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LETTER

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Lithospheric controls on the formation of provinces hosting giant orogenic gold deposits

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Abstract Ages of giant gold systems (>500 t gold) cluster within well-defined periods of lithospheric growth at continental margins, and it is the orogen-scale processes during these mainly Late Archaean, Palaeoproterozoic and Phanerozoic times that ultimately determine gold endowment of a province in an orogen. A critical factor for giant orogenic gold provinces appears to be thickness of the subcontinental lithospheric mantle (SCLM) beneath a province at the time of gold mineralisation, as giant gold deposits are much more likely to develop in orogens with subducted oceanic or thin continental lithosphere. A proxy for the latter is a short pre-mineralisation crustal history such that thick SCLM was not developed before gold deposition. In constrast, orogens with protracted pre-mineralisation crustal histories are more likely to be characterised by a thick SCLM that is difficult to delaminate, and hence, such provinces will normally be poorly endowed. The nature of the lithosphere also influences the intrinsic gold concentrations of potential source rocks, with back-arc basalts, transitional basalts and basanites enriched in gold relative to other rock sequences. Thus, segments of orogens with thin lithosphere may enjoy the conjunction of giant-scale fluid flux through gold-enriched sequences. Although the nature of the lithosphere plays the crucial role in dictating which orogenic gold provinces will contain one or more giant deposits, the precise siting of those giants depends on the critical conjunction of a number of province-scale factors. Such features control plumbing systems, traps and seals in tectonically and lithospherically suitable terranes within orogens.

Keywords Orogenic gold · Giant gold deposits · Metallogeny · Tectonics · Lithosphere · Endowment

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Introduction

Many orogens throughout the geological record contain gold provinces, but only a small percentage of these provinces contain one or more giant deposits (i.e. ≥500 t Au), or even several world-class gold deposits (≥100 t Au). The specific causes for the spatial and temporal imbalance in crustal gold endowment have puzzled explorers and research geologists for decades. In attempting to resolve this paradox, emphasis has commonly been placed on deposit-to camp-scale investigations (e.g. Robert and Brown 1986; Caddey et al. 1991; Phillips et al. 1996; Rowins et al. 1997; Wilde et al. 2001; Allibone et al. 2002; Distler et al. 2004; Weinberg et al. 2004). Studies at these scales have been successful in outlining the principal features and genetic characteristics of the orogenic style of gold mineralisation. However, given that many small and giant orogenic gold deposits share multiple deposit-scale geological and geochemical commonalities (e.g. Hodgson 1993; Clark 1996; Cooke and Pongatz 2002; Leahy et al. 2003), the recognition of parameters that are critical to the formation of giant gold systems is likely to require a broader scale approach. Here, such a broader scale view is taken by considering the theoretical first-order requirements for the formation of a province that contains at least one giant deposit rather than those factors that control the formation of a giant gold deposit itself.

It is postulated that the overall endowment of a given gold province, as well as the formation of giant gold deposits within it, is controlled, at a fundamental level, by factors that operate at the orogen to lithosphere scale. The proxies or signals of these fundamental requirements are then sought from data available in the geological record. The potential key elements required in the formation of these systems are derived from assessment of broad-scale features that are common to the majority of gold provinces that host giant ore systems. An improved understanding of the critical parameters that define giant ore systems, in turn, aids in the formulation of exploration models aimed at discriminating between more and less gold-favourable orogens, and parts of orogens, hence executing a reliable, scientifically based, global targeting strategy.

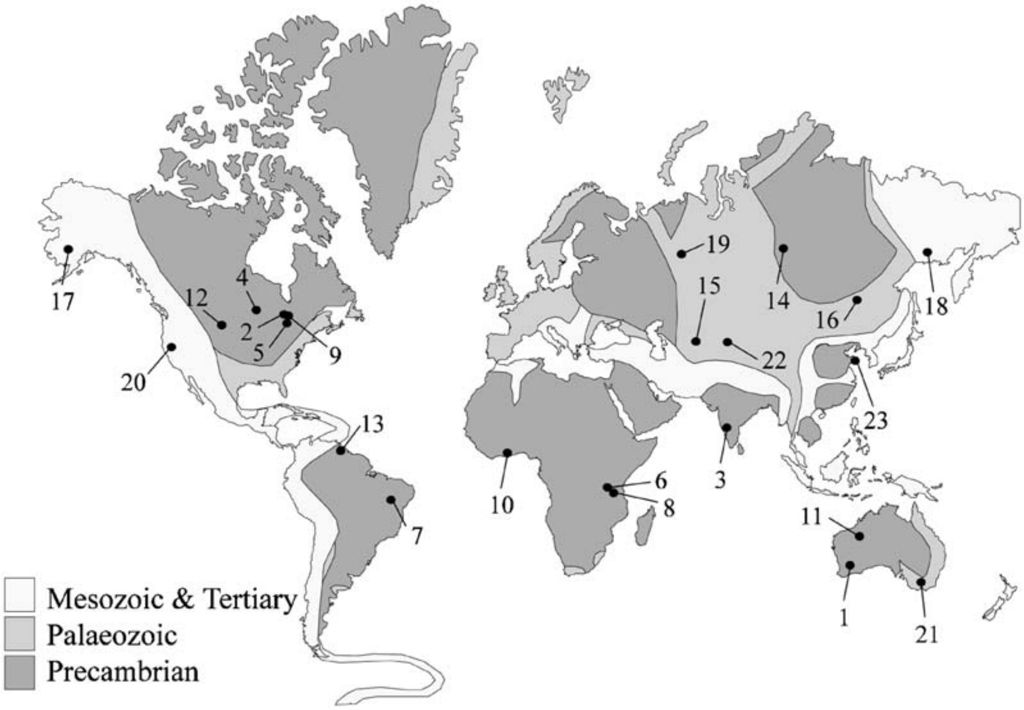
Characteristics of giant orogenic gold systems

