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Invited review article

Orogenic gold: Common or evolving fluid and metal sources through time

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ABSTRACT

Orogenic gold deposits of all ages, from Paleoarchean to Tertiary, show consistency in chemical composition. They are the products of aqueous-carbonic fluids, with typically 5–20 mol% CO_2, although unmixing during extreme pressure fluctuation can lead to entrapment of much more CO_2-rich fluid inclusions in some cases. Ore fluids are typically characterized by significant concentrations of CH_4 and/or N_2, common estimates of 0.01–0.36 mol% H_2S, a near-neutral pH of 5.5, and salinities of 3–7 wt.% NaCl equiv., with Na > K> > Ca,Mg. This fluid composition consistency favors an ore fluid produced from a single source area and rules out mixing of fluids from multiple sources as significant in orogenic gold formation. Nevertheless, there are broad ranges in more robust fluid-inclusion trapping temperatures and pressures between deposits that support a model where this specific fluid may deposit ore over a broad window of upper to middle crustal depths.

Much of the reported isotopic and noble gas data is inconsistent between deposits, leading to the common equivocal interpretations from studies that have attempted to define fluid and metal source areas for various orogenic gold provinces. Fluid stable isotope values are commonly characterized by the following ranges: (1) $\delta^{18}O$ for Precambrian ores of +6 to +11‰ and for Phanerozoic ores of +7 to +13‰; (2) δD and $\delta^{34}S$ values that are extremely variable; (3) $\delta^{13}C$ values that range from −11 to −2‰; and (4) $\delta^{15}N$ of +10 to +24‰ for the Neoarchean, +6.5 to +12‰ for the Paleoproterozoic, and +1.5 to +10‰ for the Phanerozoic. Secular variations in large-scale Earth processes appear to best explain some of the broad ranges in the O, S, and N data. Fluid:rock interaction, particularly in ore trap areas, may cause important local shifts in the O, S, and C ratios. The extreme variations in δD mainly reflect measurements of hydrogen isotopes by bulk extraction of waters from numerous fluid inclusion generations, many which are not related to ore formation. Radiogenic isotopes, such as those of Pb, Sr, Nd, Sm, and Os, measured on hydrothermal minerals are even more difficult to interpret for defining metal source, particularly as the low-salinity ore fluids transport limited amounts of these elements and significant amounts of these may be locally added to the minerals during alteration reactions at the sites of gold deposition. Noble gas and halogen data are equally equivocal.

Fluid exsolution from granitoids emplaced into the upper and middle crust, metamorphism of the crust, or fluids entering trans-crustal fault zones from below the crust all remain as permissive scenarios associated with orogenic gold formation, as the abundant geochemical data are equivocal. However, geological and geochronological data weigh heavily against a magmatic-hydrothermal model in the upper to middle crust. There is no universal temporal association between orogenic gold and magmatism, and where there is an overlap in age, there is no specific type of magmatism consistently associated with gold formation, nor element zonation around any specific pluton. A crustal metamorphic model for fluid and metal sources is very consistent with geological, geochronological, and geochemical data, although metamorphism on a regional scale that releases these components into major fault zones can be associated with many processes along active continental margins. These can include crustal thickening and radiogenic heating, slab rollback and heating during crustal extension, or subduction of a spreading ridge heating the base of an accretionary prism. In rare examples where Phanerozoic orogenic gold deposits are hosted in Precambrian high-grade metamorphic terranes, fluids and metals must, however, enter a transcrustal fault system from a subcrustal source. This could either be a devolatilized, subducted, relatively flat, perhaps stalled slab and its overlying sediment, or the corner of the fertilized mantle wedge that releases a fluid during a thermal event.

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Contents

1. Introduction

Prior to the 1990s, there were a wide variety of terms for gold only-type (e.g., Phillips and Powell, 1993) hydrothermal deposits in metamorphic belts. These included geographical terms such as Motherlode-, Bendigo-, Homestake-, and Korean-types; host-rock terms such as turbidite-, slate-, BIF-, intrusion-, greenstone-, or volcanic-hosted; terms that had depth and temperature implications, such as mesothermal; mineralization style terms, such as replacement, stockwork, or vein-type deposits; or combinations of these terms (e.g., Poulsen et al., 2000; Robert et al., 2007). At times, the deposits were expressed as various hybrid subtypes based upon trace-element geochemistry (e.g., Safonov, 2010).

Gebre-Mariam et al. (1995) and Groves et al. (1998), followed by Goldfarb et al. (2001, 2005), pointed out that these deposits, whether of Precambrian or Phanerozoic age, had many features in common. These included (1) very late to post-peak metamorphic timing, although, in some locations, still under transpressive stresses of a subduction/active margin setting, and with a few controversial Archean deposits that have been argued by some authors to show a prograde metamorphic overprint; (2) located most consistently in a metamorphosed fore-arc or back-arc location (Fig. 1); (3) formation in broad thermal equilibrium with country rocks as indicated by alteration assemblages and equivalent-temperature wallrock assemblages, and a lack of telescoped zonation such as that exhibited by deposits formed under high geothermal gradients; (4) hydrothermal addition of K, S, CO_2, H_2O, Si, and Au, with variable additions of As, B, Bi, Na, Sb, Te, and W, but low base-metal contents; and (5) supralithostatic H_2O–CO_2–CH_4–N_2–H_2S, low-to-moderate salinity ore-forming fluids that may have undergone phase separation during advection and gold deposition. Based upon these similarities, the deposit group was defined by the now widely-accepted term “orogenic gold deposits”.

Similar aqueous-carbonic fluids to those associated with orogenic gold are also described from a few other gold deposit types, which have led to some confusion in the literature. Carlin-type gold deposits in Nevada, USA, although characterized by aqueous-carbonic fluids (e.g., Cline et al., 2005), are notable for their lower ore-fluid CO_2 content

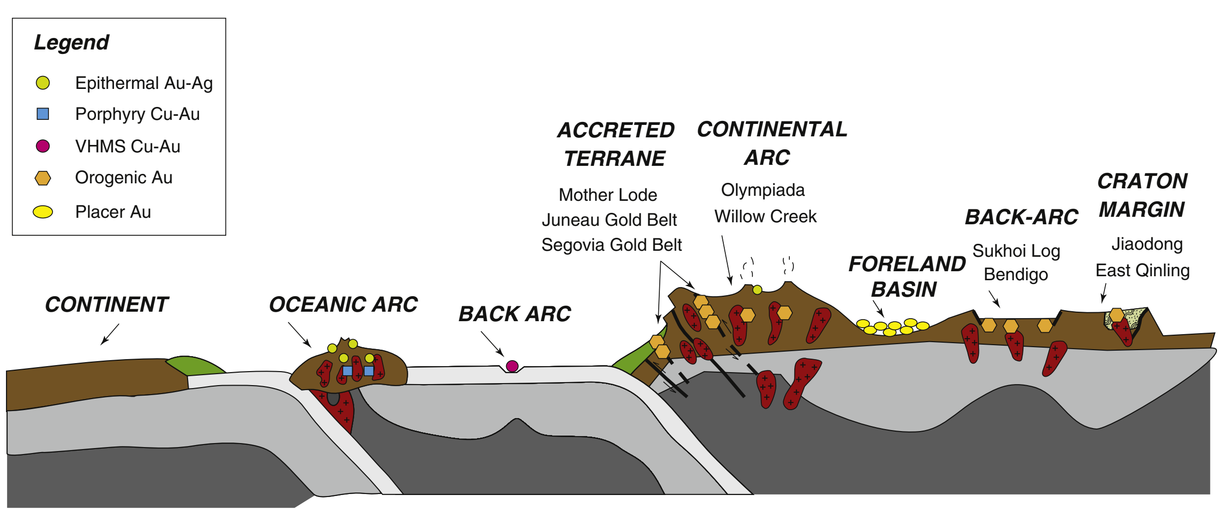

Fig. 1. Tectonic setting of orogenic and other gold deposit types. The orogenic gold deposits may be located in metamorphosed fore-arc and back-arc regions of active continental margins, as well as along the sheared margins to continental arc batholiths. In the case of eastern Asia, orogenic gold deposits are located along the margins of the decratonized North China block.

relative to orogenic gold deposits and their restriction to non-metamorphic sedimentary-rock environments along the North American craton margin. It is thus argued that the Carlin-type deposits of Nevada are a distinct deposit type. Two clusters of deposits in south-central China are Carlin-like, but have many distinctions from the Nevada deposits and are probably best classified as shallow epizonal orogenic gold deposits (Cline et al., 2013; Goldfarb et al., 2014).

Reduced intrusion-related gold deposits (RIRGD) are similarly recognized as a separate deposit group (Lang et al., 2000; Thompson et al., 1999), but with ore fluids similar to those that characterize the orogenic gold deposits (Baker, 2002). The RIRGD include the Fort Knox deposit in Alaska, the generally subeconomic deposits of adjacent Yukon, and a small past-producer at Timbarra in New South Wales. Based on the Phanerozoic examples, the RIRGD are suggested to have generally formed in continental margin sedimentary rock sequences close to craton margins that may also host tin and/or tungsten deposits. Most importantly, they show a close spatial and temporal association with specific granites derived from metasomatized sub-continental lithospheric mantle (e.g. Mair et al., 2011) and, as such, are characterized by thermal disequilibrium with their host rocks, leading to zoning of metals and alteration, at temperatures of >500 °C to <300 °C, surrounding the causative central intrusion (e.g., Hart et al., 2002). Such deposits are not considered in detail further in this paper, as their fluid source(s) contrasts with those of orogenic gold deposits, except where they are briefly discussed below under potential magmatic-hydrothermal source models.

Having defined orogenic gold deposits as a specific deposit type, by analogy with other deposit types, there would normally be the implication that they were deposited from a similar hydrothermal fluid with a consistent fluid and metal source. However, in the case of orogenic gold, there are two main complicating factors in such sources, which lead to extensive variability between interpretations from different studies. First, as orogenic gold deposits form at crustal depths of between 3 and 15 km (Groves, 1993; Groves et al., 1998; Kolb et al., 2015; Fig. 2), and there are no giant deposits younger than about 50 Ma (Goldfarb et al., 2001), all evidence for fluid source is circumstantial. As discussed below, long fluid flow paths make interpretations of data from fluid inclusions and isotopic studies equivocal. This situation is complicated by the fact that even if source regions are similar, different processes at or near gold depositional sites will complicate interpretation of ore fluid chemistry (Phillips and Powell, 2015). Second, orogenic gold deposits have formed over an exceptionally long time range, from the Paleoarchean to the present, a range matched only by that of VMS deposits (Groves et al., 2005), and thus a range encompassing major changes in the thermal state of the Earth, its tectonic regimes, and the hydrosphere and atmosphere (e.g., Cawood and Hawkesworth, 2014; Kerrich et al., 2005). As a result, most Archean deposits are sited in volcanic rock-dominated sequences (greenstones) that include subvolcanic intrusions and BIF units, with lesser, commonly clastic sedimentary-rock sequences. Many Proterozoic deposits are sited in similar sequences, but there are a significant number hosted by thicker, more extensive sedimentary-rock sequences. In the Phanerozoic, the situation is almost the reverse of that in the Archean, with many deposits within clastic sedimentary-rock sequences, although volcanic rock-hosted deposits are present. Deposits hosted by pre-ore granitic intrusions, which may be a few million or few hundred million years older than the ores, are represented throughout time.

Fluid and metal source constraints are presented below and evidence is evaluated in terms of source models proposed by various authors. Typical studies of such components in the ore-forming systems have focused on constraints from fluid inclusion and isotope data. Such an issue was evaluated in great detail by workers such as Kerrich (1986a, 1987, 1989a) more than two decades ago, but a re-evaluation is required in light of much new geological, geochemical, and geochronological information, and the present-day, more globally widespread, research on gold deposits. The questions of whether there was a common fluid and metal source throughout geological time or a source that evolved in concert with a changing Earth are subsequently considered, as well as whether resolution of source has implications for exploration models.

2. Equivocal geochemical evidence for source

For many mineral deposit types, fluid inclusions, and either or both stable and radiogenic isotopes, provide strongly indicative to unequivocal evidence of fluid source. This is not the case for orogenic gold

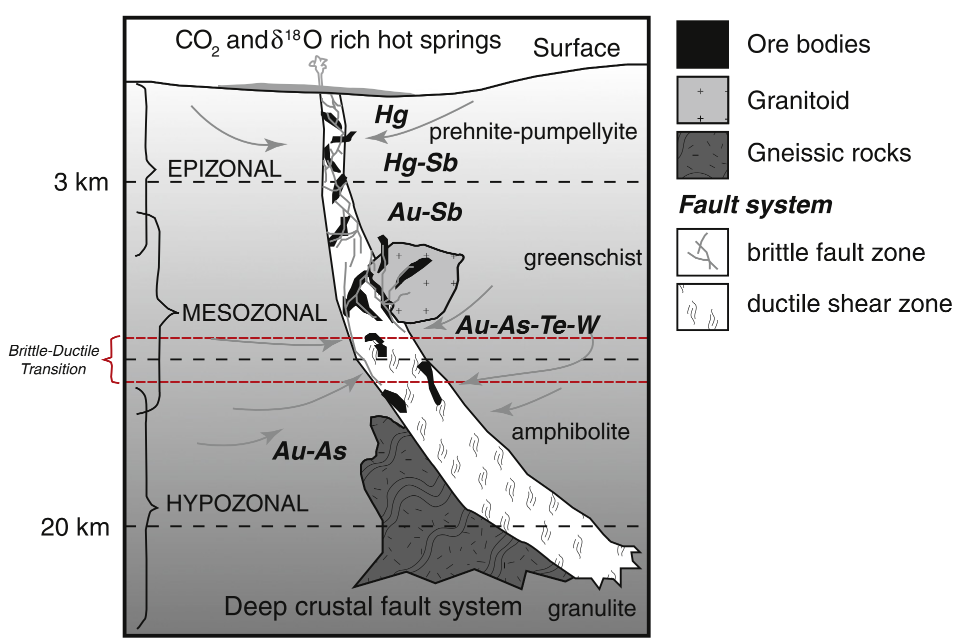

Fig. 2. Orogenic gold deposits can form over a variety of depths, from as shallow as 3 km to as deep as 20 km, typically during late orogenic shifts from compressional to transpressional or transtensional regimes. The majority of deposits form in the greenschist facies or at the greenschist–amphibolite boundaries from aqueous-carbonic, high $\delta^{18}O$ fluids that have moved upward along trans-crustal fault zones.
Modified after Groves et al. (1998).

deposits, where controversy has continued through to the present despite our increased ability to measure metals in single fluid inclusions or detect very low isotopic concentrations. The main reason for this uncertainty appears to be the extremely complex geologic setting of this deposit type, with highly variable host rocks, a broad range in P–T conditions of ore formation (most commonly reported between 1 and 5 kb and 220 to 450 °C), and deposition of ores along second and third order splays to regional structures (Figs. 1, 2) that commonly extend down to mantle depths. In the latter case, such structures are not only the conduits for ore fluids, but for other fluids and gases, as well as melts, which are derived from various depths at different locations along the hundreds of kilometers of fault strike length.

2.1. Fluid inclusion constraints

There are many uncertainties with interpretation of fluid inclusions in orogenic gold deposits. Much of this uncertainty reflects the fact that orogenic gold deposits are structurally-hosted ores, which typically formed at relatively great depth and were uplifted to the surface over tens of millions of years. As a result, fluid inclusions in orogenic gold deposits comprise assemblages of numerous generations trapped during post-ore fluid migration, many of which are unrelated to ore formation, and those that are syn-ore may commonly have undergone post-entrapment modification (e.g., Kerrich, 1976). Thus, without a comprehensive understanding of fluid-inclusion assemblage paragenesis, which is typically difficult to develop for this type of gold deposit, fluid inclusion studies of orogenic gold deposits may result in very equivocal results. Some of the complication includes the fact that primary fluid inclusions may be broadly synchronous with gold deposition in some quartz veins during one main fluid event (Ho et al., 1985), or, more commonly, the quartz veins and gold were deposited during multiple seismic events (e.g., Robert et al., 1995). Therefore, as early quartz is refractured, it may be noted that much of the gold endowment may be sited in fractures in already-formed quartz veins (Wilson et al., 2013). In the latter case, the gold would post-date entrapment of fluids in the more primary inclusions in the older quartz. This cyclic evolution of an orogenic vein system means multiple fluid-inclusion generations may trap samples of the metal-bearing fluid (Boullier and Robert, 1992). Thus, although primary inclusions are normally examined, secondary inclusions may be more appropriate for study in some cases (e.g., Yardley and Bodnar, 2014) if they relate to a later hydrofracturing event that brought a large volume of gold into the hosting vein system.

Despite these issues, the more careful studies of fluid inclusion assemblages in quartz from orogenic gold deposits nevertheless emphasize a relatively consistent ore-forming fluid. Garofalo et al. (2014) compared fluid inclusion characteristics of ore-related inclusions from typical Phanerozoic and Neoarchean deposits. They note a relatively consistent H_2O–NaCl–$CO_2 \pm CH_4$ ore-related fluid, as has been reported most commonly in the literature during the past four decades and which is likely characteristic of a single main-fluid source, with limited fluid evolution reflected by a consistency in fluid composition. This is in agreement with the review by Ridley and Diamond (2000), which summarizes the results of many studies as indicating a typical XCO_2 of 0.10 to 0.25 for an ore-forming aqueous-carbonic fluid, with minor CH_4, trace to minor N_2, 3–7 wt.% NaCl equivalent, and a near-neutral pH of about 5.5 at moderate ore-forming temperatures. They also conclude that the salinity generally is defined by Na > K> > Mg and Ca, although precipitation of muscovite or K-feldspar from such a fluid will be favored over paragonite or albite because of the greater supersaturation of K relative to Na (e.g., Kerrich and Fyfe, 1981).

