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INVITED PAPER

# Orogenic gold: is a genetic association with magmatism realistic?

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## Abstract

Many workers accept a metamorphic model for orogenic gold ore formation, where a gold-bearing aqueous-carbonic fluid is an inherent product of devolatilization across the greenschist-amphibolite boundary with the majority of deposits formed within the seismogenic zone at depths of 6–12 km. Fertile oceanic rocks that source fluid and metal may be heated through varied tectonic scenarios affecting the deforming upper crust (≤ 20–25 km depth). Less commonly, oceanic cover and crust on a downgoing slab may release an aqueous-carbonic metamorphic fluid at depths of 25–50 km that travels up-dip along a sealed plate boundary until intersecting near-vertical structures that facilitate fluid migration and gold deposition in an upper crustal environment. Nevertheless, numerous world-class orogenic gold deposits are alternatively argued to be products of magmatic-hydrothermal processes based upon equivocal geochemical and mineralogical data or simply a spatial association with an exposed or hypothesized intrusion. Oxidized intrusions may form gold-bearing porphyry and epithermal ores in the upper 3–4 km of the crust, but their ability to form economic gold resources at mesozonal (≈ 6–12 km) and hypozonal (≈ > 12 km) depths is limited. Although volatile saturation may be reached in magmatic systems at depths as deep as 10–15 km, such saturation doesn't indicate magmatic-hydrothermal fluid release. Volatiles typically will be channeled upward in magma and mush to brittle apical roof zones at epizonal levels (≈ < 6 km) before large pressure gradients are reached to rapidly release a focused fluid. Furthermore, gold and sulfur solubility relationships favor relatively shallow formation of magmatic-hydrothermal gold systems; although aqueous-carbonic fluid release from a magmatic system below 6 km would generally be diffuse, even if in cases where it was somehow better focused, it is unlikely to contain substantial gold. Where reduced intrusions form through assimilation of carbonaceous crustal material, subsequent high fluid pressures and hydrofracturing have been shown to lead to development of sheeted veins and greisens at depths of 3–6 km. These products of reduced magmatic-hydrothermal systems, however, typically form Sn and or W ores, with economic low grade gold occurrences (< 1 g/t Au) being formed in rare cases. Thus, whereas most moderate- to high-T orogens host orogenic gold and intrusions, there is no genetic association.

**Keywords** Orogenic gold · Intrusion-related gold · Metamorphism · Magmatism · Crustal fluids

## Introduction

The dominant characteristics of gold deposits in metamorphic rocks, or the so-called orogenic gold deposits, have been well described and summarized for more than 30 years (e.g., Robert et al. 1991; Groves et al.1998; Goldfarb et al. 2005). However, the source of fluids and metals (Fig. 1), and thus the genetic model(s), have been long controversial (e.g., Sillitoe and Thompson 1998). Many studies accept the fact that deposits classified as orogenic gold are the consequences of crustal metamorphic processes. Other work favors a magmatic genesis for many deposits with the characteristics of orogenic gold. In fact, during the past 20 years there has been a notable swing from metamorphic back to

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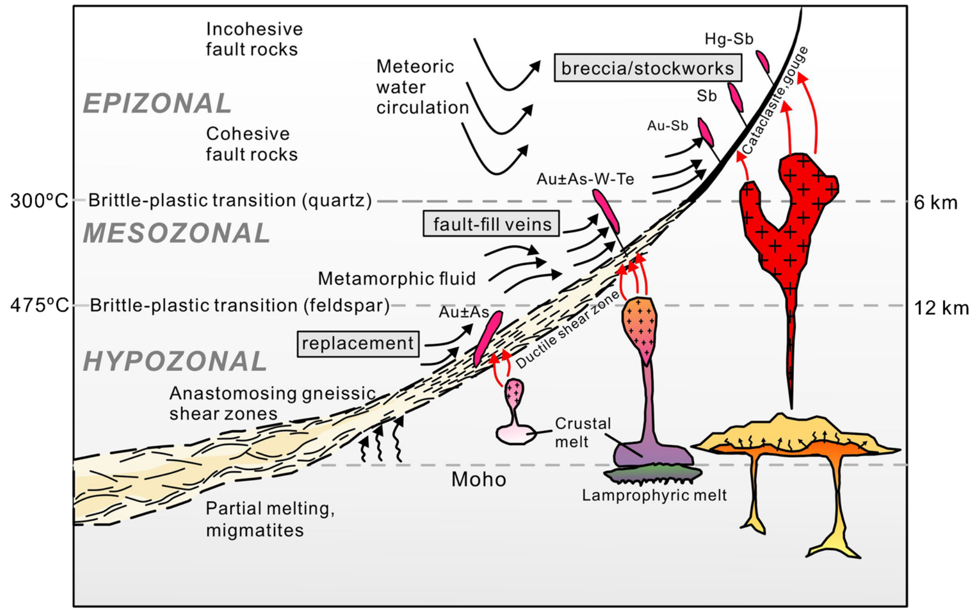



**Fig. 1** Orogenic gold deposits are located adjacent to first-order structures as breccia and stockworks formed at depths as shallow as 3–6 km, fault-fill and extensional vein networks formed in the brittle-ductile regime generally at 6–12 km, and replacement-style ores in the deeper ductile crust. Many genetic models for generation of aqueous-carbonic ore-forming fluids favor prograde metamorphism of marine crustal rocks. Nevertheless, some models argue for magmatic system fluid release at a variety of depths or even from a subcontinental lithospheric mantle reservoir. Figure modified after Groves et al. (1998) and Fossen and Cavalcante (2017)

magmatic-hydrothermal processes for gold genesis in both Phanerozoic accretionary belts and Precambrian greenstone belts, although supporting evidence for such a magmatic genetic link may be quite weak (e.g., Groves et al. 2009). In some cases, these gold deposits are nevertheless still referred to as orogenic gold deposits but with a hypothesized magmatic origin, whereas, in other cases, authors classify these same deposits as intrusion-related deposits. Almost all the world's largest gold deposits in metamorphic terranes seem to now be characterized by this magmatic versus metamorphic genetic controversy. As pointed out by Sillitoe (2020), these controversial deposits have been suggested as genetically related to either reduced intrusions (Pogo, Muruntau, Zarmitan) or to oxidized intrusions (Canadian Malartic, Kirkland Lake, Jiaodong, Golden Mile) by various studies in the recent economic geology literature.

Temporal or simply spatial associations with granitoids are often taken as an indication of genetic association. But as we will show in this overview, much in the petrological literature is inconsistent with a magmatic-hydrothermal origin for orogenic gold. Fluids exsolved from melts will form porphyry, skarn, replacement, and epithermal gold deposits in the shallow crust (Fig. 2A, B); this is not the issue, as most ore deposit types form in the upper 5–6 km of the crust (Skinner 1997; Seedorff et al. 2005). But we argue it is highly unlikely that gold-bearing deposits formed at depths below about 5–6 km, which are the levels of formation of most orogenic gold deposits (Fig. 2A, C), would contain fluid or metal sourced from a magma. Epizonal orogenic gold deposits (Fig. 1) do form in the upper 6 km of the crust, but the more abundant large mesozonal deposits form near the brittle-ductile transition at 6–12 km depth and hypozonal deposits form in the ductile regime at depths of perhaps 15 or 20 km (Gebre-Mariam et al. 1995; Groves et al. 1998). As eloquently stated decades ago by Giggenbach (1992), geologists commonly support a magmatic contribution to ore formation with "more or less artistically executed magic arrows marked magmatic fluid or even less specific magmatic input pointing up from some nether regions where anything could happen." Thirty years later, much in our literature on gold deposits still supports Giggenbach's observations. We have many new techniques and measure many new parameters, with resulting data that are typically equivocal (Goldfarb and Groves 2015), and yet the arrows indicating a hidden granite at depth as a fluid and metal source are prevalent in much of the orogenic gold literature.

There are a variety of fluid types that are widely recognized to be present in the upper 15–20 km of the crust. These include seawater, basinal brines, meteoric water, magmatic fluid, and metamorphic fluid (Yardley and Bodnar 2014). Little evidence exists for involvement of the former three shallow fluid types in orogenic gold formation (Goldfarb and Groves 2015). Thus, it is both metamorphic water and magmatic water that have been most consistently implicated in various studies as potential contributors to orogenic gold formation.

Both metamorphic and magmatic fluids are generated in situ and thus tend to generate high fluid pressures (Steele-McInnis and Manning 2020) resulting in channelized fluid migration, mass transport, and precipitation of hydrothermally derived minerals. Both metamorphic fluids from crustal heating (Goldfarb et al. 1991) and magmatic fluids released from rapidly ascending magma (Tosdal and Richards 2001) are likely to be moving through orogenic belts during changes from a compressional regime to a more neutral far-field stress regime. They may therefore show a broad

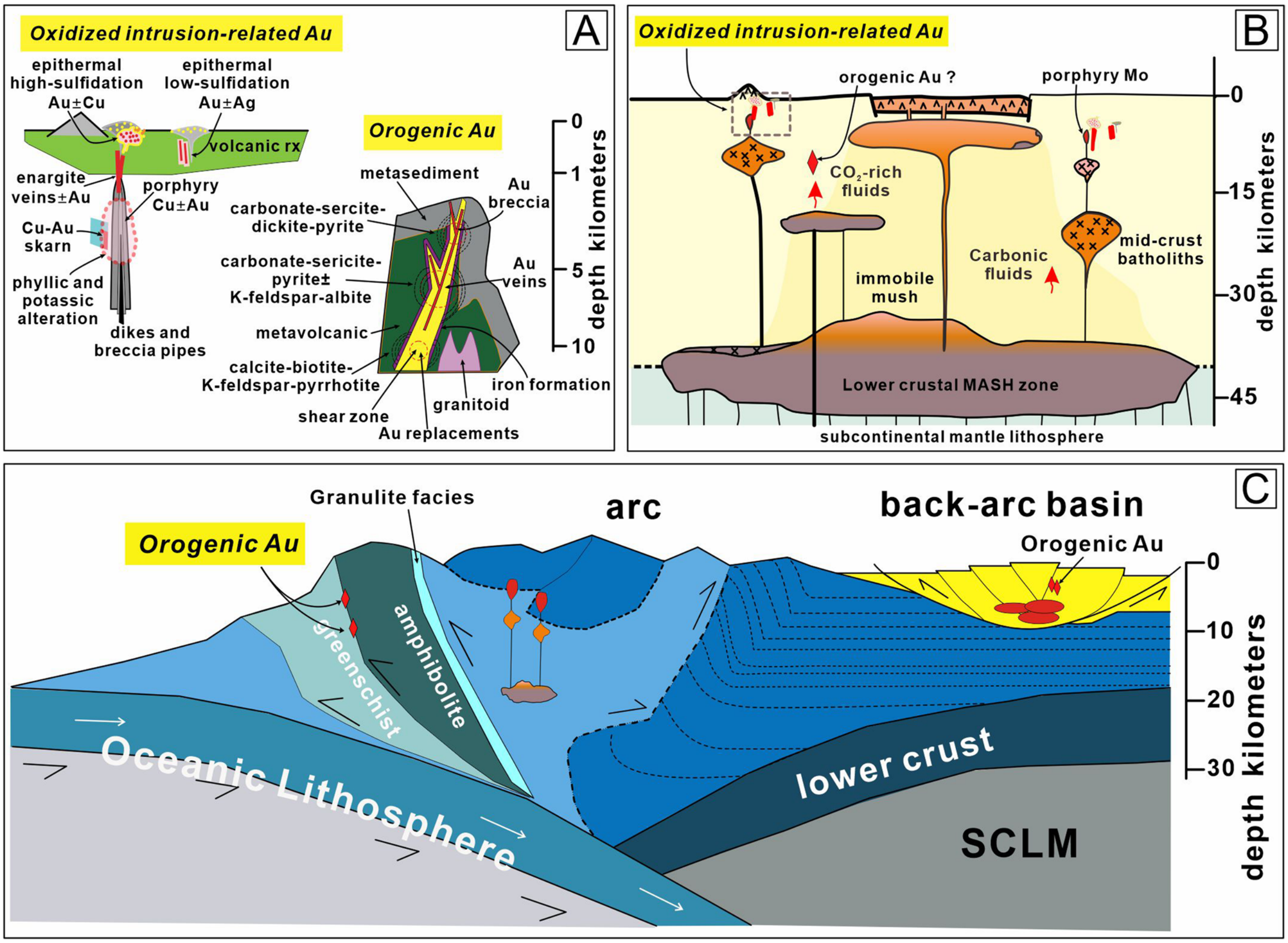



**Fig. 2** **A** Depending on geothermal gradient and orogenic architecture, orogenic gold deposits can form between 3 and 15–20 km depth at temperatures between about 200 and 500 °C, with variation in mineralization style and mineralogy reflecting difference in temperature and host rock (e.g., Groves 1993). Oxidized intrusion-related gold deposits typically form within 3–4 km of the surface, and include auriferous epithermal, skarn, and porphyry deposits (figure after Simmons et al. 2020). Porphyry deposits that are economic for gold develop at depths that are shallower than those that are gold-poor (Sillitoe 1997; Chiaradia 2020). **B** Oxidized intrusion-related Cu-Au and Au deposits form from magmatic-hydrothermal fluids exsolved from melt (± meteoric water) within 5 km of the surface and that are characteristically aqueous in character. Porphyry Mo deposits tend to form in a similar manner at depths that may be 1–2 km deeper than Cu and Cu-Au porphyries (figure after Audétat and Simon 2012). Any $CO_2$ in a melt is generally degassed at deeper crustal levels and prior to saturation of $H_2O$ in the melt that leads to formation of intrusion-related Au. **C** Orogenic gold tends to form from aqueous-carbonic fluid in fore-arc and back-arc metamorphic settings of active continental margins most commonly at depths of 6–12 km, but can be also formed at somewhat shallower and deeper locations depending on the local thermal structure. In some gold belts they may show a temporal and/or spatial association with magmatism. They may show a temporal overlap with oxidized intrusion-related gold deposits (e.g., epithermal veins, Au-rich porphyries) that form in the upper 3 km of many subduction-related arcs

temporal overlap during orogeny (Figs. 1 and 2C). Magmatic fluids tend to be released from roof zones of crystallizing igneous bodies, whereas ore-forming metamorphic fluids tend to migrate horizontally down pressure gradients into large-scale fault systems and then upward during seismic-related pressure cycling events. The $H_2O$, $CO_2$, and $H_2S$ in the magmatic fluid will be sourced from devolatilization of the subducting slab leading to the melting in the overlying mantle wedge and (or) from local melting of crustal rocks during the ascent of primary basaltic magma. These same volatiles may be products of crustal prograde metamorphic events at moderate temperatures, most commonly between 350 and 500 °C, and can be contributed by the breakdown of hydrous silicates, organic matter, and diagenetic pyrite (Tomkins 2010; Evans and Tomkins 2020). As higher metamorphic P–T conditions are reached, hydrous minerals are less stable and fluids produced between middle amphibolite and granulite conditions are likely to be highly carbonic with limited $H_2O$ and $H_2S$. Fluid inclusion observations from lower crust granulite facies environments consistently show co-existing nearly pure $CO_2$ fluids and highly saline brines (Touret et al. 2016); the source of any $H_2O$ in the latter is not well understood. Nevertheless, such $H_2O$-poor fluids are not typical of orogenic gold deposits, which characteristically vary between about 80 and 95 mol percent $H_2O$ (Goldfarb and Groves 2015). This helps explain why orogenic gold deposits are generally not hosted in high-grade metamorphic rocks unless orogenesis includes thrusting of high-grade rocks over lower grade rocks with ore deposition taking place subsequently in the upper allochthon.