Orogenic gold deposits (Groves et al. 1998) are considered in this study because these represent an economically important class of mineral deposit type that, for centuries, has provided a significant source of global gold production. It has long been recognised that orogenic gold deposits of all ages and across all continents are characterised by several unifying geological, structural, geochemical and isotopic characteristics (e.g. Goldfarb et al. 2001 and references therein). Given the evidence for a modified form of plate tectonics in the Archaean and Palaeoproterozoic times (Groves et al. 2005 provide a summary of evidence and references), these similarities lend strong support to the notion that, throughout space and time, orogenic gold deposit formation can be considered more or less a logical consequence of the processes involved in accretionary to collisional tectonics along active continental margins. In most orogens where there is evidence for subduction/accretion and addition of new crust, gold metallogeny closely followed the peak of regional metamorphism of the immediate host rocks (e.g. Stüwe 1998) although there are some important exceptions (e.g. Mesozoic gold in the Precambrian North China Craton; Goldfarb et al. 2001; Zhou et al. 2002). Despite this, there are significant variations across orogens and gold provinces of all ages in terms of their overall endowment in orogenic gold and the distribution and number of giant deposits within them (Fig. 1). Worldwide, there are currently 23 recognised giant orogenic gold deposits and districts that are hosted in 16 gold provinces of predominantly Late Archaean, Palaeoproterozoic and Late Neoproterozoic–Phanerozoic ages (Fig. 1).

The dominantly structurally controlled deposits are hosted by a variety of mafic igneous (particularly Archaean giants), felsic igneous and coarse- to fine-grained marine metasedimentary rocks and iron formations (particularly Palaeoproterozoic and Phanerozoic giants) that are invariably associated with convergent plate margins and occur within close proximity of major translithospheric structures that typically are compressional to transpressional–transtensional shear zones (Hodgson 1989). The large-scale conduits, which originally may have been terrane sutures, are characterised by high degrees of non-linearity, with large ore systems preferentially developed in second- and third-order structures within damage zones of misalignment and relay zones (e.g. Cox 1999; Cox et al. 2001), as indicated by fractal studies (Weinberg et al. 2004). Overprinting hydrothermal assemblages in most giant deposits indicate that multiple events, some improving rheology or reactivity and some depositing gold, were common along these flow paths over typical time frames of a few tens of millions of years or less (Groves et al. 2003). Gold grades are highly variable among giant deposits, ranging from 1.1 g/t for the Las Cristinas resource to 21.3 g/t in parts of the Campbell-Red Lake deposit, and have historically changed, even for a given giant, because of varying world economics and improvements in mining technologies. Large felsic intrusions that were more or less synchronous with mineralisation generally occur at, or within a few kilometres of, the deposits, providing evidence for abnormal thermal gradients in the crust; however, there are notable exceptions both spatially (e.g. Golden Mile; Phillips et al. 1996) and temporally (e.g. Bendigo; Bierlein et al. 2001a). In almost all examples where the deposits are geochronologically well constrained, peak P–T conditions during metamorphism of the immediate country rocks reached lower greenschist to lower amphibolite conditions within a few million to tens of million years before ore formation. However, Muruntau, currently the largest known orogenic gold deposit, as well as several other deposits with >100 t of contained gold in the Tien Shan orogenic belt, may post-date peak metamorphism of the immediate host rocks by as much as 150 m.y. (e.g. Kempe et al. 2001; Wilde et al. 2001) if geochronological data are shown to be robust. Linglong, in very high-grade metamorphic rocks of the North China Craton, provides a unique example where a giant deposit post-dates metamorphism of the host terrane by two billion years (Zhou et al. 2002).

The importance of orogen- to lithosphere-scale processes

It is evident from the syntheses of Goldfarb et al. (2001) and Groves et al. (2003) that giant orogenic gold deposits, despite some broad unifying characteristics, are of several age groups and, in detail, have different types of host structures and host rocks, and depths of formation. They thus mimic the deposit-scale variations shown by giants of other deposit styles (e.g. Cooke and Pongatz 2002). In view of these deposit-scale variations, terrane- to lithosphere-scale processes are implicated as being far more critical in determining in which orogen global giants are likely to be located and where they will be absent. Accepting the existence of some form of Archaean plate tectonics, virtually all giant orogenic gold deposits are situated in orogens built by the accretion and underplating of one or more allochthonous terranes and their associated oceanic crust to



Archean:

1 Golden Mile, Yilgarn Craton
(2.6 - 2.64 Ga; 1984 t)
2 McIntyre-Hollinger, Canadian Shield
(<2.67 Ga; 987 t)
3 Kolar, Dharwar Craton
(>2.55 Ga; 838 t)
4 Campell-Red Lake, Canadian Shield
(<2.87 - >2.71 Ga; 799 t)
5 Kirkland Lake, Canadian Shield
(<2.67 Ga; 797 t)
6 Geita, Tanzanian Craton
<2.64 Ga; 788 t)
7 Morro Velho, Sao Francisco Craton
(<2.71 Ga; 654 t)
8 Bulyanhulu, Tanzanian Craton
(<2.64 Ga - >2.55 Ga; 543 t)
9 Dome, Canadian Shield
(<2.68 Ga; 509 t)

Proterozoic:

10 Ashanti, West African Craton
(2.1 Ga; 2070 t)
11 Telfer, Paterson Orogen
(700 - 600 Ma; 1564 t)
12 Homestake, Trans-Hudson Orogen
(1.75 Ga; 1237 t)
13 Las Christinas, Amazon Craton
(2.14 - 2.06 Ga; 964 t)
14 Olimpiada, Siberian Craton
(800 - 600 Ma; 700 t)

Phanerozoic:

15 Muruntau, Tien Shan Orogen
(285 Ma; 5290 t)
16 Sukhoi Log, Siberian Craton
(380 - 365 Ma; 1048 t)
17 Donlin Creek, Alaska
(74 - 68 Ma; 793 t)
18 Natalka, Russian Far East
(135 Ma; 716 t)
19 Berezovkoe, Uralide Orogen
(< 328 Ma; 715 t)
20 Grass Valley, California
(145 - 140 Ma; 664 t)
21 Bendigo, Lachlan Orogen
(440 Ma; 660 t)
22 Kumtor, Tien Shan Orogen
(285 Ma; 600 t)
23 Linglong Camp, Yanshanian Orogen
(123 Ma; 500 t)