There are generally significant amounts of H_2S, assumed to be important carriers of the gold, in most fluids. Estimates for concentrations of H_2S from fluid inclusion studies in various gold provinces have mainly ranged between about 0.01 and 0.36 mol% (e.g., Bottrell and Miller, 1989; Goldfarb et al., 1989; Mernagh and Bastrakov, 2013; Yardley et al., 1993). These estimates are remarkably similar to those from direct measurement by LA-ICPMS of 57–1840 ppm S (approximately 0.006 to 0.18 mol%) for individual fluid inclusions in barren metamorphic veins from medium-grade metamorphic facies rocks in the central European Alps (Rauchenstein-Martinek et al., 2014). Measured concentrations of 3–30 ppb Au in these fluids were interpreted as representing significant undersaturation with respect to gold. However, the similar nature of the estimates between these barren veins and the mineralized veins described above suggests that fluids need not be saturated with gold until changing chemical conditions trigger precipitation of the metal. The reduced state of the sulfur is consistent with an ore-fluid redox state that is normally more reducing than the hematite–magnetite buffer (Phillips and Evans, 2004; Phillips and Powell, 1993).

Hydrogen, as well as longer-chain hydrocarbons than methane, are reported in the ore-related fluid inclusions for some orogenic gold deposits (Gaboury, 2013; Goldfarb et al., 1989; Guha et al., 1990). Hrstka et al. (2011), for example, reported as much as 6 mol% H_2, as well as significant C_2H_6 and HCO_3^- concentrations, from Laser Raman Micro Spectroscopy studies of individual fluid inclusions from the Libcice orogenic gold deposit in the Bohemian Massif, Czech Republic. However, the significance of hydrogen, ethane, propane, and other higher hydrocarbons is unclear, because these could easily be the products of reactions between C-, O-, and H-bearing volatiles in fluid inclusion cavities during uplift-related drops in pressure and temperature (Tsunogae and Dubessy, 2009). In the Hrstka et al. (2011) study, heat from post-ore magmatism in the Bohemian Massif was suggested to have mobilized hydrogen from organic matter in the country rocks at temperatures >500 °C, thus yielding H_2 rather than CH_4, with the former diffusing into fluid inclusions closest to quartz grain boundaries during recrystallization of the quartz. Thus, such post-gold modification of ore-stage fluid inclusions by addition of H_2 might be expected in other sedimentary rock-hosted orogenic gold deposits, particularly where the sedimentary rocks are relatively reducing and there is nearby younger magmatism and associated contact metamorphism.

Different studies of orogenic gold deposits from different gold districts have shown enormous variability from almost pure H_2O to almost pure CO_2 to very CH_4-rich fluids. Nevertheless, most authors view the parent to be a single low-salinity H_2O–CO_2–CH_4 fluid with about 5–20% CO_2 and an order of magnitude lower $CH_4 + N_2$, with <200 ppm S. Because metal precipitation is commonly controlled by transient huge pressure drops (Sibson et al., 1988; Weatherley and Henley, 2013), phase separation may occur both along the fluid flow path and probably more commonly at the gold depositional site. This would explain some of the more extreme variability reported in fluid-inclusion volatile compositions. In West Africa, a fluid that is 70% CO_2 at Damang (White et al., 2013), or essentially pure CO_2 in the Ashanti belt (Schmidt Mumm et al., 1997), most likely is the product of extreme unmixing of an aqueous-carbonic system (White et al., 2015). Fluid unmixing during pressure-driven ore-fluid migration can eventually lead to some of the relatively high-salinity aqueous fluids recognized in a limited number of deposits (e.g., Neumayr and Hagemann, 2002). Chi et al. (2009) described pure CO_2 ore-related fluid inclusions at Campbell-Red Lake, Abitibi, Canada, and favored a large carbonic fluid component from granulite facies metamorphism, rather than extreme unmixing of an aqueous-carbonic fluid from greenschist to amphibolite facies sources. Although pyrite to pyrrhotite prograde desulfidation reactions are unlikely at such high metamorphic conditions, Chi et al. (2009) described significant H_2S concentrations in the carbonic fluid based upon a Laser Raman study.

Uemoto et al. (2002) presented a model of an ore fluid that had been slightly modified by reaction with rock types of differing oxidation state along subsidiary structures before mixing at the depositional site. More recently, mixing of fluids with different sources has been proposed (Neumayr et al., 2007; Walshe et al., 2003), but this appears physically unreasonable because the ore fluid is clearly overpressured and would drive resident fluids out of the system, not mix with them. Also, much of the mixing hypothesis is based upon the presence of iron oxide minerals in association with more reduced gold-related assemblages, which Evans (2010) has shown may be the product of a single fluid undergoing changing water–rock ratio during infiltration into the ore-hosting country rocks.

Realistically, the non-aqueous volatile-rich nature of the fluid inclusions indicates that the ore fluid cannot be meteoric water, nor a magmatic-hydrothermal fluid derived from a high-level intrusion (e.g., Kerrich, 1989b). The consistency of fluid inclusion compositions in orogenic gold deposits indicates models that implicate mixing of fluids from multiple sources should be ruled out in the majority of the deposits. The fluid could be a crustally-derived or crustally-modified fluid that was likely slightly more CO_2-rich in the Precambrian than in the Phanerozoic ore-forming systems. As noted by Phillips and Evans (2004), the consistent CO_2-rich nature of these fluids is likely a critical factor in providing the near-neutral pH buffering required for high gold solubility as a gold-hydrosulfide complex. The source area could be from a wide range of crustal levels, assuming a metamorphic origin and recognizing desulfidation reactions could occur over a broad range of metamorphic temperatures depending on the overall country rock assemblage. Ferry (1981) noted the conversion of pyrite to pyrrhotite in metamorphism of graphitic schist will take place in the range of 400–575 °C; Tomkins (2010) argued that the concurrent release of sulfur was associated with chlorite breakdown mainly under lower-amphibolite facies metamorphic conditions. Nevertheless, deep crustal/mantle magmatism or derivation of fluids from subcreted oceanic crust or metasomatized subcontinental lithosphere is the source options which cannot be ruled out by the fluid-inclusion volatile composition alone.

2.2. Stable isotopes

Stable isotope studies are typically applied to define sources for oxygen, hydrogen, carbon, sulfur, and nitrogen that are recognized from fluid inclusion work to be the important volatile components of the hydrothermal fluid. However, interpretation of stable isotope data is far from straightforward because of a number of problems. These include (1) fluid–rock interaction along the flow path, (2) fluid–rock interaction at the sites of ore formation, (3) overlap of isotopic values for different source areas, and (4) uncertainties in permissive isotopic ranges for specific source areas. As orogenic gold deposits are generally associated with massive fluid flow along a fault conduit, the first of these problems, however, may only be significant early during fluid release at depth and initial hydrofracturing. Once fluids are channelized along main faults, the hydrothermal system is highly fluid-dominant and significant exchange along the flow path is unlikely. Thus, fluid $\delta^{18}O$ ratios are unlikely to undergo significant modification along the pathway.

The uniformity of oxygen isotope values for fluids interpreted to form orogenic gold deposits has been widely recognized for many decades (e.g., Kerrich, 1987, 1989c; Nesbitt, 1991). These data are almost always obtained from measurements of $\delta^{18}O$ for gold-bearing quartz and then fluid values are calculated based on estimated trapping temperatures from fluid inclusion studies of the same quartz. Precambrian fluids tend to range in $\delta^{18}O$ between +6 and +11‰ (McCuaig and Kerrich, 1998), whereas Phanerozoic values range most consistently between +7 and +13‰ (Bierlein and Crowe, 2000). The slight differences may reflect a slightly lighter oxygen fluid source in the Precambrian relative to the Phanerozoic, such as igneous rather than sedimentary rock, assuming that a model of metamorphic devolatilization at depth (see below) of the main terrane lithologies that host the gold provinces of each age is favored (e.g., Goldfarb et al., 2005).

Many workers report significant variations in ore fluid $\delta^{18}O$ for a given deposit, although measured values from quartz for most veins in a deposit are essentially identical. This variability is commonly introduced when a wide range of fluid inclusion homogenization temperatures is interpreted to reflect a wide range of vein formation temperatures at a deposit. Such a wide range of temperatures is inconsistent with the lack of significant metal zoning over vertical extents of as much as 2–3 km in some deposits and the consistent alteration phases at most deposits despite ore formation during dozens of episodic flow events. It is most likely that, when $\delta^{18}O_{quartz}$ measurements for a deposit are clustered within a range of no more than about 1–2‰, the ore-forming temperature is actually consistent and any fluid inclusion measurement variability reflects measurement of many post-ore inclusions and/or inclusions that have undergone post-entrapment modification. It is consequently not atypical to find some workers arguing for a late influx of meteoric water, or for fluid mixing to implicate a second fluid in ore deposition, by using some of the low-temperature homogenization measurements that are from inclusions unrelated to the ore, and then to calculate some lower $\delta^{18}O$ fluid values, whereas all $\delta^{18}O_{quartz}$ measurements are essentially identical (e.g., Ramsey et al., 1998; Vallance et al., 2004; Wen et al., 2015).

The equivocal nature of δD data from numerous orogenic gold deposits has been pointed out for many years (e.g., Pickthorn et al., 1987). Many workers tend to analyze mechanically or thermally-extracted fluid-inclusion waters to define the δD composition of ore-forming fluids in the deposits, such as Nesbitt et al. (1986) for ores of the Canadian Cordillera. However, such easily obtained fluid represents a bulk extraction of fluid inclusion waters from many generations of fluid inclusions within gold-bearing quartz. As these are structurally-hosted gold deposits that have been uplifted to the surface over many millions of years (e.g., Craw et al., 2010; Goldfarb et al., 1986, 1989; Stuwe, 1998; Taylor et al., 2015), they will have trapped multiple generations of inclusion waters, typically with significant amounts being unrelated to the older ores. Furthermore, structurally-bound water in the quartz will also lead to lower δD measurements during bulk extraction (Baatartsogt et al., 2007). Invariably, resulting analyses yield δD values that reflect at least some significant component of meteoric water, but such data are relatively meaningless. Relatively D-enriched values of −20 to −80‰ for δD are consistently measured on hydrous alteration minerals, mainly micas, and associated fluid values are rarely compatible with any important contribution of isotopically light meteoric water. Only in some relatively shallow epizonal orogenic gold deposits, where hydrothermal clays may exist along with sericite/muscovite as important silicate alteration phases, minor amounts of meteoric water enter the ore-forming hydrothermal systems (e.g., Donlin Creek, Alaska: Goldfarb et al., 2004; Taiwan: Craw et al., 2010).

It is unlikely that meteoric water will reach the deeper crustal levels where many of the orogenic gold deposits have formed. Menzies et al. (2014) studied very young (<1000 ka) quartz veins that formed and underwent additional ductile deformation at >6–8 km depth along the Alpine Fault zone. South Island, New Zealand. They interpreted the δD from fluid inclusions, ranging between −84 and −42‰, to suggest that meteoric waters could circulate down into the ductile crust and form vein systems along major transcrustal fault systems. However, again, these data are from bulk analyses of fluid inclusions in very deformed quartz and do not convincingly prove such a process as important in orogenic gold vein formation. It also highlights the problem in using δD data for defining fluid source areas in regions where meteoric waters are relatively D-enriched, such that a meteoric water signature would also overlap both the metamorphic and magmatic water fields. Furthermore, such a meteoric-water hydrogen signature must be evaluated in terms of paleogeographic location and age of ore formation, commonly an impossible task.

Further ambiguity may characterize the meaning of the determined δD of the ore-forming fluids, if a significant amount of the measured hydrogen was derived from breakdown of organic material (e.g., Goldfarb et al., 1989; Peters et al., 1991) at relatively low to moderate temperatures. If the methane was an important component in an evolving aqueous-carbonic fluid, then immiscibility could lead to formation of methane-dominant fluid inclusions. Thus, in epizonal and some mesozonal orogenic gold deposits in metasedimentary rock sequences, any crustally derived methane could be an important component, as is documented in many fluid inclusion studies. In the central Alps, such inclusions were shown to be characterized by δD values of −100 to −130‰ (Tarantola et al., 2007), and in some cases these "organic waters" can be as light as −250‰ (e.g., Sheppard, 1986). Therefore, discrimination between a metamorphic and meteoric fluid would be impossible using δD values for orogenic gold deposits where significant methane was noted in ore-related fluid inclusions.

Determining whether carbon in the ore-forming fluids, and ultimately in the hydrothermal carbonates, is derived from carbonates, organic material in the crust, or magmas from a variety of potential source regions is also difficult. Slightly negative carbon isotope compositions are relatively consistent in a majority of deposits, whether calculated from measurements on carbonates or measured directly on CO_2 extracted from fluid inclusions. Kerrich (1989c) and McCuaig and Kerrich (1998) noted that a great many orogenic gold deposits are characterized by $\delta^{13}C_{fluid}$ values between −11 and +2‰, with relatively consistent values at individual deposits indicating that fluid mixing is likely to be insignificant. Luders et al. (2015) argued that the more negative values reflect decarbonation of organic-rich sedimentary rocks, and the more positive values commonly relate to greenstone belt devolatilization, although it is noted that many of the parameters described here that can influence fluid $\delta^{13}C$ indicate such a generalization cannot be universally applied. The fact that the cumulative data from most deposits define a $\delta^{13}C$ fluid range of more than 9‰ suggests that, even when considering the possibility of minor shifts in composition at gold deposition sites, a solely mantle carbon source for the orogenic gold-forming fluids is not possible because a narrower $\delta^{13}C$ range would be expected (Kerrich, 1989c). Furthermore, the minimal variation in $\delta^{13}C$ for individual deposits is consistent with the above conclusions from the oxygen isotope data that fluid-dominated hydrothermal systems formed the orogenic gold deposits (McCuaig and Kerrich, 1998).

There are many exceptions to the above generalizations concerning $\delta^{13}C$ data. In contrast to the typical range for $\delta^{13}C$, some orogenic gold deposits (e.g., Meguma, Nova Scotia, Canada; Pine Creek, Northern Territory, Australia; Ashanti, West Africa) may contain hydrothermal carbonates that are as light as −20 to −30‰, which have been interpreted to indicate a large contribution of biogenic carbon into the ore-forming fluid from the fluid source region (Kontak and Kerrich, 1997). However, in some cases, the possibility of significant fluid buffering by carbonaceous host rocks, such as in the Loulo district in Mali (Lawrence et al., 2013), may also lead to development of extremely negative values at the sites of gold ore deposition and thus, in some cases, difficulties in defining source-area $\delta^{13}C$ signatures. Wilson et al. (2013) described a large shift from −14.0 to +4.1 in $\delta^{13}C$ during progressive ore deposition events at Bendigo, which was interpreted to reflect a temperature decrease, CO_2/CH_4 ratio decrease, or input of carbon from additional sources. The presence of both CO_2 and CH_4 in fluids, where ratios may have changed drastically due to later phase separation and disequilibrium events, could also cause such uncommonly broad ranges and ^{13}C-enrichment within a deposit. The Sawayaerdun orogenic gold deposit, located in carbonaceous sedimentary rocks along the Xinjiang–Kyrgyzstan border in the southern Tian Shan, records $\delta^{13}C$ values as high as +10‰ for CO_2 released from fluid inclusions (Chen et al., 2012). Such high values were interpreted to reflect strong fractionation of carbon in the graphitic host rocks, such that the ore fluids were enriched in ^{13}C. Nevertheless, the significance of what is being analyzed during measurement of bulk fluid inclusions is important to consider because hydrothermal carbonate measurements for the same deposit are all between about −5 and 0‰ (Yang et al., 2007). In summary, it is apparent the extreme variability that is possible in $\delta^{13}C$ for ore fluids or for ore-related carbonates in orogenic gold deposits makes it very difficult to use such data to clearly define a carbon source for the ore-forming fluids.

Nitrogen isotopes measured from hydrothermal muscovite, biotite, and K-feldspar of orogenic gold deposits reflect the nitrogen in the hydrothermal fluids that may substitute as NH_4^+ for K^+ in these mineral phases. Most reported $\delta^{15}N$ values show a distinct variation reflecting deposit age. Neoarchean deposits from the Yilgarn, Superior, Dharwar, and Zimbabwe cratons have values between about 10–24‰ (Jia and Kerrich, 1999; Kerrich et al., 2006); Paleoproterozoic deposits from West Africa and the Trans-Hudson of Canada range from approximately 6.5 to 12‰ (Jia and Kerrich, 2004); and Phanerozoic gold ores from Victorian goldfields, the North American Cordillera, and various Chinese orogens range from 1.5 to 10‰ (Jia et al., 2001, 2003; Mao et al., 2003b). This variability has been related by Kerrich et al. (2006) to secular variations in crustal rocks that reflect large-scale Earth processes. It is important to point out that a mantle nitrogen contribution would have a negative $\delta^{15}N$ value, typically about −6 to −5‰, and meteoric waters, if assumed to be involved in ore formation, contain very little dissolved nitrogen (Jia et al., 2003). One complication is the rare case of the large Mesozoic gold deposits that are hosted by Neoarchean rocks in the North China block (e.g., Goldfarb and Santosh, 2014). Measurements of $\delta^{15}N$ for these deposits are much lower than the likely ratios for exposed Archean basement rocks, suggesting a subcrustal source for the nitrogen in this case. Further ambiguity regarding interpretation of $\delta^{15}N$ data includes the fact that hydrothermal muscovite from the Devonian Charters Towers district in Queensland has values of 8–17‰ (Kreuzer, 2005), which are much higher than those from other Phanerozoic ore systems.

