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Research paper

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

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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

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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.

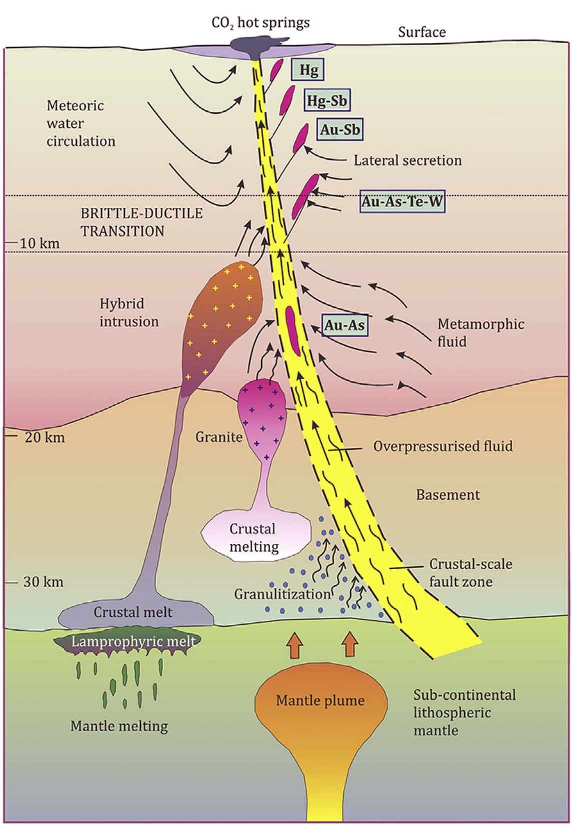

Figure 1. Schematic representation of the variety of previously proposed (mostly non-viable) models for gold and fluid sources in the crust: from meteoric water circulation and lateral secretion, magmatic-hydrothermal fluid exsolution from various granite types, to granulitization and metamorphic devolatilization 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 genesis of orogenic gold deposits. Lateral secretion models (e.g., Boyle, 1979; Saager et al., 1982) are almost certainly invalid due to the limited volume of metamorphic fluid and metals available to produce high-tonnage or high-grade gold deposits (e.g., Glasson and Keays, 1978) even if lateral flow was dominant, which appears unlikely (e.g., Ord and Oliver, 1997). Similarly, a model in which mantle CO_2 was advected through the lower crust to produce granulites and a CO_2-rich pseudo-metamorphic fluid (e.g., Fyon et al., 1984; Cameron, 1988; Santosh and Omori, 1988; Touret and Huizenga, 2012; Fu and Touret, 2014) are not supported by associations between granulites and gold nor by CO_2 contents of fluid inclusions, available carbon isotope data, or theoretical considerations, as originally discussed by Kerrich (1989).

Such considerations have led to general acceptance of a metamorphic model for orogenic gold that promotes metamorphic devolatilization of supracrustal/intrabasinal rocks under greenschist- to amphibolite-facies conditions, with upwards advection of resultant metamorphic fluid and released metals to the site of formation of orogenic gold mineralization at higher crustal levels (e.g., Kerrich and Fyfe, 1981; Phillips and Groves, 1983; Colvine et al., 1984; Goldfarb et al., 1986, 1988; Groves et al., 1987; Cox et al., 1991; Powell et al., 1991; Bierlein and Crowe, 2000; Goldfarb et al., 2001, 2005; Phillips and Powell, 2010; Tomkins, 2010; among many others). This model and its potential limitations are outlined below, as synthesised from the references above and the exhaustive review of Goldfarb and Groves (2015).

3. Supracrustal metamorphic model: strengths and weaknesses

The supracrustal or intrabasinal metamorphic model for orogenic gold deposits is the only one of those discussed above that has the potential to provide a universal model to explain the extraordinary longevity of the deposit type throughout Earth history (Goldfarb et al., 2001). Its strengths are that it requires no specific associations with host rock types, as most lithologies are mineralized in gold provinces globally, nor any association with any specific type of intrusion. It is also consistent with the broadly late-metamorphic and late-deformational timing of gold deposition, and the stable and radiogenic isotope data that are internally ambiguous but collectively suggest long and complex fluid pathways that intersected a variety of rock types (Ridley and Diamond, 2000). The typical low-salinity H_2O-CO_2 ($\pm$ CH_4, N_2) fluid is also that expected from metamorphic devolatilization of supracrustal rocks.

