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LETTER

The Boring Billion: A key to resolving controversy on ore-fluid source models for orogenic gold deposits?

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Abstract

Orogenic gold systems are arguably the most variable mineral system globally in terms of an extreme range of depositional depths, corresponding P–T conditions and wallrock alteration assemblages, structural controls and styles, and element associations. This diversity has ignited controversy on genetic models for the two decades since orogenic gold became a widely accepted term. From the diverse genetic models proposed, the two groups of fluid-source models that meet most genetic constraints are the following: (1) deposition from crustal fluids via metamorphic devolatilization at the amphibolite-greenschist transition, or potentially even deeper under specific tectonic conditions, and (2) deposition from sub-crustal fluids either by direct devolatilization of subducted oceanic crust and overlying sediment wedge or of previously metasomatized and fertilized mantle lithosphere. Both models normally postulate gold deposition within a geodynamic system that evolves from extension through compression into syn-gold transpression. Crustal metamorphic models normally invoke subduction-driven geodynamic systems that involve advection of crustal metamorphic fluids up crustal-scale faults. In contrast, sub-crustal devolatilization models involve subduction-related processes as both geodynamic drivers and gold sources with fault-controlled fluid conduits extending to below the Moho. The overall lack of orogenic gold and other subduction-related mineral systems during the unique Boring Billion (1.8–0.8 Ga) period provides an important constraint on this genetic debate. Boring Billion orogens had varying geodynamic drivers, asthenosphere upwelling, and low-P metamorphic terranes with crustal-scale faults, all parameters consistent with formation of orogenic gold systems, during subduction-independent accordion-type tectonics. The absence of orogenic gold during the Boring Billion provides critical evidence against the crustal metamorphic model and furthers the sub-crustal model which requires subduction as both the geodynamic driver and auriferous fluid source.

Keywords Boring Billion · Orogenic gold · Auriferous fluid source · Crustal metamorphic model · Sub-crustal model · Subduction · Metasomatized mantle lithosphere

Introduction

The term orogenic gold was defined by Groves et al. (1998) to describe a structurally controlled group of ore deposits that formed in convergent margin settings and were deposited in broad thermal equilibrium with their crustal host rocks from low-salinity H_2O-CO_2 fluids at crustal depths ranging from 2 to potentially > 20 km (Gebre-Mariam et al. 1995). Although the terminology is generally accepted (Goldfarb et al. 2005), the arguably unique diversity of the group in terms of depth of deposition, corresponding P–T conditions, and consequent variation in wallrock alteration and ore assemblages, plus structural controls and orebody styles has led to promotion of numerous conflicting genetic models which can only be resolved in terms of a mineral systems approach (Wyman et al. 2016). Goldfarb and Groves

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(2015) review all models and refute all near-surface meteoric fluid models and syn-sedimentary models. More recently, Goldfarb and Pitcairn (2023) argue that magmatic-hydrothermal models are not applicable for even individual orogenic gold deposits, with Hertzog et al. (2023) providing irrefutable geochronological data to show that Malartic-Val d'Or in Quebec, with its long-held magmatic-hydrothermal model, formed over 50 Myr after magmatism. Thus, crustal or sub-crustal metamorphic models seem to be the only viable potentially universal genetic models for orogenic gold systems.

The key objective of this contribution is to provide a brief overview of the competing ore fluid source models and demonstrate how the Boring Billion (1.8–0.8 Ma) provides critical evidence that constrains these models and favors models involving a sub-crustal source intimately related to subduction processes.

Crustal metamorphic model

Until about 2015, there had been widespread acceptance of an early model (Phillips and Groves 1983) for an auriferous fluid source derived from metamorphic devolatilization of largely supracrustal rocks under amphibolite-facies conditions within the continental mid-crust. Dominant upwards advection of resultant metamorphic low-salinity H_2O-CO_2 (+/−CH_4, N_2) fluid, sulfur, and metals from the breakdown of pyrite to pyrrhotite is advocated along complex continental fluid pathways (Ridley and Diamond 2000) to the higher crustal level of depositional sites (Goldfarb et al. 2005; Phillips and Powell 2010; Tomkins 2010). A schematic model is shown in Fig. 1A, with the variety of potential geodynamic settings to provide the thermal driver for regional crustal metamorphism to drive orogenic gold systems shown in Fig. 1B to F.