## Fluid production from crustal metamorphic devolatilization

The association between metamorphism of crustal rocks and orogenic gold has been widely accepted for more than 40 years (Henley et al. 1976; Kerrich and Fyfe 1981; Phillips and Groves 1983). There is little argument that metamorphism of crustal rocks leads to a fluid capable of forming an orogenic gold deposit (Fig. 3). Devolatilization across the greenschist-amphibolite boundary in both metasedimentary and mafic metavolcanic rocks will produce an $H_2O$-$CO_2$-$H_2S$ fluid capable of gold transport (Phillips and Powell 2010). This would place most fluid release at temperatures somewhere between 350 and 500 °C, depending on the rock assemblage undergoing the prograde event (Fig. 3A). Desulfidation is associated with syngenetic/diagenetic pyrite being converted to pyrrhotite during prograde metamorphism (Tomkins 2010). The presence of organic matter in the rocks as a source of carbon facilitates a greater gold-transporting S component within the metamorphic fluid (Finch and Tomkins 2017). As a consequence, metasedimentary rock sequences may be particularly effective in producing a gold-rich fluid during their devolatilization history (e.g., Pitcairn et al. 2015). The water comprising the dominant fluid component is mainly released during garnet growth at the expense of hydrous minerals, most often being chlorite (Dragovic et al. 2018). In many orogenic belts, uplift occurs under near-isothermal conditions for tens of millions of years, such that the auriferous $H_2O$-$CO_2$-$H_2S$ fluid migrates along a retrograde PTt curve as lithostatic load is reduced relative to fluid pressure (Fig. 3B; Goldfarb et al. 1986; Stuwe et al. 1993).

Studies in the metasedimentary rocks of New Zealand and Scotland, as well as in greenstone belts of Canada, confirmed that the various elements commonly enriched in orogenic gold deposits are initially mobilized during the rising metamorphic temperatures (Fig. 4). Gold and arsenic are released from enrichments in sedimentary pyrite (Pitcairn et al. 2006) and tungsten from detrital rutile (Cave et al. 2017). Although definitive studies are still lacking, tellurium

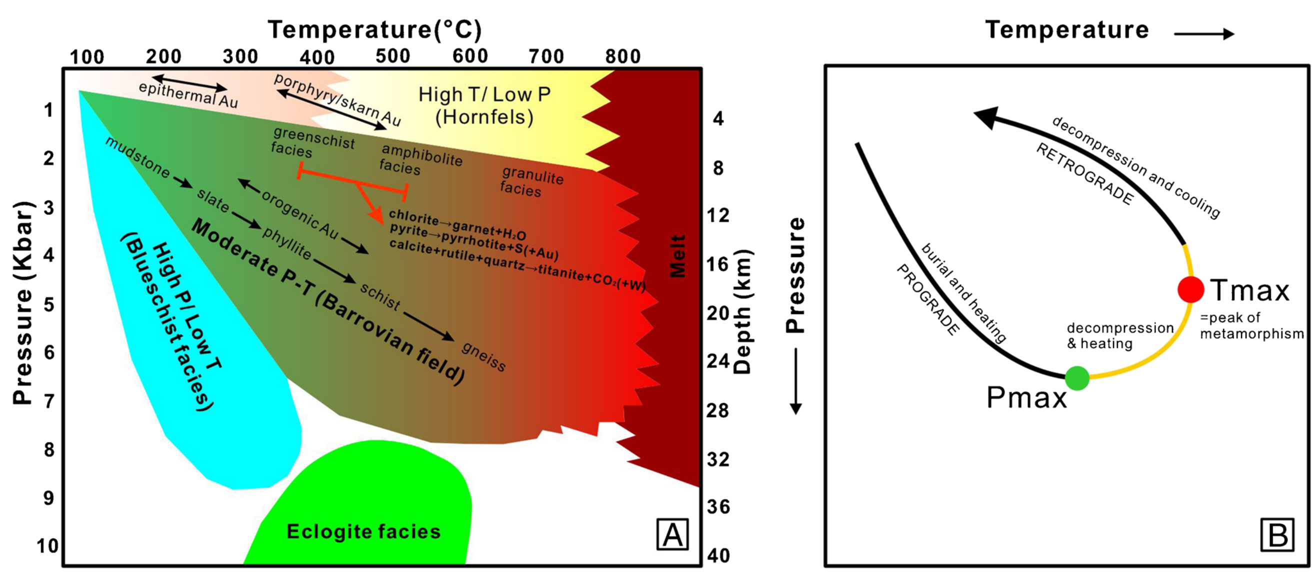



**Fig. 3** **A** The metamorphic model for orogenic gold reflects prograde breakdown of pyrite, chlorite, carbonate, rutile, epidote, and other minerals in sedimentary and volcanic rocks as they become unstable in the area of the greenschist/amphibolite boundary along a moderate P–T path to release hydrothermal components that include $H_2O$, $CO_2$, S, Au, As, and W. Thus, orogenic gold is inherent to most Barrovian metamorphic belts. Low thermal gradients in blueschist belts explain why such belts generally lack orogenic gold. **B** Depending on the mineral assemblages, orogenic gold can form anywhere from maximum burial depth of fluid/metal source rocks to a few tens of millions of years after their thermal metamorphic peak during decompression. Changing stresses and associated rapid exhumation allow for increased fluid pore pressure relative to decreasing lithostatic load, and thus hydrofracturing and horizontal flow into large near-vertical sutures or fault systems (Goldfarb et al. 1991). During early near-isothermal decompression in active orogens (e.g., Vry et al. 2009), temperatures will still rise many tens of degrees during initial decompression, which could lead to the contribution of additional large fluid volumes to the trapped metamorphic fluid already being released from pore spaces

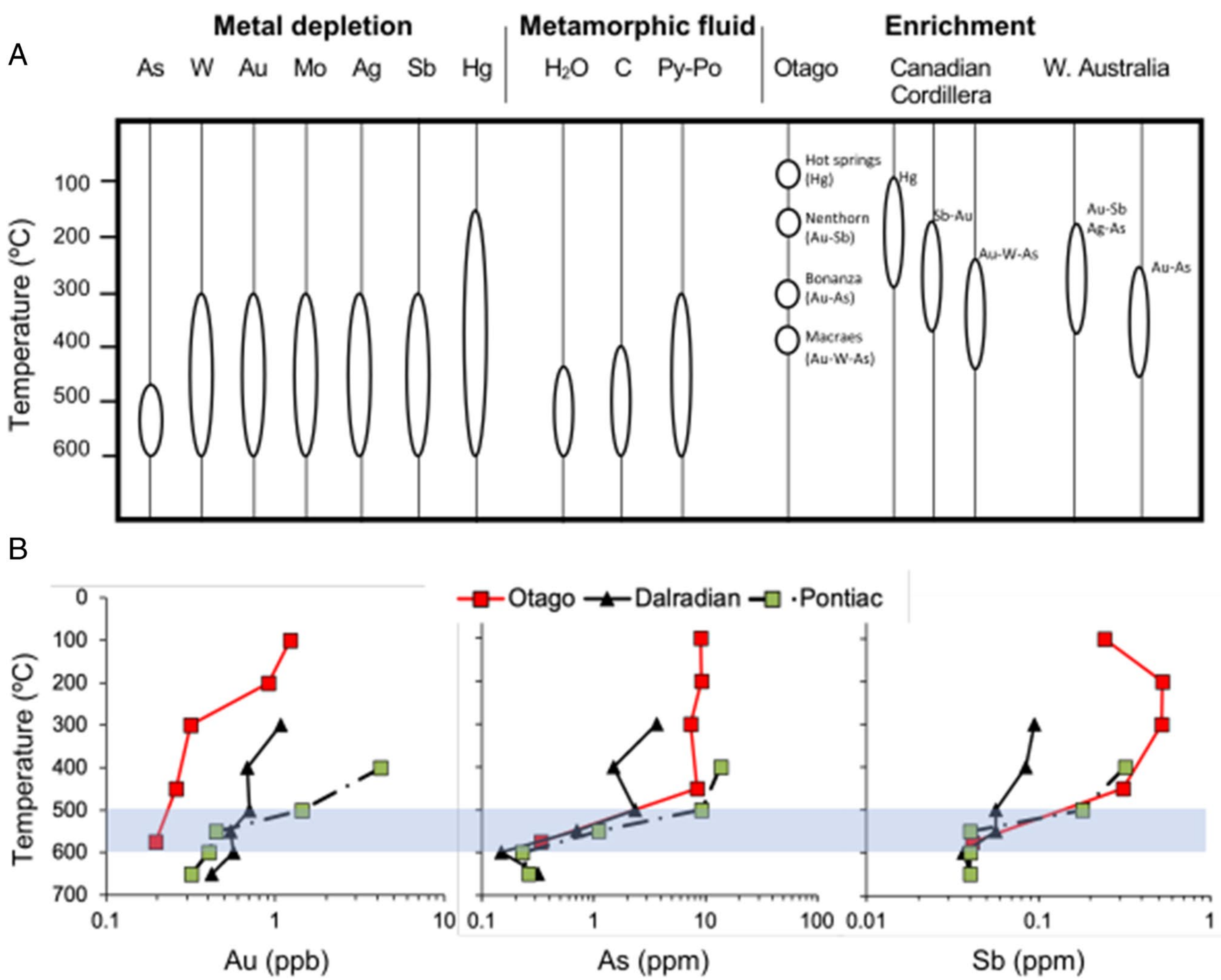



**Fig. 4** **A** A is a photograph of a vein. A summary of the vertical zonation of metal mobility, metamorphic fluid production and enrichment of orogenic gold deposits from Otago, the Canadian Cordillera, and Western Australia (Barnes et al.1978; McKeag and Craw 1989; Nesbitt et al. 1989; Goldfarb et al. 1991; Hagemann et al. 1994; McCuaig and Kerrich 1998; Groves et al. 1998). **B** Mean Au, As, and Sb concentrations of metamorphosed rocks plotted against metamorphic temperature for the three different orogens, i.e., Otago Schists (New Zealand), Dalradian (Scotland), Pontiac terrane of the Abitibi Belt (Canada). Mean values are based on multiple sample analyses at each metamorphic grade (Pitcairn et al. 2006, 2015, 2021). The blue bar represents the window of metamorphic fluid production

and bismuth, associated with gold in many orogenic gold deposits, are likely released from organic material in black shales during the decarbonization reactions or alternatively from pyrite nodule conversion to pyrrhotite in the shales (Large et al. 2011; Thomas et al. 2011; Gregory et al. 2015). No one genetic model is applicable to all orogenic gold provinces; rather every orogenic belt is characterized by a unique scenario that leads to the heating of young rocks for the first time, be that in a fore-arc or back-arc tectonic setting. For example, Goldfarb et al. (2001) describe crustal thickening, slab rollback and crustal thinning, subduction of a slab window, and plume impingement as tectonic events that may control the thermal structure of an orogen. Such metamorphism may also be considered "intrusion-related" where regionally extensive contact metamorphism can form broad zones of greenschist and amphibolite facies rocks (e.g., Barton et al. 1991) and elements such as As, Au, Bi, Sb, and W are concentrated in the associated fluid phase (Finch and Tomkins 2017). Whereas most studies on metal mobilization have been focused on Phanerozoic settings, both in fore-arc and back-arc regions, Pitcairn et al. (2021) provide evidence for fluid and gold sources in underthrusted Archean metasedimentary rocks within the gold-rich Abitibi subprovince (Fig. 4). In contrast, Patten et al. (2020) show evidence that orogenic gold ores elsewhere in Canada's Superior Province, as well as in the Paleoproterozoic of the Central Lapland Greenstone Belt, were sourced from metamorphosed metavolcanic rocks. Trace element signatures and gold contents of deposits will vary depending on relative proportions of graywacke, black shales, and volcanic rocks in a source terrane.

In summary, any new material added to a continental block and heated through medium-grade metamorphic conditions for the first time is capable of forming an orogenic gold deposit if the resulting fluid is well focused. In other words, orogenic gold deposit formation is an inherent consequence of crustal metamorphism as long as rocks being metamorphosed contain adequate amounts of widely disseminated pre-metamorphic pyrite grains with many tens to hundreds of ppb background concentrations of gold; if more locally disseminated or massive pyrite is present, this may provide even a more favorable scenario for epigenetic gold formation (e.g., Neoproterozoic East Africa and Archean Abitibi Subprovince). Metasedimentary rocks with an abundance of sedimentary pyrite and organic matter are a particularly favorable source rock, but magmatic sulfides in volcanic rocks are also a permissive source. This ore-forming metamorphism typically takes place at 10 ± 5 km, being particularly well localized at the base of the crustal seismogenic zone (Sibson 2004). Some orogenic gold deposits form as deep as 15–20 km and at temperatures higher than 500 °C (Groves 1993; Kolb et al. 2015), where significant C-O–H-S fluid generation may still take place above the greenschist-amphibolite boundary given the right mineral assemblages (e.g., Evans and Tomkins 2020). In such deeper ductile crustal environments, widespread hydrofracturing and silica precipitation will be hindered due to lack of large pressure drops such that most gold ores will appear as broad zones of replacement style mineralization mainly in Fe-rich lithologies (Figs. 1 and 2A).

## Fluid production from slab devolatilization

An increasing temperature–pressure regime along a subducting slab can lead to devolatilization and production of a metamorphic fluid phase below an upper lithospheric plate or an asthenospheric wedge (Fig. 5). Such volatiles will not only be $H_2O$-dominant, but can contain significant amounts of $CO_2$, as well as some $N_2$, with overall fluid volume likely controlled by amount of sedimentary material and altered basalt at the top of the underthrusted plate (e.g., Epstein et al. 2021). There is no reason that such a fluid would not be similar in composition to that produced during devolatilization of the above described accreted metasedimentary and metavolcanic rocks, and they are just as

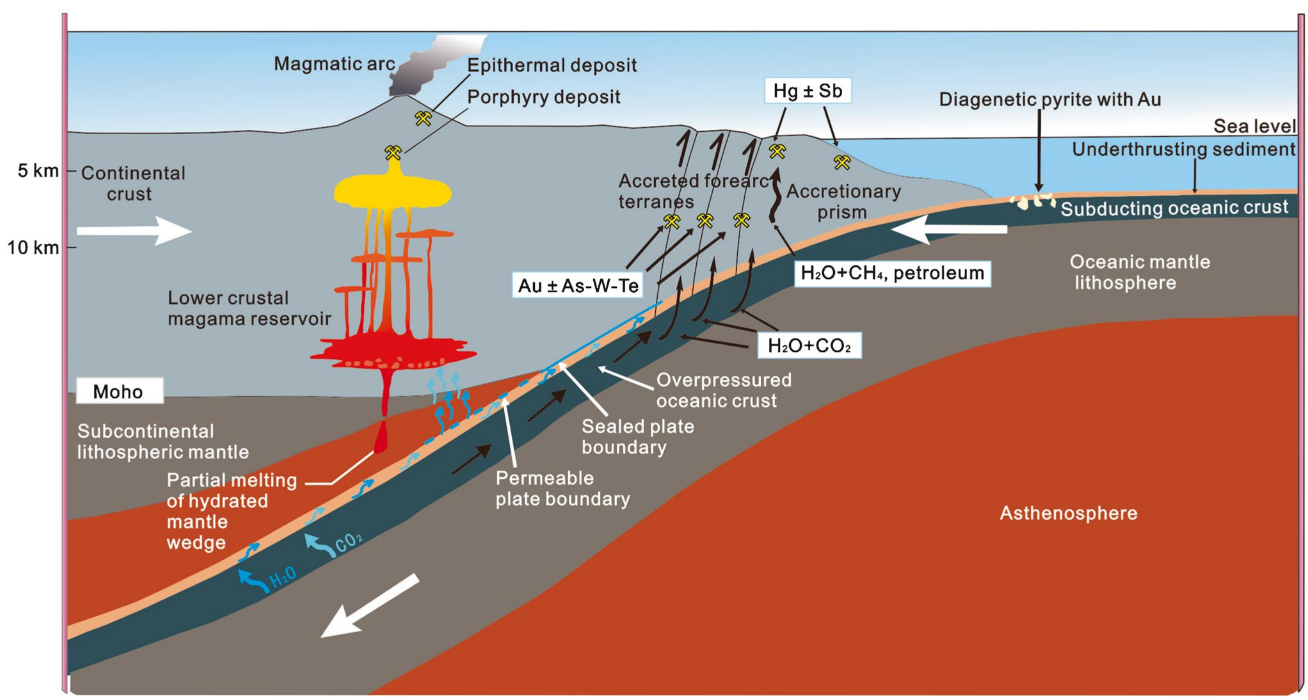



**Fig. 5** Model where ore-forming fluid for orogenic gold may be produced from metamorphism of top of lower underthrusted plate, rather than from heating of rocks in the accretionary prism and accreted terranes that were accreted onto an upper plate. Below about 50 km, any devolatilization can lead to melting of the mantle wedge and arc plutons. Between about 20 and 50 km depth, lower temperature aqueous-carbonic fluids can be channeled along the plate interface until deep crustal faults, commonly terrane sutures, intersect the base of the upper plate and move upward during seismic events to form orogenic gold deposits. Further seaward, compaction-related release of $H_2O$-$CH_4$ pore waters in the accretionary prism and from sediments on the downgoing plate, as well as initial petroleum migration from burial metamorphism, can form shallow Hg-rich deposits (with Sb and perhaps Au)

likely to carry gold and related metals. Fluid devolatilization will take place at relatively deep levels along the slab interface after compaction first releases most pore waters within the subducting sediments at depths of the upper few tens of kilometers. These initial methane-rich pore fluids and any petroleum migrating from initial breakdown of organics can lead to formation of near-surface Hg deposits (Fig. 5), such as observed in the California Coast Ranges, which may also be enriched in elements such as Sb and Au. Thermal conditions where deep devolatilization will induce melting or mantle wedge fertilization are generally taken as about 50 km; Grove et al. (2006), for example in their slab subduction modeling, assume mantle temperatures only are hot enough for vapor-saturated melting at slab interface depths of at least 55 km. Intermediate depth fluid escape, perhaps at depths of 25–50 km, is likely to be highly channelized (e.g., Plumper et al. 2017), with fluids migrating upward along the interface between the lower and upper plates until they intersect more vertical structural heterogeneities including major transcrustal fault zones (Fig. 5). Seismic studies of modern-day subduction zones indicate that such steeply-dipping faults defining terrane boundaries in accretionary terranes provide important fluid escape routes (Tauzin et al. 2017). Significant fluid transport up-dip along a sealed plate boundary until reaching such faults transecting the fore-arc hangingwall is commonly suggested from seismic studies of continental margin megathrusts (Audet et al. 2009; Sibson 2013; Halpaap et al. 2018; Egbert et al. 2022).

