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Research paper

The giant Jiaodong gold province: The key to a unified model for orogenic gold deposits?

David I. Groves [a,b], M. Santosh [b,c,d,*]

[a] Centre for Exploration Targeting, UWA, Crawley 6009, WA, Australia
[b] Centre for Tectonics Resources and Exploration, Department of Earth Sciences, University of Adelaide, SA 5005, Australia
[c] State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Beijing 100083, China
[d] Division of Interdisciplinary Science, Faculty of Science, Kochi University, Kochi 780-8520, Japan

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ABSTRACT

Although the term orogenic gold deposit has been widely accepted for all gold-only lode-gold deposits, with the exception of Carlin-type deposits and rare intrusion-related gold systems, there has been continuing debate on their genesis. Early syngenetic models and hydrothermal models dominated by meteoric fluids are now clearly unacceptable. Magmatic-hydrothermal models fail to explain the genesis of orogenic gold deposits because of the lack of consistent spatially – associated granitic intrusions and inconsistent temporal relationships. The most plausible, and widely accepted, models involve metamorphic fluids, but the source of these fluids is hotly debated. Sources within deeper segments of the supracrustal successions hosting the deposits, the underlying continental crust, and subducted oceanic lithosphere and its overlying sediment wedge all have their proponents. The orogenic gold deposits of the giant Jiaodong gold province of China, in the delaminated North China Craton, contain ca. 120 Ma gold deposits in Precambrian crust that was metamorphosed over 2000 million years prior to gold mineralization. The only realistic source of fluid and gold is a subducted oceanic slab with its overlying sulfide-rich sedimentary package, or the associated mantle wedge. This could be viewed as an exception to a general metamorphic model where orogenic gold has been derived during greenschist- to amphibolite-facies metamorphism of supracrustal rocks: basaltic rocks in the Precambrian and sedimentary rocks in the Phanerozoic. Alternatively, if a holistic view is taken, Jiaodong can be considered the key orogenic gold province for a unified model in which gold is derived from late-orogenic metamorphic devolatilization of stalled subduction slabs and oceanic sediments throughout Earth history. The latter model satisfies all geological, geochronological, isotopic and geochemical constraints but the precise mechanisms of auriferous fluid release, like many other subduction-related processes, are model-driven and remain uncertain.

1. Introduction

Groves et al. (1998), following Gebre-Mariam et al. (1995), defined the term orogenic gold deposit to obviate the necessity to refer to a wide variety of terms for a coherent group of commonly vertically-extensive, gold-only deposits that formed in broad thermal equilibrium with their wallrocks from low-salinity H_2O-CO_2 ore fluids at depths from 2 to 15 km, and arguably 20 km in the crust (Groves, 1993; Kolb et al., 2015). This term has been widely accepted (e.g., Goldfarb et al., 2001, 2005, 2014; Bierlein et al., 2006), although there is still some discussion on terminology (e.g., Phillips and Powell, 2015), and a heated debate on the genesis of orogenic gold deposits is ongoing. Goldfarb and Groves (2015) provided an exhaustive review of these genetic models and the various geological, geochemical, isotopic and fluid-inclusion constraints on these models. This review is used, comprehensively, to briefly summarize these models with a view to provide a holistic, coherent and unified model for orogenic gold deposits of all ages, in a similar way to development of coherent minerals-system models for other mineral deposit groups. The deposits of the giant Jiaodong

* Corresponding author.
E-mail addresses: msantosh.gr@gmail.com, santosh@cugb.edu.cn (M. Santosh).
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orogenic gold provinces are emphasized as the key to development of the all-embracing model for ore fluid and metal source.

It is recognized that (reduced) intrusion-related gold systems or (R)IRGDs (e.g., Thompson et al., 1999; Lang et al., 2000; Baker, 2002) formed from a similar ore fluid to the orogenic gold deposits, but that they differ in that the ore systems are zoned around causative intrusions due to thermal disequilibrium with the wall rocks (e.g., Hart et al., 2002). They are, however, a rare group of largely uneconomic deposits (e.g., Goldfarb et al., 2005; Goldfarb and Groves, 2015), and are not discussed further here. Furthermore, although the Carlin gold deposits also formed from low-salinity H_2O-CO_2 fluids (e.g., Cline et al., 2005), they are quite distinctive from orogenic gold deposits in a number of features (Goldfarb and Groves, 2015; Groves et al., 2016), and are not discussed below.

2. Potential fluid and metal sources for orogenic gold deposits

Kerrich (1983) was arguably the first to assess the various models for what are now termed orogenic gold deposits, listing syngenetic-exhalative, magmatic-hydrothermal (tonalite-, lamprophyre- or oxidised magma-associated), and metamorphic (regional metamorphic devolatilization, lateral secretion, mantle/granulitization) models as the major suggested genetic concepts for fluid and metal generation. A meteoric fluid model was added by Nesbitt (1991). All of these models are shown schematically in Fig. 1.