This crustal metamorphic model can explain mesozonal to epizonal orogenic gold deposits (Gebre-Mariam et al. 1995), where peak greenschist-facies metamorphic conditions were broadly synchronous with peak to retrograde metamorphic timing of gold mineralization, as summarized by Goldfarb et al. (2005) and numerous other authors. However, it has significant weaknesses as a universal model because gold-rich fluids would have to be extracted from devolatilization of variable volcanic and sedimentary source rocks at different times during Earth evolution (Pitcairn et al. 2006; Patten et al. 2022) in different geodynamic settings. A major weakness of the crustal metamorphic model for Precambrian orogenic systems is the significant group of hypozonal (Gebre-Mariam et al. 1995) deposits worldwide that were deposited in mid- to upper-amphibolite facies domains. Kolb et al. (2015), with an exhaustive reference list, describe 22 such deposits worldwide with 11 from Western Australia where the crustal continuum was first formalized (Groves 1993). To generate the auriferous fluid at > 15 or even > 20 km depth, Kolb et al. (2015) invoke a special case of nappe stacking or extensional unroofing in evolved orogens to provide P–T gradients to generate a potential, but unlikely (Goldfarb and Groves 2015), mixture of metamorphic and anatectic ore fluids. Multiple sulfur isotope ratios of Neoarchean orogenic gold deposits in Western Australia (Caruso et al. 2022) suggest that local supracrustal rocks did not supply significant sulfur for gold-related sulfides but that this sulfur came from a sub-crustal homogenized reservoir that contained recycled mass-independent fractionated sulfur (MIF-S) isotope signatures. Like Kolb et al. (2015), Caruso et al. (2022) also invoke near-Moho depth crustal anatectic melts as a source of ore fluids but show lithosphere-scale faults in their model and also suggest potential input from metasomatized mantle lithosphere. The strong spatial, and even temporal, relationship of Yilgarn orogenic gold deposits to lamprophyres and sanukitoids (Smithies et al. 2018) is however strongly indicative of a direct link to metasomatized mantle lithosphere rather than crustal anatexis.

Sub-crustal models

Phanerozoic mesozonal to epizonal orogenic gold deposits are generally consistent with the crustal metamorphic model (Goldfarb et al. 2005). However, as for the Precambrian terranes discussed above, there are well-documented hypozonal deposits such as the Jurassic Danba deposit in China (Zhao et al. 2019; Wang et al. 2020), and some late Carboniferous to early Permian (315–285 Ma) orogenic gold deposits of the Variscan belt in the Massif Central of France (Bouchot et al. 2005), and also some ~ 370 Ma lode gold deposits, including Beaver Dam and Cochrane Hill, hosted in amphibolite-facies turbidite sequences in the Paleozoic Meguma Group, Nova Scotia, for which Kontak et al. (1990) suggest derivation from a sub-crustal source. Other potential Phanerozoic hypozonal deposits include Muteh (Moritz et al. 2006) and Kašperské Hory (Ackerman et al. 2019).

Recent research on orogenic gold deposits, particularly those adjacent to the North China and Yangtze craton margins, has also negated crustal metamorphism as a universally viable fluid source model (Li and Santosh 2017). For example, Deng et al. (2020) show that auriferous ore fluids arose during Cretaceous asthenosphere-upwelling-related devolatilization of metasomatized mantle lithosphere on the margin of the North China Craton, which was fertilized during Triassic subduction of gold-enriched pyritic sedimentary rocks from the northern margin of the Yangtze Craton. More recently, Wang et al. (2023) use mercury isotopes as tracers to demonstrate that orogenic gold deposits on craton margins that experienced subduction of oceanic crust contrast with those that experienced subduction of continental crust, with Δ^{199}Hg values of the gold deposits