Proponents of the model suggest that auriferous aqueous-carbonic fluids (Phillips and Powell, 2010) are released during greenschist- to amphibolite-facies metamorphism of supracrustal rocks in the mid crust (e.g., Powell et al., 1991). Calculations indicate that up to 5 vol.% of both pelitic and mafic volcanic rocks can be converted to such fluid (e.g., Fyfe et al., 1978; Elmer et al., 2006), providing an adequate fluid flux for even giant deposits (e.g., Phillips and Powell, 2010). Such fluids are envisaged to have had migrated to regional fault systems, with which all major deposits are spatially associated, and moved upwards at supralithostatic pressures to deposit gold plus related elements and silica during pressure fluctuations related to seismic events along the fault networks (e.g., Cox et al., 1991). Although such deposition appears to have preferentially occurred in rheologically favourable rocks close to the ductile-brittle transition, deposits formed over a total crustal range from 3 to 15 km and possibly deeper (e.g., Groves, 1993). Both sulfidation reactions and phase separation were involved in gold deposition from a normally reduced, near-neutral fluid carrying gold as a thiosulfide complex. From a tectonic viewpoint, orogenic gold deposits may occur in terranes where metamorphism was caused by a variety of crustal- to mantle-related processes (Goldfarb et al., 1998). However, gold deposition was broadly coincident with a change in far field stress with resultant transition in deformation from compression to transpression, more rarely transtension, during accretion (e.g., Goldfarb et al., 1988) with concomitant uplift and lowering of lithostatic pressure (e.g., Groves et al., 1987; White et al., 2015).

In a supracrustal metamorphic model, the source rocks for fluid and metals must have changed with time, as discussed in detail by Goldfarb and Groves (2015). In the Phanerozoic, host basins are dominated by sedimentary rocks, commonly turbidite sequences, which host the gold deposits. Mafic volcanic rocks are present in some gold provinces but are not ubiquitous. Hence, metamorphism of a sedimentary source rock is most likely to have produced the ore fluid in the metamorphic model. In contrast, most Precambrian terranes that host orogenic gold deposits, particularly those of Archean age, are dominated by ultramafic to felsic volcanic rock sequences below the crustal level of gold deposition, with ubiquitous mafic rocks the most likely source of auriferous fluid in this model. Specific gold-enriched source rocks have been suggested for both Phanerozoic and Precambrian gold provinces (e.g., Glasson and Keays, 1978; Tomkins, 2010; Large et al., 2011; Steadman et al., 2013), but these are not common to all orogenic gold provinces, are commonly volumetrically insignificant, and cannot be an important factor in any holistic metamorphic model for orogenic gold.

Despite the obvious strengths of the supracrustal metamorphic model, there are some weaknesses, particularly for the Precambrian deposits. These are discussed below, first for Phanerozoic deposits and then for Precambrian examples.

The Phanerozoic deposits fit the model well in that all significant deposits are in greenschist-facies domains (Goldfarb et al., 2005), and research by Pitcairn et al. (2006) on the Otago Schists of New Zealand shows that it is feasible to release significant Au, As, Bi, Sb, Te and W during greenschist- to amphibolite-facies metamorphism of thick turbidite sequences. However, it is still not clear how such fluids can migrate laterally on a kilometre scale into the regional-scale faults that control gold mineralization at the first-order structural scale. Authors such as Ferry (1994) showed that such lateral flow is possible, particularly if induced by external tectonic perturbations such as drainage caused by dilatant fault zones (e.g., Sibson, 1992), but most authors such as Ord and Oliver (1997) suggested that vertical advection would be dominant. Hence there may be a mass balance problem in terms of the amount of gold transported via lateral flow. Furthermore, Ridley (1993) suggested that the high fluid pressure in the regional-scale faults promotes outward flow down pressure gradients into subsidiary faults that host the gold ores. Hence, the mechanism that could promote fluid flow from the metamorphic belt into the regional-scale faults at depth and then back into the rock sequences at higher crustal levels is unclear. The fact that gold mineralization normally postdates regional metamorphism in host sequences, that is it is retrogressive (e.g., Wilson et al., 2013), in some instances by several million years (e.g., Perring et al., 1987; Nesbitt, 1991), is another potential problem for both Phanerozoic and Precambrian deposits. This problem is generally overcome by models that suggest that peak metamorphism is attained earlier at deeper crustal levels than at the crustal level of gold deposition (deeper-later model of Stuwe, 1998). However, this does not completely explain why early greenschist-facies metamorphism involves grain-boundary fluid migration with pervasive metamorphic fabrics and assemblages and ubiquitous, totally barren, quartz veins in contrast to the focussed fluid flux that can produce high-grade gold shoots later in the metamorphic history. A possible solution is provided by Goldfarb et al. (1988) who suggested that a change in far-field stress from compression to transpression might have unlocked metamorphic fluid reservoirs stored in the mid to upper crust as the overlying greenschist-facies domains with their deformational fabrics cooled. This does not completely explain why the fluid was suddenly capable of depositing large quantities of gold when there is no recorded evidence that the earlier fluid was gold-bearing from studies of ubiquitous metamorphic rocks.