It is critical to note that whereas such a fluid and metal source for orogenic gold is permissive, most accretionary orogens undergo a complex thermal history commonly associated with syn- to post-subduction terrane amalgamation, back-thrusting of accretionary rock sequences, and inverted Barrovian metamorphic events. Much of the volume of oceanic material added to the active continental margin will therefore be heated and devolatilized in the growing upper plate (accreted terranes) as described above. Formation of orogenic gold from metamorphism of the upper parts of a subducting slab is a simple geometry that only explains ore formation in rare cases (e.g., eastern China). For example, Goldfarb et al. (1998, their Fig. 3) show a simplistic model of fluids being produced from the subducting Pacific plate as it was thrusted below oceanic terranes previously accreted to the North American margin. But, in actuality, sediments on the upper parts of the downgoing plate are largely accreted to the fore-arc margin as a series of terranes and only a small percentage of the fertile marine sedimentary rock volume is subducted below the backstop. Thus, the fluids produced at the greenschist-amphibolite boundary were released and migrated into and upward along major terrane-bounding fault systems during orogenic events within material recently added to the upper plate along the growing margin. In other words, the source material would no longer be part of the subducting lower plate but would be parts of the upper plate that most commonly would be undergoing initial stages of isothermal uplift within the orogen (e.g., Fyfe and Kerrich 1985; Goldfarb et al. 1986).

A simple model for orogenic gold deposit formation via fluid and metal sourced from a downgoing lower plate may be most applicable in active margins that are non-accretionary. For example, the giant Jiaodong orogenic gold province in eastern China may be a product of such a tectonic event (Goldfarb and Santosh 2014), where Mesozoic Paleo-Pacific slab subduction is recorded below the North China cratonic block with structurally reactivated Precambrian rocks still comprising the East Asian continental margin. Sibson (2013) points out that shear stress relief along the slab interface can lead to the uncommon example of large orogenic gold deposits forming extensional vein swarms, which is the case in the Jiaodong province. Groves et al. (2020) stress such a subcrustal model characterizes orogenic gold in general, but work on metamorphism of metasedimentary and likely metavolcanic oceanic rocks theoretically (Tomkins 2010) and from actual field studies (Pitcairn et al. 2006) makes it clear that the ore-forming process, no matter the model, reflects moderate temperature metamorphism of any fertile oceanic rock sequence. This process need not take place in the subcrustal environment and, in fact, the required large fluid volumes produced by devolatilization events will typically be released in areas of the upper crust of most active margins because it is at depths between about 5 and 15 km where moderate to high thermal gradients will favor the required greenschist-amphibolite facies development. Furthermore, many orogenic gold provinces form in metamorphosed back-arc sequences during compression inversion (e.g., Sibson and Ghisetti 2018), whereas any fluid released from a downgoing slab below such a tectonic setting would become soluble in an arc or back-arc mantle melt (e.g., Hyndman et al. 2015) and not be able to directly generate a gold deposit. Therefore, in summary, the rocks being metamorphosed to produce much of the known orogenic gold endowment are indeed originally part of a subducting slab but, when devolatilized, those rocks, as well as any incorporated closing fore-arc or back-arc basins, have already become a part of the overriding plate (Fig. 5).

## Fluid exsolution from oxidized magma

The ability to focus significant volumes of fluid into a confined cupola region near the top of a magma chamber and to discharge fluids to form a brittle metal-bearing fracture system is well accepted as critical to the formation of many economic magmatic-hydrothermal ore systems (Shinohara and Hedenquist 1997; Cloos 2001). However, a critical question is whether a significant volume of exsolved fluid capable of forming a large gold-only deposit and with a remarkably consistent volatile composition ($XH_2O = 0.80–0.95$, $XCO_2[\pm CH_4, N_2, H_2S] = 0.05–0.20$) is likely to be released from magmas or mushes into sub-solidus rocks at depths below about 6 km. This would be a required process if magmatic models implicated for many large gold deposits in metamorphic terranes are accepted as valid.

Although magmatic systems in active continental margin settings typically extend continuously downward in networks of crystal-rich mushes to at least the mid-crust (Cashman et al. 2017), most magmas rise in the crust to depths of at least 4–6 km before they undergo significant amounts of volatile degassing (e.g., Lowenstern et al. 1991; Rasmussen et al. 2022). Granite melts with somewhere between 4 and 6% $H_2O$ will not begin significant volatile exsolution until melt pressures decline to about 1–2 kbar (Fig. 6); it is only under conditions where calculations suggest an initial water composition exceeding 6% $H_2O$ that saturation will unmix large volatile volumes at levels deeper than about 6 km. Because $CO_2$ is highly insoluble relative to $H_2O$ in melt, much of any contained $CO_2$ will be lost from a magma during early crystallization before large amounts of more soluble $H_2O$ begin to degas as has been shown using models assuming initially about 3.5–5 wt% $H_2O$ (Hedenquist and Lowenstern 1994; Newman and Lowenstern 2002; Lesne et al. 2011). In these cases, release of an aqueous-carbonic magmatic-hydrothermal fluid resembling that of orogenic gold deposits would seem to be improbable at depths deeper than about 5 km. More hydrous felsic magmas with at least 6–8 wt% $H_2O$ could, given reasonable constraints, be theoretically capable of degassing and releasing a gold-bearing fluid at mesozonal and hypozonal depths that resembles what is consistently seen in orogenic gold deposits with 5–20 mol percent $CO_2$ (Fig. 7). However, although some calculations do invoke such a high initial $H_2O$ content (Blundy et al. 2010; Urann et al. 2022), it is unlikely that superhydrous melts (> 4–6 wt% $H_2O$) are common enough to account for the wide distribution of orogenic gold deposits or could produce the remarkably consistent volatile composition observed in orogenic gold deposits. Furthermore, as described below, many other arguments also are inconsistent with deep release of a gold-bearing magmatic-hydrothermal fluid.

Many natural magmatic systems have been accepted to be volatile saturated from the base of the seismogenic zone, typically at 9–12 km depth, up to the near surface (Baker and Alletti 2012; Edmonds and Woods 2018), yet it is critical to note that saturation does not imply fluid release for a number of reasons. Hydrous magmas that form shallow ore systems may actually undergo large amounts of $H_2O$ exsolution in the mid-crust (Urann et al. 2022). In many porphyry deposits where PTX properties of magmatic-hydrothermal systems have been argued to show fluid saturation at 5–10 km depth, the exsolved volatiles, often present as supercritical fluid, are channeled upward within the magmatic system to shallower crustal areas before release (Richards 2011). This relatively buoyant fluid would rapidly ascend up sinuous channels or "fingers" within the melt's dense crystal mush to be focused

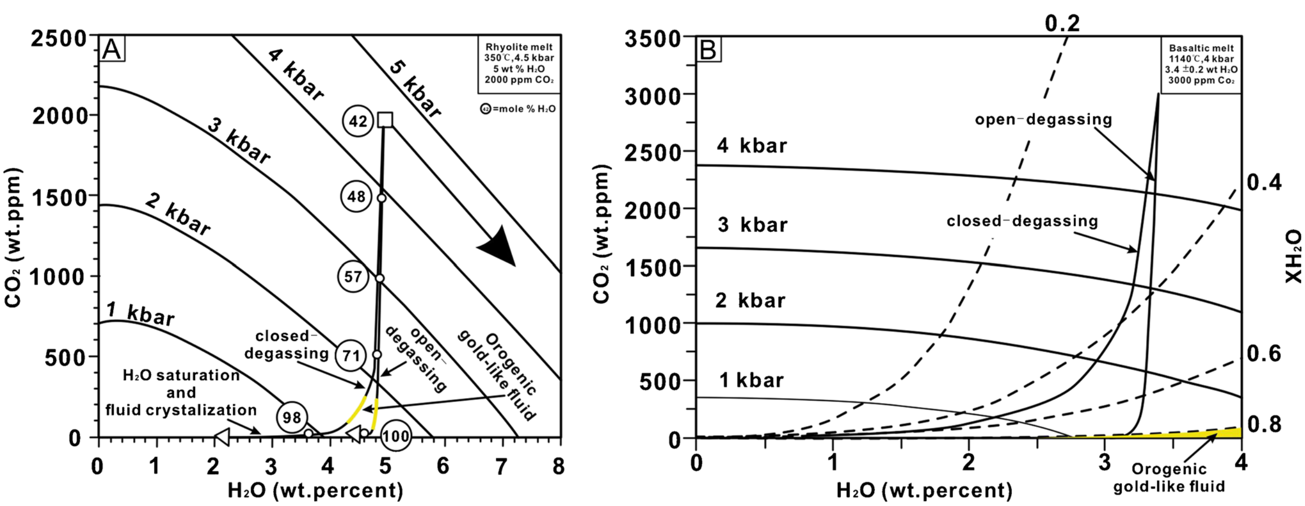



**Fig. 6** **A** Magma degassing for a representative rhyolitic melt ascending from about 17 km with initial 5 wt% $H_2O$ and 0.2 wt% $CO_2$ as modeled by Lowenstern (2001). Almost all $CO_2$ is lost from the melt prior to loss of significant $H_2O$ beginning at about 3 to 5 km (1 to 1.5 kb) for an open versus closed system, respectively. The volatile composition released from the melt would not approximate that of most orogenic gold deposits until the magma had reached depths of about 5 km from the surface. Numbers in circles relate to mol% $H_2O$ in the aqueous-carbonic fluid phase. **B** Magma degassing for a representative basaltic melt ascending from about 15 km with initial 3.4 wt% $H_2O$ and 0.3 wt% $CO_2$ from Audétat and Simon (2012) after Spilliaet et al. (2006). Significant aqueous-carbonic fluid release resembling that of orogenic gold ($XH_2O = 80–95\%$) would not be possible until very shallow depths. Stippled lines equal XH2O with mole ratios from 0.2 to 0.8

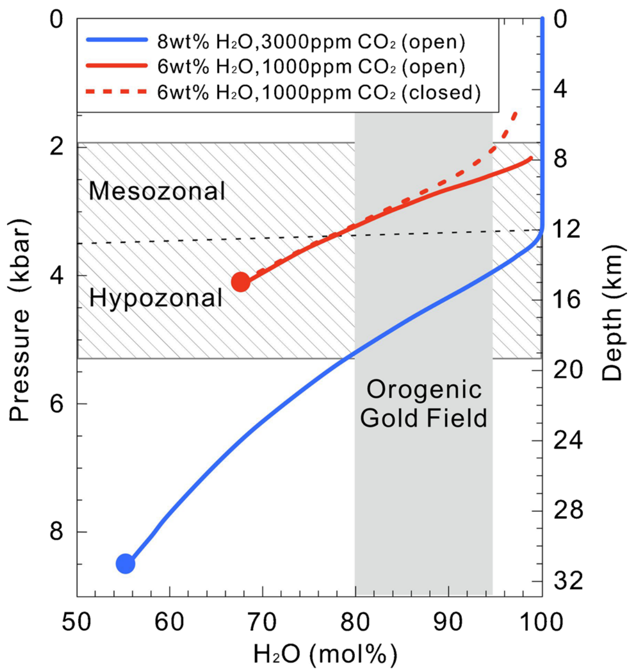



**Fig. 7** Hydrous magmas with initial 6–8 wt% $H_2O$ can be modeled using VolatileCalc to show how aqueous-carbonic fluids resembling those characterizing most orogenic gold deposits can be generated at mesozonal and hypozonal depths (courtesy by Jon Blundy). For example, felsic melts are modeled with initial compositions as shown and first reaching saturation at pressures of about 8 kb (8 wt% $H_2O$) and 4 kb (6 wt% $H_2O$). Fluids typical of orogenic gold (80–95 mol% $H_2O$) may characterize these modeled magmatic-hydrothermal systems at depths of 7–19 km and thus significantly below those of gold-bearing porphyry and epithermal deposits. Yet to form an orogenic gold deposit at these depths, it remains uncertain as to whether (1) a fluid unmixed from melt at pressures > 2 kb would contain significant S and Au and (2) a large fluid volume could be focused and released, as opposed to being channeled upward within the magma and mush

at shallow ore-forming levels (Parmigiani et al. 2016, 2017; Degruyter et al. 2019; Blundy et al. 2021). The high-water contents in closed systems will commonly lead to accelerated ascent of the magma itself (Annen et al. 2006; La Spina et al. 2022). In some cases, the volatiles may remain for a period of time as liquid-rich layers within the crystallizing mush before rising to such a roof zone (Christopher et al. 2015; Parmigiani et al. 2016). The forceful expulsion of volatiles at the top of the magmatic system is typically driven by pressure gradients between supralithostatic conditions reached within the highest point of a crystallizing intrusion and the near-hydrostatic conditions in rocks above the igneous body roof (Lamy-Chappuis et al. 2020). Such gradients required for voluminous and focused fluid flux into surrounding rocks and conduits would mainly be expected in the uppermost crust and not within the seismogenic zone at 6–12 km where mesozonal orogenic gold deposits are widespread. At mesozonal levels with confining pressures greater than about 1.5–2 kb (deeper than 4–6 km), there is little deformation of crystal-bearing magma or mush and this is argued to restrict magmatic volatile permeability at depth (Parmigiani et al. 2016) suggesting a more passive and diffuse release of volatiles, if any release at all into surrounding country rocks. Whereas deformation of the mush may be limited, country rocks surrounding magmatic systems in these relatively higher pressure areas may undergo strong ductile deformation, with consequential limited development of surrounding permeable conduits and thus further suggesting a restricted environment for focused volatile escape from a magmatic mush system at depth (Christopher et al. 2015).

