less abundant.

Fluids. Fluid inclusion studies have revealed the presence of four main types of fluids in the orogenic gold deposits: (1) two- to three-phase H_2O-CO_2 fluids with variable quantities of CH_4, N_2 and dissolved salts; (2) CO_2-rich inclusions with variable contents of CH_4, N_2 and H_2S and low to undetectable H_2O contents; and (3) low to medium saline two-phase H_2O fluids with or without CO_2.

The presence of CO_2 in the fluids is entirely consistent with the carbonatization of the host rocks of orogenic gold deposits. This CO_2-rich nature distinguishes the fluids associated to the orogenic gold deposits with respect to fluids encountered in other major classes of ore types. This feature is cited as evidence for a deep origin of the ore-forming fluids, like granulitization of the lower crust or progressive fluid release under amphibolite facies conditions.

The fluid groups 2 and 3 described above are typically interpreted as resulting from unmixing of fluid 1. Phase separation is often cited as the trigger of gold deposition. However, unmixing is not systematically associated with gold deposition and other processes such as fluid-rock interaction or fluid cooling have been invoked.

Reported salinities of fluids associated to gold deposition are typically below 10 wt% NaCl equiv. In Alpine and Variscan deposits, halogen systematics based on bulk fluid extraction has been interpreted as reflecting deep circulation of meteoric water during gold ore formation.

The combination of the fluid inclusion and other data suggest a pressure-temperature range of ore formation of 1-3 kbar and 250-350°C. Some shallow deposits may have formed as low as 0.5 kbar and 150°C, and deeper deposits under higher pressures up to 5 kbar and higher temperatures of 700°C.

Environmental impact. The environmental impact of the orogenic gold deposits may be relatively large, especially in those cases when the accompanying dominant sulfide is arsenopyrite (FeAsS). Such deposits are abundant and arsenopyrite is in the vast majority of cases regarded as waste. It may be modified during processing of the ores, for example in hydrometallurgical or pyrometallurgical technologies. This modification may partially or completely release arsenic from arsenopyrite and allow for the escape of this element into the environment. The problem may be compounded where abundant pyrite is available and acid mine drainage develops. A lot of research goes into immobilization of arsenic from these and other types of deposits in the waste piles.

Genetic model. The orogenic gold deposits were in general formed from moderately reduced fluids with a nearly neutral to weakly alkaline pH at all crustal levels. The fluids maintained approximate thermal equilibrium with the rocks through which they circulated, but their chemical composition was progressively modified through fluid-wallrock interaction and/or mineral precipitation during their ascent.

Modelling of metamorphic processes, fluid production and fluid circulation may explain conflicting temporal relationships between gold-bearing quartz veins and peak-metamorphism. In Barrovian-type metamorphic terrains, lower crustal levels experience prograde metamorphism later than shallow crustal levels, with a time difference of up to 50 m.y. Such calculations show that veining in upper crustal levels can be coeval with metamorphism at deeper crustal levels, therefore explaining the post-peak metamorphic setting of orogenic gold deposits, and the relatively long-time gap in certain cases between peak-metamorphism of the immediate host rocks and the gold-bearing quartz veins. Similar calculations for terrains where magmatic underplating or magmatic intrusions are the cause of metamorphism indicate that quartz veining can be both pre- and post-metamorphic.

There is a consensus that the main complex responsible for gold transport in orogenic gold deposits is $Au(HS)_2^-$. $Au(HS)^0$ may become predominant under low pH conditions. Gold-chloride complexes are generally considered to be negligible under the physico-chemical conditions prevailing in orogenic gold deposits.

Because of the difficulties in defining a unique source of gold and the ore-forming fluids, a number of genetic models have been proposed. The main models are: (1) granulitization of the lower crust due to CO_2-enriched fluids from the mantle accompanied by felsic magmatism; (2) magmatic fluids exsolved from tonalite - trondjemite - granodioritic intrusions; (3) fluids produced by metamorphic processes; and (4) deep circulation of meteoric water.

There has been a tendency in the late 1980s and early 1990s to classify gold deposits located within deformation zones under a single category named mesothermal, with the understanding that they were formed by the same process regardless of their age and geographic location. In fact, the orogenic gold deposits formed at a variety of crustal levels, and Groves et al. (1998) proposed different names based on the depth of formation: epizonal for < 6 km, mesozonal for 6-12 km, and hypozonal for > 12 km.

References

Bierlein, F.P., Murphy, F.C., Weinberg, R.F., Lees, T., 2006: Distribution of orogenic gold deposits in relation to fault zones and gravity gradients: Targeting tools applied to the Eastern Goldfields, Yilgarn Craton, Western Australia. *Mineralium Deposita*, doi 10.1007/s00126-005-0044-4.

Foster, R.P., ed. (1991) – Gold metallogeny and exploration. Blackie and Son Ltd, Glasgow and London, 432 p.

Fyfe, W.S., Kerrich, R., 1985: Fluids and thrusting. Chemical Geology 49, 353-362.

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

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

Keays, R.R., Ramsay, W.R.H., Groves, D.I., eds. (1989) – The geology of gold deposits: the perspective in 1988. Econ. Geol. Monograph 6, 667 p.

Lindgren, W. (1933) - Mineral deposits. McGraw-Hill, New York and London, 930 p.

Macdonald, A.J., ed. (1986) – Gold'86 : An international symposium on the geology of gold deposits. Konsult Internat. Inc., Ontario, 517p.

Ramsay, W.R.H., Bierlein, F.P., Arne, D.C., eds. (1998) – Mesothermal gold mineralisation in space and time. *Ore Geol. Rev Special Issue*, **13**, 1-406.