As noted above, the metamorphic model for Precambrian deposits has similar problems to its Phanerozoic equivalents. In addition, it is not so clear that ore components can be derived from greenschist- to amphibolite-facies metamorphism of mafic volcanic rocks as it is from turbidites. For example, Pitcairn et al. (2015) demonstrated that, although gold can be liberated in similar concentrations from basalt, in the examples studied from New Zealand, arsenic, the most common associated element in Precambrian orogenic gold deposits, is not liberated during amphibolite-facies metamorphism. A potentially insurmountable problem for the supracrustal model is the occurrence of a significant number of deposits, including the giant Hutti and Kolar deposits in India (e.g., Sarma et al., 2011), in mid- to upper-amphibolite facies domains that have alteration assemblages that formed under similar P-T conditions to the metamorphosed host rocks (Colvine et al., 1988; Groves, 1993; Knight et al., 1993; McCuaig et al., 1993; Neumayr et al., 1993; Bloem et al., 1994; Miller and Adams, 2013). Several proponents of the metamorphic model have argued that these deposits formed under lower P-T conditions and were subsequently metamorphosed under amphibolite-facies conditions (e.g., Tomkins and Mavrogenes, 2002; Tomkins et al., 2004; Tomkins and Grundy, 2009; Phillips and Powell, 2009). However, recent research by Kolb et al. (2015) has demonstrated that a number of these deposits clearly formed under broadly amphibolite-facies conditions, except where they were overprinted during a later, unrelated orogenic event. Hence, the fluid source must have been deeper than the 15 km (possibly up to 20 km) depth of deepest deposit formation. Additional evidence for a deep source, below the supracrustal sequences hosting the gold deposits, is provided by lead isotope evidence from the Neoarchean gold province of Western Australia. Importantly, Neoarchean greenstone belts can give more-meaningful source area data than for Phanerozoic terranes because much of the lead in the ores may be dominated by the relatively low concentration of lead that is being carried in the ore fluids (e.g., Goldfarb et al., 2005). Browning et al. (1987) and McNaughton et al. (1993), among others, showed that the lead isotope ratios from the giant Eastern Goldfields Province of the Yilgarn Craton reflect the age and composition of the basement rocks to the supracrustal greenstone belts, implicating a deeper source for the auriferous ore fluids. In confirmation that this is not an isolated instance, orogenic gold deposits throughout the Paleozoic of Ireland (Standish et al., 2014) are characterized by highly variable lead signatures, reflecting many different lithologies, including the basement.

In summary, although the supracrustal metamorphic model satisfies the majority of constraints from geological, geochronological, geochemical, isotopic and fluid inclusion data, there are a number of weaknesses in terms of a unified model. The Precambrian examples provide the greatest problems, with evidence that ore fluids were derived from below 15 km depth and carry components that must have been derived from the basement to the gold-hosting greenstone belts. Furthermore, there is doubt that all metal components can be derived from greenschist- to amphibolite-facies metamorphism of a basaltic rock, the only volumetrically viable source in the greenstone belts, in contrast to evidence suggesting that such components can be derived from sedimentary sources. There is also the problem of definition of the precise mechanism by which ore fluid migrated laterally on a kilometre scale into the regional-scale faults that clearly control the location of gold districts and provinces. Finally, the model does not adequately explain the conjunction of apparent late- to post-metamorphic timing in host sequences precisely at the time that a change in far-field stresses promoted a change from compression, represented by the metamorphic fabrics in the host rocks, to transpression or transtension, demonstrated by the geometry of the orogenic gold ore bodies.