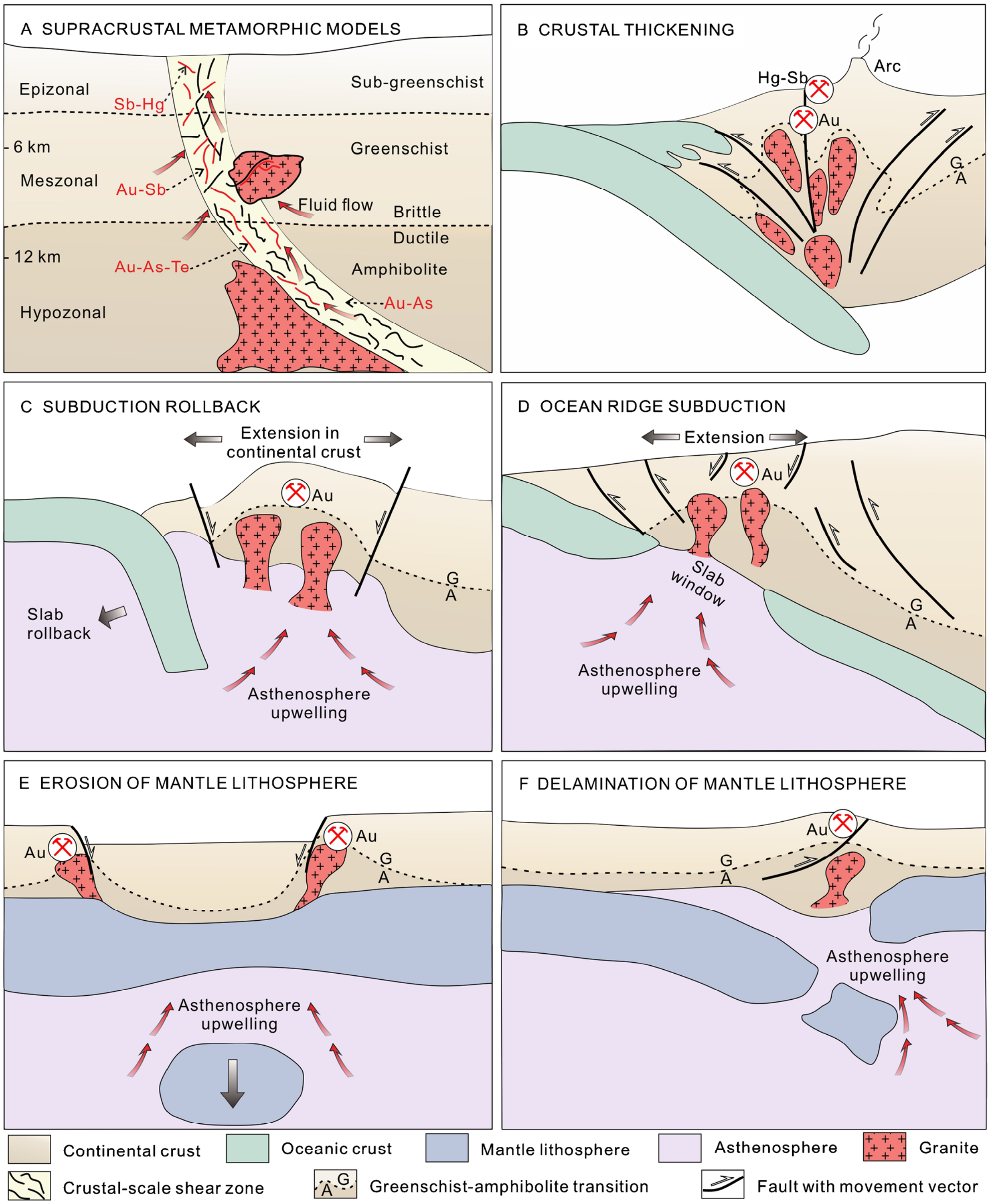

Fig. 1 **A** Schematic crustal metamorphic model for orogenic gold deposits: modified from Groves et al. (1998). **B–F** Subduction-related geodynamic settings for orogenic gold deposits based on crustal metamorphic model. Modified from Goldfarb et al. (2001), the key reference that shows multiple tectonic scenarios, with mantle plume impingement on subduction zone removed. **E** Now accepted as representing a subcrustal fluid model (Goldfarb and Santosh 2014)

reflecting that of the crust responsible for metasomatism of mantle lithosphere. Other Chinese gold deposits on these craton margins, including those of Qinling, Ailaoshan, and Huangjindong, support sub-crustal auriferous fluids (Wang et al. 2022).

A coherent sub-crustal mineral system model for orogenic gold deposits

A potentially universally applicable (Wyman et al. 2016) orogenic-gold mineral system model with two endmembers is shown in Fig. 2.

Based on discussion above, the fertility parameter of the orogenic gold mineral system must be represented by a sub-crustal S-bearing H_2O-CO_2 fluid containing Au plus Ag, As, Bi, Sb, Te, and W. Unfortunately, the precise origin of this fluid or metal source is equivocal despite multiple fluid inclusion or stable and radiogenic isotope studies (Goldfarb and Groves 2015). Thus, the ultimate sub-crustal source must be deduced indirectly from parameters such as geodynamic setting and tectonic timing.

As noted above, orogenic gold deposits are formed in accretionary or collisional tectonic environments related to subduction within convergent margins. This explains the common late- to post-metamorphic timing in host sequences (Vielreicher et al. 2010; Zhao et al. 2019; Hertzog et al. 2023, among many others), coincident with a change in plate motions and related far-field stresses that instigated the transition from compression to transpression, reflected in the geometry of the orogenic gold orebodies (Groves et al. 2018). In the absence of evidence for underlying or adjacent older mantle lithosphere, the only viable sub-crustal source of metal- and S-bearing fluid appears to be subducted oceanic crust and its overlying sediment wedge (Wyman et al. 2016). Slab devolatilization causes release of S, Au, and other metals to the fluid via breakdown of sedimentary pyrite to pyrrhotite (Large et al. 2009) and can be accompanied by extensive upward fluid-flux along slab-mantle boundaries (Katayama et al. 2012; Dixon et al. 2017) into accretionary terrane margins. Resultant over-pressured ore fluids can then be injected via injection-driven seismic swarms (Cox 2016) from lithosphere- to crustal-scale fault zones to deposit orogenic gold in lower-order structural traps at shallower crustal levels (Fig. 2A).