Fig. 1 Map showing distribution of Archaean, Proterozoic, Palaeozoic, Mesozoic and Cenozoic terranes; also shown are the locations of the 23 recognised giant orogenic gold deposits/districts [all production + resource figures from Geological Survey of Canada world gold data bank and Goldfarb et al. (2001)]. Giant deposits are listed in age group categories and then in decreasing order of gold endowment (*t*=tonnes Au) pre-existing continental margins. In fact, age data confirm that the giant deposits formed essentially during periods in Earth history when mantle plume activity and/or plate movements produced major lithospheric growth at active continental margins (Condie 2000). Taking into account the deterioration of resolution and preservation with increasing ages, available geochronological data (summarised in Goldfarb et al. 2001) constrain the formation of giant orogenic gold systems to age clusters of such crustal and lithospheric growth (Poudjon Djomani et al. 2001) in the Late Archaean (from 2.7 to 2.55 Ga), Palaeoproterozoic (2.1–1.8 Ga), Late Neoproterozoic (700–600 Ma), Late Palaeozoic (455–340 Ma) and Mesozoic–Cenozoic (285–70 Ma) as shown in Fig. 2. It is improbable that orogens formed at other times will contain giant deposits because they were not times of major crustal growth.

The importance of asthenospheric thermal input that can trigger and, more importantly, sustain crustal devolatilisation and melting has been recognised previously as a major driving force for the initiation of giant orogenic gold systems (e.g. Hodgson 1993; Kerrich et al. 2000; Bierlein et al. 2001b, 2004; Goldfarb et al. 2001). This is because the fundamental driver for large orogenic gold systems is a focused, high fluid flux that requires an effective thermal engine. Evidence in support of an association between ore formation and simultaneous mantle processes comes from the common presence of mafic to ultramafic intrusions, including sodic lamprophyre dykes that most likely signal asthenospheric input (Rock 1991), along first-order lithospheric, near-vertical fault zones in, or adjacent to, almost all of the giant gold deposits (Fyfe and Kerrich 1984; Rock et al. 1990; Groves et al. 1998; Bierlein et al. 2001c; Goldfarb et al. 2001). Thus, it appears that the occurrence, extent and timing of lithospheric instability play a vital role in the formation of giant orogenic gold deposits.

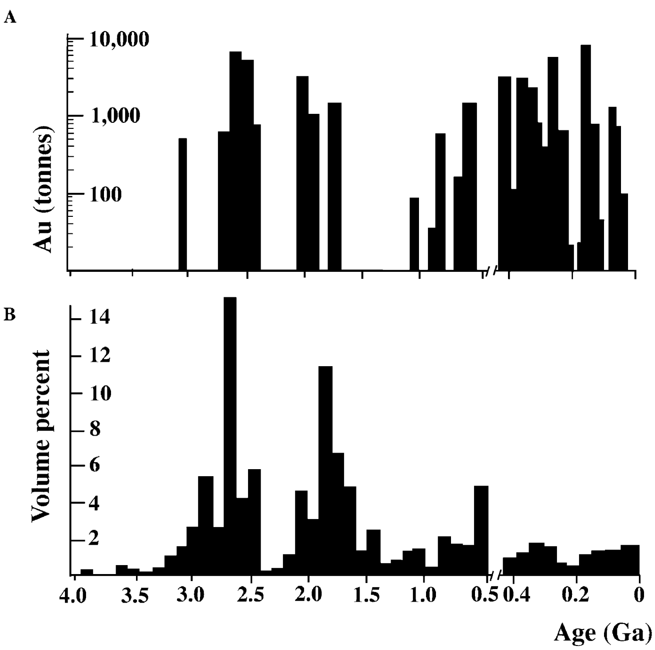


Fig. 2 **a** Temporal distribution of orogenic gold deposits in relation to **b**, which shows the temporal evolution of continental crust growth (modified from Condie 2000). The giant Witwatersrand deposit is not shown as the authors consider it a palaeoplacer

High heat flux from the mantle, and consequent high fluid flux in the crust, can be linked to lithospheric instabilities that result from: (1) crustal overthickening due to underplating of slices of oceanic terranes to the accretionary wedge during seaward growth of the margin (Kerrich and Wyman 1990; Foster and Gray 2000), (2) mantle plumes impacting on subduction, bringing hot asthenosphere into contact with shallow crustal rocks (Condie 2004), or (3) erosion or delamination of subducted oceanic lithosphere to enlarge the overlying mantle wedge (Collins 1994; Kerrich et al. 2000; Wortel and Spakman 2000). These scenarios are shown on a schematic composite diagram in Fig. 3, which also indicates provinces where such processes operated. Therefore, and in addition to the broader age and lithospheric constraints outlined above, the specific crustal history of, and impact of mantle heat on, terranes within the host orogen is implicated as being critical in defining whether giant gold deposits are likely to be present.