Sulfur isotope signatures are extremely variable for orogenic gold deposits; much of the reported data for all ages of deposits range between about 0 and +10‰ (Golding et al., 1990; Kerrich, 1987, 1989c; Nesbitt, 1991; Partington and Williams, 2000). However, reported $\delta^{34}S$ values have been shown to be as low as −20 and as high as +25‰ for sulfide minerals from orogenic gold deposits. There is no unique signature for the sulfur isotope composition of an orogenic gold-forming fluid. Changes in redox and other chemical parameters at the site of gold deposition can only shift sulfur compositions a few per mil, so the variability is unlikely to be due to variable sulfide precipitation conditions. Thus, a single homogeneous sulfur reservoir, such as the mantle, cannot be the source of sulfur contributed to orogenic gold systems. As the sulfur is also the complexing agent for the gold, understanding sulfur source may be critical in defining the gold source region(s).

At least for the Phanerozoic deposits, $\delta^{34}S$ compositions vary with age of host rock. This was interpreted by Chang et al. (2008) and Goldfarb et al. (1997) to indicate that the sulfur source was required to be disseminated syngenetic/diagenetic pyrite in the terranes being devolatilized at depth. The sulfur was gained by the ore-forming fluids during metamorphic conversion of the pyrite to pyrrhotite, as described by Goldfarb et al. (1989) for deposits in the Juneau Gold Belt.

In contrast to the conclusions above for the $\delta^{34}S$ data, recent work showing an absence of mass independent fractionation (MIF) for sulfur isotopes from the gold deposits of the Yilgarn craton has suggested instead a felsic magmatic or mantle sulfur source, and has been further interpreted to eliminate meteoric water or metamorphism of metasedimentary rocks in the ore formation process (Xue et al., 2013). This is consistent with a scenario such that felsic volcanic or mafic/ultramafic rocks, which would lack MIF sulfur because it couldn't circulate to the deeper ocean floors given the abundance of dissolved iron in the Archean oceans (Andy Tomkins, written commun., 2015), are permissive sulfur sources. Similar near-zero $\Delta^{33}S$ for gold-related sulfides in the Val d'Or district of Canada also indicate a magmatic source for the sulfur in the ore-forming fluid, although the slightly positive values for the Canadian Malartic deposit were interpreted to reflect an important sulfur source from the metasedimentary rocks of the surrounding Pontiac Group (Sharman et al., 2014). Ore-related sulfides from the Quadrilatero Ferrifero province, Brazil, exhibit an unquestionable mass independent fractionation effect, with positive $\Delta^{33}S$ and, therefore, a sulfur source that must be supracrustal, either greenstones or metasedimentary rocks (Buhn et al., 2012). Rather than all the abovementioned sources being likely contributors of sulfur to the orogenic gold deposits, it is more likely that there is still much to be learned about the meaning of some of these mass independent fractionation relationships.

The presence of tourmaline in many orogenic gold deposits has led some workers to consider boron isotopes as tracers of ore-fluid source regions. Tourmaline from Val d'Or camp gold deposits ranges in $\delta^{11}B$ from about −17 to −8‰, with the relatively wide range characteristic of single veins and no obvious trends with changing tourmaline elemental compositions (Beaudoin et al., 2013). Fluid $\delta^{11}B$ values of −5 to +13.5‰ were calculated as representative of the ore-forming fluid. Such a range was noted to be typical of many other deposits where such isotopes have been recently measured and is interpreted to reflect addition of varying contributions of local host-rock boron to the tourmaline, hindering definitive interpretation of original fluid source.

2.3. Radiogenic isotopes

The usefulness of lead isotopes to suggest a lead source for gold-related sulfide grains, and by inference the source of the gold, is not clear. Curti (1987) showed lead isotopes to indicate a distal lead source in Paleozoic metapelites for the Tertiary orogenic gold deposits of the European Alps. In mafic metavolcanic rock-hosted Neoarchean Yilgarn deposits, lead data were shown to reflect the granite-gneiss basement of the greenstone belts (Browning et al., 1987; Perring and McNaughton, 1992; Qiu and McNaughton, 1999). McCuaig and Kerrich (1998) interpreted that much of the lead data indicated a deeper and more radiogenic source rock than the host rocks for orogenic gold deposits. Lead isotopic studies commonly indicate a felsic source, normally interpreted to be a spatially-associated granitic intrusion, although some studies show a lead signature that lies between many of the different lithologies of a region (Ridley and Diamond, 2000). Meffre et al. (2008) interpreted lead isotope data for Sukhoi Log as supporting a variety of sedimentary-rock crustal sources.

Importantly, Goldfarb et al. (1997) pointed out that in the Juneau gold belt of southeastern Alaska, the giant Treadwell and Alaska–Juneau deposits, which formed coevally on opposite sides of a terrane-bounding fault, had strikingly different lead isotope values for ore-stage sulfides. The measured values reflect a very primitive host-rock on one side of the fault and a much more-radiogenic host rock on the opposite side, such that the isotopic values mainly measure the host-rock lead ratios and provide no information about the source area for the transported gold. This is consistent with the original observation of Kerrich (1983) that little lead is mobilized in the low-salinity fluids that characterize orogenic gold deposits and thus lead isotopes provide little definitive information about the source of any lead, and, by inference, any gold, which would have been moved from a distal gold source reservoir. As further evidence of the limited usefulness of lead isotope data from orogenic gold deposits, Goldfarb et al. (1997) also noted how ratios for sulfides varied between flysch-, mélange-, and granitoid-hosted orogenic gold deposits throughout the Chugach terrane of south-central Alaska. Similarly, Haeberlin et al. (2003, 2004) pointed out that the lead isotope signatures for the ore-related sulfides in deposits of the Pataz district, Eastern Cordillera, Peru, reflected the signature of the host batholith that was 20 m.y. older than the gold event.

The lead isotope data are, therefore, equivocal. Because of the low lead concentrations in the orogenic gold hydrothermal fluids, a relatively lead-rich host rock is likely to be a major lead contributor to the measured isotopic ratios, which therefore must reflect, at least to some degree, the host rocks and not the lead in the gold source area(s). In contrast, low-lead host rocks, such as those in many Neoarchean greenstone belts, may give more-meaningful source area data 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 (Goldfarb et al., 2005). Orogenic gold deposits throughout the Paleozoic of Ireland (Standish et al., 2014) are characterized by highly variable lead signatures, reflecting many different basements and overlying lithologies. In such a case, the lead values could easily reflect numerous reservoirs that might have been present in the gold source area, as was suggested by the authors, and additional variability added from local lead in the ore deposit traps, as described above.

Strontium isotopes have, in places, been interpreted to show that strontium was derived from basement rocks below auriferous Neoarchean greenstone belts because isotope ratios, similar to lead, seem to be more radiogenic than those of the greenstones (Kerrich, 1989c; Mueller et al., 1991). In the Paleozoic Meguma terrane, strontium data were interpreted to reflect a significant mantle component, with values altered along the flow path and at the site of gold deposition by the host metasedimentary rock sequence (Kontak and Kerrich, 1997; Kontak et al., 1988). In other studies, Miller et al. (1995) at Kensington, Alaska, and Kempe et al. (2001) at Muruntau, Uzbekistan, favored a local wallrock source for both Sr and Nd, whereas Böhlke and Kistler (1986) discussed multiple strontium sources in the host rock terranes distal to the Mother Lode deposits.

It is possible that the isotopic compositions simply reflect element abundance in the interpreted source rocks; lead is an order of magnitude more abundant in granites and strontium an order of magnitude more abundant in the basic-intermediate volcanic rocks than other rocks in many lithostratigraphic sequences. Thus, neodymium isotopes suggest a komatiitic source, at least in Precambrian greenstone belts, presumably because REE are typically stable in the hydrothermal systems (e.g., Kent et al., 1995; Tourpin et al., 1991). McCuaig and Kerrich (1998) summarized the rare cases of REE enrichment in orogenic gold deposits as reflecting input from high-salinity alkali magmatic hydrothermal fluids unrelated to the gold event or changes in absolute abundances due to volume changes associated with wallrock alteration under high water–rock ratios. The Sr and Nd isotopes of ore-related hydrothermal minerals in the Jiaodong province of eastern China overlap both ore host-units (Li et al., 2013), crustally-derived Jurassic granitoids, and, less significantly, the Archean basement gneiss, which further implicates a trap, and not necessarily a source area that must be at depth (e.g., Goldfarb and Santosh, 2014), for defining the radiogenic isotope signature.

With the increased application to Re–Os dating of sulfides in orogenic gold deposits, and the geochemical affinity between gold and osmium, some workers have recently tried to use Os ratios to define Os source, and thus gold source. For example, Lawley et al. (2013) suggested that Os data from the Lupa deposit (Tanzania) tend to favor a mantle Os source. However, they do note the large amount of uncertainty in their calculated Os ratios because of the small concentration of common osmium that is characteristic of many sulfide analyses. Initial $^{187}Os/^{188}Os$ data for ore-related sulfide from the Niassa gold belt of northern Mozambique indicate a juvenile source with a mantle-like signature. This source was suggested to be Neoproterozoic metagabbro and metasedimentary rocks hosting the Pan-African gold ore or more distal Neoproterozoic–early Paleozoic lower mafic crust, but only non-juvenile felsic igneous crustal rocks were viewed as non-permissive source material for the "ore fluids" (Bjerkgard et al., 2009). Significantly, and perhaps relevant to many orogenic gold deposits, McInnes et al. (2008) pointed out that abundant radiogenic osmium in metasedimentary rocks of the Callie deposit in the Tanami district of northern Australia, which would mix with any osmium in the hydrothermal fluids, would make interpretation of $^{187}Os/^{188}Os$ data difficult. Similarly, Ootes et al. (2011) stated that if there was any juvenile Os in the gold-depositing systems at Yellowknife, Canada, it would be masked by the determined radiogenic crustal component.

In conclusion, all radiogenic isotope data appear to be ambiguous because of the highly variable concentrations of the radiogenic elements and relatively important contributions of these elements into the hydrothermal minerals in the ore formation environment. Phillips and Powell (2009) noted that elements such as Rb, Sr, Nd, Sm, Re, Os, Pb, Th, and U are not mobile in the low salinity ore-forming fluids responsible for orogenic gold deposits. Thus, these metals are not very useful in providing constraints on the source area of gold and related ore metals.

2.4. Noble gases

Noble gas isotope analyses have been reported for many orogenic gold deposits during the past decade. Magmatic fluids are typically reported to be characterized by $^{40}Ar/^{36}Ar$ ratios of 10,000 and values of about 1.3 for Ra (where Ra represents measured values of $^{3}He/^{4}He$ relative to that ratio of present-day air, which is 1.38×10^{-6}), surface fluids by $^{40}Ar/^{36}Ar$ of 300–800, mantle fluids by 6–8 Ra, and crustal fluids by <0.05 Ra (Fu et al., 2012). These isotopes too are measured from bulk-extraction fluid-inclusion waters from auriferous quartz and thus present the problem described above of measuring data for many generations of trapped fluid, from the time of quartz vein deposition to final stages of uplift to the surface. Furthermore, because orogenic gold deposits occur along major fault zones that are interpreted to continue down to mantle depths, such faults may facilitate upward leakage of mantle-derived rare gases into shallower fluid and magma reservoirs.

Therefore, whereas mantle-derived noble-gas isotope values may be reported for some orogenic gold deposits, such values may mean nothing regarding the source of H, O, C, N, S, or metals. For example, Mao et al. (2003a) reported a mantle source for the Dongping orogenic gold deposit in northern China based on a 5.2 Ra value, but very negative $\delta^{34}S$ data indicate a non-mantle sulfur source. Similarly, Zhang et al. (2008) presented Ra values of 0.4–2.4 for the deposits of the Jiaodong province, interpreted as evidence of mantle involvement in ore formation, whereas all $\delta^{34}S$ data from the ore-related sulfides are more positive than mantle values. For gold deposits in Victoria, Fu et al. (2012) suggested that $^{40}Ar/^{36}Ar$ ratios of less than 1500, coupled with ^{36}Ar concentrations of 2.6–58 ppb, are representative of a deep metamorphic source area that could be either a metavolcanic or metasedimentary unit. Values of Ra of 0.2–0.4 Ra for the Muruntau and Zarmitan deposits in Uzbekistan were suggested to indicate mantle involvement in ore formation, and low $^{3}He/^{36}Ar$ ratios for some inclusion waters extracted from sulfides at the latter deposit were interpreted to indicate significant mixing of meteoric waters with mantle and deeper crustal fluids (Graupner et al., 2006, 2010). At Campbell-Red Lake, Chi et al. (2006) reported Ra values of 0.008–0.011 for fluids extracted from arsenopyrite and 0.016 for fluids from gold, as well as $^{40}Ar/^{36}Ar$ ratios of 762–6119 for these samples, all argued to be consistent with a crustal fluid. Li et al. (2012) used both He and Ne isotopes to call upon a mantle source for the ore fluids in the Mesozoic East Qinling gold deposits along the southern margin of the North China block, although Goldfarb and Santosh (2014) suggested that the ultimate fluid source for similar ore-forming fluid in the Jiaodong gold province on the eastern side of the former North China craton, now with an eroded lithospheric keel, was metamorphism near the top of a subducting plate. Kendrick et al. (2011) interpreted noble gas data, coupled with halogen ratios, to support the mixing of a magmatic methane fluid with a more traditional aqueous-carbonic fluid to precipitate gold in the St. Ives goldfield of the Yilgarn craton. There is no question regarding the accuracy of all the noble gas concentration measurements, but the meaning of these data and thus their usefulness for identification of metal or fluid source is questionable.

2.5. Halogens

In the Italian Alps, Yardley et al. (1993) suggested that anomalous concentrations of the halogen species measured in fluid inclusions in small orogenic gold veins represent an important meteoric water contribution to ore formation. Böhlke and Irwin (1992) conducted laser analyses of single fluid inclusions from the California orogenic gold deposits and interpreted resulting Cl, Br, and I data as supporting their derivation from organic-rich sedimentary rocks. Variable ratios for I/Cl and low ratios for Br/Cl for fluid inclusions from Victoria gold ores were interpreted by Fu et al. (2009, 2012) to represent metamorphism of argillaceous rocks deeper in the volcano-sedimentary basement.

2.6. Trace element data

The geochemical enrichments of orogenic gold deposits have been well summarized (e.g., Goldfarb et al., 2005; Groves et al., 1998; Kerrich, 1983; Phillips and Groves, 1983). The most consistent anomalies are characterized by elevated Ag, As, Au, B, Bi, Sb, Te, and W. Many of these elements, including As and Sb, reflect a fluid dominated by sulfide complexes and with low salinity (e.g., Kerrich, 1983). Many workers have argued that elevated Bi, Te, and W are indications of a fluid with a magmatic source, but that is now recognized as not necessarily correct. For example, deposits in the Otago schist belt of New Zealand were commonly developed for tungsten ore, despite no granitoids within the gold province (Henley et al., 1976). Pitcairn et al. (2006) have demonstrated that most of these elements are lost from detrital minerals in metasedimentary rocks during prograde metamorphism and will enter an evolving metamorphic fluid phase. Whether the same pattern holds for metavolcanic rock-dominant terranes, such as those defining the auriferous Precambrian greenstone belts, is still unclear.

2.7. Summary

In summary, as interpreted by workers such as Kontak and Kerrich (1995) and Ridley and Diamond (2000), the almost universally equivocal fluid inclusion, stable and radiogenic isotopes, noble gas, halogen, and trace-element data are at best interpreted to indicate deeply-sourced, overpressured, advecting fluids. Due to the complex, multistage history of vein formation and of the unroofing of the deeper parts of the ore-hosting shear zones, relating a specific fluid inclusion assemblage to the main gold depositing event is difficult and has led to contradictory interpretations regarding the significance of certain PTX data. Furthermore, typically the same data ranges obtained from different isotopic studies have been alternatively interpreted to indicate a magmatic-hydrothermal, metamorphic, or sub-crustal fluid and metal source-areas. Based on the deposits interpreted to have formed at the deepest crustal levels, at least in some cases, these fluids must have been derived from at least 10–15 km, and arguably 20 km depth in the Archean, the latter perhaps reflecting differences in crustal thermal structure and/or tectonic regimes on earlier Earth. Geological and geochronological constraints on the source of ore fluid and metals, focused on the various models that have been published, are discussed below sequentially and their validity vindicated or rejected, at least in terms of a universal source. This is an approach that was similarly first taken 30 years ago by Kerrich (1983) in weighing the evidence at that time for possible source of fluids and gold in these types of deposits.

3. Current models for orogenic gold formation

Given the continuing equivocal nature regarding the significance of much of the geochemical and isotopic data for the ore-forming fluids, as presented above, it is perhaps not surprising that debate still rages regarding the genesis of the orogenic gold deposits. This has become particularly more complex as modern mining of these deposits is becoming dominated by low-grade, high-tonnage ores that would have been considered simply distal geochemical anomalies a few decades ago (Fig. 3). Consequently, interpretation of what is an orogenic gold deposit and what is not has become more difficult.

