On the source of orogenic gold

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Gold has historically been a key strategic commodity, and the study of gold deposit formation has long been investigated. Debate on the genesis of so-called "orogenic gold deposits" (>75% of gold recovered through history; Phillips, 2013), continues largely because it is difficult to reliably identify the source of gold. In this issue of *Geology*, Gaboury. (2013, p. 1207) identifies a geochemical tracer in orogenic gold deposits, ethane (C_2H_6), which must be sourced from carbonaceous metasedimentary rocks.

Orogenic gold deposits (Böhlke, 1982) dominantly form in metamorphic rocks in the mid- to shallow crust (5–15 km depth), at or above the brittle-ductile transition, in compressional settings that facilitate transfer of hot gold-bearing fluids from deeper levels (Goldfarb et al., 2005; Groves et al., 1998; Phillips and Powell, 2009). The term "orogenic" is used because these deposits likely form in accretionary and collisional orogens (Groves et al., 1998). Transfer of weakly oxidized, low-salinity fluids to the sites of gold deposition is controlled by earthquake events (Cox, 2005; Sibson et al., 1988), allowing fluids to rapidly traverse large thicknesses of crust. This rapid rise takes the fluids out of equilibrium with their surroundings, promoting destabilization of the gold-carrying hydrosulfide complexes [$Au(HS)_2^-$ and AuHS]. The chemical cause of gold precipitation, facilitated by a temperature-pressure decrease, varies from place to place, and mechanisms such as fluid-rock reaction (Evans et al., 2006), boiling (Weatherley and Henley, 2013), fluid mixing (Bateman and Hagemann, 2004), and chemisorption on surfaces of pyrite and arsenopyrite (e.g., Möller and Kersten, 1994) have been proposed. We can investigate the cause of gold deposition by sampling rocks where precipitation occurred, and structures through which fluids flowed. In contrast, the question where the gold comes from is more difficult, because the potential sources are distant to the sampled gold deposits.

There are two plausible sources for the gold: (1) metamorphic rocks, from which fluids are generated as temperatures increase; and (2) felsic-intermediate magmas, which release fluids as they crystallize. Gold-bearing magmatic-hydrothermal deposits are enriched in many elements, including S, Cu, Mo, Sb, Bi, W, Pb, Zn, Te, Hg, As, and Ag (e.g., Goldfarb et al., 2005; Richards, 2009). Such deposits have been referred to as gold-plus deposits (e.g., Phillips, 2013), but most orogenic gold deposits fall into the alternative group of gold-only deposits, and are more enigmatic. These are characterized by elevated S and As, and have only minor enrichments in the other elements. The current dominant opinion is that metamorphic rocks are the source for these deposits (Goldfarb et al., 2005; Phillips and Powell, 2010).

In the early 1990s, the Crustal Continuum Model (Groves, 1993) was developed to explain the occurrence of orogenic gold deposits in metamorphic rocks of granulite to sub-greenschist facies. It was suggested that gold deposits can form at almost any depth in the crust, at temperatures from 750 ºC to 180 ºC. More recently, it was shown that large fluid volumes cannot migrate effectively through rocks hotter than ~650 ºC (Tomkins and Grundy, 2009; Phillips and Powell, 2009). Then, the continuum was further constrained by showing that the most fertile metamorphic fluids are released over ~500–550 ºC, with little fluid released beyond ~550 ºC (Tomkins, 2010). These constraints are consistent with observations that most orogenic gold deposits occur in greenschist to lower amphibolite facies rocks (Groves, 1993).

Xue et al. (2013), however, used the $\Delta^{33}S$ signature of sulfur in four Archean orogenic gold deposits to suggest a granitic source. The same result was independently obtained for different Archean deposits using the signature of noble gases and halogens in fluids released by crushing of gold-associated quartz-carbonate veins (Kendrick et al., 2011). In some Phanerozoic slate belts, however, there can be little debate about a metamorphic source. For example, metamorphism of turbidites in New Zealand's Southern Alps caused Au, S, and As release from diagenetic pyrite, allowing gold deposit formation in the absence of intrusions (Pitcairn et al., 2006). Similarly, in the more globally significant Victorian goldfields (Australia), there are no intrusions coeval with the largest gold deposits (e.g., Wilson et al., 2013), whereas a 35-km-thick sequence of fertile metamorphic rocks underlies the deposits.