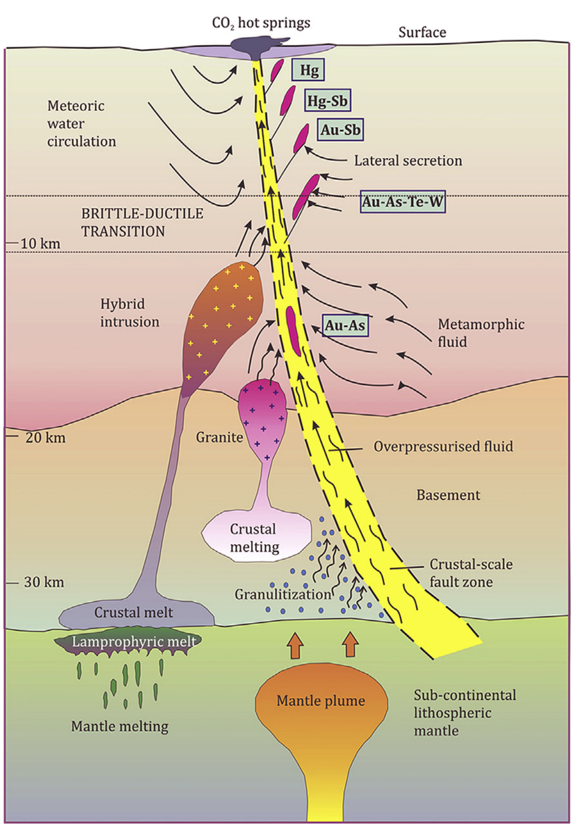

Figure 1. Schematic representation of the variety of previously proposed (mostly non-viable) models for gold and fluid sources in the crust: from meteoric water circulation and lateral secretion, magmatic-hydrothermal fluid exsolution from various granite types, to granulitization and metamorphic devolatilization processes. Syngenetic-exhalative model is not shown, but could be represented by the hot springs at surface in the figure. Figures from Groves et al. (1998) and Goldfarb et al. (2005) used as a base for this figure.

Goldfarb and Groves (2015) discussed each of these models in detail with exhaustive references to individual examples in places. The following brief discussion of the less-viable models is adapted from Goldfarb and Groves (2015), and then followed by a more thorough discussion of the more-viable, more generally-accepted models.

Early syngenetic-exhalative models (e.g., Hutchinson and Burlington, 1984; Hutchinson, 1987) were shown to be inconsistent with field evidence that demonstrated the deposits were structurally-controlled, syn- to late-metamorphic deposits with stratiform BIF-hosted deposits formed by sulfidation of magnetite (e.g., Phillips et al., 1984). Similarly, meteoric fluid models have been shown to be based on invalid calculations and interpretations of stable isotope data largely derived from fluid inclusions, as summarized by Goldfarb and Groves (2015).

Various magmatic-hydrothermal models were in vogue for a variety of mineral deposits from about 1900 to 1960, and have been proposed for orogenic gold deposits over the past 40 years or so by a number of authors, most recently including Mueller (1992), Walshe et al. (2003), Wall et al. (2004), Hall and Wall (2007), Neumayr et al. (2007), Bath et al. (2013) and Helt et al. (2014). Goldfarb and Groves (2015, and references therein) discussed these models at length for a number of specific examples and rejected the magmatic-hydrothermal concept as a viable unifying model for orogenic gold deposits. In general, granitic intrusions may be pre-, syn- or post-gold in the same terranes (e.g., Hughes et al., 1997; Goldfarb et al., 2008), or even absent in some, for example in the Otago gold province of New Zealand. In most cases where robust geochronological studies have been conducted, the gold deposits and proposed fertile granitic intrusions are not the same age (e.g., Goldfarb et al., 2005; Goldfarb and Groves, 2015; and references therein; Vielreicher et al., 2015). Furthermore, the proposed parent granitic rocks have no consistent composition or oxidation state within or between terranes. In some cases, lamprophyres and other more mafic intrusions are close in age to the gold deposits (e.g., Vielreicher et al., 2010), but are volumetrically minor and could not have provided the large volumes of fluids required to form the gold deposits. Although stable isotope data are broadly permissive of a magmatic-hydrothermal fluid, they, combined with the occurrence of some deposits that formed at over 15 km depth and conflicting radiogenic isotope ratios, are indicative of long fluid pathways (e.g., Kontak and Kerrich, 1995; Ridley and Diamond, 2000) that effectively exclude exsolution of ore fluids from granitic intrusions at any reasonable crustal depth. Redox changes, commonly invoked in fluid mixing models (e.g., Walshe et al., 2003; Neumayr et al., 2007) can occur via rock reaction (e.g., Evans et al., 2006) or even during episodic fault rupturing along fluid channelways (e.g., Yamaguchi et al., 2011). It can be concluded that magmatic-hydrothermal processes cannot explain the genesis of individual deposits let alone provide a universal model for orogenic gold formation. Hybrid magmatism with a mixed metasomatized sub-continental lithospheric mantle (SCLM) and crustal source is interpreted to provide the source of fluid and metals for other gold and gold-copper deposit types (e.g., Groves et al., 2010; Mair et al., 2011; Hronsky et al., 2012; Griffin et al., 2013), but cannot have been responsible for formation of economic orogenic gold deposits on the basis of age considerations, lack of volumetrically significant intrusions from this source, and lack of underlying SCLM in some cases (e.g., Goldfarb and Groves, 2015; Groves and Santosh, 2015). Similarly, models involving devolatilization related to emplacement of mantle plumes into the lower crust (e.g., Bierlein and Pisarevsky, 2008; de Boorder, 2012; Webber et al., 2013) lack credible supporting evidence.

This effectively leaves metamorphic models as the only viable possibilities if a universal or near-universal model is sought for the