A subduction-related model must be adapted for orogenic gold provinces sited on craton margins as in eastern China. Here, as summarized by Deng et al. (2020) and Wang

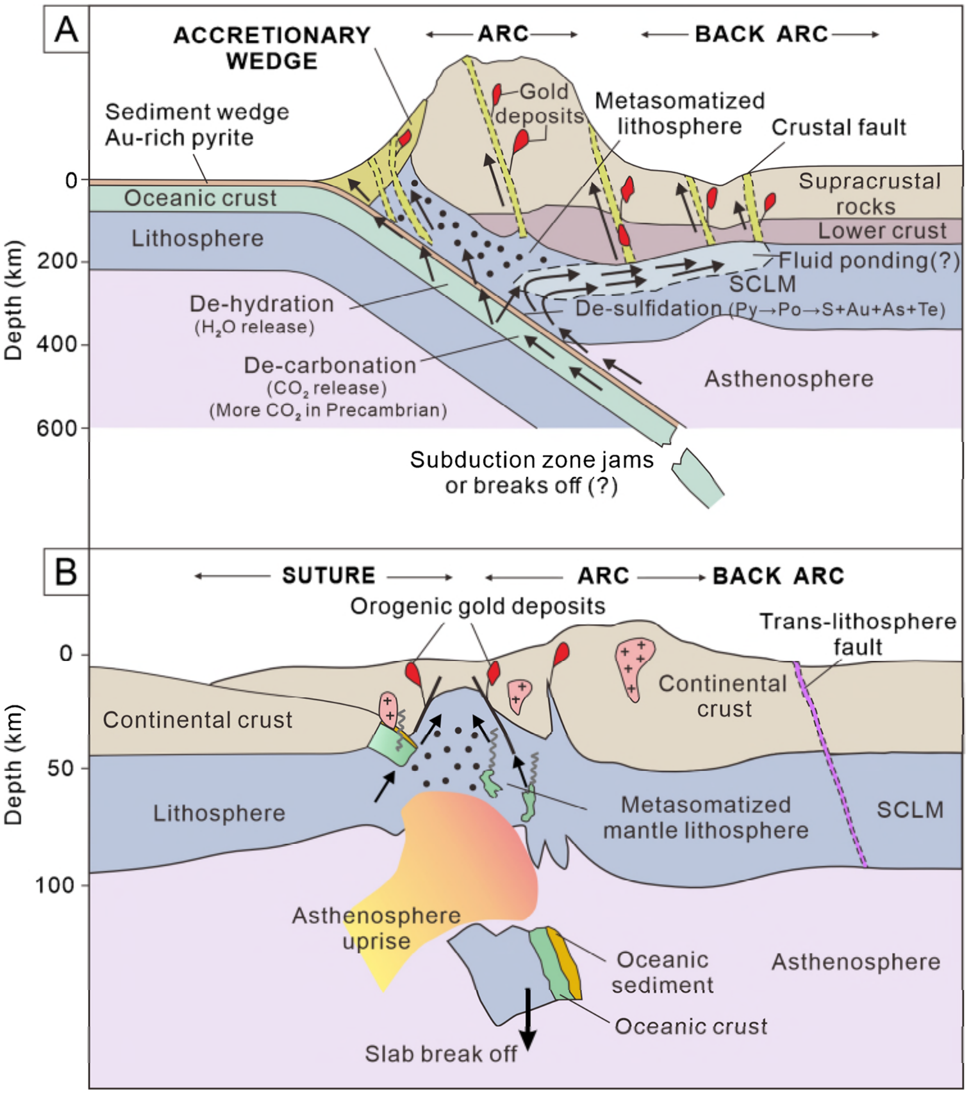

Fig. 2 Schematic representation of subduction-based models for ore-fluid source for orogenic gold deposits. **A** Direct subduction model modified from Groves et al. (2020). **B** Two-phase subduction model involving a metasomatized and fertilized mantle lithosphere source of fluid and metals adapted from Zhao et al. (2021)