Despite the fact that some magmas crystallize, differentiate, and have been argued to release large volumes of fluid at depth, Rasmussen et al. (2022) summarize data from 225 studies of more than 100 arc magmas and estimate a water saturation depth mode of 4–6 km for subduction-related magmas. This has been interpreted to indicate the most common region of large fluid release from magma leading to increased melt viscosity and widespread stalling of magma ascent at those depths (Plank et al. 2013; Rasmussen et al. 2022). Stalling is essential for metal concentration, because if the magmatic plumbing system reaches the near surface in an open system, then much of the degassing will result in a loss of metals into the surrounding atmosphere. Thus, oxidized intrusion-related gold deposits (e.g., Sillitoe 1991; Hart 2007), including porphyry, skarn, and epithermal ores (Fig. 2A, B), form at shallow crustal levels where large fluid releases are most expected a few kilometers below the surface. Deeper level formation of widespread orogenic gold is inconsistent with depths that most magmatic systems are shown to undergo large-scale volatile release.

Numerical models show the most efficient fluid flow and the majority of magmatic-hydrothermal ore formation to be concentrated at and above the apical parts of plutonic bodies. Release of large amounts of fluid from a magma is commonly supported by a porphyritic texture, as a fluid-rich magma will enhance crystal growth and sudden fluid release causes rapid nucleation and a fine-grained groundmass. In contrast, widespread miarolitic cavities in an intrusion indicate limited fluid focusing (Lerchbaumer and Audétat 2013) and thus difficulties in the intrusion itself forming a large ore deposit. Typically, magma chambers at depths below about 10 km or relatively flat intrusive bodies are unlikely to form ore deposits because of the need to develop a brittle fluid conduit to facilitate fluid release (Audétat 2019). In the relatively deepest (6–7 km) porphyry systems that are Mo dominant, source stocks for hydrothermal fluids below the ores in the roof zones lack significant alteration and thus indicate fluids exsolved at depth move upward through the molten deep parts of intrusive complexes and get released in the solidified cupola regions (Audétat and Li 2017).

It is widely acknowledged from the porphyry deposit literature that gold-rich magmatic-hydrothermal ores form at shallower levels than gold-poor ores. Epithermal gold deposits are located above associated Cu-rich porphyry ores (Fig. 2A, B). Large gold-rich porphyry ores, whether related to calc-alkaline bodies emplaced in subduction settings or alkaline bodies emplaced in more neutral geodynamic settings, are formed at notably shallower levels than gold-poor porphyries (Sillitoe 1997; Murakami et al. 2010; Chiaradia 2020). This could reflect, in part, shallower magma bodies undergoing relatively late sulfide saturation and maintaining higher concentrations of gold than those that differentiate at deeper levels (Hao et al. 2022). At depths below about 3 km in systems where metal transport is related to sulfur complexing, rapid cooling of exsolved fluid leads to Cu precipitation during fracturing of a cupola generally at depths of 3–5 km, whereas gold solubility is shown to be little impacted by the cooling and the gold remains in a dense vapor phase (Heinrich et al. 2004; Murakami et al. 2010). Shallower fluid release is dominated by rapid coeval precipitation of Cu and Au during expansion of the escaped vapor phase and the resulting formation of large intrusion-related gold deposits predominantly occurs within 3 km of the surface.

It is worth noting that the epithermal and porphyry gold ore-forming magmatic-hydrothermal aqueous fluids released in the upper few kilometers of the crust consistently lack high $CO_2$ contents. In contrast, epizonal orogenic gold deposits, which may form at 3–6 km depth (Groves et al. 1998), as well as commonly shallower associated Hg-Sb ores without clear association to causative intrusions (e.g., Studmeister 1984; Goldfarb et al. 1990; Hart and Goldfarb 2017), are argued to have formed from an aqueous-carbonic fluid with local enrichments of liquid hydrocarbons. This difference may be due to early escape of $CO_2$ from a magmatic system, perhaps by a passive diffusive degassing period, and particularly by the overwhelming $H_2O$ volume within the magmatic volatile phase as $H_2O$ saturation is reached on almost any degassing path (Figs. 6 and 7). The destabilization of magmatic systems by $CO_2$ flushing into upper crustal magma reservoirs has been proposed by Caricchi et al. (2018), but nevertheless it is extremely rare to have a causative magmatic-hydrothermal ore-forming fluid with > 1–2 mol% $CO_2$ in such porphyry or epithermal environments (e.g., Ridley and Diamond 2000). Furthermore, the sulfur that is typically called upon to transport gold in orogenic gold systems tends to follow the $H_2O$, in contrast to Cl, and would commonly not be released from an oxidized melt during deep degassing, but rather during shallow degassing of a $CO_2$-poor gold-forming fluid (Fig. 8; Spilliaet et al. 2006).

As a consequence of the above depth-related features, most Cu- and Au-rich porphyry deposits, and related skarn ores, form no deeper than about 2–5 km (Sillitoe 2010; Richards 2018). Fluid exsolution may be slightly deeper for highly fractionated felsic and viscous oxidized magmas associated with Au-poor porphyry Mo deposits (Fig. 2B). However, these deeper and rarer magmatic-hydrothermal systems still form at shallower levels than most orogenic gold deposits; contain ore-related fluid inclusions with abundant highly saline brine assemblages (Audétat and Li 2017) that are extremely rare to see associated with any orogenic gold deposit; and, as shown by melt inclusion data from Climax-type deposits, little $CO_2$ remains in the mineralizing silicate melts at depths of pluton emplacement (Audétat and Li 2017). Thus, even such relatively deeply emplaced evolved melts release Mo-bearing magmatic-hydrothermal ore-forming fluids that are distinct from fluids associated

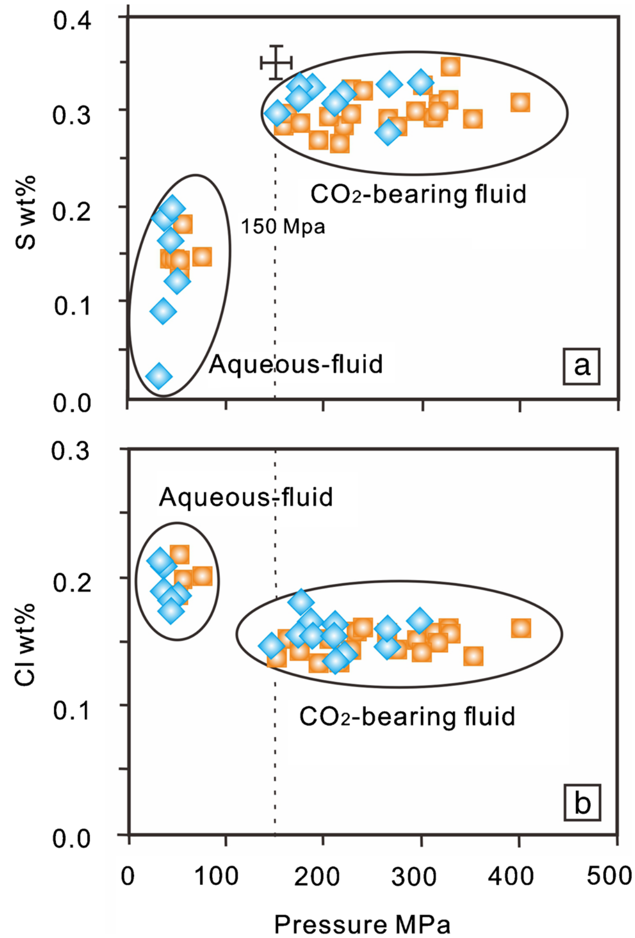



**Fig. 8** Melt inclusion data from a couple of different eruptive events (different symbols) for **a**) S and **b**) Cl during pressure-related degassing from Mt. Etna, Italy from Spilliaet et al. (2006). Note that unlike Cl, the S tends to follow $H_2O$ and is exsolved after essentially all $CO_2$ is lost to the system and thus above depths of about 5.5 km (1.5 kb). Thus, it would be difficult for gold-sulfur complexing responsible for orogenic gold formation in (mesozonal) and below (hypozonal) the brittle-ductile transition zone to be related to magmatic processes

with orogenic gold deposits. Furthermore, as pointed out by Graney and Kesler (1995), the presence of significant $CH_4$ and $N_2$ in magmatic vapors, commonly detected at the percent level in ore fluids forming orogenic gold at any crustal level, is restricted to S-type melts and would thus be unlikely characteristic of oxidized magmatic systems.

The above features indicate that it would require extraordinary conditions such that this fluid degassed at pressures greater than 1.5–2.0 kbar would contain enough sulfur and gold to form a large orogenic gold deposit. Some recent models have suggested magmatic fluids released at deep crustal levels may pick up Au and S through leaching of fertile lithologies along their flow path (e.g., Smithies et al. 2018). However, in the atypical scenario where a large volume of magmatic fluid was released at great depth, it is doubtful that such a fluid could become sufficiently enriched in Au and S to form a large orogenic gold deposit. The required fluid focusing into a large deep crustal fault zone would favor a high water:rock flow system that is typical of orogenic gold. Under such a flow regime, the channelized supercritical fluid would interact with small volumes of rock therefore requiring super Au-rich country rock along the shear zone in order to obtain appreciable amounts of gold and sulfur from the conduit wallrocks, a scenario that is extremely unlikely. It would, therefore, be difficult to form the well-recognized large mesozonal or hypozonal orogenic gold deposits via any model of magma degassing.

## What about mantle involvement in gold-forming oxidized magmas?

Many models now invoke the need for an enriched SCLM (sub-continental lithospheric mantle) as a source for fluids and metals that form orogenic gold ores, commonly with fluid release from an oxidized mantle magma again being the ultimate source of the ore-forming components. Hronsky et al. (2012), for example, speculate gold-enriched zones in the upper mantle may be important for gold metallogeny in all deposit types, with gold mobilized both in silicate melts and mantle fluids. The refertilization and oxidation of depleted mantle, preserved below continents for billions of years because of its negative thermal buoyancy coexisting with a positive chemical buoyancy, is a consequence of metasomatism due to slab subduction. Tassara et al. (2020) describe how the oxidation of silicate melts rising through such an enriched SCLM can lead to S and Au enrichment in magma prior to ascent and magmatic-hydrothermal processes at shallow crustal levels. Subsequent melting of the newly enriched mantle, commonly due to slab delamination or rollback allowing asthenospheric upwelling, is expressed as shoshonitic or at least high-K calc-alkaline magmatism (Feeley 2003). This relatively alkalic magmatism related to Farallon plate subduction below the North American continent, for example, can be most directly related to alkalic magmatic-hydrothermal deposits such as Cripple Creek (Kelley et al. 2020) and other gold deposits in the Laramide Rocky Mountains province. However, there is no evidence for such K-rich melts consistently being the dominant form of magmatism spatially and temporally associated with orogenic gold.

Gold may be locally enriched in areas of refertilized SCLM (e.g., González-Jiménez et al. 2020), but that does not indicate such enriched mantle is a genetic prerequisite for an orogenic gold deposit. Xenoliths and mafic dikes with a mantle origin may be enriched in gold, but similarly that does not suggest capability of directly forming an economic gold deposit. Lamprophyres are common in or near many large orogenic gold deposits and at one time were suggested to be important in the ore-forming process (Rock et al. 1989), particularly in models where they would migrate from the mantle to interact with upper crustal rocks producing gold-rich felsic melts. Again, there is a lack of supporting evidence that such felsic melts would exsolve and release substantial Au- and S-bearing fluids at depths of formation estimated for many giant orogenic gold deposits. Furthermore, direct degassing of such isolated dikes is unlikely to produce the fluid volumes required for large gold accumulations, and many such dikes either pre-date or post-date the gold events and solely were emplaced along the same structures that facilitated fluid migration (Kerrich 1991; Goldfarb and Groves 2015). Smithies et al. (2018) show that water-rich diorites and granodiorites along gold-hosting translithospheric structures in the Yilgarn craton may be classified as evolved sanukitoids that were larger volume cumulate products from lamprophyric mantle magmas. But their stated "moderately deep" emplacement releasing large fluid volumes that would scavenge significant gold along ascent and then form so-called proximal intrusion-related gold deposits at shallower levels (e.g., Witt et al. 2020) is problematic. As mentioned above, even if a large fluid volume is released at depth, the required subsequent leaching of enough gold under conditions of high W:R ratio along a major flow conduit to form a large gold orebody is difficult to explain.

The Jiaodong gold province in the North China block of eastern China contains abundant syn-gold lamprophyre dikes derived from metasomatized SCLM. Saunders et al. (2018) suggest that the volatiles and metals associated with these world-class gold deposits were also derived from an enriched lithospheric mantle, with the gold contributed from asthenospheric melts and not a devolatilizing paleo-Pacific slab. The gold deposits are suggested to have been formed at relatively shallow levels where melts could theoretically exsolve large S- and Au-rich fluid volumes. Wang et al. (2021) suggest SCLM-derived hydrous basalts erupted coevally with the gold event could represent causative magmas that formed the gold deposits. They also however show, significantly, that the xenoliths of the SCLM are depleted, not enriched in Au relative to primary mantle and argue it is only the volatile-rich nature of the basalts that enriched their hypothesized causative magmas with gold. But furthermore, again such shallow basaltic magmatism would likely be expected to show widespread hypabyssal intrusion emplacement and formation of epithermal-style precious metal veins, which is not what is observed in the Jiaodong province. Some workers argue that a SCLM source can be defined by consistent S and O isotope ratios of ore-related minerals across an orogenic belt (e.g., Zhao et al. 2021), but the reported values are consistent with orogenic gold deposits worldwide and are not indicative of any type of "mantle signature."

Convincing evidence is also lacking for gold ore-forming fluid release directly from the mantle. There are some arguments for such deep fluids, perhaps from depths of even 40–50 km, migrating to the near surface but most of these are based upon interpretation of noble gas isotopes (e.g., Chen et al. 2019). Because many orogenic gold deposits are spatially associated with trans-crustal faults, there is no reason why both mantle-derived magmas and some volatiles may not be transported into the upper crust from deeper parts of the lithosphere. However, most $H_2O$ in the lower crust or upper mantle will be stored in hydrous mineral phases or dissolved in melts (e.g., Touret et al. 2016). Although $CO_2$ mantle degassing may occur in certain tectonic settings (Newton et al. 1980, 2019), the $H_2O$ and $H_2S$ concentrations that are universally associated with orogenic gold-forming fluids would be lacking in such a fluid source. Studies of preserved fluid inclusions from xenoliths of lithospheric mantle consistently indicate $CO_2$ degassing with subordinate to undetectable $H_2O$ (e.g., Roedder 1965; Frezzotti and Touret 2014; Sandoval-Velasquez et al. 2021). Similarly, many studies of orogenic gold deposits implicate mantle fluids based on helium isotope ratios from fluid inclusion waters extracted from ore-related minerals (e.g., Jiaodong Peninsula deposits: Mao et al. 2008). However, even if helium is moving up along trans-crustal fault zones, there is no accompanying evidence of $H_2O$, $CO_2$, S, or metals being transported from sub-crustal reservoirs.

Perhaps more significant is the fact that many Phanerozoic orogenic gold provinces cannot be related in any way to enriched SCLM because such continental basement does not exist below the ore-hosting accreted oceanic terranes that comprise the seaward side of the orogens. In the Cordilleran orogen of North America, gold districts in southern Alaska (Fig. 9) and in the California Foothills belt all are located above solely oceanic lithosphere that was accreted to the craton margin as it was built seaward (Goldfarb and Groves 2015). The tectonic evolution of older orogens is much less understood, but Oliver et al. (2020) indicate there is no evidence in data from the giant Paleoproterozoic Obuasi deposit in West Africa that supports any type of contribution to ore formation from sub-crustal magmatic sources.