Twenty-five to 30 years ago, Kerrich (1983, 1989b, 1991) summarized the models for orogenic gold formation as lamprophyre-, tonalitic magma-, or oxidized felsic magma-sourced, metamorphic dehydration, lateral diffusion, syngenetic-exhalative, and mantle/granulitization. At the same time, an overview by Nesbitt (1991) also indicated that a meteoric fluid model was highly supported based on stable isotope data. Today, a variety of the metamorphic, magmatic, and mantle models are still favored by different workers, and are evaluated below. The syngenetic and meteoric models are no longer widely accepted, particularly in light of much new geochronological and geochemical data. Furthermore, Kerrich (1991) and Wyman and Kerrich (1989) provided strong evidence against a lamprophyric magma source based upon the fact that Archean shoshonitic magmas have background concentrations of gold and related metals; many lamprophyres are not the same age as gold mineralization where they occur in the same district; many lamprophyres are derived from subduction zone magmatism and not gold-enriched mantle; and most gold-bearing lamprophyres are located in continental rift and oceanic arc environments, which are tectonic settings that lack orogenic gold.

3.1. Magmatic-hydrothermal source in upper to middle crust

In the period from 1900 to 1950, magmatic-hydrothermal models were common for many ore deposit classes, including those that are now termed orogenic gold deposits. Boyle's (1979) book on gold deposits marked somewhat of a watershed in that it aired several alternate models for the deposits, including lateral secretion models, as an alternative to models that involved auriferous fluid exsolution from granite intrusions. Magmatic-hydrothermal models fell out of favor in the 1980s to early 1990s, when gold research blossomed due to the high gold price and resultant intensive exploration. Exceptions included the classification of some Yilgarn craton gold ores as skarn deposits by Mueller (1992), although Groves (1993) pointed out that these hypozonal lodes were better classified as orogenic gold deposits with high-temperature skarn mineralogy as a stable alteration assemblage. Furthermore, intrusion-related gold deposits were summarized by Sillitoe (1991) to not only include porphyry, skarn, and epithermal gold ores, but also vein deposits spatially associated with granites and suggested to be of magmatic-hydrothermal origin. These included the deposits of the Segovia gold belt (Colombia) and the Jiaodong gold province, the giant Muruntau deposit, and the Charters Towers deposit (Queensland). The late 1990s and early 2000s saw a renewal of interest in what were commonly termed reduced intrusion-related gold systems (RIRGS: Thompson and Newberry, 2000; Thompson et al., 1999) and thermal aureole gold deposits (TAGS: Wall et al., 2004). Many world-class to giant gold deposits have been subsequently classified as RIRGS (Fig. 4) or TAGs (Fig. 5), including Kumtor, Muruntau, Vasilikovskoye, and Sukoi Log in Asia, Wallaby in Australia, Obuasi in West Africa, and Pogo in Alaska (Hall and Wall, 2007). These deposits have characteristics that resemble most orogenic gold deposits and it is argued here that it should be classified as such. None of these deposits show the vertical extensional vein sets, thermal disequilibrium, and alteration/metal zonation characteristic of magmatic-hydrothermal deposits. Although deposits such as Fort Knox, Dublin Gulch, and Scheelite Dome, with low gold grades typical of magmatic-hydrothermal Au ± Cu deposits, are definitely best classified as RIRGS of Alaska and Yukon (Hart et al., 2002), the inclusion of the high gold-grade Pogo deposit (12 g/t Au), located in the same region, within this group of ores makes little sense. However, the controversial issue that really needs to be addressed is whether the above world-class gold deposits, which are typical orogenic gold deposits, have a magmatic-hydrothermal fluid and metal source, and thus whether such a magmatic model is critical for the formation of many giant orogenic gold deposits.

In assessing magmatic-hydrothermal fluid models, a major and broad constraint is that, based upon many gold provinces, the timing of gold mineralization relative to that for granitic intrusion is extremely variable. Goldfarb et al. (2008) indicated that in the North American Cordillera, ores can pre-date, be coeval with, or post-date magmatism; Hughes et al. (1997) noted the same variability in eastern Australia. Based upon material from provinces where relatively robust age data are available, it is evident that granitic intrusions exposed within orogenic gold provinces have no constant age relationship to the deposits. Robust geochronology in the provinces of the Yilgarn craton of Western Australia indicates that the granites that host, or are spatially associated with, gold deposits are inevitably older than the ores (e.g., Wallaby; Salier et al., 2005: Cleo-Sunrise; Brown et al.,2002: Kalgoorlie; Vielreicher et al., 2010, 2014). In the Victorian Lachlan province, which includes the Ballarat and Bendigo deposits, the granite intrusions are about 60 million years younger than the most productive gold deposits (Bierlein et al., 2001), and in the South Island of New Zealand there are no major granite intrusions exposed in the gold-hosting Otago terrane. Even if a few dikes or plutons in a province have a similar

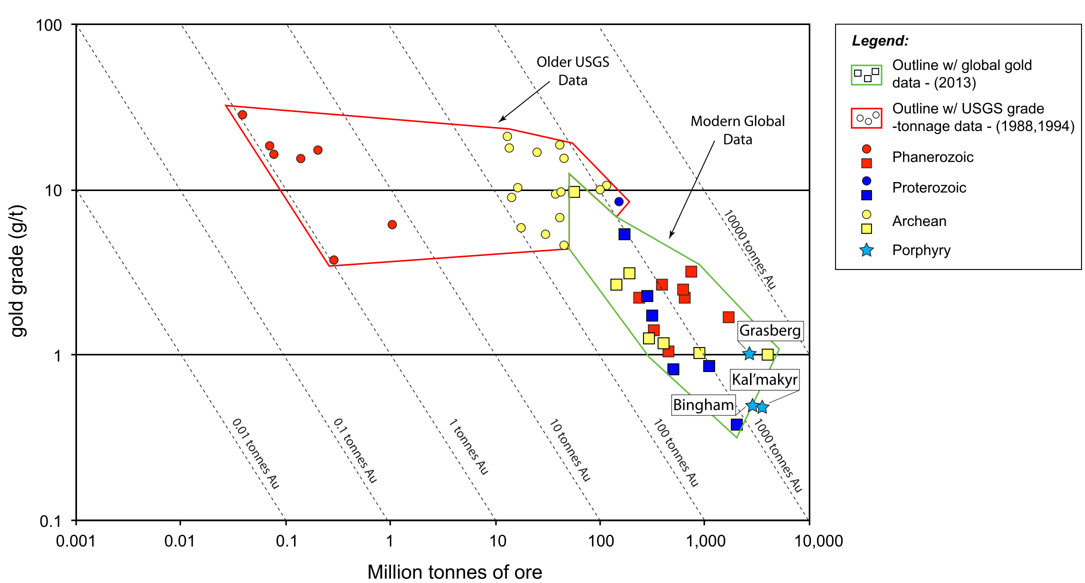

Fig. 3. Grade–tonnage relationships for the largest orogenic gold deposits as reported by USGS (Bliss and Jones, 1988; Klein and Day, 1994) about 25 years ago and resource relationships for orogenic gold deposits as of 2013 (Natural Resource Holdings, 2014). Note that the plotted USGS Phanerozoic data of Bliss and Jones (1988) are quite low in tonnage because these data were reported as three orders of magnitude too low; they should overlap the Precambrian deposits of Klein and Day (1994), with between 100 and 1000 tonnes Au. Importantly, over time, industry has moved from mining high-grade, mainly vein-hosted ores to today's low-grade, higher tonnage ores that include large volumes of altered wallrock. Present-day orogenic gold resources are becoming similar to resources reported for giant gold-rich porphyry deposits.

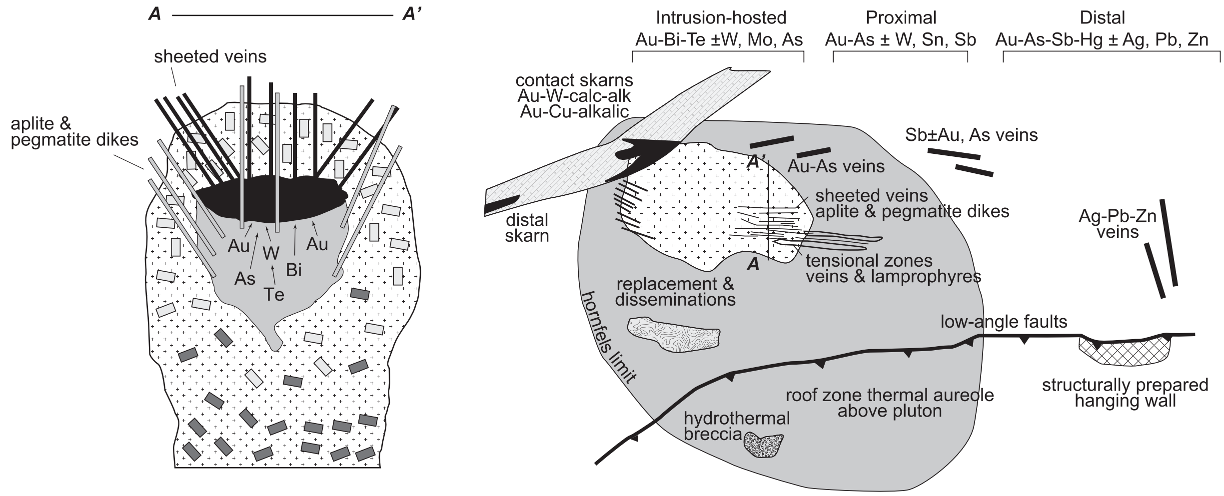

Fig. 4. Reduced intrusion-related gold system (RIRGS) model of Hart et al. (2002) includes auriferous sheeted vein arrays in the cupola of reduced intrusions along craton margins, such as Fort Knox in Alaska and other occurrences in adjacent Yukon, which form low-grade (<1 g/t Au at Fort Knox) bulk-minable targets that are typically uneconomic. The magmatic control on such deposits is well represented by the mineral and metal zoning surrounding the causative stock and the sheeted ore veins. The RIRGS have similar fluid inclusion, isotope characteristics, and W, Te, and Bi enrichments to most orogenic gold deposits, which has led some workers to classify many orogenic gold deposits as RIRGS and to have magmatic fluid and metal sources.

age to the gold deposits, the deposits are commonly numerous and distributed for hundreds of kilometers along major structures, whereas igneous bodies proposed to be auriferous fluid sources commonly do not have the same spatial pattern.

In addition, compositions of granites are extremely variable between different provinces of orogenic gold deposits, as noted by Kerrich (1991). For example, problems with calling upon an association with tonalitic magmas include: (1) an abundance of tonalite prior to 3 Ga, but a paucity of gold; (2) the widespread distribution of Neoarchean tonalites in the Abitibi gold province, but gold ores are localized along structures in just one part of the province; and (3) stable and radiogenic isotope data are commonly inconsistent with a magmatic fluid and metal source (Kerrich, 1986b, 1987). Similarly in the Abitibi belt, Kerrich (1991) noted that many oxidized felsic intrusions pre-dated gold deposition and solely served as competent physical traps for vein formation. The same holds for the young gold ores of southern Alaska, where all types of pre-ore intrusions serve as favorable competent host units. A few hundred kilometers inland from the subduction zone, early Tertiary ores of the Juneau gold belt were deposited within gabbro, quartz monzonite, and monzodiorite of variable ages that provide competent older host lithologies for the largest gold resources, and those of the Willow Creek are hosted by a tonalitic subduction-related batholith. Roughly coeval ores in the more seaward accretionary prism are partly hosted by flysch-melt granite and granodiorite stocks and dikes (Goldfarb et al., 1997).

Wall et al. (2004) suggested that the world's largest orogenic gold deposit at Muruntau is sourced from a granite located 3–4 km below the deposit (Fig. 5). Supporting evidence was stated as contact

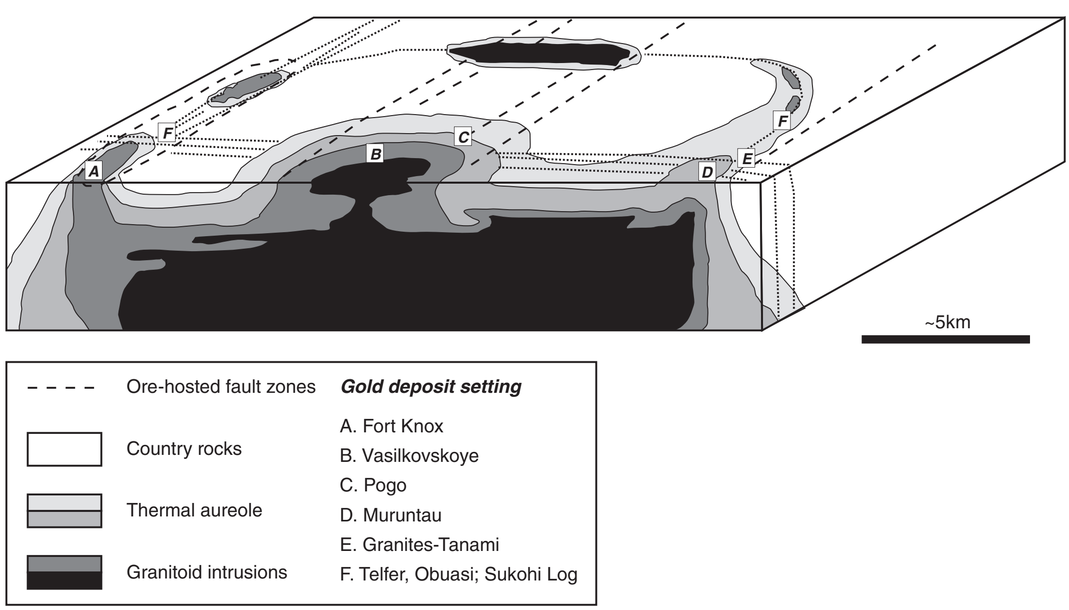

Fig. 5. The thermal aureole tag model of Wall et al. (2004) suggested that many giant deposits in metamorphic rocks, which are mainly classified as orogenic gold deposits in this present paper, are zoned surrounding a causative buried ilmenite-series pluton. Fluids are exsolved from the fractionated granitoid, from devolatilization in the contact aureole of the intrusion, or from convection of surrounding meteoric water. The causative, commonly putative, pluton is interpreted to have formed from mixing of crustal and mantle melts and crystallized at depths >5 km. Many ores are stated to be concentrated within structures related to pluton emplacement. Recognition of roof zones of these buried plutons is stated as a key target for exploration using this magmatic model.
Figure after Hall and Wall (2007).

metamorphism/magmatism dated at the same age as the gold event and ores with anomalous As, Bi, K, Mo, S, Sb, and W. However, core samples from the granite show that the small plug at depth is totally unaltered, and the element anomalies are in no way solely indicative of a fluid exsolved from a melt, particularly given the carbonaceous pelites that make up much of the country rock. Molybdenite is typically not abundant in orogenic gold deposits, yet it is indeed locally anomalous in Muruntau. But it has been noted to be enriched in some orogenic gold deposits (e.g., McCuaig and Kerrich, 1998), so its presence need not indicate a magmatic source. Similarly, Hall and Wall (2007) suggest that deposits such as Pogo, Kumtor, Vasilkovskoye, Obuasi, Morila, Wallaby, and Campbell–Red Lake are examples where large gold volumes have been deposited in the roof zones to buried, mainly reduced intrusions (Fig. 5), but there is little direct evidence for involvement of magmatic-hydrothermal fluids.

Sillitoe (2008) noted that a distinction between pluton-related and orogenic gold deposits could be meaningless, if a magmatic ore fluid model is favored to reflect formation of orogenic gold deposits. He further classified the ores of the Pataz–Parcoy belt in the Eastern Cordillera of the Andes and the Segovia gold belt in the northern Central Cordillera of Colombia as oxidized pluton-related deposits, in contrast to the reduced nature of the gold-associated granitoids described by Hall and Wall (2007). The setting of these Cordilleran-style gold belts resembles that of the Sierra Nevada foothills in California, Juneau gold belt in southeastern Alaska, and Willow Creek in south-central Alaska, with deposits localized near or within sheared margins of large subduction-related batholith complexes. Recent dating by Leal-Meija (2011) suggests that the 88 Ma gold ores in Segovia are much younger than the Jurassic rocks of the host batholith and, similarly, the 315 Ma veins in the margin of the Pataz–Parcoy batholith are 25 m.y. younger than the magmatism that produced adjacent intrusions (Haeberlin et al., 2004). In the latter case, however, Witt et al. (2014) argued that the post-batholith argon ages on hydrothermal mica from the gold deposits may have been reset by post-ore thermal events, although they themselves indicate no magmatism after ca. 332 Ma. Thus, without better supporting data, classification of these ductile–brittle vein systems along the margins of the Cordilleran batholiths as products of magmatic-hydrothermal systems is difficult to justify.

The intimate spatial association between China's most significant lode gold deposits in the Jiaodong province and Jurassic and Cretaceous batholith complexes continues to lead many workers to invoke a magmatic-hydrothermal model. In this rare example where Phanerozoic gold deposits are hosted by Precambrian rocks, ore fluid geochemistry, ore and alteration mineralogy, and particularly the structural setting of the ores, led Goldfarb and Santosh (2014) to argue that these should be classified as orogenic gold deposits. A magmatic-hydrothermal fluid source has been argued for the deposits based upon: (1) the close spatial association of lamprophyre and diorite dikes and plutons with the gold deposits, (2) the lack of carbonate alteration of ore-hosting granitoids, (3) vertical zoning of metals and fluid inclusion temperatures, and (4) hydrogen and oxygen isotope data (Li et al., 2015), as well as (5) a hypothesized voluminous causative granite at depth (Song et al., 2015). However, the spatial association and limited carbonate alteration are not definitive, the buried causative intrusion and vertical zoning are not supported with strong evidence, and the stable isotope data are equivocal. The lack of temporal association between the gold and adjacent batholiths, the actual lack of significant vertical zoning, and the localization of orebodies as products of regional flow along major fault systems, are not consistent with fluid exsolution from a number of upper crustal magmas (e.g., Goldfarb and Santosh, 2014).