Tectonic and lithospheric constraints on terranes hosting giant orogenic gold systems

It is suggested in this study that the thickness of SCLM at the time of gold mineralisation controls the potential for giant gold deposits. This is because orogenic gold deposits generally form late in the history of an orogen (e.g. Goldfarb et al. 2001) but before the SCLM beneath it has been emplaced and stabilised. The formation of thick SCLM will shield continental crust from asthenospheric heat input and thereby will hinder subsequent tectonothermal events, including large-scale fluid release required to form giant orogenic gold deposits. In contrast, if the SCLM is not yet stabilised or the earlier SCLM is partly delaminated, asthenospheric heat input will be greater: for example, the thinner the lithosphere in oceanic back-arc or strongly rifted continental margin settings, the greater the potential for high heat flux from asthenospheric upwelling. Therefore, trace element systematics, Sm–Nd and Lu–Hf isotopic fingerprinting of volcano-intrusive successions, sensitive high resolution ion microprobe U–Pb dating of zircons and the recognition of inherited zircon populations within these rocks should all provide important clues as to the tectonic evolution and anatomy of any terrane within an orogen. In other words, if these data show gold formation to pre-date establishment of a stable SCLM (as is commonly determined from xenolith work; e.g. Griffin et al. 2003), then the environment would be favourably endowed and possibly be an important region to explore within for a giant orogenic gold deposit. In agreement with this, examination of available time constraints on orogenic gold deposits and their host terranes (e.g. Goldfarb et al. 2001) suggests that orogens comprising relatively immature terranes of all ages that are characterised by primitive, oceanic-character crust are generally well endowed and tend to contain giant gold deposits, whereas those with a significant pre-history or

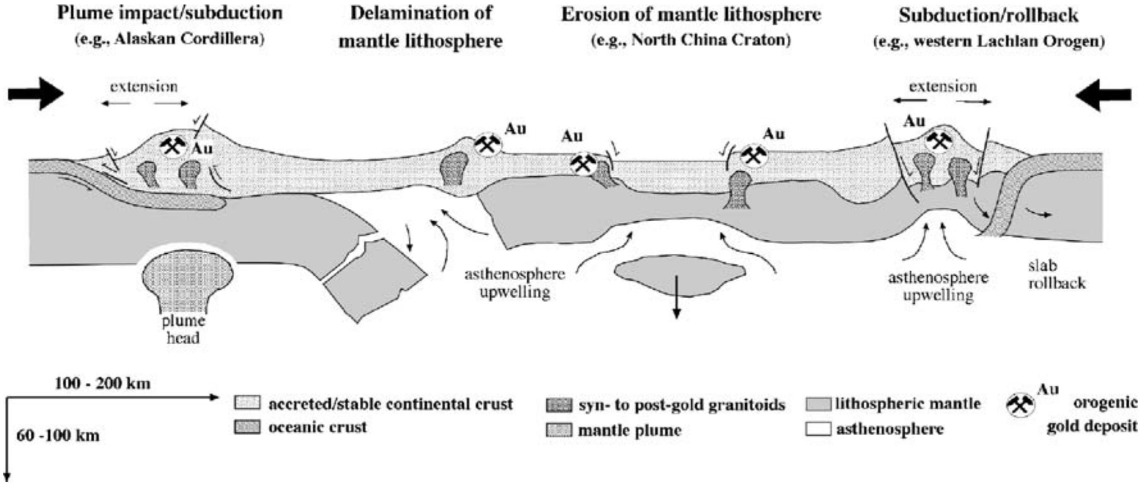


Fig. 3 Possible causes for lithospheric instabilities required to trigger the sudden onset and extensive occurrence of crustal melting, hydrothermal circulation and giant gold deposit formation [modified and integrated from figures in Goldfarb et al. (2001)]

pericratonic association may contain gold ores but not giants. The endowment of gold provinces within Archaean orogens is used below to test these critical relationships between pre-gold crustal history, SCLM thickness and asthenospheric upwelling.

Archaean examples

Virtually all Archaean greenstone belts that host giant gold deposits have linear geometries and are characterised by petrogenetic associations that are typical of fore-arc to back-arc environments. Each of these belts developed on, or near the edges of, pre-existing basement (as indicated by, for example, inherited zircons, xenocrysts and Sm–Nd signatures linked to sub-arc mantle melting) at ca. 2.7 Ga or showed evidence for intra-continental rifting during or just before gold ore formation that occurred in many orogens at ca. 2.65 Ga. As this timing of orogenic gold mineralisation was broadly synchronous worldwide and linked to the greatest period of crustal growth during Earth history (e.g. Groves et al. 2005), it is possible to compare crustal pre-histories in orogens before this event. Figure 4 shows the interpreted length of crustal pre-history, overall gold endowment and the presence or absence of giant gold deposits in each orogen. It is evident that there is a broad inverse relationship between the duration of pre-2.65 Ga crustal history and whether a giant gold deposit occurs.

The best endowed Archaean orogen is the southern Abitibi belt of the Superior Province, Canada (e.g. Wyman 2003), with a recorded production of 11,819 t of gold from, inter alia, two giant deposits (McIntyre–Hollinger, Kirkland Lake) and six world-class deposits. Gold mineralisation is developed in greenstone belts that comprise oceanic crust formed within about 50 m.y. of initiation of pre-ore volcanism and is characterised by very few, if any, xenocrysts and by primitive ε_{Nd} values. The well-endowed Eastern Goldfields Province of the Yilgarn Craton, Western Australia (e.g. Barley and Groves 1990; Champion and Sheraton 1997) has produced ≥5,132 t of gold (Fig. 4). The giant Golden Mile deposit at Kalgoorlie and numerous world-class deposits all lie in one specific province of the Yilgarn Craton where the dominant greenstone component formed less than 70 to 50 m.y. before gold deposition, and where there is little evidence for >2.9 Ga continental basement. This can be compared to the relatively poor gold endowment and lack of a giant gold deposit in the flanking orogens (e.g. Southern Cross; Fig. 4) where Late Archaean gold deposits are sited in both ca. 3.0–2.9 Ga and 2.7 Ga greenstone belts. Similar to the Abitibi belt and the Eastern Goldfields Province, the spatially restricted gold-mineralised orogen of the Dharwar Craton, with a gold endowment of approximately 2,332 t and a giant gold deposit at Kolar, had a short pre-history before gold mineralisation, although this occurred at ca. 2.55 Ga (Chadwick et al. 2000) rather than at ca. 2.65 Ga as in the other cases. The well-endowed (995 t) Rio das Velhas greenstone belt in Brazil, containing the giant Morro Velho deposit, had a similarly short crustal history before gold mineralisation at ca. 2.67 Ga (Lobato et al. 2001). The Sukumaland greenstone belt of Tanzania, with an endowment of 776 t and two giant deposits (Geita and Bulyanhulu) despite its immature exploration history, appears to essentially mirror the other well-endowed provinces in terms of its crustal evolution, although there are limited robust geochronological data (Borg and Krogh 1999; Chamberlain et al. 2004; Manya 2004).