et al. (2022), subduction plays a critical role in fertilizing the mantle lithosphere which through its devolatilization related to asthenosphere upwelling provides auriferous fluids (Fig. 2B). The precise mechanism for fluid release via devolatilization without clear evidence for involvement of magmatic-hydrothermal fluids or direct involvement of magmatism is problematic. Instead of direct devolatilization of volatile-bearing silicate minerals, it is possible that fluids released by the devolatilization of metasomatized lithosphere may be transported through magmatic conduits, particularly basaltic melts that evolve in batches and produce hydrous basic melts at the Moho (Caricchi et al. 2018; Collins et al. 2020). These underplated magmas eventually fractionate through melting-assimilation-storage-homogenization (MASH) processes producing dacitic upper crustal melts, the crystallization of which releases CO_2 and H_2O rich fluids (Touret et al. 2022). Such mechanisms appear to apply for high crustal level IRGDs which form from magmatic-hydrothermal fluids exsolved from hybrid melts during extension related to orogenic collapse (Mair et al. 2011). However, they cannot apply to hypozonal orogenic gold deposits (Goldfarb and Pitcairn 2023) where direct devolatilization or exsolution from hydrous basic melts at the Moho during transpressional orogeny must apply.

As Begg et al. (2023) explain that Archean lithosphere may underlie up to about 67% of the continental crust, and orogenic gold deposits are formed on continental margins, it is possible that all orogenic gold deposits formed from metasomatized mantle lithosphere as postulated by Hronsky et al. (2012).

In contrast to the crustal metamorphic model of Fig. 1, the mineral system models in Fig. 1B to F require a lithosphere-crust continuum in structural architecture to provide an effective orogenic gold plumbing system. The first-order lithosphere-scale structures commonly contain abundant lamprophyre and related dykes that indicate fluid conduits with a lithosphere connection (Rock et al. 1989). They are also defined by magnetotelluric subvertical structures that extend to the Moho with zones of anomalous resistivity termed “Fingers of God” (Heinson et al. 2018; Robertson and Thiel 2019) as shown by Groves et al. (2020, their Fig. 9).

Orogenic gold systems are anomalous hydrothermal systems in that they formed at crustal depths of mostly > 5 km (Groves et al. 1998) and have enhanced preservation potential because of their late-orogenic timing. Orogenic gold systems on craton margins were particularly well preserved because of thick buoyant sub-continental lithosphere keels (Griffin et al. 2013) beneath or adjacent to them. Orogenic gold deposits thus formed and were preserved during most orogenic events in Earth history (Fig. 3) except for the Boring Billion from 1.8 to 0.8 Ga, with discussion below examining whether this provides an important discriminant between competing crustal and sub-crustal genetic models.

Tectonics and metallogeny in the Boring Billion

The assembly of Columbia at ca. 2.0 to 1.8 Ga, like the prior assembly of Kenorland, witnessed a normal convergent margin metallogeny rich in orogenic gold and VMS Cu–Zn-Pb systems. The Earth then entered the Boring Billion phase from 1.8 to 0.8 Ga, a transitional static period in terms of the evolution of global tectonics, the atmosphere, and oceans, prior to the assembly and breakup of Rodinia (Santosh and Groves 2023). Unlike the history of previous supercontinents, extensive breakup, and continental drift during the transition from Columbia to the assembly of Rodinia was limited, with Roberts (2013) suggesting that Columbia remained as a quasi-integral continental lid until at least 1.3 Ga with several failed break-up attempts. Columbia underwent only minor modifications when it was amalgamated into the Rodinia supercontinent at ca. 1.1 to

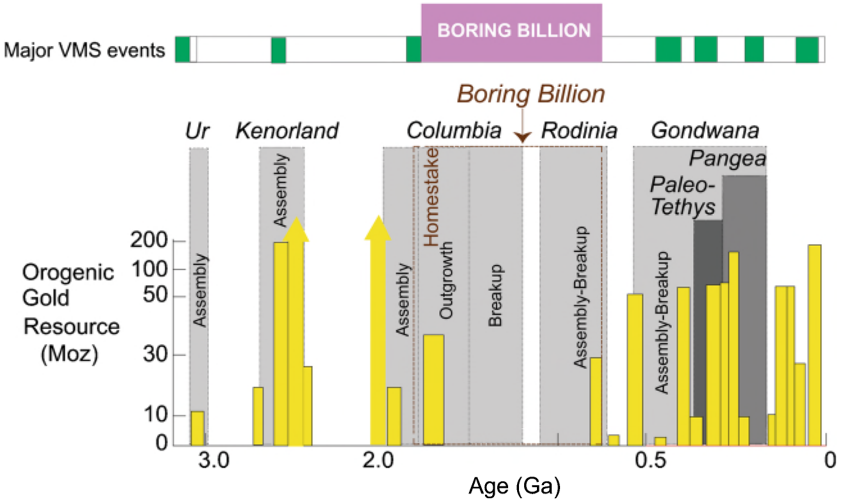

Fig. 3 Temporal distribution of orogenic gold systems updated from Goldfarb et al. (2005), mainly with data from Western Australia and eastern China as globally significant gold producers, in terms of the supercontinent cycle and Boring Billion. All histograms of deposit sizes should be considered indicative rather than definitive as it is impossible to obtain accurate resource data for several countries. Major periods of VMS Zn-Pb-Cu mineralization also shown. Modified and adapted after Santosh and Groves (2022)