The ore fluid is clearly a metamorphic fluid but the evidence above suggests a source below the supracrustal sequences that host the gold deposits. As argued above, this cannot be the lower crust, nor the metasomatized lithosphere, nor a mantle plume and associated granulitization. Similarly, the ore fluid is unlikely to be exactly the same fluid that caused regional metamorphism of supracrustal rocks and related quartz veins with no evidence of any gold enrichment. This specific metamorphic ore fluid appears to have been liberated at a unique time in the orogenic cycle during a change in far-field stress. As orogenic gold deposits are inevitably formed in accretionary or, less commonly, collisional tectonic environments related to subduction (Goldfarb et al., 2001, 2005), and not in other types of metamorphic belts, this suggests a fundamental relationship to a change in plate motion.

In seeking an explanation and a unified model, it is important to view those deposits that cannot have formed from a metamorphic fluid derived from within the host supracrustal sequences because they had been metamorphosed to at least the amphibolites-facies hundreds to thousands of million years previously. Such Tertiary deposits occur along the Megashear Zone in the Proterozoic–Phanerozoic terranes of northern Mexico (Iriondo, 2001; Goldfarb et al., 2007) and Cretaceous deposits occur in the Archean–Proterozoic terranes of the North China block. The giant Jiaodong gold province of the latter (e.g., Wang et al., 1998; Goldfarb et al., 2007; Goldfarb and Santosh, 2014; Yang et al., 2014) is discussed below in an attempt to solve the problems discussed above and seek to develop a unified model that can explain the origin of all orogenic gold deposits of all ages.

4. The giant Jiaodong gold province: the exception or the key to a unified model

The giant Jiaodong gold province in the eastern half of the North China block (Li et al., 2015a; Song et al., 2015; Yang and Santosh, 2015; Yang et al., 2016a) represents a region of major lithospheric erosion of originally thick buoyant Archean sub-continental lithospheric mantle or SCLM (Griffin et al., 1998; Santosh, 2010), caused by anomalously complex Mesozoic slab subduction from the north, south, and east. This led to slab devolatilization, subsequent melting, and voluminous granitic magmatism (Windley et al., 2010). The associated Yanshanian orogeny, that occurred within the decratonized North China block, was typified by basement uplift, regional extension, ca. 165–90 Ma granite intrusion, and ca. 130–120 Ma gold formation within the eastern margins of this highly modified cratonic basement (Goldfarb and Santosh, 2014; Yang and Santosh, 2015). The structural control and more protracted period of gold mineralization argue against a magmatic-hydrothermal fluid model, and the Precambrian high-grade metamorphism of the basement rocks clearly invalidates a supracrustal metamorphic-devolatilization fluid model for the gold event. Despite this, the widespread gold episode correlates with changing far-field stresses and plate reorganizations as interpreted for other orogenic gold provinces.

For these reasons, the Jiaodong deposits have generally been classified as orogenic gold deposits (Wang et al., 1998; Goldfarb et al., 2001, 2005; Yang et al., 2016a). Although they are commonly hosted by older granites, they show no close spatial relationship to granitic intrusions of the same age, nor evidence of metal zonation related to thermal gradients around hot intrusions. However, they do show a clear structural control along regional faults, and ore and wallrock-alteration mineralogy, fluid inclusion compositions and stable isotope chemistry are similar to more typical orogenic gold deposits, particularly of epizonal type (Yang et al., 2016b).