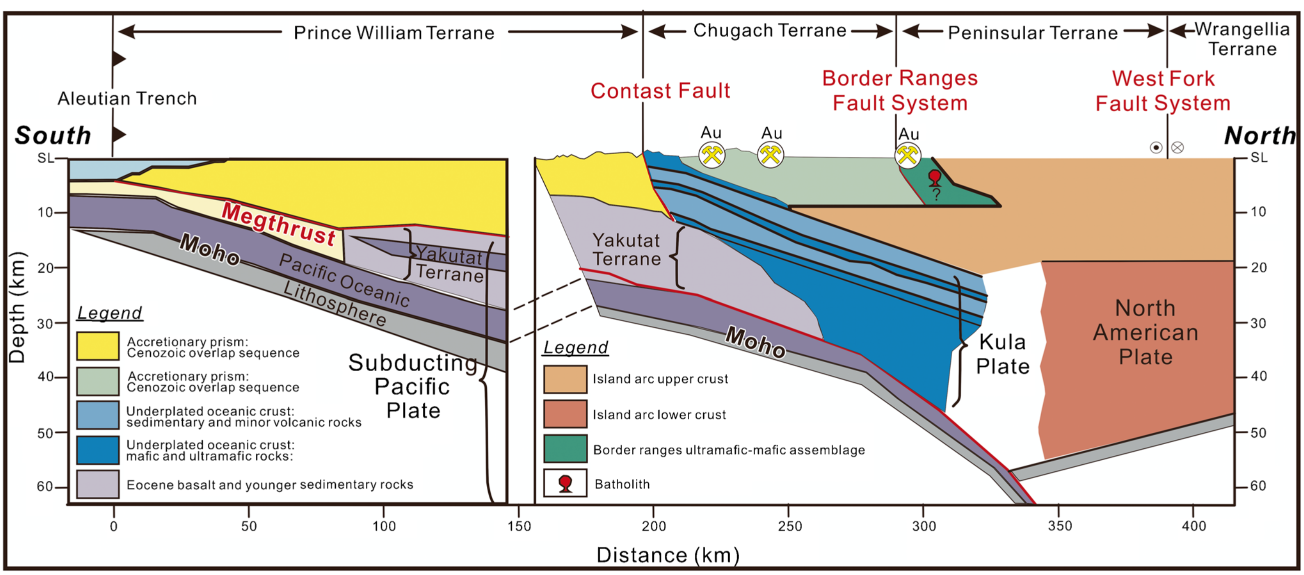



**Fig. 9** Crustal architecture of south-central Alaska after Brocher et al. (1994). Orogenic gold districts in the fore-arc (Chugach Mountains) and subduction-related batholith margin (Willow Creek) overlie a basement of oceanic crust and lithospheric mantle outboard of the North American continental lithosphere. Similar lithospheric profiles characterize the Juneau Gold Belt and Mother Lode further south along the North American Cordillera. These observations along a young active continental margin indicate that enriched subcontinental lithospheric mantle is not a necessary critical factor for generating orogenic gold systems

In summary, (1) limited voluminous potassic magmatism associated with most orogenic gold deposits over space and time; (2) the lack of any continental lithosphere below young orogenic gold-bearing provinces; (3) the lack of evidence, as described earlier, for voluminous S- and Au-bearing fluid release from a magmatic system at depths of 6–15 km; and (4) little support for mantle streaming of a fluid with $H_2O > CO_2$ all provide strong argument against a genetic association between orogenic gold and enriched subcontinental lithospheric mantle.

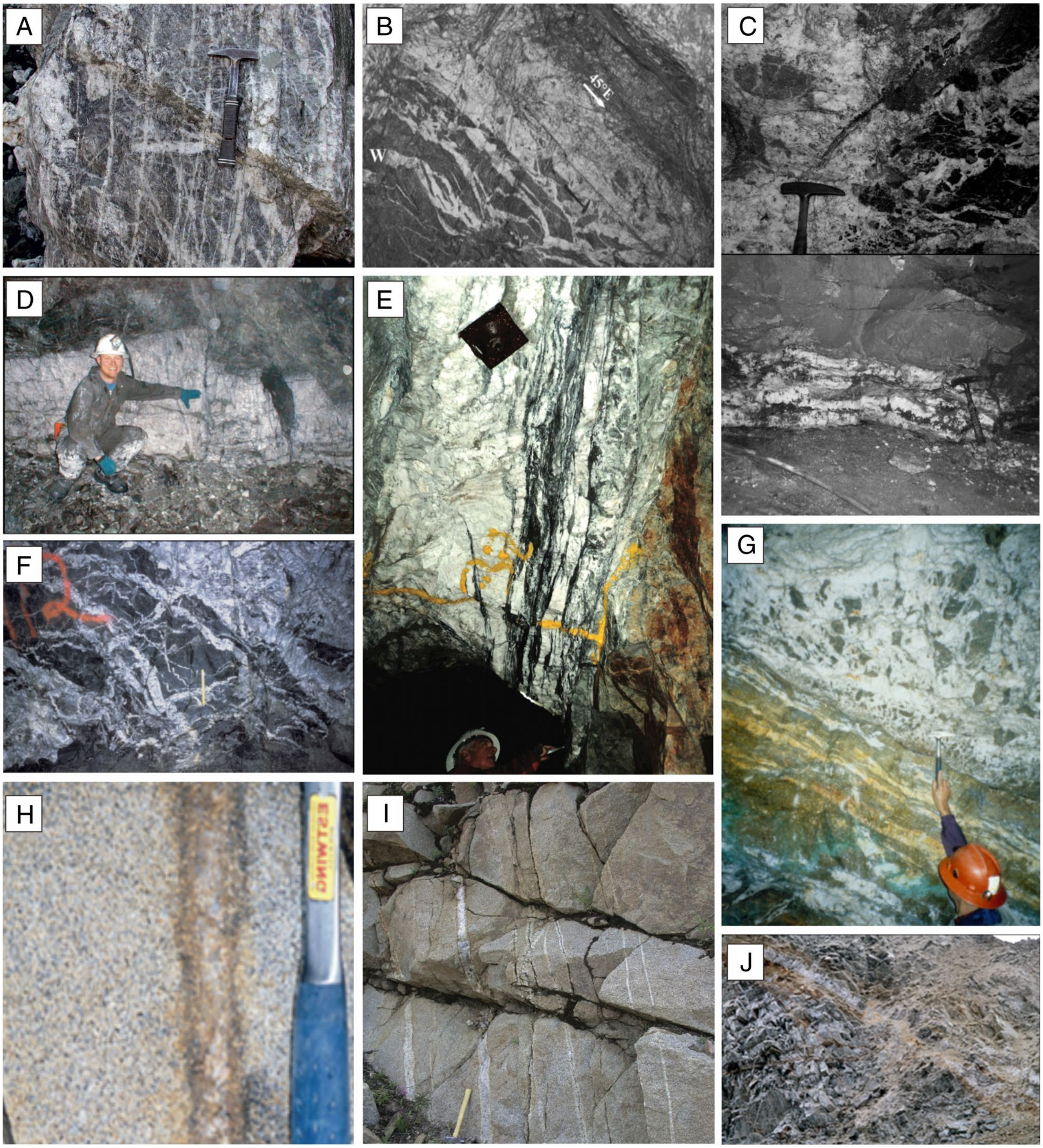
## The reduced intrusion-related gold deposits

Although most gold deposits of suggested magmatic-hydrothermal origin are related to oxidized magmas, there is a much smaller group of gold deposits that are indicated to be genetically associated with reduced magmas (Thompson and Newberry 2000). In contrast to the oxidized gold-rich magmatic-hydrothermal deposits that form within 3 km of the paleosurface, reduced intrusion-related gold deposits (RIRGD) are reported to form significantly deeper (Baker 2002; Sillitoe 2020). These are typically described as auriferous sheeted veins or greisens estimated to have been deposited at depths of 3–6 km in plutonic roof zones (Thompson et al. 1999), and thus at the same depths of deeper, although gold-poor, porphyry systems. Fluids are aqueous-carbonic (e.g., Fort Knox: McCoy et al. 1997; Dublin Gulch: Maloof et al. 2001) and thus resemble fluids of metamorphic origin that are common to orogenic gold deposits formed at all crustal levels. The $CO_2$-rich nature of the magmatic-hydrothermal ore fluids is reflective of a strong crustal sedimentary rock component assimilated into the melt that enhances fluid-melt unmixing at higher pressures (Thompson et al. 1999; Baker 2002) and resultant fracturing of the intrusion roof zone.

The reason the group of commonly accepted RIRGD is much smaller than that associated with oxidized intrusions likely reflects both the overall lower gold content in reduced melts and greater solubility of the gold in more deeply exsolved magmatic fluids. As first described by Thompson et al. (1999), the RIRGD ores are commonly located in Sn or W provinces landward of continental arcs; may be enriched in Bi, W, As, Sn, Mo, Te, and Sb; could have a very low sulfide content; frequently have quartz, K-feldspar, albite, sericite, and carbonate as alteration minerals; exhibit many different mineralization styles, but most consistently sheeted veins; and are characterized by aqueous-carbonic ore fluids with variable salinity. Many of these characteristics also are associated with orogenic gold deposits, which therefore makes discrimination of some deposits difficult. Similar to many arc-related oxidized magmatic systems, the RIRGD magmas also could be partly sourced from enriched lithospheric mantle. Petrogenetic studies by Mair et al. (2011) indicate the causative reduced magmatic systems in the eastern Tintina Gold Belt cannot have been formed via widespread crustal melting and are instead the product of fractional crystallization of and crustal assimilation by mantle-derived magmas.

The most representative examples of these deposits are those in the eastern part of the Tintina Gold Belt, which are presently being mined at Fort Knox in Alaska and Dublin Gulch in adjacent Yukon. Estimated formation depths are between about 3 and 5 km and the deposits occur as sheeted quartz-K-feldspar veins (sometimes referred to as pegmatite veins) in the roof zones of reduced and variably porphyritic ca. 92 Ma calc-alkaline granite to subalkaline granodiorite intrusive complexes (Fig. 10H, I). Features representative of the magmatic to hydrothermal transition in these deposits include the presence of pegmatites, aplite dikes, miarolitic cavities, and unidirectional solidification textures. The gold-bearing veins at Fort Knox contain < 1% sulfide and the gold is mostly associated with Bi-bearing minerals and molybdenite, whereas at Dublin Gulch veins may contain up to five percent pyrite-arsenopyrite-pyrrhotite. Studies of plutons of the Sierra Nevada batholith in California indicate that vertical cooling joints in the roofs of plutons may be the sites of self-sealing, single-pass fluids that form hydrothermal veins resembling those in the RIRGD (Bartley et al. 2020). Larger pipe-like conduits may host aplite and pegmatite dikes along with the hydrothermal veins, both from materials ascending into the roof zones within the inwardly crystallizing mush (Bartley et al. 2018) as is observed in the Tintina Gold Belt deposits. Their complex association may thus be spatial and not necessarily genetic. Interaction of fluid with the crystallized part of the intrusion and (or) lack of overpressurization leading to hydrofracturing could explain the formation of such sheeted vein styles of mineralization along the permeable conduits rather than development of a porphyry ore style.

An important feature of these sheeted vein systems is their lower grades compared to many vein-type ores in orogenic gold deposits. At Fort Knox, grades of bulk tonnage sheeted veins (Fig. 10H) have averaged about 0.6 g/t Au. Cross-cutting shears, perhaps related to the broadly coeval surrounding orogenic gold event, historically upgraded the 8 Moz of produced ores to about 0.9 g/t Au (Fig. 10J) and the present remaining resource of about 1 Moz was most recently estimated averaging 0.3 g/t Au. The main mineralization at Dublin Gulch also averages 0.6 g/t Au (Fig. 10I). These types of sheeted vein systems may be present in many reduced intrusive bodies in Sn-W provinces (e.g., Timbara, NSW, Australia: Mustard 2001) where melts include




significant volumes of volatile-rich sedimentary material, but due to their low grade they are prospective bulk tonnage targets only where good infrastructure exists and when gold prices are high. As discussed below, many other gold deposits have been placed into this RIRGD but their genetic association with such reduced magmatic systems is commonly lacking in supporting evidence and, in some cases, the intrusions are not even reduced.

## Controversial world-class deposits in metamorphic rocks

The majority of giant gold deposits in metamorphic terranes are argued to have either metamorphic or magmatic origins by different workers within the recent literature. These include many of the best studied Neoarchean, Paleoproterozoic, and late Neoproterozoic-Phanerozoic examples, which

◂**Fig. 10** Gold-bearing quartz vein styles from metamorphic terranes. Although with many similarities to classic and high-grade orogenic gold deposits (**E**–**G**), many of these vein deposits (**A**–**D**) have been argued to be world-class intrusion-related ore systems. **A** High-grade stockwork-sheeted vein network from Muruntau, Uzbekistan, within K-feldspar- and biotite-altered hornfels (from Seltmann et al. 2020). **B** Brittle-ductile chloritic-shear, massive auriferous quartz vein, and associated breccia in lamprophyre from Pataz gold belt, Peru (from Haeberlin 2000). **C** Brecciated (top) and laminated (bottom) gold-bearing veins hosted in the Segovia batholith and adjacent meta-sedimentary rocks, Colombia (courtesy Juan Carlos Molano and Camilo Dorado, Universidad Nacional de Colombia Departamento de Geociencias). **D** Main stage, shallow-dipping, brittle gold-bearing extensional quartz vein, with enclosed bands of sulfides reflecting multiple fluid pulses, which was formed along earlier shallow biotite- and quartz-rich shears, Pogo deposit, Alaska. **E** Laminated fault-fill vein at Bralorne, Bridge River district, British Columbia (from Hart and Goldfarb 2017). **F** Brittle stockwork-breccia veining from Red Lake, Canada (photo courtesy of Benoit Dubé). **G** Brittle-ductile fault-fill vein-breccia system with most of the gold resource present as tellurides, Kensington deposit, Alaska. **H** Typical narrow sheeted gold-bearing quartz-K-feldspar vein with $<1\%$ sulfide and very thin alteration halo in a pluton roof zone. Together such veins comprise a bulk-minable resource that averages about 0.6 g/t Au at the Fort Knox reduced intrusion-related gold deposit (RIRGD), Alaska. Unlike porphyry-style magmatic-hydrothermal deposits, RIRGD lack wide-spread alteration zones reflecting a voluminous fluid release event in a roof zone. **I** Typical RIRGD sheeted vein array in pluton roof zone that defines a bulk minable 0.6 g/t Au resource at Dublin Gulch, Yukon, Canada. (J) Higher-grade, overprinting late NE-striking shears that average 0.5-m in width could represent an orogenic gold overprint at Fort Knox. They increased the historic grade to about 0.9 g/t Au

show many of the same features (Fig. 10A–G) regardless of whether or not there is a clear association with magmatism. Although, as stressed above, most evidence strongly indicates an ore genesis that is inherent to metamorphism of oceanic rocks, we argue that a number of important factors have led to controversy regarding ore genesis. First, gold ore formation in association with magmatism, particularly with oxidized magmatic systems, is well proven within the upper 3–5 km of the crust (Fig. 2A). It is consequently assumed by many workers that the same melt types would simply release more $CO_2$-rich, although Cu-poor, large fluid volumes at greater depths to form a much different style of structurally controlled gold mineralization (Fig. 2B). Such assumptions ignore many of the issues described above that are recognized from studies of magmatic systems. These deeper magmatic-hydrothermal models typically stress geochemical and mineralogical aspects of studied gold ores as documentation of a magmatic fluid source, an inference which is then used to conclude the fluids and metals were exsolved from a deeply emplaced intrusion type that may or may not be recognized regionally. Second, the presence of some silicate alteration phases in orogenic gold deposits and many magmatic-hydrothermal ores that are indicative of stability at a certain temperature common to both, including sericite or biotite-K-feldspar, indicates that these minerals cannot be used to discriminate a gold deposit type. Third, most giant orogenic gold deposits are presently mined by open pit where some studies focus on very localized geological anomalies that are exposed in the extensive workings and commonly are unrelated to the ore-forming event. Finally, whether it is a series of dikes in a pit or a suggested unexposed pluton nearby defined by geophysical study, without an all-encompassing investigation, it is easier to implicate a point source for fluids and metals rather than attempting to understand a much broader regional process. Below, we summarize some specific recent examples of the controversy.

## Giant deposits in metamorphic terranes sometimes argued to be related to oxidized magmas

**Yilgarn craton** The Fimiston deposit mined by the Golden Mile open pit in the Yilgarn craton is the world's largest Archean lode gold deposit and is historically accepted to be an orogenic gold deposit (Phillips and Groves 1983; Hagemann and Cassidy 2000). Nevertheless, Tripp et al. (2020) describe synvolcanic low- and high-sulfidation epithermal-like textural features that are overprinted by later deformation and metamorphism. Such features have even led to classification of the Fimiston ores as a giant shallow-level epithermal-like deposit (Clout 1989) with similarities to Emperor and Cripple Creek (Bateman and Hagemann 2004). Such epithermal-like features are however limited in their extent and some, such as hydrous silica, may have even developed during open-space vein formation at great depth as pressures dropped during hydrofracturing (Weatherly and Henley 2013). In support of this process, Dubé et al. (2004) note that at the Red Lake deposit in Canada, some colliform-crustiform gold-bearing veins appear to have formed at mesozonal depths.