0.9 Ga with external accretionary belts incorporated into internal Grenville-type high-grade metamorphic collisional belts. The largely low-strain accordion-style tectonic regime in internal orogenic belts (Collins 2002) appears to have been typified by intermittent extension, rifting, and asthenosphere upwelling followed by compression and closure of extensional basins. As expected, there is limited evidence of subduction from preserved geological assemblages, with a general absence of convergent-margin mineral systems, including orogenic gold and VMS (Fig. 3), which both preceded and proceeded the Boring Billion.

As discussed extensively by Santosh and Groves (2023), the anomalous accordion-style tectonics resulted in formation and preservation of an equally anomalous metallogenic bonanza. Varying degrees of rifting, asthenosphere upwelling, intermittent magmatism, and induced hydrothermal circulation resulted in a variety of giant IOCG, carbonatite REE, lamproite diamond, unconformity U, SEDEX, and BHT deposits, particularly in northern Australia (Huston et al. 2016). In contrast, there was an overall absence of undoubted orogenic gold deposits apart from a few provinces with < 1 Moz Au orogenic gold deposits in rare greenschist domains in the Grenvillian Sunsas belt of the Amazon Craton (Goldfarb et al. 2001) and potentially several in the Kibaran Orogen of Central Africa (Pohl et al. 2013). The Early Neoproterozoic Kibaran Orogen includes an extensive Sn-Ta–W-Au metallogenic belt with a strong association with syn-orogenic peraluminous ilmenite-series granite magmatism, but the Twanziga deposit (1.8 Moz Au), with saddle reefs and stockworks in an anticlinal hinge in low metamorphic grade host rocks, has all the hallmarks of an orogenic gold deposit including lack of an obvious magmatic source (Pohl et al. 2013). The Boring Billion, however, does just include the solitary giant 1.74 Ga BIF-hosted Homestake deposit in South Dakota (Bell 2013) which formed during outgrowth of Columbia. Although the retrograde metamorphic setting and structural geometry of ore zones and nature of alteration haloes resemble those of orogenic gold systems worldwide (Groves et al. 2018), Santosh and Groves (2023) point out numerous anomalous features that are more akin to those of intrusion-related gold systems (Hart et al. 2002). As such, Homestake is not discussed further here.

Discrimination between genetic models

The key question is whether lack of orogenic gold systems in the Boring Billion can discriminate between alternative genetic models. As the Boring Billion represents an evolutionary change in tectonics, it is only possible to discriminate between models at that geodynamic scale (Pirajno 2016).

Essentially, most geodynamic variants of the crustal metamorphic model involve asthenosphere uprise as the heat and energy source to promote metamorphic devolatilization of supracrustal successions (Fig. 1B–F), normally at the amphibolite-greenschist transition and broadly equivalent ductile–brittle transition, providing auriferous fluids. These must then migrate laterally, a problematic process, to crustal-scale faults that act as conduits for upward fluid flow towards depositional trap sites (Fig. 1A). Although the tectonic setting is considered as one of subduction, auriferous fluids are not directly generated by subduction-related processes in the crustal metamorphic model (Goldfarb and Pitcairn 2023).

Goldfarb et al. (2001) provide an exhaustive discussion on the problematic issue of the lack of widespread Mesoproterozoic orogenic gold systems even in tectonic settings, such as major accretionary orogens along the margins of South and North America and the Paleoproterozoic to Mesoproterozoic collisional orogens of Australia, where they might be expected based on crustal metamorphic models. Based on analysis of comparisons between various 1.8–0.8 Ma Australian and North American orogens and younger gold-endowed orogens, they present a series of potential scenarios in different orogens which could explain the dearth of orogenic gold systems. These include exposures at crustal levels below normal metamorphic devolatilization domains, particularly in Grenvillian orogens (Rivers 2015) on accretionary external lithosphere margins, and lack of syn-collisional thermal drivers, subduction and accretion, transcurrent structures, and/or volatile- and gold-poor crustal rock sequences, or crustal thickening and rapid crustal uplift. However, the characteristic Mesoproterozoic accordion-style tectonics involved rifting and associated asthenosphere uprise with subsequent compression and rift closure: a similar but more subdued deformation sequence to that in convergent margin settings. Furthermore, Roberts et al. (2015) conclude that preserved Mesoproterozoic orogens demonstrate a similar range of metamorphic and deformation conditions and histories to those that preceded and proceeded the Boring Billion. As an example, Rubenach (1992) shows that in one of the world's great Mesoproterozoic metallogenic belts, the Mount Isa Orogen, syn-deformational low-P regional metamorphism resulted in a variety of metamorphic domains as in orogens of disparate ages.