The vast majority of orogenic gold (excluding Witwatersrand, South Africa) is from three periods in geologic time: the Neoarchean (ca. 2700-2400 Ma), a second period in the Paleoproterozoic (ca. 2100-1800 Ma), and a third period from ca. 650 Ma continuing throughout the Phanerozoic (Goldfarb et al., 2001). Two explanations have been offered for this timing: (1) because orogenic gold deposit formation requires accretionary tectonics, the major periods of formation coincided with periods of continental growth (Goldfarb et al., 2001), and (2) during the Phanerozoic, increased ocean oxygenation facilitated uptake of gold in biogenic and diagenetic pyrite, which became the gold source during later accretion and metamorphism (Tomkins, 2013). The first explanation must be correct to some extent, but cannot explain the relative lack of gold during the formation of Rodinia; the second requires that gold can be sourced from carbonaceous metasedimentary rocks.

Some proponents of the metamorphic source model suggest that hydrated mafic rocks are the source for fluids and gold (Powell et al., 1991; Phillips and Powell, 2009, 2010; Wilson et al., 2013), but thermodynamic calculations suggest that metamorphism of pyritic carbonaceous sedimentary rocks can generate much more fertile fluids than mafic rocks (Tomkins, 2010). For mafic and metasedimentary rocks, the most fertile fluids are generated during high-temperature, low-pressure metamorphism, constraining the tectonic settings where gold deposits are likely to form. Inverted backarc basins should be the ideal tectonic setting, because heat propagating through the crust as a consequence of rifting continues throughout the period of backarc inversion (heat flow is much slower than tectonic plate movements). This continued heat through-flow drives widespread high-temperature, low-pressure metamorphism of the ideal source rocks during the ideal structural period, allowing contemporaneous gold concentration across the very large regions where these deposits are found (Tomkins, 2010).

Independent suggestions that carbonaceous metasedimentary rocks are an ideal source came when development of laser ablation mapping allowed recognition that biogenic and diagenetic pyrite grains contain elevated Au, As, and other elements enriched in orogenic gold deposits (Large et al., 2011, 2009; Thomas et al., 2011). In contrast, mafic rocks are comparatively deficient in As, Ag, Pb, Zn, and Sb.

Gaboury (2013) makes two important points: (1) C_2H_6 was found in Detour Lake, Canada's largest gold deposit, where there are no known adjacent carbonaceous metasedimentary rocks, and (2) this orogenic deposit is hosted in upper greenschist facies metamorphic rocks, relatively close to the greenschist-amphibolite transition where metamorphic fluids

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are generated. Point 2 implies a short fluid pathway from the site of liberation to the site of gold deposition, thus lessening the chance of contribution from multiple sources, making it probable that carbonaceous metasedimentary rocks were the source. Gaboury also explains the occurrence of CO_2-rich–H_2O-poor fluids at many large gold deposits through the reaction of C_2H_6 with H_2O to form CO_2, implying that carbonaceous metasedimentary source rocks are globally important.

Many questions remain about the source of orogenic gold. Some form of the continuum model may remain valid, with a temperature range of ~550–300 ºC (cf. Phillips and Powell, 2009), involving formation of deposits from the deeper levels of the brittle-ductile transition to the shallow reaches of earthquake failure planes. The Archean and Paleoproterozoic orogenic gold-forming systems appear to be subtly different from the Phanerozoic ones, in terms of tectonics, source rocks, and deposit settings; thus, we need to be careful about extrapolating from one group to the other. One important unanswered question is the time needed to form orogenic gold deposits. If they form quickly, igneous sources might be more probable, but if they form over extended periods, metamorphic sources would be more probable. In terms of metamorphic sources, Gaboury's (2013) work adds weight to the evidence suggesting that carbonaceous metasedimentary rocks appear chemically more favorable, though mafic rocks remain a plausible source.

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