Evidence from many studies shows the Fimiston ores formed at temperatures of at least 350 °C and a depth of approximately 10 km, as summarized by A.G. Mueller et al. (2020a, b), although these authors argue for an I-type magmatic origin. They conclude that $\delta^{18}O$ fluid values of 8.2–9.8‰, high Sr isotope ratios of a variety of hydrothermal minerals, and the presence of tellurides and V-rich micas in high-grade ores are evidence for exsolution of a fluid with $X_{H2O} = 0.85$ from a monzodiorite suite of intrusions emplaced somewhere below 10 km. McDivitt et al. (2021) similarly call upon a deep magmatic fluid based upon also (1) an argument that MIF $\Delta^{33}S$ and $\delta^{34}S$ values of diagenetic pyrite in a local slate differs from values of mineralization-related pyrite and (2) spatial association between the gold and pre-ore porphyry dikes. A similar argument using MIF $\Delta^{33}S$ data has been used to discredit the possibility of a metamorphic fluid for formation of other large orogenic gold deposits in the Yilgarn craton (e.g., Kanowna Belle: Sugiono et al. 2021). In all such examples, however, there continues to be no spatial association with any exposed causative intrusion, nor explanation about what atypical petrological process causes an aqueous-carbonic fluid to be unmixed and released from melts at depths below 10 km to form a series of gold-only deposits throughout a terrane. Indeed, McDivitt et al. (2022) in arguing for a magmatic-hydrothermal model based on dating of minerals in syn-ore dikes state that the petrotectonic formation processes "remain cryptic" for the Au-Te ore at Fimiston.

**Abitibi greenstone belt** Many of the largest deposits in the Superior Province of Canada have been defined as magmatic-related deposits by some workers, particularly where a part of the mineralization is hosted by alkaline to subalkaline intrusive rocks that are widespread in the greenstone terranes. The world-class Canadian Malartic has been alternatively referred to as a porphyry, syenite-associated disseminated, oxidized intrusion-related, mesozonal stockwork-disseminated replacement, or orogenic gold deposit type in the recent literature. A magmatic model similar to that summarized for the Fimiston deposit was proposed for the Canadian Malartic ores, with a mid-crustal monzodioritic intrusion exsolving an oxidized fluid that migrated through much of the crust and deposited gold at a depth of about 10 km (Helt et al. 2014). The evidence for such a fluid was argued to be stable isotope data ($\delta^{18}O$ fluid values of about 5–10‰, δD values of − 52 to − 45‰, and $\delta^{34}S$ values of -4.5 to + 3.3 ‰); K-feldspar and biotite in the alteration assemblage; locally anomalous amounts of Te, Bi, W, and Mo; and ratios of major elements in bulk extraction fluid inclusion waters from mineralized quartz. But these characteristics do not discriminate in any way between a magmatic and metamorphic source reservoir (e.g., Beaudoin and Raskevicius 2014; De Souza et al. 2019) and a magmatic model is entirely speculative (De Souza et al. 2020). The Kirkland Lake deposit was suggested to be an epithermal-like magmatic deposit based upon spatial association with alkaline intrusions, presence of gold-bearing tellurides and molybdenite, high Au:Ag ratios, and potassic alteration defined by abundant sericite (Ispolatov et al. 2008). The bulk of the gold ore at the Hollinger-McIntyre deposit surrounds a small Cu-Mo-Au porphyry such that the spatial association led many workers to favor a genetic association, although geological and geochronological evidence precludes any such relationship (Dubé et al. 2020). The complexities at some of these large deposits are likely the product of overprinting of different mineralization types and is discussed in a brief later section.

**Other Archean greenstone belts** A link between the Archean gold and magmatism has also been stressed for the Geita goldfields in Tanzanian greenstone belts (Dirks et al. 2020). The Mg- and F-rich biotite and the associated K-feldspar in the hydrothermal alteration, Bi-bearing tellurides, and Au/Ag ratios of about 1 are stressed as linking gold to widespread magmatism in the greenstone belt. In addition, an association with porphyry dikes, widespread emplacement of K-rich granites, and a post-accretionary timing during an extensional regime have all been stated to further support such a link (Kwelwa et al. 2018). Nevertheless, these arguments remain speculative without any proven connection to a magmatic source.

**Central Asia orogenic belt** Similar argument have been used to justify for a significant magmatic-hydrothermal component as being associated with genesis of many of the giant gold deposits hosted in Neoproterozoic and Phanerozoic accretionary belts. The world's largest orogenic gold deposit, Muruntau (Figs. 10A and 11), has been tied to mantle magmatism based upon elevated He isotope ratios for fluid inclusions extractions and an unradiogenic initial Os measurement of arsenopyrite (Morelli et al. 2007). A polygenetic origin including a major magmatic component for Muruntau has been further noted based upon other noble gas isotopes from fluid inclusions; high Br/Cl ratios of inclusion waters; K-feldspar and biotite alteration phases; lamprophyre dikes along gold-hosting structures; and anomalous amounts of As, Sb, Bi, Mo, W, and Pt in some of the mineralization (Graupner et al. 2001, 2006; Wall 2004). Wall (2004) presented the so-called TAG (thermal aureole gold) model where gold mineralization at Muruntau formed in hornfelsed rocks at sites 3–4 km above causative intrusions emplaced at depths somewhere from > 6 to 10 km (Figs. 11 and 12). Although a large amount of metamorphism and devolatilization occurred below Muruntau via heating during asthenospheric upwelling and related magmatism (Seltmann et al. 2020), workers have argued that the majority of the gold was sourced from a hypothesized sill-like batholith (Hall and Wall 2007), which theoretically could be oxidized or reduced in nature.

Other Paleozoic giant central Asian orogenic gold deposits also within carbonaceous sedimentary rock-dominant terranes are equally controversial in origin based upon many of the same presented arguments. This includes Kumtor where ages of gold and spatially/temporally related alkalic magmatism is used to hint at contributions from the lithospheric mantle (Mao et al. 2004). Sheeted veins in the ore-hosting intrusion; a W-Bi-Sb association with gold; minor ilmenite in some host intrusions; 2–30 ppb Au measured in amphibole, biotite, and ilmenite grains in the host rocks; and as much as 300 ppb Au determined in some aplite and pegmatite dikes cutting these rocks were all considered as suggestive of a magmatic contribution to ore formation at Zarmitan (Abzalov 2007), although as noted below in this case the causative intrusion was suggested to be relatively

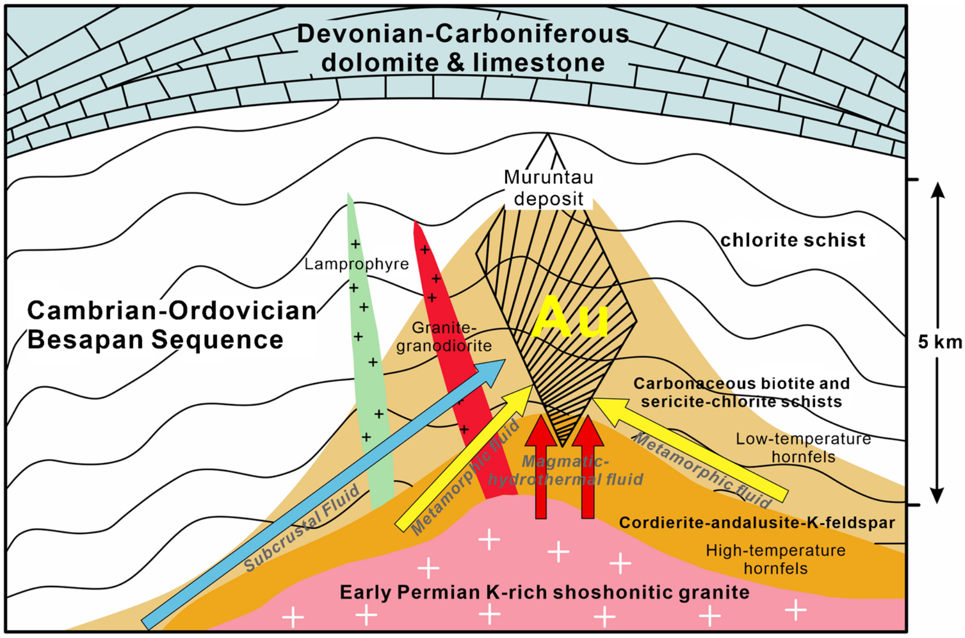



**Fig. 11** Proposed genetic models for formation of Muruntau (after Kempe et al. 2016; Seltmann et al. 2020), world's largest orogenic gold deposit, include an ore fluid released from the mantle and a fluid released from an intrusion about 4 km below the deposit; neither is a likely scenario based upon many arguments presented in this paper. Alternatively, as discussed in Seltmann et al. (2020), a magmatic and/or mantle thermal event superimposed a contact metamorphic overprint on previously regionally metamorphosed sediments. The contact metamorphism caused further metamorphic upgrading of the sedimentary rocks that probably led to further devolatilization and concentration of ore-forming fluids in a locally carbonaceous and brittle broad hornfels zone

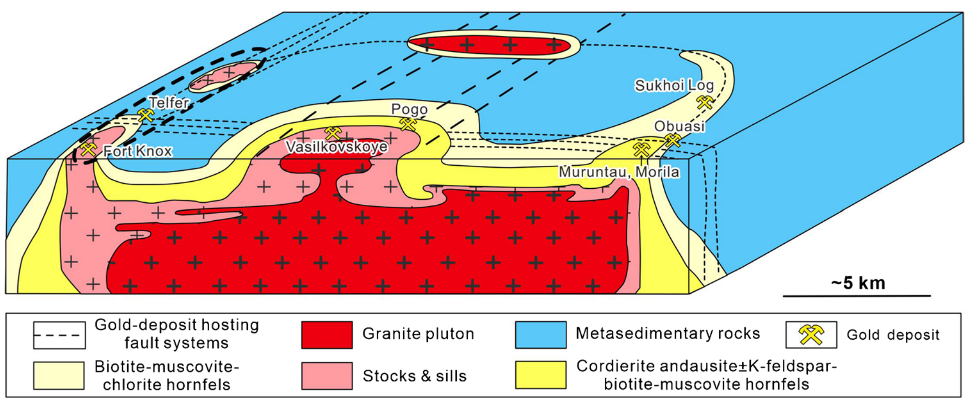



**Fig. 12** The Thermal Aureole Gold or TAG model of Wall et al. (2004) and Hall and Wall (2007). The model argues that many giant lode gold deposits, that are defined as orogenic and intrusion-related by various workers, formed from magmatic-hydrothermal fluids released from large, fractionated, commonly reduced, hydrous (2.5–4 wt% $H_2O$) plutons emplaced at depths of 5–10 km or deeper. Deposits are suggested to form in favorable structures in granitoid roof zones (e.g., Fort Knox, Vasilkovskoye) or in thermal aureoles adjacent to the causative intrusions (e.g., Pogo, Muruntau, Telfer, Obuasi, Morila, Sukhoi Log). Whereas some of these deposits may reflect low-gold grade sheeted vein systems formed in roof zones of plutons emplaced at 5 km (Fort Knox) or high-gold grade deposits formed from metamorphic fluids generated from magmatic heat (Muruntau), release of a large volume of gold-bearing magmatic-hydrothermal aqueous-carbonic fluid from plutons emplaced below 5 km is improbable

reduced. Helium isotopes were also considered to be indicative of mantle input (Graupner et al. 2010). A magmatic contribution at Bakyrchik is assumed based upon near-zero $\delta^{34}S$ isotope values and broadly coeval mafic dikes (Soloviev et al. 2020).

Damdinov et al. (2021) argued that the presence of As-, Bi-, Sb-, and Te-bearing mineral phases; the presence of Ag- and Sb-rich sulfosalts; calculated $\delta^{18}O$ values for auriferous quartz of about 6–7‰ and measured $\delta^{34}S$ sulfide values of about −4 to +5‰; and restriction of ores to granitoid hosts rather than shear zones could identify Neoproterozoic and early Paleozoic gold deposits of a magmatic orogen in the East Sayan region of Russia. Causative intrusions could be either oxidized or reduced, and these were defined as an orogenic gold subgroup that formed from a magmatic fluid.

**Other Phanerozoic accretionary orogens** Despite sometimes conflicting age relationships, workers have suggested magmatic-hydrothermal origins for many Phanerozoic gold provinces along the margins of subduction-related batholiths. In the South American Cordillera, Sillitoe (2008) termed the Segovia belt in Colombia and Pataz-Parcoy belt in Peru to be oxidized pluton-related gold deposit types (Fig. 10B, C). The classification emphasized both belts being hosted in I-type, calc-alkaline linear batholiths stated to be genetically related to the gold ores. This is in contrast to the orogenic gold deposit classification of the geologically and geochemically very similar ores in the North American Cordillera of Alaska's Juneau gold belt (Fig. 11G) and California's Mother Lode belt (Goldfarb et al. 2008), which are located along the margins of similar linear subduction-related batholiths. Haeberlin et al. (2004) noted that the Carboniferous gold deposits in the Pataz batholith generally formed 15 myr after crystallization of the igneous rocks. Nevertheless, Witt et al. (2016) favor a magmatic-hydrothermal model arguing that argon ages on hydrothermal sericite of ca. 314–312 Ma were likely reset during deformation and the batholith-hosted veins, formed at depths of 13 ± 4 km (Haeberlin 2002), had a magmatic origin sometime between ca. 340 and 320 Ma. Evidence for such a magmatic fluid was described as absence of high gold grades with changing vein dips, locally massive pyrite-arsenopyrite volumes with an abundance of Pb–Zn sulfides, and some highly saline fluid inclusions. Wiemer et al. (2021, 2022) hypothesize the deep mineralizing fluid in the Pataz-Parcoy belt was expelled from a melt by repetitive seismic ruptures represented by incremental vein texture and termed these "intrusion-related orogenic" gold deposits. An even larger age spread between Segovia batholith emplacement and gold formation characterizes the ca. 88 Ma gold ores of the Segovia belt hosted in the 160 Ma dioritic intrusions (Leal-Mejia et al. 2010). An intrusion-related model is however suggested by Shaw et al. (2019) that relates the linear belt of gold deposits to the ca. 96–58 Ma composite Antioquian batholith. Supporting evidence is defined as similar Pb isotope measurements for pyrite in the 88 Ma Segovia belt veins and in 60 Ma gold occurrences in the Antioquian batholith, as well as the age overlap between the veins and a stock in the northeastern edge of the Antioquian batholith that is just about 10 km west of the gold belt. Nevertheless, a large ductile shear zone separates the Segovia gold belt and host batholith from the Antioquain batholith with perhaps a few hundreds of kilometers of offset in the Late Cretaceous and early Tertiary (Keenan and Pindell 2009), thus making the significance of the spatial association unclear.

## Giant deposits in metamorphic terranes sometimes argued to be related to reduced magmas

Commonly cited global examples of RIRGD (see Sillitoe 2020, Table 7), many of which are notably high in gold grade when compared to the well discussed North American deposits at Fort Knox and Dublin Gulch, are equally problematic as far as possessing good supporting evidence of magmatic association; many are nevertheless in fact included within the TAG model of Wall et al. (2004; Fig. 12).