It appears that all conditions were suitable for formation of orogenic gold systems in terms of the crustal metamorphic model in which there is no requirement for a direct subduction source of auriferous fluids. In contrast, a direct or indirect subduction-related source is the essence of the sub-crustal genetic model. The lack of VMS and, to a lesser degree, Sn-W and porphyry Cu-Au (-Mo) systems in Mesoproterozoic orogens suggests the lack of subduction-related convergent margins, as strong preservation conditions are indicated by excellent preservation of SEDEX and BHT-type base-metal systems and unconformity-related U deposits, all formed at relatively shallow crustal levels over thick lithosphere (Santosh and Groves 2023).

In terms of the potential influence of preservation of the products of subduction-related processes, the Mesoproterozoic IOCG systems, which formed via processes involving metasomatized mantle lithosphere (Groves et al. 2010), provide the most convincing indirect evidence. Interestingly, there are, albeit small, gold-only deposits in both the Gawler Craton, to the west and southwest of the giant Olympic Dam deposit (Ehrig et al. 2017), with its abundant mafic–ultramafic and lamprophyre intrusions (Huang et al. 2016), and in the Eastern Succession of the Mount Isa Orogen to the south-southwest of the Ernest Henry IOCG deposit (Lilly et al. 2017). The brief discussion below is important because it emphasizes the spatial association of globally rare orogenic gold deposits with IOCG deposits that have an undoubted genetic connection to metasomatized mantle lithosphere.

In the Gawler Craton, there are three relatively poorly documented gold-only deposits, Tarcoola, Tunkilla, and Weednanna (Fig. 4: Hand et al. 2007). Tunkilla (~ 1 Moz gold) has the characteristics of an orogenic gold deposit, being in a regional shear zone with gold in pyrite-bearing quartz veins with associated sericite and chlorite alteration (Gordon et al. 2017). The smaller (~ 0.1 Moz Au) but better documented Tarcoola deposit comprises pyrite-bearing quartz veins deposited by low-salinity fluids at temperatures ranging from 340 to 100 °C (Hein et al. 1994), typical of orogenic gold systems. There is little documentation of the ~ 0.15 Moz Weednanna deposit, but it appears to be similar to Tunkilla and Tarcoola (Alliance Resources Ltd ASX Announcement 8 April 2022).

In the Mount Isa Orogen, the isolated ~ 0.5 Moz Au high-grade gold-only Tick Hill deposit is a lineation-parallel plunging D3-related quartz vein system with albite, amphibole, epidote, and chlorite overprinted by K-feldspar and sericite alteration within amphibolite-facies host rocks. It has been related to IOCG systems (Le et al. 2021), but the strong structural control, presence of quartz and silicification, lack of Cu but presence of Bi are not features of IOCG systems (Groves et al. 2010). Instead, the deposit has the features of orogenic gold.