As noted above, however, in contrast to the normal situation where orogenic gold deposits formed within 50–200 my of the deposition of their host supracrustal sequence (Goldfarb et al., 2001), the Jiaodong deposits formed at ca. 126–120 Ma, some 2 Ga after the oldest host rocks in the North China block were deposited and experienced high P-T metamorphism (Yang et al., 2014; see review in Goldfarb and Santosh (2014)). Importantly, prograde metamorphism of supracrustal host rocks cannot have provided auriferous fluids and a sub-crustal source must have provided the fluid and metals that are interpreted to have advected up the Tan Lu and other crustal-scale fault systems (Fig. 2) in the province (Goldfarb et al., 2007). Deep crustal-basement sources are highly unlikely, as discussed more generally above, implicating a sub-crustal source. Although the metasomatized SCLM may be gold-enriched (e.g., Griffin et al., 2013) and may be the source of magmas and fluids for some gold and gold-copper deposits (e.g., Hronsky et al., 2012), this magmatic-hydrothermal model can effectively be ruled out for orogenic gold formation generally (Groves and Santosh, 2015), as discussed above. However, direct devolatilization of an overlying frozen mantle wedge cannot be completely ruled out as a fluid source under specific conditions (e.g., Wyman et al., 2008).

This leaves the subducted oceanic crust and overlying sediment wedge as the most viable fluid and metal source. Goldfarb and Santosh (2014) and Goldfarb and Groves (2015) evaluated how these could have provided the source of the Jiaodong ore fluids, with Fig. 3 adapted from their model. Basically, devolatilization of a subducted slab can result in extensive upward fluid-flux along slab-mantle boundaries (e.g., Sibson, 2004; Peacock et al., 2011) into fore-arc or accreting terrane margins. Such metamorphic fluid release occurs when the base of the fore-arc mantle wedge becomes fully hydrated (Katayama et al., 2012). At this stage, the oceanic slab will devolatilize, together with its overlying pyrite-bearing oceanic sediment wedge. The latter is important as most proponents of specific source rocks for formation of orogenic gold

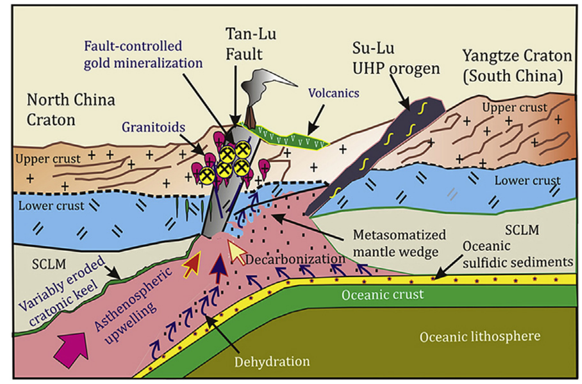

Figure 3. Schematic illustration of the slab devolatilization model for the formation of orogenic gold deposits of the giant Jiaodong gold province as described in the text. Adapted from Goldfarb and Santosh (2014) and Goldfarb and Groves (2015).

deposits stress the importance of gold-enriched pyrite in sediments or sedimentary rocks, as gold and related elements can be released to the fluid via breakdown of pyrite to pyrrhotite (e.g., Large et al., 2009, 2011; Steadman et al., 2013). The highly sheared serpentinized layer at the bottom of the corner of the mantle wedge may provide a particularly permeable zone for slab dewatering at slab depths of less than 100 km and temperatures of 650 °C (Kawano et al., 2011). Over-pressured fluids (e.g., Sibson, 2013) could then migrate up-dip, channelling into crustal-scale fault zones at higher crustal levels to eventually deposit orogenic gold deposits at even shallower levels in lower-order structures (e.g., Breeding and Ague, 2002; Hyndaman et al., 2015).

Goldfarb and Santosh (2014) applied this model to the giant Jiaodong orogenic gold province, suggesting that the Tan Lu fault system carried the auriferous fluid derived from slab devolatilization up to higher crustal levels to deposit gold in the numerous deposits in the province. An important factor in such a model is the trigger to cause fluid release in the slab and sediment wedge. As discussed by Seno and Kirby (2014), such a trigger might be the end of subduction or stalling of the slab during subduction, which could