**Commonly cited non-North American RIRGD examples** Vasilkovskoe in northern Kazakhstan occurs as a subvertical stockwork system within a sheared oxidized, not reduced, granodiorite complex and the gold event is about 100 myr younger than the Ordovician magmatism (Khomenko et al. 2016). Salave in the northwestern part of the Iberian Massif of Spain occurs as a series of stacked parallel lenses of mainly fine, disseminated, auriferous arsenopyrite within the sheared margin of a slightly reduced granodiorite and in the adjacent metasedimentary rocks (Rodriguez-Terente et al. 2018). Absolute age relationships led Mortensen et al. (2014) to suggest that Salave is probably an orogenic gold deposit with a spatial–temporal association to Variscan magmatism. The Morila deposit in Mali is an example of a large deposit of auriferous quartz veinlets hosted in a fold hinge in hornfelsed schist that is spatially associated with oxidized intrusions. It has been called a Paleoproterozoic RIRGD gold deposit due to reduced sulfide phases in the ores such as pyrrhotite and loellingite (McFarlane et al. 2011) but such classification given the structural setting and nature of the magmatism seems very challenging (Goldfarb et al. 2017). Early structural studies of the Neoproterozoic Telfer deposit in Western Australia described features typical of shear zone-related orogenic gold ores (Vearncombe and Hill 1993; Hewson 1996) leading to a genetic model that involved contact metamorphism producing a highly saline metamorphic fluid capable of transporting the Au and Cu in the deposit (Rowins et al. 1997). The local geology includes shelf sequences and, as stressed by Yardley and Graham (2002), metamorphism of such units may produce a fluid that is quite saline. The rheological controls on the stacked reefs within anticlinal domes with ductile shearing and brittle faulting in the locally carbonaceous metasedimentary host rocks would be consistent with such a model. But the unusually high Cu content of the gold ores (≤ 1000 ppm in the hypogene ore: Maidment et al. 2017), along with the saline fluids in some fluid inclusions and K:Ca > 1 and high Fe, Mg, K, and Na in the inclusions has led to a now common classification as a

RIRGD (Schindler et al. 2016). Although no intrusions are exposed within 10 km of the deposit, Wilson et al. (2020) suggest that geophysical data might indicate a 40-km-long reduced batholith may have episodically released Cu- and Au-rich magmatic fluid over a period of 40 myr. Whereas many workers provide evidence and arguments for all these above world-class gold deposits to be classified as RIRGD, they clearly are different from the well-studied Tintina Gold Belt RIRGD and their connection to magmatic-hydrothermal processes is far from definitive.

**Cretaceous Alaskan deposits** Other world-class gold deposits are even more controversial, listed alternatively as either orogenic or RIRGD origin in the recent economic geology literature, particularly other deposits in the Alaskan part of the Tintina belt and giant deposits in central Asia (see Sillitoe 2020, Table 11). Both Pogo and Donlin Creek have been described as examples of RIRGD (Szumigala et al. 1999; Thompson and Newberry 2000), but they look nothing like the Fort Knox and Dublin Gulch deposits and any genetic association with intrusions, reduced or oxidized, is equivocal (Rhys et al. 2003; Goldfarb et al. 2004). A magmatic-hydrothermal origin for the high-grade Pogo deposit (Fig. 10D) has been suggested based upon oxygen and sulfur isotope values, a Au–Ag-As-Bi-Te-Pb geochemical signature, early biotite alteration, an association with regional extension, a spatial–temporal association with reduced felsic to intermediate intrusions, and a mineralization timing that post-dates metamorphism of the host rocks (Smith et al. 2000; Rhys et al. 2003). Low Br/Cl ratios in Pogo fluid inclusions are stated as consistent with a magmatic source (Baker et al. 2006). The thick, shallowly-dipping stacked auriferous quartz veins (Fig. 10D) formed at an estimated 7 km depth at ca. 104 Ma and overprint 109–107 Ma granitic dikes in the mine area, but a causative intrusion for the ores remains unrecognized (Rhys et al. 2003). The 70 Ma Donlin Creek deposit formed within the upper few kilometers of the crust has been suggested to represent a low-sulfidation (Ebert et al. 2000) or sub-epithermal stockwork-like system adjacent to a causative porphyry body (Ebert et al. 2003), the latter classification perhaps resembling some magmatic-hydrothermal ores of the Colorado Mineral Belt (Bundtzen and Miller 1997). Again, however, a spatial–temporal association with a nearby porphyritic intrusion only allows speculation regarding genesis (Goldfarb et al. 2004).

**Central Asia orogenic belt** The RIRGD classification is not well justified for any of the central Asian deposits. Zarmitan occurs within a series of reverse-slip faults as a 7-km-long vein swarm along a granitoid-metasedimentary rock contact (Abzalov 2007). Support for the magmatic model includes the ilmenite-bearing nature of the felsic intrusions; anomalous concentrations of Te, W, Bi, and Sb in the gold-bearing ribbon-type veins; and the existence of some sheeted veins. Yet descriptions of the ores show little difference from most orogenic gold deposits where heterogeneous stress zones control mineralization along granitoid margins (Groves et al. 2018). The TAG model of Wall et al. (2004), as mentioned above, shows the giant Muruntau deposit to be in the thermal aureole of the roof zone of a sill-like and water-rich intrusion (Figs. 11 and 12). A deep drill hole 1 km from the 5300 t Au deposit intersected an ilmenite-bearing syenogranite at 4 km depth (Kempe et al. 2016; Seltmann et al. 2020) but there is no evidence whatsoever that this particular reduced intrusion has anything to do with formation of this enormous gold-bearing ore system.

## Summary

Where gold-bearing fault-fill quartz veins (Fig. 10C, E) and stockwork systems (Fig. 10A, F) are hosted by or near intrusive bodies, particularly oxidized intrusive systems, the involvement of a magmatic-hydrothermal fluid has been widely debated (Sillitoe 2020). Even when no intrusive rocks are present, workers may call for a magmatic origin for orogenic gold. For example, abundant aqueous fluid inclusions and very low δD measured for bulk extraction fluid inclusions were taken as evidence of a large magmatic component in the Macraes gold deposit (deRonde et al. 2000) despite no intrusive rocks recognized anywhere in the South Island of New Zealand host terrane. Ridley and Diamond (2000) note that because we don't know the full subsurface architecture, one cannot fully rule out a magmatic-hydrothermal origin for the New Zealand orogenic gold deposits. Yet, as we explain below, not only do the above-described magmatic systematics argue against such a genetic model for most mesozonal and hypozonal deposits formed in metamorphic belts, but the consistently repeated and supposedly supporting features calling upon a magmatic model for these controversial deposits are extremely problematic.

It is also important to note that one must be careful in classifying a deposit as magmatic-hydrothermal based upon criteria used to define the small group of RIRGD. As stressed by Hart (2007), these deposits are associated with felsic, ilmenite-series plutons that lack magnetite. The critical characteristics argued as definitive of this group of deposits (Thompson and Newberry 2000) relate to gold ores genetically associated with their causative reduced intrusions. Defining gold ores hosted by oxidized intrusions as intrusion-related based upon comparisons with deposits such as Fort Knox and Dublin Gulch, located within reduced igneous bodies, makes no sense. For example, Zhao et al. (2022) state a similarity between these deposits in the Tintina Gold belt and the Unkurtash gold deposit in central Asia. The Unkurtash deposit is, however, hosted in a magnetite-bearing granodiorite that is also associated with Cu-Au skarns.

Thus, Unkurtash may or may not be intrusion-related, but if so, then it is certainly an oxidized intrusion-related deposit and many features associated with the RIRGD classification are not applicable.

## Discussion

### Evaluation of characteristics suggested to support magmatic input to orogenic gold

A number of mineralogical, geochemical, isotopic, and geological characteristics are commonly proposed to be indicative of magmatic-hydrothermal fluid input into orogenic gold systems. Many of these characteristics, such as alteration mineralogy or stable isotope compositions, are used as supporting evidence for this ore genesis model but taken independently can clearly be interpreted in multiple ways and thus have been also cited as supporting non-magmatic genetic models. Other characteristics such as noble gas isotopes as discussed earlier may indeed indicate a magmatic source of that specific component but not of the $H_2O$, S, Au, and associated metals required to form the deposit. These characteristics passively support a favored genetic model rather than actively discriminate between different genetic models. Below, we evaluate some of the more commonly cited independent characteristics stated to indicate the input of Au-bearing magmatic-hydrothermal fluid to orogenic gold deposits.

Metamorphic fluids commonly have low salinities (3–7 wt% NaCl eq.), so that deposits enriched in base metals, particularly Cu and Pb, have been suggested as sourced from a magmatic fluid as this higher salinity fluid (5–15 wt% NaCl equiv: Audétat and Edmonds 2021) would be more capable of transporting these elements. Where abundant base metals are present, they are typically local concentrations within a much broader gold resource and are rarely economically recoverable. Examples include the Gara deposit in the Loulo mining district, Mali, where locally high base metal contents and high-salinity fluid inclusions have been interpreted as an indication of either a magmatic fluid source or a fluid produced from metamorphism of an evaporative unit (Lawrence et al. 2016; Lambert-Smith et al. 2020). The typical low-salinity fluids have been modeled to show that only 2–5% of the total Cu, Pb, and Zn within a typical metapelite will be mobilized during metamorphic events that release significant Au and As volumes during chlorite dehydration and pyrite desulfidation of the same rocks (Zhong et al. 2015). Recent work has shown that metasedimentary basins that include evaporite sequences can generate saline metamorphic fluids during prograde metamorphism, which may then precipitate a more polymetallic style orogenic gold deposit (Evans and Tomkins 2020), although these almost never contain economic concentrations of such base metals. Boron isotope analyses of tourmaline in a few orogenic terranes (e.g., Lambert-Smith et al. 2016) also confirm evaporites can contribute to the ore-forming fluid. Many Paleoproterozoic gold deposits in Finland are characterized by high concentrations of Cu, Ni, and (or) Co, and have been referred to as “atypical orogenic gold deposits” (Eilu et al. 2007; Eilu 2015). These base metal-rich gold deposits are hosted in mafic and ultramafic rocks and thus the enrichment in these metals reflects local wall rock alteration reactions with the sulfur in the hydrothermal fluids. In summary, high base metal contents in orogenic gold deposits are rare but can be produced by saline metamorphic fluids in belts where evaporitic rocks were present in fluid source areas or by interaction with wall rock in deposit trap areas. As such, this characteristic should not be used as evidence of magmatic fluid input.

Strong enrichment in Mo, Bi, W, and (or) Te, either in the form of elemental concentrations or in the form of Au-Bi telluride minerals, is commonly cited as an indication of magmatic fluid input from both oxidized or reduced intrusions (e.g., Morelli et al. 2007; Mueller et al. 2020a; Mathieu 2021). This suite of elements may less commonly include Sn (e.g., Augustin and Gaboury 2019). But all these elements are enriched in orogenic gold deposits of all ages. Deposits showing particularly high enrichments of these elements and where Au occurs as Au-tellurides, such as the Golden Mile deposit in Australia (approximately 20% of Au is hosted in tellurides; Shackleton et al. 2003) and Kirkland Lake in the Abitibi belt of Canada, are commonly suggested to have a magmatic fluid input. Spence-Jones et al. (2018) suggest that just a high Te content in some orogenic gold deposits may be a signature of magmatic fluid input. It should be noted, however, that not all deposits where a large proportion of the gold occurs as gold-bearing telluride minerals are interpreted to have formed from magmatic fluid input (e.g., the Mustajärvi deposit in Finland: Mueller et al. 2020b).

Although enrichments of these elements in magmatic-hydrothermal deposits is well accepted (e.g., Thompson et al. 1999), these elements can be mobilized through other processes such as metamorphism of specific rock types. Molybdenum, Bi, and Te are commonly enriched along with Au, As, and Sb in organic matter and in diagenetic pyrite in black shales (e.g., Large et al. 2007, 2011; Gregory et al. 2015; Parnell et al. 2017). During diagenesis these elements are released from organic matter and incorporated into growing diagenetic pyrite. They are mobilized from the rock by metamorphic fluids which drive the transition from pyrite to pyrrhotite which does not host these elements (e.g., Pitcairn et al. 2006; Large et al. 2007, 2011; Parnell et al. 2017). Critical for the mobilization of these elements from metasedimentary rocks is the composition of the host sedimentary rock. Greywacke sequences where initial concentrations of Mo-Bi-Te are low may not mobilize large proportions of these metals during metamorphism (e.g., Pitcairn et al. 2021). Metamorphism of black shales enriched in C and S (C + S > 1 wt%), such as those in the Kittilä and Savukoski groups of the Central Lapland Greenstone belt, Finland, drives significant mobility of As, Sb, Mo, Te, and Sn during prograde metamorphism (Patten et al. 2022). Cave et al. (2016) show that metamorphic conversion of detrital rutile to titanite, broadly coeval with the pyrite to pyrrhotite conversion event, will release significant amounts of W into the fluid.

It is clear, therefore, that enrichments in Mo-Bi-Te-W ± Sn in orogenic gold deposits can be caused by a number of processes and do not necessarily imply input of magmatic fluids. Enrichment of these elements may instead commonly imply the occurrence of C- and S-rich black shales in the source area stratigraphy that has undergone metamorphism. The timing of enrichment of these elements in orogenic gold deposits is typically paragenetically late relative to pyrite and arsenopyrite. For example, more than 90% of all gold in the Kensington gold deposit (Fig. 10G) in the Juneau gold belt occurs as calaverite that overprints early barren pyrite in the ore-bearing veins (Heinchon 2019). It is possible, at least for Te, Bi, and Mo, that interaction of later fluid pulses with early formed sulfides leads to changes in fluid redox and changes in mineral paragenesis.

Many of the above-described world-class gold deposits were stated to be related to oxidized magmas based upon potassic alteration phases. In her review of intrusion-related gold systems in the Abitibi greenstone belt, for example, Mathieu (2021) includes K-alteration as evidence of magmatic fluids. Potassic alteration is nevertheless extremely common in orogenic gold deposits of all ages and host rock compositions and is in no way exclusively the product of magmatic fluid reactions. As noted by Groves (1993), biotite and K-feldspar define a common alteration assemblage in many orogenic gold deposits in which slightly higher temperatures favor these phases over white mica. Potassic alteration can clearly be developed from magmatic fluids but it is not evidence for magmatic fluid input. It is also a well-recognized product of metamorphic fluid flow where $K^+$ cations are commonly mobilized by mineral exchange reactions that buffer pH (e.g., Evans and Tomkins 2020).

The occurrence of specific alteration minerals such as sulfates, including barite and anhydrite, as well as oxide minerals such as hematite, has been suggested to imply involvement of an oxidized fluid (Cameron and Hattori 1987; Mathieu 2021). This is significant as metamorphic fluids are generally considered to be reduced and therefore alteration driven by oxidized fluids is commonly interpreted to be of magmatic origin. Examples of oxidized alteration assemblages spatially associated with orogenic gold deposits include the hematite- and anhydrite-bearing alteration assemblages at Hollinger-McIntyre in the Abitibi belt (Cameron and Hattori 1987; Mathieu 2021). There are two key points to make regarding the interpretation of this style of alteration. First, it is particularly important to ascertain whether the alteration minerals are genetically related to the orogenic gold mineralization or occurred during an earlier porphyry-style mineralization phase. For example, based on cross-cutting relationship between mineralized quartz-carbonate veins and hematite-altered anhydrite-bearing porphyry bodies, Mathieu (2021) classifies the Hollinger-McIntyre system as a porphyry deposit overprinted with an orogenic gold system and therefore that the oxidized alteration assemblage is not genetic to the main stage of quartz-carbonate vein Au mineralization. Second, the occurrence of hematite as an alteration mineral may not indicate oxidized fluids. In their investigation of the alteration assemblage surrounding the Golden Mile mineralization in Western Australia, Evans et al. (2006) show that pyrrhotite-magnetite alteration assemblages in equilibrium with $H_2S$ bearing fluid can transition to pyrite-hematite-magnetite assemblages in equilibrium with $SO_4$ due to a combination of cooling and wall rock alteration without the requirement for an oxidized ore-forming fluid.