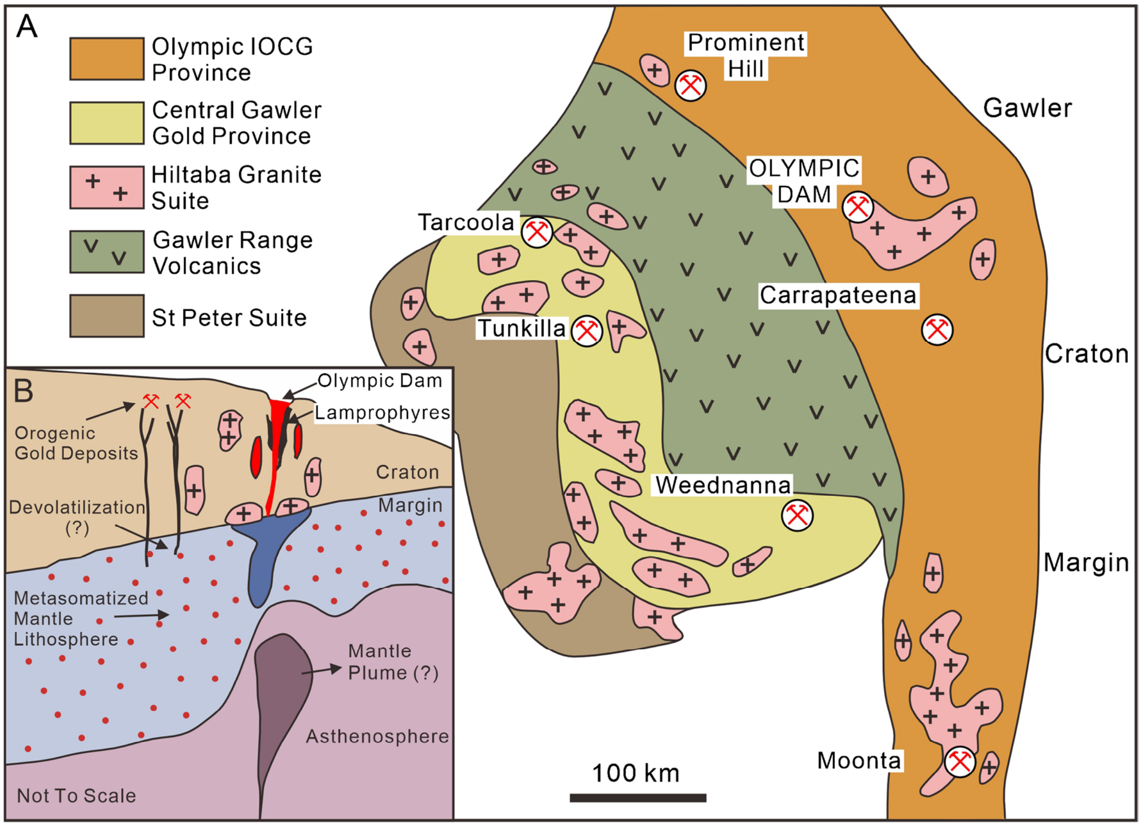

Fig. 4 Distribution of world-class to giant IOCG deposits and small orogenic gold deposits in the Gawler Craton. **A** Geological map showing distribution of IOCG deposits, including the giant Olympic Dam deposit, and the Tarcoola, Tunkilla, and Weednanna orogenic gold deposits: modified from Hand et al. (2007). **B** Schematic model for the generation of Olympic Dam from devolatilization of metasomatized mantle lithosphere: modified from Groves et al. (2010), with possible scenario for distal orogenic gold deposits in largely unfavorable host rock sequences

The presence of these relatively small orogenic gold deposits in what is essentially a magmatic-hydrothermal province dominated by IOCG deposits is reminiscent of the situation in the Kibaran Orogen of Central Africa described above where Twanziga lies within a Sn-Ta–W magmatic-hydrothermal province (Pohl et al. 2013). It is also interesting that the solitary giant 1.74 Ga Homestake deposit has characteristics that appear intermediate between those of orogenic gold deposits and magmatic-hydrothermal IRGDs (Santosh and Groves 2023).

In summary, the lack of widespread undoubted orogenic gold deposits in the Boring Billion is inconsistent with the crustal metamorphic model as there were orogens with crustal-scale structures, thermal and metamorphic conditions, and exposed sequences representing the ductile–brittle transition similar to those in well-mineralized orogens. In contrast, the sub-crustal devolatilization model, which requires subduction to produce auriferous fluids directly or indirectly, is consistent with lack of evidence for other mineral systems, particularly VMS systems, formed in preserved subduction settings associated with the supercontinent cycle. Where Mesoproterozoic IOCG systems provide indirect evidence of subduction-related metasomatism of the mantle lithosphere, there do appear to be, albeit small, orogenic gold deposits in the same terranes.

Conclusions

The past 25 years have seen diverse genetic models on orogenic gold which progressively focussed on processes like generation of auriferous fluids via crustal metamorphism or by sub-crustal devolatilization of subduction slabs and overlying sediment wedges or of mantle lithosphere metasomatized and fertilized by those slabs. The fundamental difference is that crustal metamorphic models do not require fluids via subduction-related processes but that sub-crustal models do. The Boring Billion from 1.8 to 0.8 Ga offers a potential scenario to resolve the conflicting genetic models because it was a period in which orogenic gold systems were extremely rare to absent. The Mesoproterozoic orogens had variable geodynamic settings and tectonic histories but they included terranes that involved similar asthenosphere thermal energy sources, low-P metamorphic conditions with domains of both greenschist- and amphibolite-facies metamorphism, crustal thickening, and crustal-scale faults: parameters equivalent to earlier and later orogens rich in orogenic gold. The missing ingredient is direct evidence for preservation of subduction-related environments with their ubiquitous attendant VMS Cu–Zn-Pb deposits and subsequent porphyry Cu-Au and Sn-W deposits. This, together with the, albeit rare, occurrence of orogenic gold deposits in Mesoproterozoic IOCG provinces that overlie metasomatized mantle lithosphere, strongly favours a sub-crustal genetic model. This strengthens the argument for a universal sub-crustal model that can also explain the occurrence of deep-crustal hypozonal deposits, the undeniable involvement of subduction-related auriferous fluids in orogenic gold deposits around the margins of the North China and Yangtze cratons, and the sub-Moho lithosphere-scale faults and associated lamprophyre intrusions, among other lines of evidence.

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Declarations

Conflict of interest The authors declare no competing interests.

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