The recent change in the definition of an economic orogenic gold deposit (Fig. 3) has further complicated the ability to define if a source is magmatic or not. The Malartic deposit in the Abitibi belt was historically mined by underground methods and the orebodies were typically high-grade veins along shear zones. Modern open-pit mining at Malartic includes a resource that is dominated by what might be described as low-grade alteration distal to the original high-grade veins, but also about 30% of the ore is being mined from what is clearly a low-grade (<0.5 g/t Au) porphyry deposit that predates the shear zone-hosted ore by about 20 m.y. (De Souza et al., 2015). Thus, some of the ore being mined today is unquestionably of magmatic-hydrothermal origin, but this would not have been economic ore unless the more widespread shear-related mineralization with higher gold grades was also present. Helt et al. (2014) defined Malartic as an oxidized example of an intrusion-related gold deposit, although such a deposit type is normally regarded as reduced (e.g., Thompson and Newberry, 2000), in part because of the porphyry mineralization. Other supporting evidence presented for Malartic as a whole, which they regarded as indicative of a solely magmatic-hydrothermal source for most of the resource, is not convincing. This evidence includes widespread K-feldspar–biotite–carbonate alteration, bulk extraction chemistry of fluid inclusion waters that differ from metamorphic brines, a fluid with $K > Na + Ca$, $\delta^{13}C$ for carbonates between −8 and −4‰, and hematite in the alteration sequence, all of which can be products of magmatic or non-magmatic hydrothermal systems. Malartic is thus another example of a hybrid deposit (e.g., Groves et al., 2003), where there is indeed an early oxidized porphyry with low-grade magmatic-hydrothermal gold, but it has been overprinted by a large reduced orogenic gold event of which fluid source need not be magmatic (cf Wallaby and Granny Smith deposits in Western Australia: Groves and Santosh, 2015).

Trace element data have been used recently in some studies of what previously have been called orogenic gold deposits to suggest that magmatic-hydrothermal fluids were critical in ore formation. In the St Ives camp in the Yilgarn craton, Bath et al. (2013) suggested that high K and enrichments of F in biotite and apatite distal to, and in the footwall of, the East Repulse deposit relate to a nearby intrusion that exsolved a magmatic-hydrothermal fluid. They argued that decreases in concentrations of both elements inward towards the ore zone reflected a steep thermal gradient, which is typical of a magmatic-hydrothermal deposit. Traces of oxidized minerals, such as anhydrite, celestine, and barite in the footwall were stated to be additionally consistent with an exsolved magmatic ore fluid, and it was argued that the zoning in F and K is inconsistent with a reduced fluid traveling from the vein outward and being oxidized (e.g., Evans, 2010; Evans et al., 2006). However, the localization of the element and mineral anomalies within an area of footwall granitoids could easily indicate that, rather than any type of zoning, anomalies in K and F might just reflect local wallrock contributions to distal alteration assemblages.

It must be concluded that a magmatic-hydrothermal model cannot be a universal panacea to explain fluid source. Furthermore, there can be no temporal evolution of source as granite-gold relationships show no consistent pattern through geologic time. During the most recent decades, despite extensive new high-precision geochronology and improved analytical techniques, there are few new data to support formation of orogenic gold from magmatic-hydrothermal fluids. Fluids that exsolved from a melt emplaced into the upper or middle crust, therefore, are not the source for this type of mineral deposit.

3.2. Metamorphic crustal fluid

Boyle (1976, 1979) stressed the concept of lateral secretion of gold and other metals from hosting metamorphic-rock sequences to explain the deposits that are now termed orogenic gold deposits. Saager et al. (1982) subsequently concluded that the background sulfides in metavolcanic and metasedimentary country rocks provided the gold during the secretion process. Problems with such a model include: (1) many elements show an outward zoning perpendicular to the auriferous veins, (2) the process is inconsistent with the multiple episodes of hydrofracturing that characterize many deposits, (3) oxygen isotopes show a disequilibrium between veins and highly altered rocks with the more distal wallrocks, and (4) the secretion would make it difficult to explain the concentration of precious metals relative to base metals within locally formed veins (Kerrich, 1983). Furthermore, mass balance calculations suggested that such local source areas could not supply enough of the required gold and sulfur to form large orogenic gold deposits (e.g., Glasson and Keays, 1978). For example, Phillips et al. (1987) calculated that a crustal source area of 500 km^3 would be required to form the giant Golden Mile deposit, implicating regional scale, not local scale processes.

The concept of a metamorphic fluid source was discussed in great detail through the 1980s by Colvine et al. (1984), Goldfarb et al. (1986, 1988), Kerrich and Fryer (1979), Kerrich and Fyfe (1981), and Phillips and Groves (1983), among others. In this model, gold and other ore components, including S, were considered to have been released into metamorphic fluids during greenschist- to amphibolite-facies metamorphism (e.g., Powell et al., 1991; Tomkins, 2010), such that most orogenic gold deposits are located in medium-grade metamorphic rocks (Fig. 6). These fluids were envisioned to have been eventually focused into regional fault systems and moved upward, depositing gold and silica somewhere between about 15 and 3 km (Fig. 2) during seismic events with concomitant periods of major pressure fluctuations (e.g., Cox et al., 1991). Such ore deposition has been considered to most typically occur in rocks of favorable rheology close to the brittle–ductile transition within a late-orogenic tectonic setting characterized by regional uplift (Goldfarb et al., 1986; Groves et al., 1987; Phillips et al., 1996; White et al., 2015) and changing far-field stresses (Fig. 7). It is important to note that the gold in the ore forming-fluid in such a metamorphic model is dissolved and transported at the onset of devolatilization; it is not leached from a specific lithology along the fluid flow path (Phillips and Powell, 2010). Most published fluid inclusion and stable isotope data summarized above are consistent with the concept of a fluid in equilibrium with the crustal metamorphic rocks.

A potential problem raised with the metamorphic model is that the gold deposits are much younger, commonly tens of millions of years younger, than the metamorphism of the ore host rocks (Nesbitt, 1991; Perring et al., 1987), although, as discussed below, there are a few Precambrian examples where deposits are metamorphosed. The post-peak metamorphic timing of gold deposition at crustal levels undergoing retrograde metamorphism, however, has been explained in terms of the earlier attainment of peak metamorphism at deeper crustal levels of the now cooling rocks (deeper-later model of Stuwe, 1998); in other words, fluids produced in prograde environments at depth move up

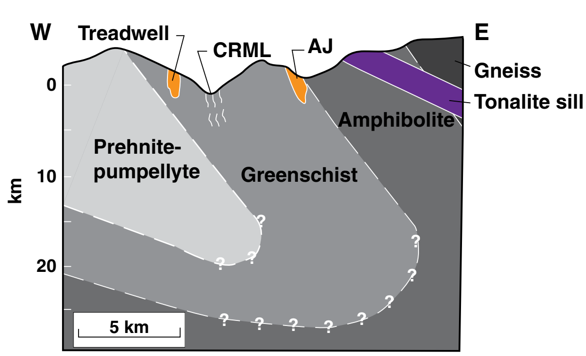

Fig. 6. The metamorphic setting of the Juneau gold belt showing the giant Alaska–Juneau (AJ) and Treadwell deposits are hosted by greenschist-facies metamorphic rocks adjacent to the trans-crustal Coast Range Megalineament (CRML) of southeastern Alaska and within an inverted Barrovian metamorphic sequence. Such an association with deposits forming in rocks subsequent to development of greenschist and other regional facies is very common and such inverted metamorphic sequences are consistent with many deformed allochthonous terranes that are accreted along active continental margins. Some important deposits, however, may be in higher-grade rocks (see Fig. 2), locally reflecting metamorphic overprinting of some Archean deposits and subcrustal fluid sources in other examples (see Fig. 11).
Figure after Goldfarb et al. (1989).

fault systems into rocks that have already been metamorphosed and devolatilized at earlier times. Thus, the continuing argument against a metamorphic ore fluid source because high precision geochronology indicates that metamorphism of ore host rocks long before ore formation (e.g., Doublier et al., 2014) may not be a valid concern. The metamorphic fluids furthermore need not always move upward into rocks that are of lower metamorphic grade. In some scenarios, as detailed by Kolb et al. (2000, 2015), complexities associated with evolving auriferous orogens result in features such as inverted metamorphic gradients (e.g., Juneau Gold Belt: Goldfarb et al., 1988), with underthrusted rocks undergoing greenschist-to-amphibolite facies devolatilization potentially leading to formation of orogenic gold ores in higher metamorphic-grade rocks at higher crustal levels. The Pogo deposit in eastern Alaska (Rhys et al., 2003) may represent one such example.

Gold events that occur late during orogeny, typically during broad changes in far-field stresses (Fig. 7) leading to strike-slip events along earlier compressional structures, regional uplift of thickened crust, and seismically-induced fluid migration (Goldfarb et al., 1991, 2007), do not place ore formation into a post-orogenic scenario, as was recently proposed by de Boorder (2012). In many Cordilleran orogens, these reflect local extensional episodes in earlier accreted terranes, whereas accretionary orogenesis was ongoing in more seaward parts to the orogeny. Hence, in gold provinces such as interior Alaska and Kazakhstan, ores may have formed during transtensional to extensional events late in the evolution of those parts of the Cordilleran and Central Asian orogens, respectively, whereas "early" orogenic events were occurring simultaneously outboard along the continental margins.

An additional problem with the metamorphic model, at least in Archean gold provinces, is the presence of a number of important orogenic gold deposits in amphibolite-facies host rocks (Fig. 2), and one even in granulite, with complex textural features. These deposits were related to metamorphic processes within the descriptive crustal-continuum model of Groves (1993), based mainly on the deposits of the Yilgarn craton of Western Australia, but also on the compilation of Colvine et al. (1988) of deposits in Ontario, Canada. Therefore these were deposits where the ore-forming fluids were produced at higher P–T conditions than the typical greenschist to amphibolite boundary region. Research on several gold deposits in the Yilgarn and Pilbara cratons in high-grade metamorphic rocks indicated that they formed at broadly peak metamorphic conditions: Barnicoat et al. (1991) on the small granulite-facies Griffins Find deposit; Bloem et al. (1994) on several mid-upper amphibolite-facies deposits in the Southern Cross Province; Knight et al. (1993,1996) on the lower- to mid-amphibolite facies Coolgardie deposits (subsequently supported by Miller and Adams, 2013); McCuaig et al. (1993) on similar grade deposits at Norseman in the Eastern Goldfields Province; and Neumayr et al. (1993) on several mid-amphibolite-facies deposits in the Pilbara Block. A broadly syn-metamorphic timing, however, has been challenged for some of these deposits. Tomkins and Grundy (2009) suggested, on the basis of textural evidence, that the Griffins Find deposit was metamorphosed at granulite facies, not formed during high-T metamorphism. On the other hand, Mueller (1997) and Mueller et al. (2004) suggested that several of the Southern Cross deposits in amphibolite-facies terranes formed as skarns tens of millions of years after peak metamorphism. These conflicting timing models on the same deposits illustrate the difficulty of textural interpretation.

In a more general paper on orogenic deposits in world-wide provinces, Phillips and Powell (2009) suggested that the giant deposits at Hemlo, Canada, and smaller deposits at Big Bell, Western Australia, Challenger, South Australia, and Renco, Zimbabwe were metamorphosed after initial formation during greenschist facies metamorphism; thus, the "deeper-earlier" model where a deposit may be pre-peak metamorphism. There is no doubt that Challenger is a metamorphosed deposit (Tomkins and Mavrogenes, 2002), but it is an atypical case because it was formed in the Archean and metamorphosed in a separate orogenic event in the Proterozoic. The recently discovered Magambazi

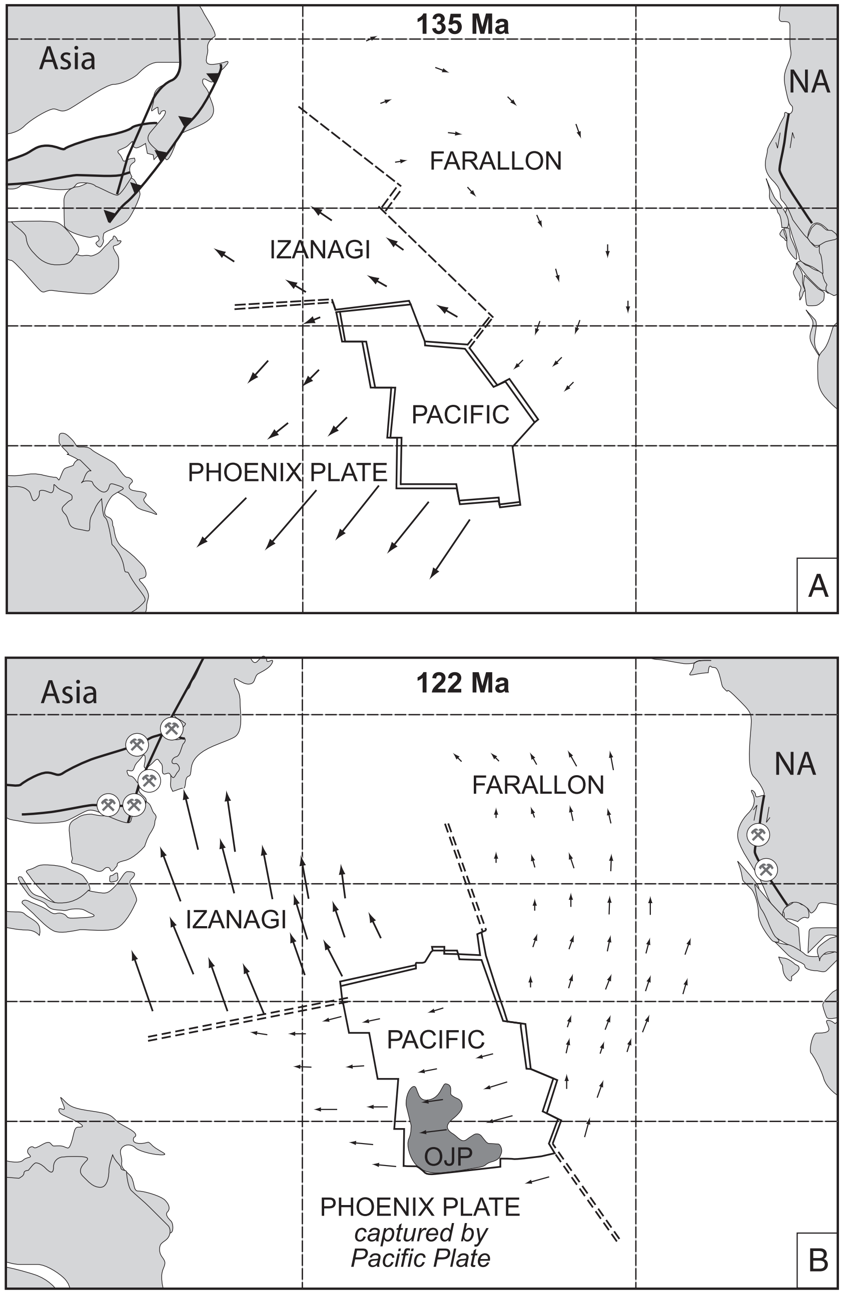

Fig. 7. Changes in far field stresses will reactivate continental margin regional fault systems, leading to seismic events, upward fluid flow, and formation of giant orogenic gold deposits. At ca. 125 Ma, the capture of the Phoenix plate by the Pacific plate led to major changes in plate motions in the northern Pacific basin and orogenic gold formation in both the Sierra Nevada foothills and eastern China.
After Goldfarb et al. (2007).

deposit in Tanzania (D.I. Groves, unpub. data, 2012) is a similar example. There also seems to be consensus that Hemlo mineralization is metamorphosed (e.g., Tomkins et al., 2004), but it is clearly an anomalous deposit with unusual metal and mineral associations that are not normally in equilibrium. Cameron and Hattori (1985) have even suggested that Hemlo was originally a sea-floor epithermal deposit that was overprinted by high-grade metamorphism. The Roberto Elenore deposit in the James Bay region of Quebec has been interpreted to be an orogenic gold deposit that both formed and was metamorphosed to high grades during the Neoarchean (Benoit Dube, oral commun., 2013).

Many workers now tend to favor a retrograde metamorphic timing for other controversial Neoarchean deposits (e.g., Kolb et al., 2015), but there is still considerable debate. Big Bell and Renco illustrate the particular difficulty of textural interpretation. Whereas Phillips and de Nooy (1988) interpreted Big Bell to be a metamorphosed orogenic gold deposit, Mueller et al. (1996) suggested it post-dated amphibolite-facies metamorphism by tens of millions of years. Kisters et al. (1998) originally interpreted the Renco deposit to have formed near the time of peak Archean granulite-facies metamorphism, whereas Blenkinsop and Frei (1996) interpreted it to have formed via retrograde metamorphism during overprinting Paleoproterozoic orogeny. It is now, however, widely accepted as having formed during retrograde upper amphibolite facies metamorphism during the Neoarchean (Kolb and Meyer, 2002). The Tropicana deposit on the edge of the Yilgarn craton similarly is hosted by mid- to upper amphibolite facies rocks, but structural data suggest formation during a Neoarchean post-peak metamorphism hydrothermal event (Blenkinsop and Doyle, 2014).