The Midlands greenstone belt of the Zimbabwe craton, with gold formed at ca. 2.66 Ga (Darbyshire et al. 1996) in greenstones with a pre-crustal history of at least 3.2 Ga (Fig. 4), importantly contains no giants despite its significant endowment of 684 t of gold. The even far less well-endowed greenstone belts in the northern Pilbara Craton (93 t Au; Zegers et al. 2002) in Western Australia and the Karelian Craton in Finland (37 t Au; Eilu et al. 2003) both lack evidence for the addition of substantial oceanic lithosphere via rifting, and instead develop on predominantly continental-character lithosphere that formed at least 200–400 m.y. before emplacement of orogenic gold mineralisation (Goldfarb et al. 2001). Similarly, major magmatism

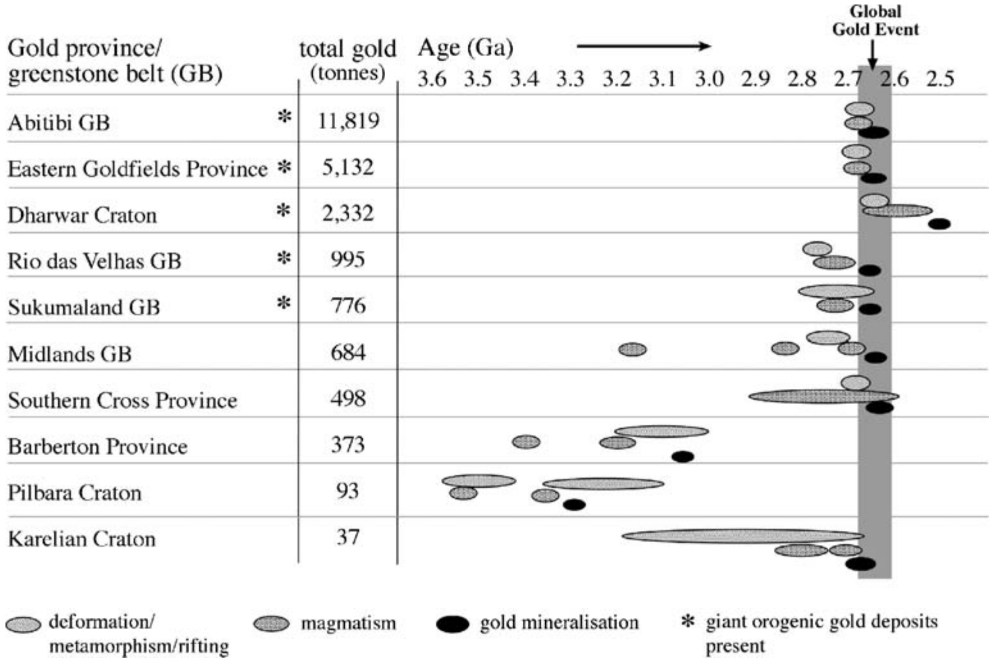


Fig. 4 Diagram illustrating the relative and absolute timing of deformation, magmatism and gold mineralisation in the Abitibi greenstone belt, Canada; Eastern Goldfields Province, Western Australia (WA); eastern Dharwar Craton, India; Rio das Velhas greenstone belt, Brazil; Sukumaland greenstone belt, Tanzania; Midlands greenstone belt, Zimbabwe; Southern Cross Province, WA; Barberton Province, South Africa; Pilbara Craton, WA; and Karelian Craton, Finland/Russia. Giant deposits listed in Fig. 1, with endowment given

and greenstone-forming events in the Barberton Province of South Africa (373 t Au) took place at ca. 3.23 Ga, thus predating ~3.08 Ga shear zone-hosted gold mineralisation by at least 150 m.y. (de Ronde et al. 1991). This was, importantly, also not a time of major crustal growth nor of related orogenic gold events globally (Condie 2000; Fig. 2b). The distinct, non-linear shape of most >3.2 Ga-old cratons, together with the abundance of equidimensional granitoids within these cratons, strongly suggests that the formation of juvenile crust in the Early Archaean was dominated by plume tectonics (Griffin et al. 2003). Deformation of these terranes would have been dominated by non-directional, radial maximum stress and fractures rather than by the development of deep-seated, linear shear zones. In such a scenario, few parts of the sequences would be aligned broadly perpendicular to the maximum principal stress, the preferred geometry for selective failure of more competent and reactive Late Archaean rock sequences (Ridley 1993). For example, the Early Archaean Pilbara Craton (e.g. Van Kranendonk and Hickman 2000; Van Kranendonk et al. 2002) generally lacks major, through-going shear zones, and rare gold deposits are hosted between batholiths mainly in shear zones where the maximum principal stress direction is locally at a high angle to the rock sequence (e.g. Zegers et al. 2002). As a consequence, the Pilbara Craton has a low gold endowment (Fig. 4) despite its excellent exposure. Furthermore, during the global ca. 2.7 Ga event, all these poorly endowed Archaean gold provinces would have been shielded from extensive tectonomagmatic events because cratonisation would already have occurred; in other words, thick SCLM keels would have already been in place at the base of most blocks of Middle Archaean crust.

From the above examples, it becomes apparent that no giant orogenic gold deposits developed before ca. 2.7 Ga, although uncertainty obviously exists as to whether a giant Middle Archaean orogenic lode gold deposit existed in the source area for the Witwatersrand placers before ca. 3.0 Ga cratonisation of most of the Kaapvaal block. The formation of Late Archaean giant gold systems was related to the first recognised of a series of episodic periods of major crustal growth with: (1) concurrent occurrence of lithospheric instabilities and asthenospheric upwelling induced by anomalous crustal thickening, (2) perturbations to accretion–subduction processes via ridge subduction, slab break-off or mantle plume interference or (3) catastrophic mantle plume events.