Skarn mineral assemblages associated with gold ores in orogenic gold provinces have sometimes been used as evidence for large-scale fluid release from hydrous magmas lower in the crust. It is critical to note that the term skarn may apply to either such a Ca-Fe–Mg-Mn silicate *assemblage* produced during high-temperature metasomatism of any rock type or to a magmatic-hydrothermal *ore deposit type* within dominantly carbonate units (Meinert et al. 2005; Phillips and Powell 2010). Hypozonal orogenic gold deposits that form in ductile settings at depths ≥ 8–12 km (Kolb et al. 2015) develop as mainly replacement style ores with calc-silicate minerals being important alteration phases at the higher temperatures (Groves 1993). Therefore, skarn-bearing gold ores formed at great depth in orogenic gold provinces, such as those of the Neoarchean Southern Cross Greenstone Belt in Western Australia estimated to have originated at 11–14 km depth (Mueller et al. 2004), are best viewed as deeper level orogenic gold deposits. The Australian examples lack any association with receptive carbonate country rocks, as is typical of gold-bearing skarn ore deposits.

As summarized in Goldfarb and Groves (2015), various geochemical parameters commonly used to implicate a magmatic-hydrothermal formation of orogenic gold can be interpreted in multiple ways. Fields for oxygen, hydrogen, sulfur, and carbon isotopes overlap for many magmatic and metamorphic fluids. Radiogenic isotopes, such as those for Pb and Sr, typically will have a large contribution from both fluid pathways and transformation of mineral phases during alteration in the deposit trap area indicating that measured ratios in hydrothermal minerals likely will not be definitive of these components in the source region (Ridley and Diamond 2000). Noble gas signatures commonly suggest a mantle-link to ore-hosting fault zones, but that does not indicate the same source for H, O, S, C, and metals that have migrated along the permeable conduit. Ratios of halogens are difficult to interpret as the measurements are usually made on bulk extractions of fluid inclusion waters from minerals that have trapped many fluid generations and many may have no association with the gold-forming event.

There are continual justifications in the literature regarding the close spatial association between dikes and gold ores (Fig. 10B) to reflect a genetic connection. For example, Sillitoe (2008) classified the Pataz belt of Paleozoic gold deposits in northern Peru as oxidized pluton-related magmatic-hydrothermal ores based on the close spatial association of mineralized quartz veins with porphyry dikes. A similar spatial association has often been used to justify a magmatic connection for the origin of Archean gold ores such as in Western Australia (McDivitt et al. 2020) and Tanzania (Dirks et al. 2020). Furthermore, as noted earlier, the observation of lamprophyre dikes in many mines recovering orogenic gold ores is typically taken as evidence of genesis, whether or not there is even an overlap in age. But the important fact remains that dikes and metamorphic fluids will tend to be located along many of the same structures, particularly where these are giant first-order fault systems, and the spatial association does not indicate genesis.

Pegmatites, as well as miarolitic cavities, are common products of crystallization (second boiling) below about 6 km (Burnham 1997). Spatial association between pegmatites and some gold deposits has led to suggestions that late, fluid-rich magmatic pulses may lead to a transition from such causative dikes into hydrothermal gold-bearing veins. For example, the Pogo deposit in Alaska has been argued to be an intrusion-related gold deposit that shows a gradation from causative granitoids to barren pegmatites and then into the auriferous ore-bearing veins (Dilworth et al. 2007). However, as pointed out by London (2018), bubble ascent in the melts to release a fluid in a rapidly forming pegmatite is not a viable process. Furthermore, he stresses miarolitic spaces in pegmatites are extremely rare and thus fluid saturation before full crystallization is not expected. A spatial association, therefore, may be present in some gold deposits between gold and pegmatites (e.g., Cawood et al. 2022) but the relationship is structural and not genetic.

Thus, when taken as isolated characteristics, high base metal content, high Mo-Bi-Te enrichments, and oxidized alteration assemblages do not uniquely support a magmatic fluid input into orogenic gold deposits. These characteristics themselves do not preclude a magmatic fluid input but they should not be used as direct evidence for involvement of magmatic fluids and following the difficulties of invoking magmatic fluid input as outlined above in this paper, these characteristics may be better explained through other processes.

## Complex overprinting in some Neoarchean intrusion-related gold deposits

Many Neoarchean gold deposits, best recognized in the Abitibi greenstone belt of Canada, have a complex history due to widespread seafloor volcanism and early greenstone belt magmatism that pre-dates regional metamorphism, much of the deformation, and most orogenic gold formation. As pointed out by Groves et al. (2003), many of these gold deposits may be modified porphyry-epithermal systems, some of which are then overprinted by orogenic gold. Turner et al. (2020) indicate that the giant Boddington deposit in Western Australia shows features of early porphyry mineralization that are overprinted by mineralization styles resembling both orogenic gold and gold skarn, with the entire system forming in events spread over a 100 m.y. period. Canadian examples could include the Pearl Lake Cu-Au–Ag-Mo porphyry at the Hollinger-McIntyre deposit and the quartz monzodiorite-granodiorite at Canadian Malartic with early quartz-molybdenite-pyrite veinlets. In contrast, a few of the Abitibi belt gold deposits, particularly syenitic in composition and with widespread albite-hematite alteration, are characterized by disseminated and stockwork-style gold mineralization that pre-dates most orogenic gold mineralization in the belt by 20–50 m.y. (Robert 2001). These include the Upper Beaver and Bachelor deposits, the latter with significant amounts of fluorite that is not expected in orogenic gold deposits. However, as indicated by Dubé and Mercier-Langevin (2020), it is critical to note that many such alkaline to subalkaline intrusions in the Abitibi belt, such as present at the Timmins West, Young-Davidson, and Canadian Malartic deposits, are simply competent host rock bodies to the later orogenic gold formation that has no magmatic-hydrothermal association. The presence of sulfates or hematite, as well as stable isotope data, in deposits such as Young-Davidson and those in the Kirkland Lake district have been suggested to reflect deep-seated magmatic-hydrothermal fluid (Mathieu 2021), but these may be related to an early intrusive event not genetically related to orogenic gold formation and, as noted above, these characteristics are not definitive of such a source. The fact that many of the quartz-feldspar porphyries, alkaline to subalkaline intrusions, and dikes of various compositions were emplaced along the fault zones that also controlled orogenic gold formation, thus serving as major magmatic and hydrothermal conduits over a long period of time, has led to much of the controversy regarding the possibility of magmatic association (Groves et al. 2003; Dube and Mercier-Langevin 2020).

Another group of Neoarchean greenstone belt-hosted intrusion-related gold deposits do, however, represent mineralization associated with subaqueous magmatism and volcanism. These deposits are particularly well identified in Canada's Abitibi greenstone belt and include epizonal oxidized intrusion-related gold systems such as those at Doyon, Westwood, Troilus, and Cote Gold (Yergeau et al. 2022). The deposits show a spatial association between Au-rich VMS ores and submarine porphyry-epithermal styles of mineralization generally related to calc-alkaline tonalites. The association is again further complicated by the overprinting regional metamorphism and deformation in the greenstones. These overprinting events would have remobilized most of the ore-related elements into relatively late formed structures. This group of synvolcanic-synmagmatic gold deposits pre-dates the widespread formation of orogenic gold deposits throughout the Abitibi greenstone belt by 50–100 m.y. (Dubé and Mercier-Langevin 2020). Whether or not the giant Neoarchean Hemlo gold deposit is part of this group is uncertain as it is characterized by enigmatic features that partly resemble seafloor VMS, orogenic, and oxidized intrusion-related gold deposits (Poulsen et al. 2020).

## Where do the Carlin gold deposits fit relative to other gold deposit types?

The genesis of Carlin-type deposits and how they relate to the intrusion-related and orogenic gold deposits described here remains highly controversial. To a degree, this partly reflects the fact that unlike the oxidized intrusion-related gold deposits and orogenic gold deposits, with models developed from examples worldwide, the Carlin gold models are essentially based upon features from one local region and time slice which is the late Eocene of the Great Basin of Nevada. The Carlin deposits do possess some features resembling distal disseminated deposits associated with oxidized intrusions, as well as epithermal gold deposits (Muntean 2018), whereas also they do have some features that resemble the gold-only deposits of Phillips and Powell (2014) that also include orogenic gold deposits.

During the past decade, a magmatic-hydrothermal model with an enriched subcontinental lithospheric mantle source has been the most accepted model for generation of the Nevada Carlin-type gold deposits (Muntean et al. 2011). Johnson et al. (2020) suggest that these mantle-derived magmas interacted with reduced and carbonaceous crust during their ascent, which would explain their gold-only metallogeny. Yet, these hypothesized causative plutons remain concealed below the sedimentary rock stratigraphy although aeromagnetic data (Ressel and Henry 2006) and petrochemical modeling of dike systems (Mercer 2021) support their presence at depth. Recent arguments favor that in contrast to shallowly emplaced plutons that form gold-bearing porphyry and epithermal ores, fluids that form the Carlin deposits are exsolved from intrusions emplaced at 6–10 km depth and migrate up steep fault systems to react with carbonates at depths of 1–3 km to form the giant gold deposits (Henry et al. 2020). Significant concerns, however, must still be addressed for this model to be fully applied. First, similar to the problem with having orogenic gold ores associated with deeply emplaced intrusions, it would require an unusual scenario to have such a voluminous Au- and S-bearing aqueous fluid release from melt at the 6–10 km depth estimate. Second, having most of such a fluid moving up faults through the ductile–brittle crust for perhaps 5–6 km until reaching reactive dirty carbonate units is difficult to imagine. Most likely, one would expect such a fluid pulse to form large fault-fill vein systems along their fluid pathways, as even in extensional regimes such as that which characterized Jiaodong in China, such a mineralization style is an expected consequence of large fluid volumes migrating along steep pathways at mesozonal depths. Third, the linear belts or trends of Carlin-type deposits extending for a few hundreds of kilometers along the length of basement faults appear more like what one would expect from some type of regional flow system rather than centered around roof zones of intrusions. Thus, if Carlin-gold deposits are the product of magmatic degassing and aqueous fluid release at mesozonal depths, then an improved modeling of the relevant Au and S fluid-melt partitioning at pressures of perhaps 2–3 kb and subsequent Au transport to epizonal levels are critical issues for further study.

## Conclusions

There is little doubt that formation of orogenic gold occurrences is an inherent consequence of prograde metamorphism. Every orogen will be characterized by its own thermal structure that controls devolatilization of fertile marine sedimentary and volcanic rocks that are added to a continent and heated through the desulfidation window (e.g., Tomkins 2010) for the first time. No one model can be applied to every orogenic gold deposit formed by such orogenesis as thermal regimes developed in accreted fore-arc terranes and inverted back-arc basins are products of the complex interplay of many lithospheric and asthenospheric processes. As long as there is sufficient diagenetic pyrite, as well as possibly fertile organic material, favorable conditions of deformation and orogenic heat can form world-class gold ores through the focusing of consequential auriferous aqueous-carbonic metamorphic fluid. In contrast to most gold deposit types, most orogenic gold ores will thus not have a local source but fluid and metal will be derived from a large volume of heated crustal material. Because different parts of a metamorphic belt follow different PTt paths, ages of orogenic gold mineralization can vary along the length of an orogen.

It is not clear as to whether a magmatic-hydrothermal system can provide a significant fluid or metal contribution to an orogenic gold deposit. A late- to post-tectonic magmatic system may theoretically overprint an orogenic gold deposit and cause some redistribution of existing metal. In addition, a regional contact-type of metamorphism can be one type of thermal event leading to the required devolatilization of the country rocks. Some experimental results have been suggested as providing indirect evidence of a magmatic-hydrothermal origin for some orogenic gold through the recognition that $CO_2$-rich fluids exsolve from hydrous magmas at mid-crustal depths and earlier stages of magmatic evolution (Hsu et al. 2019). But, as we argue above, other experimental work suggests large fluid volumes are most commonly not released from melts until they reach the upper 6 km; magma degassing at greater depths tends to focus volatiles upward within channels in the magmatic system; and much of the Au and $H_2S$ remain in the system until melts stall at about 3–6 km. Significant volumes of an aqueous-carbonic fluid being released from a crystallizing melt at mesozonal or hypozonal crustal depths to form an orogenic gold deposit remains unproven and appears unlikely. In a shallower crustal environment, it is well known that magmatic-hydrothermal aqueous fluid exsolution will form gold-bearing epithermal and porphyry deposits, as well as perhaps Carlin-type and distal disseminated gold deposits. It is improbable that these same oxidized intrusions in other cases would somehow release an aqueous-carbonic fluid to form orogenic gold deposits at the same epizonal depths. In cases where the intrusions are reduced, the rare examples of economic low-grade reduced IRGD may result, although the exact process leading to the anomalous gold remains uncertain; the gold may reflect metal enrichments in the assimilated sediments or alternatively some aspect of the role of the reduced material on magma-fluid evolution. Most epizonal orogenic gold deposits will differ from these reduced IRGD at least by mineralization style, lack of zoning, and lack of spatial/temporal association with roof zones of causative intrusion, even if ore-forming fluid chemistries remain poor discriminators.

Many other points weigh strongly against a magmatic association for orogenic gold. Mantle and intrusion-related models hypothesized for orogenic gold formation are based on interpretation of trace metal and isotope data for hydrothermal minerals, information which is shown above to be far from definitive. Late tellurides, stibnite, and (or) gold are commonly interpreted to suggest multiple fluid sources for orogenic gold but as noted earlier, orogenic gold deposits form via numerous seismic events and later fluid pulses may deposit a variety of new mineral phases as they react with earlier deposited material along the same conduit. Particularly noteworthy is the long-recognized observation that most magmatic-hydrothermal gold ores are associated with oxidized intrusions emplaced in the upper 3–4 km and thus at shallower levels than copper porphyry ore systems that are gold-poor (e.g., Sillitoe 1997). Both calc-alkaline and alkaline magmatic-hydrothermal systems that are relatively deeply emplaced tend to release a single-phase fluid and can deposit metals such as Mo and Cu upon cooling at the higher pressures at depths of 4–7 km; at the deeper end of this range, single phase fluids escaping a magma tend to form few and widely spaced quartz veins. It is not until at higher crustal levels and lower pressures where a fluid from such a melt rapidly separates into a vapor and liquid with volume expansion and hydrofracturing (e.g., Weis et al. 2012), that Cu-Au or Au will precipitate in stockwork and sheeted vein networks (Murakami et al. 2010; Chiaradia 2020). How a large volume of fluid containing significant amounts of gold would escape a melt at even higher pressures to cool and deposit orogenic gold at depths of 5–15 km is unclear and seems unlikely.

Finally, assuming a gold-bearing aqueous-carbonic fluid was derived from a deep melt, the resulting geohydrology would not seem to favor an ore-forming event. Significant fluid volumes are unlikely to escape horizontally from a crystallizing magma and would tend to be buoyant and rise in the melt. Because the magma will crystallize inward and downward, the produced fluid will be trapped in the mush. At depths below 6 km, characteristic of deeper porphyry deposits, it is doubtful that fluid volumes and pressures will be great enough to lead to fracturing of a chamber roof zone. Even assuming such is the case, then the distribution of orogenic gold in most gold provinces would remain difficult to explain. First, most orogenic gold districts host dozens of occurrences. Could this unique degassing scenario reflect dozens of intrusion roof zones all degassing at depth or one main intrusion roof zone releasing a fluid that somehow gets scattered along multiple structures? Second, most world-class orogenic gold provinces host mesozonal deposits that are spaced for hundreds of kilometers immediately adjacent to a series of deep crustal fault zones. Could causative plutons be spaced along the lengths of such zones, each individually being capable of voluminous aqueous-carbonic fluid release at depths of $10 \pm 5$ km? These scenarios seem very unlikely, as again orogenic gold deposits are very regional in distribution and thus not the type of systems that would be associated with one or a series of more local fluid and metal sources. A first-order control on metamorphic fluid focusing and orogenic gold deposit distribution are these giant fault systems, whereas porphyry and epithermal magmatic-hydrothermal deposits, although often locally controlled by faults, have a first-order control being their intrusive center. Such intrusion-related deposits don’t show a distribution pattern that resembles orogenic gold in any manner. Interestingly, and in contrast to observations on the porphyry-epithermal systems, many of the Carlin gold deposits in Nevada follow narrow linear trends for a couple of hundred kilometers that are interpreted as ancient basement faults controlling fluid flow from depth (Muntean, 2018). This therefore emphasizes an ongoing concern with the understanding of the hydrogeology controlling the Carlin deposit type.

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## Declarations

**Conflict of interest** The authors declare no competing interests.



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