In summary, the metamorphic model, with fluids being produced at depth under prograde greenschist-to-amphibolite facies metamorphic conditions and depositing orogenic gold ores in a retrograde P–T environment typically near the brittle–ductile transition (Fig. 2), is consistent with many geological and geochemical observations. Little hydrous fluid will be produced beyond the chlorite stability field above about 550 °C to 600 °C, and, furthermore, melting will begin to occur by 650 °C; hence, few orogenic gold deposits form at mid-amphibolite conditions and none at higher metamorphic temperatures (Tomkins, 2010). Although a few of the middle amphibolite facies deposits have probably formed or been remobilized on a prograde P–T curve, most appear to have formed in a peak to slightly retrograde P–T setting. The rare Precambrian deposits that do form at syn- to post-peak metamorphism at depths of 10–15 km and (or) temperatures of at least 600 °C include New Consort (South Africa), Renco (Zimbabwe), Klein Labata (South Africa), Hutti and Kolar (India), Nevoria (Western Australia), and The Granites (Northern Territory, Australia; Kolb et al., 2015). This restriction to the Precambrian may reflect a more complex thermal profile on a hotter early Earth, perhaps even influenced by episodic plume events. Furthermore, although not common, there are important Phanerozoic orogenic gold deposits in high-grade metamorphic rocks of the North China block that are not metamorphosed and these require a source below the continental crust (see section below on "subcrustal fluid source"). Last, rocks might be both metamorphosed and devolatilized by a regional or contact metamorphic event. For example, in the Meguma terrane, Kontak et al. (2011) modeled oxygen isotope data to show that ore-forming fluids were generated by both styles of metamorphism, but the two fluid events were separated by about 30 m.y.

3.2.1. Metasedimentary rock sources for Phanerozoic orogenic gold

If a metamorphic model is favored for the metals and fluids, then a much-debated question remains as to what lithological units provide these ore-forming components. Some workers have argued for gold-rich protoliths, whereas others have suggested that such gold-rich source rocks are not a requirement. As noted above, much of the geochemical data from isotopes and fluid inclusions are equivocal and do not satisfactorily solve the problem. It is also important to note that the Neoarchean and Paleoproterozoic ores in greenstone belts are dominantly associated with metavolcanic rocks, whereas the Phanerozoic gold deposits in the Cordilleran-type continental margin orogens are hosted in terranes comprising mainly oceanic metasedimentary rocks. Given that Precambrian versus Phanerozoic gold endowments in orogenic deposits are broadly equal (Goldfarb et al., 2001; Phillips and Powell, 2015), both rock types should be capable of sourcing a metamorphic gold ore-forming fluid.

The suggestion that sedimentary rocks, particularly carbonaceous and sulfidic mudstone- or shale-rich sequences, were preferentially important sources of gold-bearing metamorphic fluid has been in the literature for some time. Boyle (1966) pointed out that the sedimentary pyrite in the various clastic rocks of the Meguma Group, Nova Scotia, Canada, was a likely source for the gold and other metals in the orogenic gold deposits of the province, a view now accepted by many workers who subscribe to the metamorphic model. Some workers have stressed that black carbonaceous metasedimentary rocks, with typically abundant syngenetic/diagenetic pyrite and thus whole-rock concentrations of tens of ppb gold, are a required source to form large gold deposits in metasedimentary or even metavolcanic rock sequences (Glasson and Keays, 1978; Large et al., 2011; Tomkins, 2010). Other workers have stressed a metamorphic model without any favorable metasedimentary rock protolith; rather any pyrite-bearing lithology within the turbidite sequence as a whole may be devolatilized to yield significant S and Au to form the ores, with metamorphic phase-changes and fluid-focusing efficiency being key parameters (Paterson, 1977; Phillips, 1993).

Trace element data for metasedimentary host rock sequences that host orogenic gold deposits are compatible with a metamorphic model in which they represent the critical source areas for mineralization components. Pitcairn et al. (2006) researched prograde metamorphic sequences in the Otago Schists, a thick sequence of turbidites, with exposed transitions from amphibolite-facies to greenschist-facies domains. They showed that significant quantities of gold, and ore-related elements such as As, Bi, Sb, Te, and W, were liberated from these sedimentary sequences during the progressive metamorphic transitions, producing metal-depleted rocks at depth, with the implication that released fluid carried these elements to higher crustal levels (Fig. 8). This work and mass-balance calculations of rock volumes and gold inventory clearly show the potential for sedimentary rocks to represent a significant source of gold during prograde metamorphism. More recent work in the same region has shown how the pyrite grains in the previously studied metasedimentary rock sequences have lost much of their Ag, As, Au, Hg, and Sb at higher temperatures (Pitcairn et al., 2010). The source mineral(s) for elements such as Bi, Te, and W are still uncertain, although it has been suggested by Large et al. (2009) that Te is also enriched in diagenetic pyrite, making such pyrite also a potentially favorable source-reservoir for the element.

Volcanic rocks within or below sedimentary rock sequences have been argued to be the metal source by some researchers in Phanerozoic orogenic gold provinces. Some workers studying the middle Paleozoic gold deposits of the Victorian province (e.g., Bierlein et al., 1998; Fu et al., 2012; Glasson and Keays, 1978) argued that buried mid-crustal Cambrian volcanic rocks, and perhaps their interflow sedimentary beds, were the likely metal source for the world-class ores. Bierlein et al. (2006) stressed that oceanic volcanic rocks with elevated gold contents are a necessity for the formation of giant orogenic gold deposits, with the abundant CO_2 in the ore fluids being sourced from metamorphosed serpentinized ultramafic rocks and carbonate-rich mafic rocks (Mernagh and Beirlein, 2008) in greenstone belts or accreted oceanic terranes. Most of these arguments were based upon relatively high background-gold concentrations in the volumetrically limited metavolcanic sequences or from equivocal isotope, noble gas, and halogen data.

The limited volume of volcanic rocks in many of these Phanerozoic provinces, and the significant fluid, sulfur, and metal that may be produced from thick metasedimentary rock piles, weighs against a required metavolcanic rock source region without unequivocal evidence. For example, Bierlein and Craw (2009) noted that, although the metabasalts in the Otago Schist of the South Island of New Zealand are significantly enriched in gold, with measured concentrations of as much as 13 ppb Au, their limited volume precludes them from being a significant gold source for the South Island orogenic gold deposits. Furthermore. Pitcairn et al. (2015) noted that metabasaltic rocks in the goldfields of the South Island, New Zealand, although liberating significant gold during prograde metamorphism, did not release significant amounts of arsenic into a metamorphic fluid; rather there was a gain of arsenic in metamorphic rocks with increase in metamorphic grade.

3.2.2. A metavolcanic rock source reservoir for Precambrian orogenic gold?

The Precambrian highly-endowed orogenic gold provinces are developed in supracrustal sequences termed greenstone belts that characteristically comprise thick, lower, arc- to back-arc volcanic rock-dominated sequences that host most of the major deposits and are overlain by thick, largely unmineralized metasedimentary rock successions, except in parts of West Africa and northeastern South America. Therefore, although a sedimentary rock source for gold-bearing metamorphic fluids is plausible for Phanerozoic orogenic gold provinces, where world-class to giant deposits are hosted in thick turbidite sequences, it cannot be a valid option for Archean provinces and it is also unlikely for many Paleoproterozoic provinces.

Tomkins (2013) suggested that oxygenation of the oceans during the 2nd Great Oxygenation Event at ca. 635–510 Ma may have been critical for an abundance of gold in oceanic pyrite during the Phanerozoic. It is suggested that, at the higher oxygen levels, gold was more soluble in

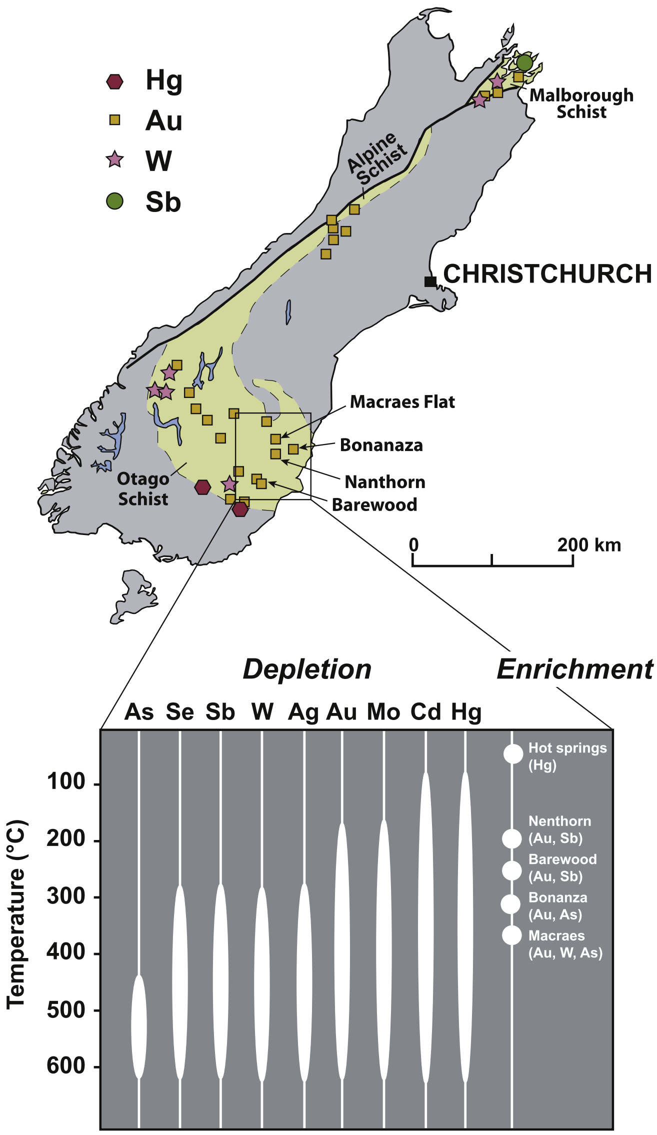

Fig. 8. Orogenic gold deposits are widespread in the schist belts of the South Island of New Zealand. Pitcairn et al. (2006) have shown that metals enriched in deposits hosted in the eastern side of the Otago schist are all depleted in the same host rocks in deeper parts of schist belt. This work elegantly indicates that in such metasedimentary rock sequences, metals, and not just fluids, are produced during prograde metamorphic events at depth.

ocean waters, and was destabilized and incorporated in marine pyrite in areas of bacterial sulfate reduction. If this hypothesis is correct, it would hold for the Phanerozoic, but not for the more reduced Precambrian oceans. Therefore, an alternative source to sedimentary rock pyrite for S and Au would be required for the older orogenic gold lodes. In contrast, Large et al. (2014) showed that Archean and Phanerozoic sedimentary pyrite had similar arsenic concentrations (no gold data were included) and Steadman et al. (2015) indicated that synsedimentary to early diagenetic pyrite in interflow shale at the Late Archean Golden Mine deposit contained anomalously high primary gold concentrations. The Archean had hotter and more voluminous volcanism (Herzberg et al., 2010), so intuitively it might be expected that there was more metal to be exhaled and incorporated in pyrite or absorbed on to pyrite surfaces.

More than 95% of all Neoarchean orogenic gold deposits are hosted in the lower parts of a metavolcanic rock-dominated sequence. They are commonly capped by metasedimentary rocks, which provide rheologic and permeability contrasts with the underlying more brittle host rocks. This repetitive geometry was a major factor in now-defunct models of the 1980s (e.g., Hutchinson and Burlington, 1984) that the gold deposits were syngenetic exhalative deposits sited at the ancient sea-floor marked by the volcanic to sedimentary rock transition. Seismic profiles across Archean terranes (Swager et al., 1997) indicate that there are no sedimentary sequences at the base of exposed volcanic successions. Hence, there is no viable crustal sedimentary rock source for metamorphic fluids. There are interflow sedimentary units, which may be carbonaceous and sulfidic shales (e.g., Vielreicher et al., 2010), within the volcanic rock sequences that host the deposits, but these are characteristically only a few meters thick and seemingly could not have provided a sufficient volume of gold-rich fluid to explain the gold inventory of the deposits, despite evidence that some may contain pyrites with very high gold contents (e.g., Steadman et al., 2015).

In Paleoproterozoic greenstone belts, there are orogenic gold deposits in (1) the lower volcanic rocks, but commonly at the contact between volcanic and sedimentary rocks (e.g., Obuasi, Ghana), (2) within the overlying to lateral sedimentary successions (e.g., Damang, Ghana), and (3) in granitic intrusions (Ahafo, Ghana) (Allibone et al., 2002; Anonymous, 2007; Leube et al., 1990). If a single fluid and metal source is envisaged for all these deposits with similar structural and mineralogical characteristics, it cannot be the sedimentary sequences in the mineralized belts, although some deposits (e.g., Obuasi) in the provinces are characterized by solely carbonic fluid inclusions, as noted above. Nevertheless, Lambeck et al. (2011), although mainly concerned with chemical traps for ores, stressed the spatial correlation between orogenic gold provinces and Paleoproterozoic supracrustal sedimentary rock sequences, particularly in northern Australia. Many of these represent back-arc basins that were metamorphosed during the growth of the Columbia (Nuna) supercontinent. Thus, it is most likely, that, if the metamorphic model is favored for the Paleoproterozoic orogenic gold deposits, some provinces must have metavolcanic-rock source regions and others metasedimentary rock source regions in the mid-crust.

Supracrustal sedimentary source rocks are improbable in Archean provinces, and thus proponents of the metamorphic model working in such terranes have concentrated on the volcanic sequences as a potential gold and fluid source. The fact that Archean sequences contain high-Mg basalts and komatiites, that are commonly extensively carbonated prior to metamorphism, lends credence to this concept, particularly as fluid inclusions from Archean deposits tend to have higher CO_2 contents than those from Phanerozoic deposits. Fyfe and Henley (1973), Groves et al. (1987), and Kerrich and Fyfe (1981) favored devolatilization of stratigraphically deep greenstones for the Archean metamorphic model. Workers have recently argued that black shales were the source of gold in the deposits of the Yilgarn craton (Steadman et al., 2013), but, again, there is no evidence to support their required hypothesis that significant volumes of pyrite-rich sedimentary rock underlie many of the productive greenstone areas.

Phillips et al. (1987) demonstrated through mass balance calculations that, even at 1–2 ppb levels in the largely basaltic to andesitic volcanic rocks, sufficient gold could be liberated during metamorphism to form even giant deposits such as Kalgoorlie because the spacing between the larger deposits is 20 to 50 km. Hronsky et al. (2012) further pointed out, on the basis of limited analytical data, that back-arc basalts that are common in the greenstone belts may represent source rocks with higher gold contents than envisaged in previous mass-balance calculations. Furthermore, large volumes of aqueous-carbonic fluid are generated during the greenschist-to-amphibolite transition during metamorphism of basalts (e.g., Elmer et al., 2006; Powell et al., 1991). Thus, lower sequences of largely basaltic–andesitic volcanic rocks are potential, but not proven, sources of fluid and metals during prograde metamorphism in Precambrian terranes. The recent study of Pitcairn et al. (2015) presents one concern as it shows that arsenic, highly anomalous in many Precambrian orogenic gold deposits, was not liberated during metamorphism of basalt in New Zealand. It is uncertain whether this applies to all basalts, and particularly Precambrian basalts as a whole.

3.2.3. Conclusions on a crustal metamorphic fluid

A metamorphic fluid- and metal-source model appears to explain most orogenic gold provinces, although much of the isotope and fluid inclusion data are equivocal, and supporting data for the Precambrian are particularly limited. The generation of the low-salinity H–C–O–S–N hydrothermal fluid is inherent to devolatilization associated with the breakdown of phases such as chlorite, carbonate minerals, and pyrite during greenschist to amphibolite facies reactions. Calculations by Elmer et al. (2006) showed as much as five volume percent of a mafic igneous rock can be converted to this type of fluid. Similar fluid volumes are described by workers for metapelite sequences (Fyfe et al., 1978), indicating that extensive fluid volumes have been produced in the mid-crust, whether within Archean greenstones or young metasedimentary rock terranes. Equally significant, is the calculation that a mafic igneous rock averaging 2 ppb Au can adequately provide sufficient gold to the hydrothermal fluid to form a giant ore system (Phillips and Powell, 2010) provided that there is a mechanism to effectively channelize or focus flow. This indicates that although likely helpful, a favorable protolith is not a necessity for forming an orogenic gold deposit, and both mafic igneous rocks, as well as sedimentary rocks are theoretically capable of sourcing fluids and most of the metals for the model.

The metamorphism required by the gold genesis model may be the consequence of various different tectonic processes. Goldfarb et al. (1998) showed that crustal thickening (Juneau gold belt), ridge subduction (Chugach accretionary prism) or slab rollback and extension (Seward Peninsula) in the Cretaceous–Tertiary of Alaska all could result in regional metamorphism (Fig. 9). Furthermore, as noted above in the Paleozoic Meguma terrane (Kontak et al., 2011), a broad contact metamorphic event driven by magma emplacement can also lead to significant devolatilization and orogenic gold formation.