Palaeoproterozoic examples

The next major crust-forming event occurred in the period from 2.1 to 1.8 Ga, with a coincident major period of orogenic gold deposit formation (Fig. 2). Although a plot equivalent to that for Archaean orogenic gold deposits (Fig. 4) is difficult to produce due to the somewhat more variable timing of the orogenic gold systems (when compared to the 2.7 to 2.55 Ga period) and the overall more limited absolute geochronology, it is evident that the largest metallogenic provinces with a giant gold deposit all have short crustal histories before gold mineralisation. For example, the Birimian greenstone belts of Ghana (2,488 t Au; Oberthür et al. 1998) have a short total crustal history between about 2.15 and 2.0 Ga (Leube et al. 1990). Gold most likely formed late during the Birimian orogen (e.g. Ashanti: Allibone et al. 2002) at ca. 2.06 Ga (Damang: Pigois et al. 2003), although robust ages for the deposits are rare. There is importantly no evidence for Archaean basement (and thus any pre-existing SCLM) and no Archaean xenocrystic zircons in granitoids in this belt (e.g. Oberthür et al. 1998). Although there are few precise data on the timing of gold mineralisation in the Trans-Hudson Orogen in South Dakota, which hosts the giant Homestake deposit (>1,244 t Au; Caddey et al. 1991), it similarly appears to have had a short history between 1.89 and 1.73 Ga (Houston 1992; Morelli et al. 2005). The Guyana Shield (>622 t), which hosts one giant (Las Christinas) and several world-class deposits (Sidder and Mendoza 1995), represents another example where there was a short crustal pre-mineralisation history, which began <2.1 Ga with orogenic gold deposition at ca. 2.0 Ga (Norcross et al. 2000). In contrast, well-documented, Palaeoproterozoic orogenic gold provinces with no giant deposits, such as Pine Creek and Tanami in northern Australia and Pilgrims Rest in South Africa, have widespread Archaean basement (Partington and Williams 2000) and thus likely had a protective significant SCLM keel already in place.

Phanerozoic examples

The Phanerozoic record is punctuated by several episodes of major crustal growth and correlated orogenic gold deposit formation (Fig. 2). Notable periods of significant gold ore formation occurred between 450 and 240 Ma, and between 190 and 55 Ma. As with Precambrian analogues, the best endowed Phanerozoic provinces with world-class to giant gold deposits are generally characterised by short crustal histories before gold mineralisation, Muruntau and Jiaodong being notable exceptions (see below). For example, crustal evolution in the western Lachlan Orogen in southeastern Australia (>2,504 t Au) commenced at ca. 510 m.y., and thus just 70 m.y. before 440 m.y. orogenic gold deposition and the formation of the giant Bendigo deposit (Foster and Gray 2000; Bierlein et al. 2001a). Similarly, the eastern Ural Mountains (>2,675 t Au), which are host to the 669 t Berezovkoe and >467 t Kochkar orogenic gold deposits (Kisters et al. 1999), developed on an oceanic sequence of lower to Middle Palaeozoic age (Puchov 1997). Temporally overlapping continental growth along the southern margin of the Siberian Craton gave rise to the Baikal fold belt (>3,421 t Au) which, although poorly documented and lacking robust geochronological and geochemical data, appears to have a short crustal history (Bulgatov and Gordienko 1999) and is host to the giant Sukhoi Log deposit (>933 t Au; Distler et al. 2004). By way of contrast, Palaeozoic accretionary systems in the Meguma Terrane of northeastern Canada (Ryan and Smith 1998), the northern Puna Terrane in Argentina (Bierlein et al. 2005b) or the part of the Lachlan Orogen in northeastern Tasmania (Bierlein et al. 2005a), which developed on epicratonic and significantly older, Middle or Late Proterozoic basement, generally do not contain giant or even world-class orogenic gold deposits.

Breakup of Pangea and terrane accretion in the Mesozoic gave rise to the development of broad fore-arc regions and the well-documented destruction along extensive subduction zones of relatively juvenile crust along the Pacific margin of North America and eastern Russia to what is now the South Island of New Zealand (Goldfarb et al. 2001). Well-endowed orogenic gold provinces that formed in terranes with relatively short crustal histories during this ca.285–55 Ma period include the Yana-Kolyma belt in the Russian Far East (>4,043 t Au; Goryachev and Edwards 1999), and the Sierra Foothills provinces (>3,110 t Au; Böhlke and Kistler 1986) and the Juneau gold belt (>310 t Au; Goldfarb et al. 1997) in the Cordilleran Orogen of the western United States.

The inverse correlation between crustal longevity or maturity of a host terrane before a major orogenic gold event and its overall gold endowment can also be illustrated at the scale of a Phanerozoic fold belt system. The Palaeozoic Tasmanides orogenic system in eastern Australia, which hosts a wide range of base- and precious-mineral deposit types, is used as an example (Fig. 5). Many of the known major mineral deposits display strong spatial and temporal relationships with distinct metallogenic provinces, and these are interpreted to relate directly to varia-