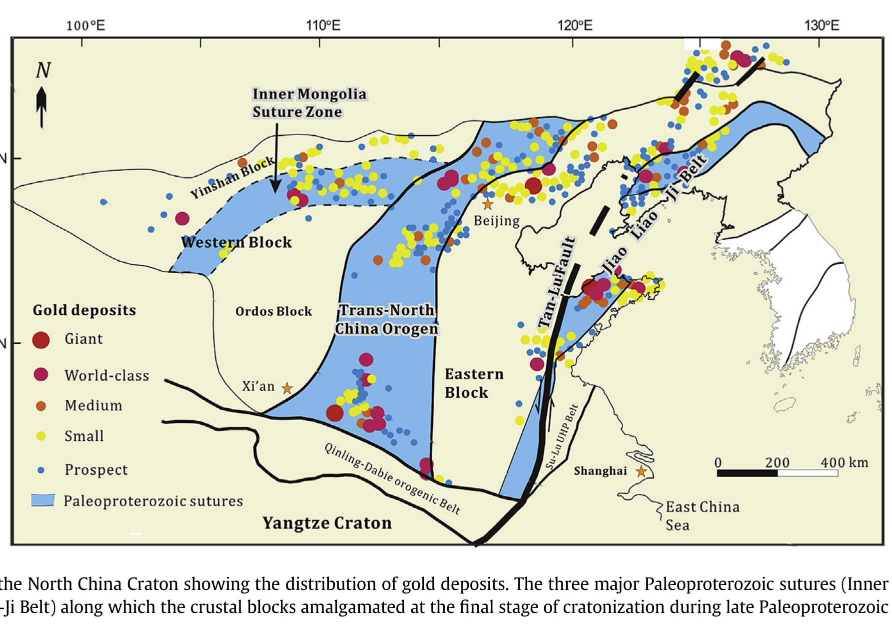

Figure 2. Tectonic framework of the North China Craton showing the distribution of gold deposits. The three major Paleoproterozoic sutures (Inner Mongolia Suture Zone, Trans-North China Orogen and Jiao-Liao-Ji Belt) along which the crustal blocks amalgamated at the final stage of cratonization during late Paleoproterozoic are also shown. Adapted from Groves and Santosh (2014).

result in a change of stress regime as plates were reorganised with subsequent switchover from compression to transpression. Wyman et al. (2008) and Wyman and Kerrich (2010) further suggested that such a devolatilization process would be favoured by flat subduction and could have extended back to the Archean.

That such fluids can be transported from the mantle to crustal levels in crustal-scale fault zones is shown by radiogenic isotope, halogen and noble gas data of the San Andreas fault system (Kennedy and van Soest, 2007; Pili et al., 2011) and the Karakorum fault zone (Klemperer et al., 2013).

Although it must be stressed that the slab devolatilization model is only a hypothetical one, because all radiogenic and stable isotope ratios and other geochemical data are equivocal for any model for the genesis of orogenic gold deposits, it is the only pragmatic model that can satisfy the available geological and geochronological constraints for Jiaodong.

Goldfarb and Groves (2015) went further in suggesting that the slab-source model is the only reasonable genetic model for the gold deposits in the potentially giant Qinling gold province on the southern margin of the North China block (e.g., Chen et al., 2008), the region marking the closure of the northernmost paleo-Tethys sea and the tectonic suturing of the Yangtze and North China Cratons (Li et al., 2015b). Goldfarb et al. (2007) also noted that the Tertiary gold deposits in northwestern Mexico and southernmost Arizona are hosted in reactivated high-grade Proterozoic basement in extensional structures within metamorphic core complexes in a similar scenario to the deposits in the North China block.