On the hotter, early Earth, there is much more limited knowledge of the broad-scale processes that drove regional metamorphism. Brown (2008) examined the secular evolution of metamorphism as it related to the Earth's changing thermal regime. He noted the limited high-pressure to ultra-high-pressure belts prior to about 600 Ma and correlated this to increased cold-slab subduction since the late Neoproterozoic. All of the abovementioned tectonic events of Goldfarb et al. (1998) that led to regional metamorphic belts would have been the product of this younger Cordilleran-style subduction–accretion orogenesis. Furthermore, the classic, commonly inverted well-developed and relatively narrow Barrovian style metamorphic belts that are the host for many Phanerozoic orogenic gold provinces (Fig. 6) are not obvious in the Precambrian. There is an obvious association of gold with greenschist and the brittle-to-ductile transition back to the Archean, but within broader areas of greenschist facies in the metavolcanic-rock dominated greenstone belts. This might reflect the greater control of plume activity on the evolution of metamorphic gradients in the older Earth environment (Fig. 9B). The effect of a more plume-controlled metamorphic event on formation of orogenic gold deposits is uncertain; if the metamorphic model is indeed correct for gold genesis in the Precambrian,

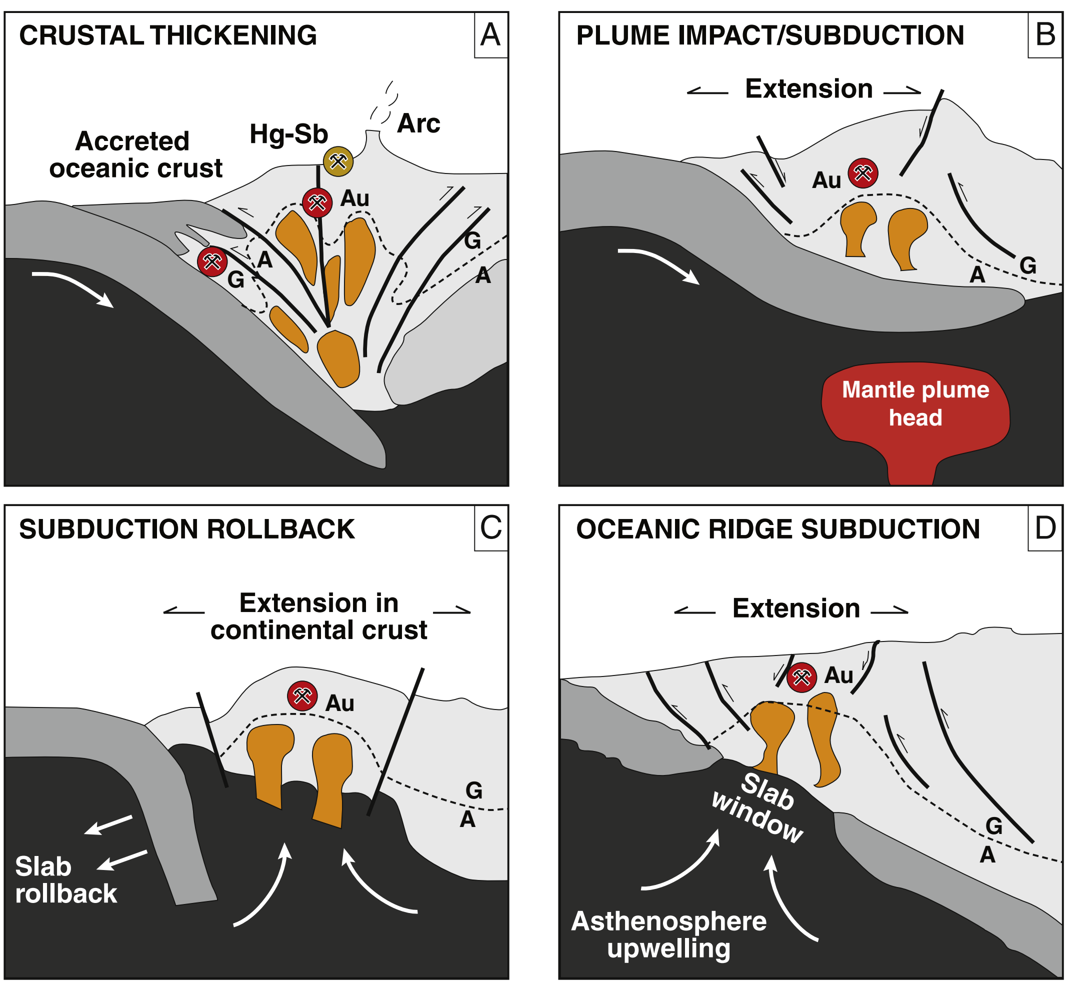

Fig. 9. Possible subduction-related scenarios that might lead to devolatilization of accreted oceanic rocks along an active continental margin. These include radiogenic heating and development of inverted Barrovian metamorphic sequences in areas of thickened crust (A); extensional structures (C) or metamorphic core complexes developing where slab rollback and asthenospheric upwelling occur; or heating the base of an accretionary prism during subduction of a spreading ridge (D). Where a mantle plume may impinge upon the base of the crust, particularly on a hotter Earth during Archean times, regional metamorphic sequences in greenstone belts may have some ultimate relationship to the thermal episode (B). Dotted line represents greenschist (G)–amphibolite (A) boundary.

then there seems to be little difference in gold endowment potential with age (except for paucity in Mesoproterozoic–early Neoproterozoic: Goldfarb et al., 2001) and thus style of metamorphism.

3.3. Sub-crustal fluid/metal source

3.3.1. Slab subduction

The above described metamorphic model for orogenic gold formation can explain many of the deposits, with ore-forming metamorphic fluids being generated within the mid-crust near the base of the seismogenic zone, and then cyclically entering into and moving upward along rupturing fault systems (e.g., Sibson et al., 1988). There are some important Phanerozoic orogenic gold deposits, however, that clearly do not fit this model. Examples include the Cretaceous orogenic gold deposits on the northern, eastern, and southern sides of the eastern North China block, and Tertiary deposits along the Megashear Zone of northern Mexico. In these cases, the Precambrian crustal rocks that host the orogenic gold deposits have experienced high-grade metamorphism long before ore formation. Crustal rocks at the surface in these anomalous Phanerozoic provinces already have been uplifted from areas where regional metamorphic temperatures were at least 500–600 °C, and thus any metamorphism of rocks at deeper crustal levels would likely lack significant sulfur and gold, as most pyrite had already converted to pyrrhotite. Perhaps more importantly, where rocks have already gone through Precambrian granulite-facies metamorphism and partial melting in northern China, there is no water remaining to form a hydrothermal fluid during much later Mesozoic tectonism.

The gold-rich eastern half of the North China block represents a region of significant lithospheric erosion and thinning of originally thick buoyant Archean sub-continental lithospheric mantle (Griffin et al., 1998), caused by complex Mesozoic slab subduction from the north, south, and east, which led to slab devolatilization, subsequent melting and magmatism, and lithospheric erosion (Windley et al., 2010). The associated so-called Yanshanian orogeny, that occurred within the decratonized North China block and not in continental margin terranes, is reflected by basement uplift, regional extension, ca. 165–90 Ma magmatism, and ca. 130–120 Ma orogenic gold formation within the three margins on the eastern half of this uplifted cratonic basement (Goldfarb and Santosh, 2014; Santosh et al., 2010). The structural control and the more protracted period of gold mineralization argue against the magmatic-hydrothermal fluid model described above, and the Precambrian high-grade metamorphism of the basement rocks argues against the above-described crustal metamorphic devolatilization fluid model for the gold event. Nevertheless, the widespread gold episode correlates with changing far-field stresses and plate reorganizations, which would have enhanced fluid flow upward along the Tan-Lu and other major fault systems (Goldfarb et al., 2007).

The Early Cretaceous deposits of China's largest gold provinces of the Jiaodong Peninsula, located on the eastern side of the North China block, provide a unique insight into the potential for subducting slabs and/or overlying mantle wedges to provide fluids and metals for orogenic gold-deposit formation. Although somewhat controversial, the Jiaodong deposits have generally been classified as orogenic gold deposits (Goldfarb et al., 2001, 2005; Wang et al., 1998). They show no close spatial relationship to granitic intrusions of similar age, or evidence of thermally-induced metal zonation, but they have clear structural control along regional faults and fluid inclusion/stable isotope chemistry identical to most other typical orogenic gold deposits. Importantly, however, whereas orogenic gold deposits typically are formed within 50–200 m.y. of the deposition of their host volcanic or sedimentary rock sequence (Goldfarb et al., 2001), the Jiaodong deposits formed at ca. 126–120 Ma, some 2 billion years after their host rocks were deposited, deformed, and metamorphosed under high P–T conditions. Thus, prograde metamorphism of supracrustal host rocks cannot have provided the auriferous fluids responsible for gold mineralization, and a sub-crustal fluid and metal source is thus required.

Upward fluid movement from devolatilization of a subducting slab is a well-recognized process in fore-arc regions (Fig. 10). In contrast, once higher temperatures are reached in arc regions, any mobile fluid phase will cause melting. Large fluid volumes can travel up-dip along slab-mantle boundaries (Peacock, 1990; Peacock et al., 2011; Sibson, 2004), eventually entering fault zones at shallower levels near the base of the crust, and subsequently forming gold deposits, as suggested for Otago (Breeding and Ague, 2002) and elsewhere (Hyndman et al., 2015). Such movement of a metamorphic fluid released from an oceanic slab, and particularly the overlying oceanic pyritic sediments, begins once the base of the fore-arc mantle wedge is fully hydrated (Katayama et al., 2012). Kawano et al. (2011) indicate that, at slab depths of less than about 100 km and temperatures of 650 °C, the highly sheared serpentinized layer at the bottom of the corner of the mantle wedge represents a particularly permeable zone for such slab dewatering.

Goldfarb and Santosh (2014) evaluated the sub-crustal possibilities for an ore-forming fluid for the Jiaodong gold deposits. The only reasonable sources for the auriferous and sulfur-bearing Jiaodong ore fluids were viewed as fluids released during progressive metamorphism of oceanic lithosphere and (or) overlying oceanic sediments (Fig. 11). It is impossible to define the paleo-Pacific slab angle below the eroded North China block lithosphere some 125 m.y. ago, but the released fluids could have traveled up-dip to the transcrustal Tan-Lu fault system. The data on enrichment of gold and related elements in syngenetic pyrite from ocean-floor sedimentary rocks by Large et al. (2009, 2011) assumes particular importance here, with such sediments being the most likely sources of Au and S for pulses of C–O–H fluid entering the major secondary faults to the Tan-Lu system. Alternatively, rather than fluids going directly into and upward along the ore-hosting structures, fluids could serpentinize the corner of the mantle wedge, adding important components such as S, C, and Au into the region above the slab, although relative fluxes of many of these components into the wedge are still very poorly known (e.g., Evans, 2012). A subsequent thermal event would devolatilize the enriched mantle wedge to release ore-forming fluid, although any fluid released at high temperature or channeled up a thermal gradient should become part of a melt. Such a fluid release event might result from cessation of subduction, a stalled slab, or a slab window, as summarized by Seno and Kirby (2014). They indicate that a thermal pulse and mantle devolatilization in the wedge would take place about 10–25 million years after subduction of a slab ceased. Wyman and Kerrich (2010) suggested that such devolatilization of a subducting slab and associated sedimentary cover could have extended back to the Archean and would be particularly favored by relatively flat slab subduction. The latter geometry would lead to a narrow depth range for release of fluids and metals at shallow levels, which were channeled into an eventual frozen and non-convecting mantle wedge that was itself devolatilized during eventual sinking of the slab.

This is again a hypothetical model that cannot be proven using any unequivocal analytical data available, although radiogenic isotope, halogen, and noble gas data are taken as indicative of such in many studies (see above) and studies of these components in many crustal-scale fault zones, such as the San Andreas fault system (Kennedy and van Soest, 2007; Pili et al., 2011) and Karakorum fault (Klemperer et al., 2013), indicate that mantle fluids reach the shallow crust. The attraction of such a model as was proposed for the Jiaodong deposits is that orogenic gold deposits inevitably form due to heating of new crust and such crust is always being subducted in the tectonic setting defined for orogenic gold, suggesting a fundamental connection. Essentially, such a sub-crustal model for metals and fluid is similar to the upper- to middle-crustal metamorphic model, in that in both cases, fluids and metals are being sourced from the volcano-sedimentary products of new oceanic material being added to an active continental margin. However, in the sub-crustal model, fluids and metals are being added directly from the oceanic material subducted below the margin and not from material accreted to a craton.

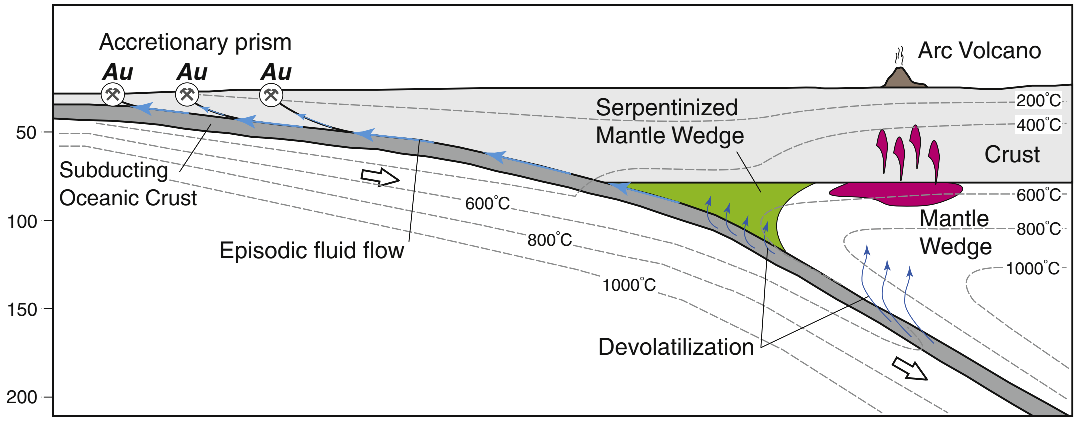

Fig. 10. Fluids released during devolatilization of a subducting slab at approximately temperatures below 650 °C and depths of 100 km may either fertilize the above mantle wedge or, particularly once the wedge is fully hydrated, travel up-dip along the interface between the slab and the overlying serpentinized wedge or base of the lithosphere. Where these slab-derived fluids intersect deep-crustal faults, they may move upward to form orogenic gold deposits. At higher temperatures along the subduction zone, fluids will cause melting of the wedge and be thus will be totally miscible within these arc regions.

World-wide there is also a temporal connection to a change from compression to transpression in orogens (e.g., Groves et al., 2000). This must be related to a change in the orientation of the maximum principal stress in the regional stress field that, at least in some younger examples (Goldfarb et al., 1991, 2007), represents a change in plate motion. Such a resulting stall in subduction of the originally convergent oceanic slab could lead to rapid heating, devolatilization, and a relatively short-lived period for advection of sub-crustal fluids up faults that extend to the Moho (e.g., Seno and Kirby, 2014).

It is therefore not unreasonable to suggest that similar sub-crustal processes may define other Phanerozoic gold provinces where high-grade metamorphic rocks host unmetamorphosed orogenic gold deposits. The southern margin of the North China craton for example, defined by the Qinling gold province, China's second largest gold producer, is also characterized by young orogenic gold deposits in Archean rocks. Nevertheless, the equivocal nature of the geochemical data, with mantle signatures for rare gas isotopes in fluids extracted from fluid inclusions, and magmatic signatures defined by hydrogen and oxygen isotope data, coupled with a spatial association with shallow crustal granitoids, have led workers such as Li et al. (2012) to call these intrusion-related gold deposits. In contrast, however, in a scenario very similar to that described above for the Jiaodong province, Chen et al. (2008) suggested that the subducting Proterozoic cover sequences on the leading edge of the underthrusted South China block were important sources for the gold ores in the overlying Neoarchean crustal rocks of the North China block. It is argued here that the structural

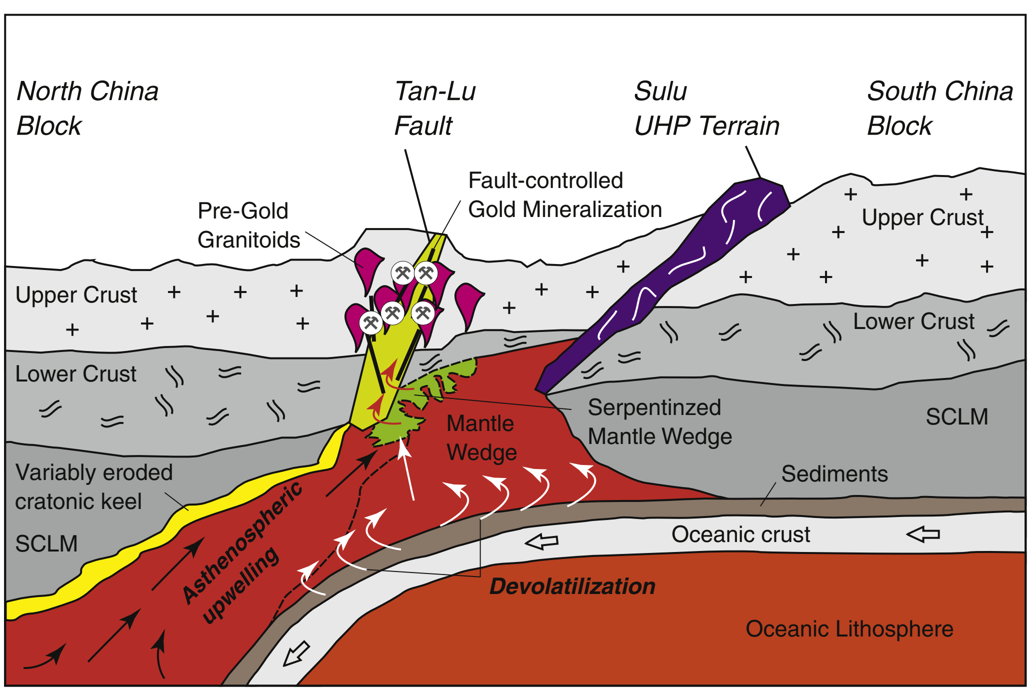

Fig. 11. Permissive scenarios for gold formation in high-grade metamorphic rocks with a subcrustal fluid and metal source. As shown by Goldfarb and Santosh (2014) and Groves et al. (in press) for the Jiaodong area of eastern China, gold formation post-dated metamorphism of the crust by two billion years. They argued that the source of the fluids and metal may have been from a ca. 125 Ma dehydration, decarbonization, and desulfidation of subducting oceanic sediment and/or the underlying basalt of the subducting paleo-Pacific plate, particularly if a relatively low slab angle characterized late Mesozoic subduction. Fluids would have been channeled into the continental-scale Tan-Lu fault system, which is rooted in the asthenospheric mantle below the greatly thinned lithosphere. Alternatively, released fluid and metal may have been temporarily stored in the fertilized mantle wedge for tens of millions of years and subsequently released into the Tan-Lu fault system by some type of heating event in the wedge at ca. 125 Ma.

setting of the young deposits in the high-grade metamorphic rocks, with ores located along deep-crustal faults and regional fold hinges, is again inconsistent with local magmatic fluid exsolution, and that a sub-crustal source, such as envisioned by Chen et al. (2008), is necessary. In northwestern Mexico and southernmost Arizona, reactivated Proterozoic crust, also defining a major crustal shear zone between Phanerozoic sequences, contains Tertiary orogenic gold ores (Iriondo, 2001). Goldfarb et al. (2007) noted that the uplifted high-grade Precambrian basement hosts the deposits in extensional features within metamorphic core complexes, similar to those that host many of the deposits of the North China block discussed above.