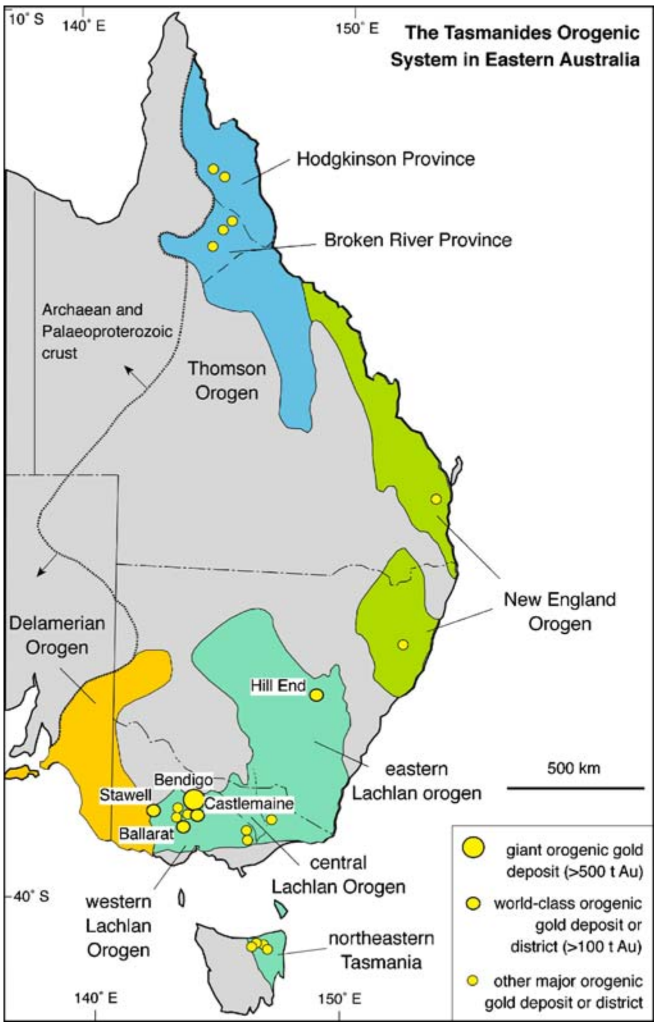


Fig. 5 Sketch map of eastern Australia showing the principal components of the Tasmanides orogenic system (Delamerian, Lachlan, New England, Thomson, Hodgkinson and Broken River). Also shown are the locations of major orogenic gold deposits and those mentioned in the text [modified from Bierlein and Crowe (2000)]

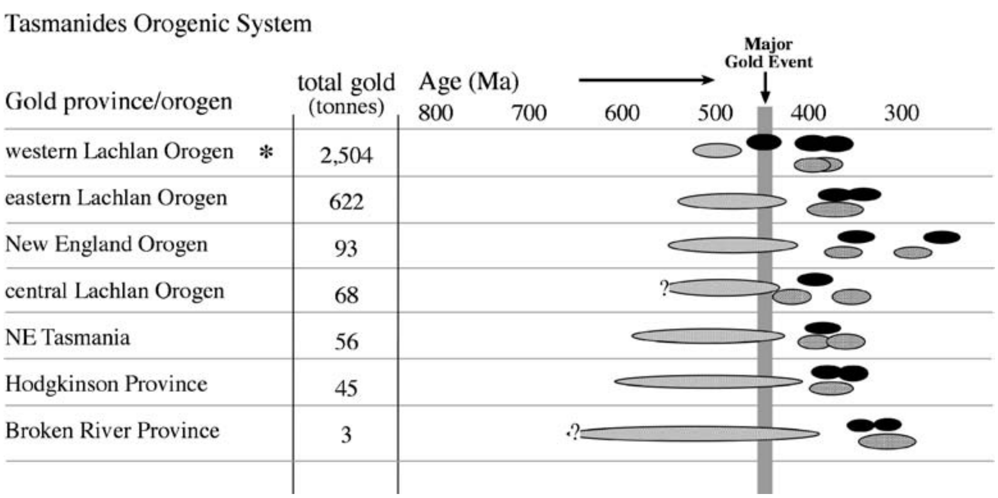
tions in the tectonic setting and lithosphere-scale processes (e.g. Walshe et al. 1995; Bierlein et al. 2002).

As indicated above, several goldfields that host major, world-class and giant orogenic gold deposits (e.g. at Stawell, Bendigo and Ballarat) in the western portion (Victoria) of the Lachlan Orogen (2504 t Au) formed above ca. 510 Ma-old tholeiites and boninites at 440 Ma, closely post-dating peak metamorphism of the gold host rocks during the eastward propagation of an accretionary system that led to the closure of an approximately 2,000 km-wide oceanic basin via low-angle subduction (Foster and Gray 2000; Bierlein et al. 2001a). In contrast, contractional deformation in the eastern segment of the Lachlan Orogen in New South Wales (622 t Au), the Lachlan Orogen in northeastern Tasmania (56 t Au; Bierlein et al. 2005a) and the Hodgkinson–Broken River Province of northeastern Queensland (48 t Au; Vos et al. 2006) was governed by the diachronous closure of several epicratonic sub-basins of rather limited extent, which developed on Neoproterozoic continental-character crust and/or previously dehydrated, less juvenile Cambrian oceanic crust (e.g. Aitchison et al. 1992; Champion and Bultitude 1994; Bruce et al. 2000; Jenkins et al. 2002; Bierlein et al. 2005a). These relationships are illustrated in Fig. 6. As shown for the Archaean orogenic gold provinces (Fig. 4), there is a strong broad relationship between crustal longevity before ca. 440 Ma and gold endowment of the different Palaeozoic gold provinces in the Tasmanides orogenic system of eastern Australia.

A major exception to this inverse correlation between crustal longevity as a proxy for lithosphere thickness and orogenic gold endowment is the North China Craton, where the Cretaceous timing of orogenic gold deposit formation (Qiu et al. 2002) post-dates the cratonisation of the host terrane by more than 2 b.y. (Zhou et al. 2002). However, this craton is a well-defined rare example of a Precambrian craton that has lost much of its SCLM via lithospheric erosion in the Jurassic (Griffin et al. 1998) when, in an extraordinary tectonic scenario, the penecontemporaneous subduction of three plates beneath the North China Craton rapidly destabilised the SCLM (e.g. Menzies and Xu 1998), producing asthenospheric heating and thermal energy levels approaching those in initially thin lithosphere. Thus, the concept of relatively thin lithosphere as a requirement for high thermal energy and consequent high fluid flux still holds, but the proxy of crustal longevity falls down in North China due to its unique tectonic history. The well-endowed (>6,221 t Au) North China Craton contains one recognised giant (Linglong), suggesting that the loss of the SCLM keel in areas of stabilised crust can once again make such ground fertile for the generation of giant orogenic gold deposits.