The question then remains whether the giant Jiaodong gold province, and the others with similar features mentioned above, are highly anomalous members of the orogenic gold clan or are the key to understanding all orogenic gold deposits in terranes of all ages. Certainly, the Goldfarb and Santosh (2014) Jiaodong model can explain the ubiquitous worldwide relationship to subduction and generation of new crust, the late-metamorphic timing of orogenic gold mineralization, and the temporal coincidence of auriferous fluid release and transition from compression to transpression if a stalled slab resulted in a change in far-field stress. It can also explain the occurrence of Precambrian deposits at crustal depths below those inferred for the supracrustal metamorphic model and the lead isotope evidence that fluids interacted with basement. It also obviates the somewhat problematic issue of extensive lateral fluid flow, as the crustal-scale faults extend to the Moho and slab-related metamorphic fluids could be channelled directly into them with subsequent upward flow. It also elegantly explains the conflicting isotopic and halogen and rare gas evidence for upper to lower crustal and mantle components. Finally, it overcomes the problem of implication of different source rocks with time as the most favoured source rocks, gold-enriched pyrite-rich marine sediments, would have been available in sediment wedges above down-going slabs throughout Earth history. Metamorphic heating would have consistently transformed pyrite to pyrrhotite, releasing gold and related elements such as Ag, As, Bi, Sb, Te and W into a sulfur-bearing ore fluid. The higher CO_2 content of the Archean ore fluids could also be explained by a greater degree of carbonation in Archean oceanic rocks due to a combination of more-susceptible high-MgO basalts and lack of CO_2 sinks. Santosh and Omori (2008) and Santosh et al. (2009) evaluated the history of CO_2 circulation through time and proposed schematic models for the Archean and post-Archean scenarios which can further enhance a model for greater degrees of carbonation of gold and fluid source rocks in the Archean (Fig. 4). The Mid Oceanic Ridge basalt, carbonated at spreading axes and during lateral transport associated with seafloor spreading, is eventually decarbonated during subduction at convergent plate boundaries. They speculated that the incorporation of carbonate into the subcontinental lithosphere by subduction was probably initiated by at least 4 Ga. Oceanic carbonates infiltrate into the deep mantle domains during subduction, with carbonated mantle underlying ancient (>2.0 Ga old) continents. The fluids released from these domains would have advected up the crustal-scale faults under steady-state creep and then migrated episodically along pressure and permeability gradients during earthquake activity into lower-order structures and/or hydraulically-fractured rock bodies above the ductile-brittle transition (e.g., Cox et al., 2001).

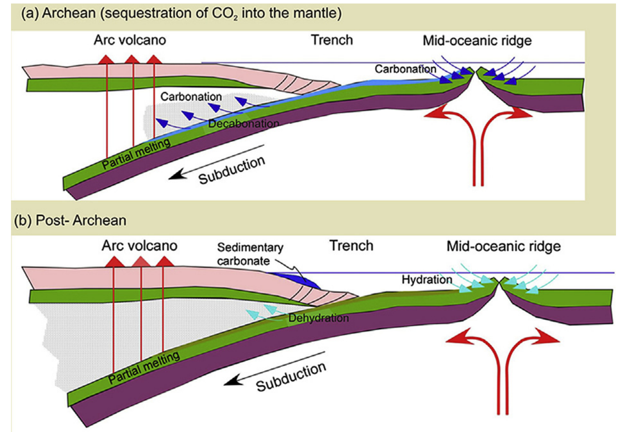

Figure 4. Schematic illustrations showing CO_2 circulation through time for Archean and post-Archean scenarios (after Santosh and Omori, 2008; Santosh et al., 2009).

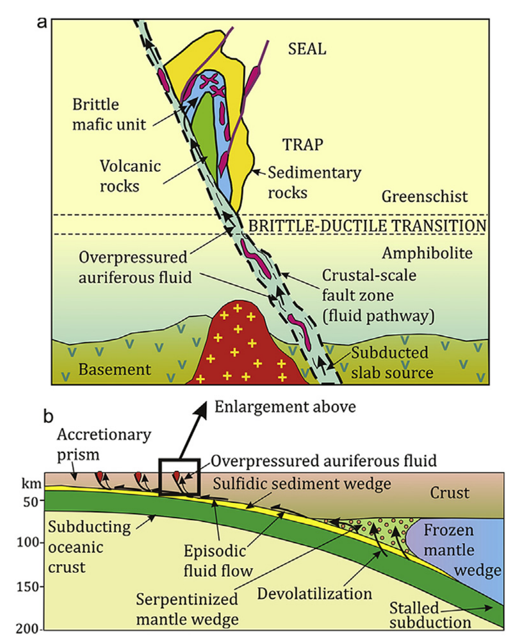

Figure 5. Schematic representation of a permissive scenario for all orogenic gold deposits, including those in high-grade metamorphic rocks, involving a subcrustal fluid and metal source from slab devolatilization. (a) Where these overpressured slab-derived fluids intersect deep-crustal faults, they advect upwards to form orogenic gold deposits in second-order structures or hydraulically-fractured rock bodies: based on Archean lithostratigraphic controls on ore bodies. (b) Fluids released during devolatilization of the subducting slab and associated sulfidic sediments at temperatures below 650 °C and depths of 100 km may either fertilize the overlying mantle wedge or, particularly once the wedge is fully hydrated, travel up-dip along the interface between the slab and the overlying serpentinized wedge or base of the lithosphere. Figure adapted from Goldfarb and Groves (2015). Detailed models are presented in Wyman et al. (2008).