Whether such a sub-crustal fluid and metal source can be universally applied to many Precambrian and Phanerozoic orogenic gold provinces cannot be determined from existing data. One of us (RJG) argues that the more typically accepted mid-crustal source is more likely, with a broad change from mafic to sedimentary source-rocks throughout Earth history, whereas the other (DIG) suggests that a sub-crustal source, with fluids coming directly from the top of a stalled slab, may be the model most consistent with formation of orogenic gold, best explaining the consistent late-metamorphic timing coincident with transition from late-orogenic compression to transpression in orogenic gold provinces of all ages. In the first model, Jiaodong is the exception, and in the second model, Jiaodong is the key end-member of the orogenic gold deposit group.

3.3.2. Other sub-crustal possibilities

Whereas ore-forming fluids and metals released from slab devolatilization represent one possible sub-crustal source, a number of other concepts have also been suggested recently. One model argues for a fluid released from gold-rich magma derived from fertile subcontinental lithosphere. Others relate to mantle magmas rising and melting the lower crust, and to emplacement of mantle plumes. Each of these is also difficult to prove, particularly given the equivocal nature of the associated geochemical data from the ore deposits.

Hronsky et al. (2012) suggested that a fertilized subcontinental lithospheric mantle (SCLM) is required to explain the gold distribution in accretionary orogens. They noted that either an auriferous hydrothermal fluid or a gold-rich magma released from the SCLM ultimately sourced most gold deposit types in active continental margins, but emphasized intrusion-related gold, Carlin-type gold and iron–oxide–copper–gold deposits rather than orogenic gold deposits. Griffin et al. (2013) subsequently also hinted at a magmatic fluid source for many gold ores, including possibly orogenic gold, where the gold in such fluids is initially added to the melts when ascending mantle magmas incorporated metasomatized SCLM that has high background concentrations of gold. In contrast to asthenospheric mantle with about 1 ppb Au and non-refertilized lithospheric mantle, the fertile SCLM may be enriched in gold by fluids above a subducted slab, particularly one being underthrust at shallow angles. It is noted from xenolith data by Griffin et al. (2013) that such enriched SCLM may contain as much as 14 ppb Au and also host pyrite with as much as 5 ppm Au. Hence, such deeply formed magmas with a SCLM component are permissive sources for fluids and metals for gold deposit types on craton margins (Groves and Santosh, 2015). However, as further pointed out by Hronsky et al. (2012), and emphasized by Groves and Santosh (2015), the well-recognized lack of spatial correlation between mantle melts and the orogenic gold deposit-type specifically remains a concern when calling upon a model that invokes involvement of gold-rich SCLM in the orogenic gold ore-forming process.

The fertilized SCLM model introduced two additional concepts to the sub-crustal ore-forming model. First, Hronsky et al. (2012) argued that subsequent to fertilization of a supra-subduction mantle wedge, gold was remobilized into the overlying upper mantle, from where it eventually was mobilized again into the crust by fluids or melts during a subsequent thermal event. This additional step is certainly possible, but again essentially impossible to prove from geochemical study of consequential gold deposits. Furthermore, at least for the North China block situation, the SCLM was actively eroding for tens of millions of years prior to the gold event and thus such a lithospheric mantle source would be questionable (e.g., Bierlein et al., 2009). Second, Hronsky et al. (2012) favored this model to be a feasible model for most orogenic gold provinces, pointing out the Victorian goldfields could have been sourced from fragments of old lithosphere below the Paleozoic metasedimentary sequences. However, many North American Cordilleran gold provinces are formed in terranes comprising oceanic crust and overlying turbidites, without any ancient SCLM at depth (e.g., Chugach accretionary prism of southern Alaska; Sierra Nevada foothills of central California). Thus a sub-crustal model calling upon a significant role from enriched SCLM seems unlikely to be a scenario that can be widely applied to the formation of orogenic gold.

De Boorder (2012) called upon basic mantle magmas melting the lower crust to release pseudo-metamorphic fluids that formed Muruntau and many of the other giant late Paleozoic orogenic gold deposits in central Asia. He noted an important temporal correlation between mantle-sourced magmatism and orogenic gold deposit formation both in the central Asia region and in the Hercynian gold deposits of southern Europe. Such a similar granulitization model for Neoarchean orogenic gold-deposit formation, arguing for the advection of mantle CO_2 through the lower crust, was previously favored by workers such as Cameron (1988) and Fyon et al. (1984), and most recently by Fu and Touret (2014). However, as outlined by Kerrich (1989b,c), there are many obvious problems that invalidate such a model, including: (1) except for the rare charnockites, the link between mantle CO_2 and granulite formation is lacking, and CO_2 flux volumes are incapable of causing regional granulitization; (2) $\delta^{13}C$ data of granulite facies minerals are not consistent with a mantle carbon source; (3) carbon in granulite facies rocks is typically of biogenic, not mantle, origin; (4) most fluid inclusion data from orogenic gold deposits are far less CO_2-rich than would be expected for a fluid produced during carbonic metamorphism; (5) granulites are not noticeably depleted in gold; and (6) in some large gold provinces, granulitization clearly is pre-gold. Thus metamorphism of the lower crust is unlikely to be an important factor in orogenic gold formation.

Bierlein and Pisarevsky (2008) called on a hybrid mantle plume/metamorphic devolatilization process for coeval formation of the orogenic gold provinces in eastern China and the California foothills, and perhaps the South Island of New Zealand. They proposed that the rich gold endowment along the margins of both the North American and Asian continents reflects an intra-oceanic plume that formed oceanic plateaus. Basalts within such plateaus were stated to be enriched in elements such as As, Au, Sb, and Te, part of the more common suite of trace elements in most orogenic gold deposits, and thus were viewed as favorable metal source reservoirs. A scenario was envisioned where fragments of a pre-180 Ma oceanic plateau, perhaps of Permian age, were subducted below both continental margins at ca. 120 Ma and devolatilized. However, as the authors stated themselves, signatures for such mantle plume-related source rocks for either magmatism or hydrothermal activity have not been recorded in the Sierra Nevada foothills and there is no evidence for this event in eastern China, so it remains a model without supporting data. Whereas metamorphism, in the crust or sub-crust, and magmatism were clearly part of Cordilleran (North America) and Yanshanian (eastern China) orogeny, the requirement of a favorable, mantle-derived protolith has not been proven.

Webber et al. (2013), similarly, noted oceanic basalts produced from mantle plumes were enriched by an order of magnitude in gold. But their enrichments for plume-related rocks, reported as ranging from 0.21 to 4.22 ppb Au, appeared to be essentially the same as background concentrations of normal MORB of 0–4.5 ppb Au. In either case, concentrations of a few parts per billion gold in basalt are typical of concentrations in many rocks and do not really reflect an enriched protolith.

It is unclear if and how a direct mantle plume could relate to orogenic gold formation. Above it is noted that fluid exsolution from a melt in the upper to middle crust, whether or not the melt is even from the mantle, is an unlikely process for orogenic gold formation. Furthermore, a fluid streaming from the mantle (e.g., Newton et al., 1980) would be much more carbonic than the 5–20 mol% CO_2 fluid typifying most orogenic gold deposits. However, as mentioned in many places above, indirect contributions from the mantle, mainly controlling thermal regimes that lead to devolatilization of sedimentary and (or) volcanic rocks, must be considered (e.g., Bierlein et al., 2006; Goldfarb et al., 1998). At least in the Phanerozoic, processes such as ridge subduction, slab roll-back, and SCLM erosion are associated with asthenospheric upwelling, high geothermal gradients, and regional metamorphism. In the Precambrian, specifics of formation and evolution of auriferous greenstone belts remain controversial, but involvement of plume episodes on the hotter Earth were clearly critical (e.g., Kerrich and Polat, 2006). It is also possible that many of the Phanerozoic subduction processes were active in the Precambrian (e.g., Wyman and Kerrich, 2010; Wyman et al., 1999), although the SCLM keels below the cratons and lack of clear Cordilleran-type orogenic belts indicates some important differences.

4. Conclusion: single deep source or temporal evolution?

Whether one envisages a constant single fluid source for orogenic gold deposits or, alternatively, a variety of fluid sources producing similar ore fluids that vary with tectonic environment or geological time is at least in part a philosophical decision. There is inevitably a philosophical division of "lumpers" vs "splitters" prevalent in all walks of scientific endeavor, including economic geology and ore genesis. As discussed above, Groves et al. (1998) and Phillips and Powell (1993), followed by Goldfarb et al. (2001, 2005), took a "lumpers" perspective to group a large number of lode gold deposits with often varied genetic, spatial, temporal, and (or) host-rock categorized nomenclature, into a single broad deposit class. The question is, having grouped these deposits into the orogenic gold category, is it most logical to assume a single coherent origin for constituent fluids, sulfur, and metals or to accept that the deposits formed during orogenic processes over virtually the entire preserved geological history of the Earth in tectonic and lithospheric settings that changed with time and hence that deposit formational processes might show compatible variation? Certainly, deposits of other metal groups show temporal variations in their genesis that are related to changes in tectonic processes, and nature of the lithosphere, hydrosphere, and atmosphere (e.g., Goldfarb et al., 2010; Groves et al., 2005; Kerrich et al., 2000, 2005), although these are generally in the nature of mineral provinces rather than being representative of variation between individual deposits.

If orogenic gold deposits do have a common fluid and metal source, then this source is limited by a number of indisputable facts. These include that (1) Jiaodong and a few other gold provinces in high-grade rocks must have fluid and metal sources in the sub-crustal regime, (2) some mainly syn- to post-peak metamorphism Archean gold deposits are hosted by amphibolite-facies rocks, and (3) some deposits have no granites in their host terrane or granites that are present are characterized by significantly different timing.

The derivation of fluids, gold, and sulfur from greenschist to amphibolite facies metamorphism of supracrustal sequences is quite viable in Phanerozoic gold provinces, where an increasing number of large deposits are hosted in sedimentary rock-dominant terranes and there are few hosted by amphibolite-facies rocks. Furthermore, there is supporting geochemical evidence (e.g., Pitcairn et al., 2006; Fig. 8) and theoretical evidence (e.g., Phillips and Powell, 2010) that gold, other metals, and volatiles were simultaneously depleted in the deeper sedimentary rocks during prograde metamorphism. If a metamorphic fluid model involves derivation of that fluid from different sedimentary rock type facies, then the mineralogical variability will result in different prograde reactions at different temperatures and crustal levels, thus partly explaining some of the broad ranges reported for ore formation along deep crustal fault systems (Fig. 2). A problem that still remains with this model is the increasing evidence for very late timing of gold deposition during very subtle deformation events that affected host rocks in which metamorphic assemblages, regional cleavage/foliations, and hosting quartz reefs had already formed (e.g., Wilson et al., 2013 at Bendigo). However, as stated above, the diachronous metamorphism during tens of millions of years to a few hundred million years of orogeny solves such a problem. In addition, orogenic gold deposits typically reflect dozens of seismic events over at least a few million years. Earlier deposited silica will always be a favorable brittle host for gold deposition during subsequent hydrofracture episodes.

In the Archean, auriferous metamorphic fluids cannot have been derived from supracrustal sedimentary rocks because these are only voluminous above the sites of gold deposition. They could have been derived from supracrustal volcanic rocks, but the occurrence of an, albeit contentious, large number of broadly syn-metamorphic deposits in amphibolite-facies host rocks could be a stumbling block. Nevertheless, as modeled by Elmer et al. (2006), if the greenstone belt is thick enough, then significant fluid volumes, with the same potential gold and sulfur concentrations as derived from metasedimentary rock sequences, could have formed many of the great Neoarchean gold provinces. Alternatively, derivation from deeper crustal fluids or from subduction zones remains viable possibilities. In most cases, however, a sub-greenstone, yet crustal, ore-forming fluid is difficult to justify because of the total lack of gold ores in the voluminous granite terranes that surround and underlie many of the greenstone sequences (Phillips and Powell, 2009). Similar arguments apply for Proterozoic deposits, although a supracrustal metamorphic fluid is more feasible due to an increasing number of deposits hosted in sedimentary sequences and far fewer deposits hosted in amphibolite-facies domains.

The major 'fly in the ointment' for a universal model in which all orogenic gold ores formed from metamorphic fluids released from progressively devolatilizing supracrustal successions, evolving from volcanic source rocks to sedimentary source rocks through time, is the recognition of high-grade rocks hosting post-metamorphic gold deposits. In the case of the North China block and of northern Mexico, ores are hosted by supracrustal rocks that were highly devolatilized, would have lost most of their metals, and even underwent partial granulitization billions of years earlier. Thus, for gold provinces such as Jiaodong, the only permissive sources would be oceanic crust and associated ocean-floor sediments that were subducted below the earlier accreted terranes and perhaps the corner of the mantle wedge (Fig. 11).

Using the principle of Occam's razor that the hypothesis with the least number of assumptions is the best, the simplest, most elegant, universal model is that all orogenic gold deposits formed throughout time from devolatilization of oceanic crust and associated carbonaceous, sulfidic sediments with gold-enriched pyrite late in the history of subduction when local plate motion was perturbed. This must remain contentious, as direct evidence will inevitably be elusive to absent and a number of tectonic scenarios can initiate the formation of metamorphic fluids. Crustal thickening and radiogenic heating, shear heating, slab roll-back and extension, subduction of a spreading ridge, plumes impinging the bottom of the crust or mantle wedge, or the thermal aureole of a giant igneous province may all cause production of the same auriferous fluid type when oceanic rocks are heated along moderate to steep gradients for the first time (Fig. 9). This orogenic gold-forming fluid may be produced directly in a fore-arc or back-arc crustal setting (Fig. 1), or at the top of a subducted slab in a sub-crustal setting (Fig. 11). In the latter case, fluid may directly enter a trans-crustal structure or refertilize the mantle wedge, with volatiles and metals being later remobilized into large structures during subsequent thermal activity. Importantly, such auriferous fluid from a sub-crustal source can migrate upwards or laterally directly into the basal part of a crustal-scale fault or shear zone obviating the problem of all crustal models where the mechanism for large-scale lateral migration of metamorphic fluid towards such faults is obscure.

The exploration significance of accepting a universal metamorphic model for orogenic gold does add some constraints for targeting purposes. There is a great deal of research on specific source areas for this deposit type, but as noted above, the abundance of fluid inclusion and isotope data are equivocal. More importantly, there are a number of metamorphic models that invoke a variety of processes and sources, including some that may have changed over Earth history. Hence, defining the specific causes of, and source sites for, the fluid and metals is interesting academically, but has limited exploration significance. What is more critical in accepting any of the specific metamorphic models for orogenic gold is the recognition that most orebodies will (1) be somehow related to major fault systems cutting volcano-sedimentary crust normally developed at most a few hundred million years earlier; (2) show a consistent chemistry, and thus broadly identical mineralogy and alteration assemblage; (3) have, if present at all, proximal igneous intrusions that will solely represent zones of pre-gold rheologically favorable rock for the location of ore-bearing structures; and (4) be preferentially, but not exclusively, located in greenschist-facies domains. It is particularly important that, in the Archean, some world-class to giant deposits may be located in amphibolites-facies domains. Areas of Phanerozoic decratonization of Precambrian cratons and consequential young orogeny within old craton margins, such as in the North China block example, define the atypical example of young gold deposits in old rocks, although these are identical in terms of all other defining parameters.

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