Thus, the slab devolatilization model, shown schematically in Fig. 5, can potentially explain the conjunction of parameters that consistently characterize the orogenic gold deposit clan. Like all models, they suffer for a lack of complete understanding of the precise processes operating at depth in the system, and in this specific case, the lack of knowledge of subduction zone geometry at the time of gold mineralization and whether analogies to fluid migration into modern fore-arcs can be made to accreted terranes containing back-arc components at the time of slab devolatilization. However, the model is considered here to be the most consistent if the fundamental concept of a unified model for orogenic gold systems, such as those for other coherent mineral deposit groups, is valid.

5. Concluding statement

There are no modern examples of orogenic gold deposits, with the youngest well-documented, but uneconomic, orogenic gold mineralization forming about 12–15 Ma ago in the European Alps, and the most recent significant orogenic gold deposit forming about 50 Ma ago (Goldfarb et al., 2001). They also form over a crustal depth range unparalleled by any other gold deposit group with the possible exception of iron-oxide copper-gold deposits (e.g., Groves et al., 2010), in very complex tectonic environments where various mantle and crustal processes could be involved in crustal heating and fluid release. Therefore, it is to be expected that their origin is controversial and that research tools such as fluid inclusions, stable and radiometric isotope ratios and other geochemical methodologies should prove equivocal. Such genetic controversy has existed for a century or so for gold-only lode-gold deposits, and continues today despite their recognition as a coherent orogenic gold deposit group by Groves et al. (1998).

If the deposit group has a coherent set of critical features, like all other deposit groups, it should share a specific origin and relate to a unified minerals-system model. Based on consistent relationships and geochronological constraints, two variants of a metamorphic model are the only possibilities of providing such a unified model: (1) a model involving devolatilization of deeper supracrustal sequences underlying the host rocks to the deposits, and (2) a model involving devolatilization of a subducted slab and overlying sediment wedge.

The supracrustal metamorphic model requires that source rocks varied from mafic volcanic rocks to sedimentary rocks from the Precambrian to Phanerozoic, that auriferous metamorphic fluid derived at greenschist- to amphibolite-facies P-T conditions was expelled to higher crustal levels and resulted in mineralization in rocks that were already metamorphosed in the same event, and that significant lateral flow of such fluid towards crustal-scale faults was possible. In such a model, the Precambrian gold deposits deposited under amphibolite-facies conditions and the young deposits formed in much older, previously metamorphosed host rocks, such as in the giant Jiaodong gold province, have to be considered anomalous exceptions to the model. It is thus not a unified model for all orogenic gold deposits of all ages.

In contrast, the slab devolatilization hypothesis, developed for the giant Jiaodong gold province, has the potential to be a unified model (Fig. 5) that can incorporate all orogenic gold deposits including the high-PT Precambrian deposits. It can explain why there is a consistent connection between post-peak metamorphic auriferous-fluid advection and change in tectonic regime due to stalling of a subducted slab, how over-pressured fluid can migrate directly upwards into crustal-scale fault zones and then down hydraulic gradients into gold depositional sites at the ductile-brittle transition, and involves a common fluid source, the slab and overlying pyritic sediment wedge, throughout geological history. It is truly a holistic model, whose only uncertainty, shared with all models, is the precise processes operating at depth: in this case exactly how fluid is channelled along the slab-mantle boundary and how this fluid can migrate ocean-wards to the accreted terranes that typically host these orogenic gold deposits.

In conclusion, it is believed that the slab devolatilization model is the model that explains most of the tectonic- to deposit-scale features of orogenic gold deposits throughout Earth history and requires less special pleading of specific explanations for individual anomalous and controversial examples. In this view, the giant Jiaodong gold province is the key to unlocking a unified minerals-system model, not the exception to a supracrustal metamorphic model.

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