An explanation for the anomalous gold endowment of the Tien Shan in central Asia, which contains the giant Muruntau deposit (>5,290 t Au; Mao et al. 2004), is less obvious. Although available data for both geological relationships and geochronology on the timing of orogenic gold mineralisation in the Tien Shan (e.g. Kostityn 1996; Kempe et al. 2001; Wilde et al. 2001; Mao et al. 2004; Wall et al. 2004) are far from robust, because minerals that appear at more than one time in the paragenetic sequence have been dated, Muruntau apparently formed during a second orogenic event (i.e. Middle–Late Carboniferous Variscan) after an earlier event (i.e. Early–Middle Ordovician Caledonian). This implies a hiatus of about 160 m.y., an anomalously long minimum period of pre-mineralisation crustal history for giant orogenic gold deposits, as discussed above. However, the auriferous system at Muruntau occurs below a Devonian–Carboniferous carbonate-rich package that, according to Wall et al. (2004), acted as a permeability seal on these systems. The deposition of these continental margin platformal sediments before ore formation at Muruntau indicates that the intervening period between the Caledonian orogenic event, which led to the deformation of the initial, Cambrian rift succession (Wilde et al. 2001; Mao et al. 2004) and shortening during the Variscan orogeny, involved extension and thinning of the lithosphere. Invoking intermittent extension of the sedimentary basin and correlated lithospheric thinning could thus provide an explanation for the thermal regime that led to the formation of the giant Muruntau deposit and explain this exception to the general correlation between short crustal pre-history and gold endowment. The anomalous continental-margin setting of the mineralised sedimentary

Fig. 6 Diagram illustrating the relative and absolute timing of deformation, magmatism and gold mineralisation in orogenic gold-hosting regions of the Phanerozoic Tasmanides orogenic system in eastern Australia (data from Walshe et al. 1995; Foster and Gray 2000; Bierlein et al. 2002, 2005a; Downes et al. 2003). Symbols as in Fig. 4. Note that Bendigo is the only giant deposit



sequences may also have been important in terms of gold and/or sulphur sources as discussed below.

Tectonic setting and gold-enriched source rocks

As argued above, lithospheric thickness at the time of an orogenic gold event may be the first-order control on province endowment and the presence, or absence, of giant gold deposits. However, other factors such as fluid and metal sources may also be critical. In most cases, the ultimate source of the gold remains undetermined and it could be argued that no specific type of source rock is required as long as the available gold can be leached and transported effectively to the site of deposition (e.g. Phillips et al. 1987). However, available field evidence, isotope patterns and scarce trace-gold data suggest that primitive oceanic crust is an enriched potential gold and sulphur source for the generation of orogenic gold systems (Keays 1987; Cawood and Fryer 1994; Haeussler et al. 1995; Bierlein et al. 2001c, 2004; Goldfarb et al. 2001; Moss et al. 2001). This is because of the generally higher abundance of gold in pyrite in these oceanic rocks and the relative ease with which the gold and sulphur can be liberated from chemically reactive sulphide minerals during their prograde metamorphism (Keays 1987). As primitive oceanic crust normally implies thin lithosphere (Condie 2005), there may well be a feedback loop between tectonic setting and lithosphere thickness which controls both high thermal energy and rock sequences with enhanced gold (and sulphur) in thin lithosphere. Trace element studies have long suggested that many of the gold-related elements are released from underplated hydrated marine metasedimentary rocks during prograde metamorphic events (e.g. Hutchinson 1993), but the lithospheric-scale relationships in North China, in particular, suggest an additional source such as a primitive oceanic subducted slab (e.g. Qiu and Groves 1999; Wyman et al. 1999). Volatile release from subducted, refrigerated oceanic slabs (e.g. Lentz 2003), with fluids either going directly into the overlying crust or serpentinising mafic and ultramafic rocks that subsequently are uplifted along major faults, may thus be important for the formation of giant orogenic gold systems.

Siting of giants within giant-bearing provinces

From the discussion above, it is apparent that tectonic and lithospheric parameters of orogens, possibly combined with the gold and sulphur fertility of leachable reservoirs, dictate whether giant gold deposits may form within them. However, GIS-based studies of gold endowment in some provinces (e.g. Groves et al. 2000) and studies of the giant gold systems themselves (e.g. Golden Mile; Phillips et al. 1996) indicate that the exact location of these giant deposits within well-endowed provinces will depend on more local-scale factors. The localisation of these giant deposits within the favourable provinces appears to involve the conjunction of a number of critical factors, which can be defined in terms of a minerals system that integrates ore fluid and metal source(s), pathways and traps (e.g. Wyborn et al. 1994; Hagemann and Cassidy 2000). These include a switchover from compressional to transpressional tectonics (e.g. Goldfarb et al. 1991), a network of long-lived translithospheric oblique-slip faults (e.g. Hodgson 1989), fault reactivation (Cox et al. 2001), fault geometry (Robert and Brown 1986), far field orientation and misalignment (Ridley 1993), presence of complex lithostratigraphic sequences with strong rheological contrasts promoting strain partitioning as summarised by Colvine (1989) and Groves et al. (2000), reactive host rocks (Phillips and Groves 1983) and the nature of displacement and relay zones between fault segments (e.g. Groves et al. 1998, 2003; Kerrich et al. 2000; Poulsen et al. 2000; Goldfarb et al. 2001). The degree of concurrence of these factors is controlled at the province scale and ultimately determines the size of individual orogenic gold deposits, as well as the overall distribution of these deposits within a given, well-endowed province; that is, many small, several world-class, and perhaps a giant ore system.

Summary and conclusions

The formation and distribution of provinces that host giant orogenic gold deposits are defined, in both space and time, by first-order controls that operate at the lithosphere scale. At the highest scale, where a given province may or may not host a giant gold deposit, the timing of gold formation can be linked to the occurrence of major lithospheric instabilities that provided the thermal engine for the gold-forming event during peak periods of continental growth. During each of these periods, and after the onset of, albeit modified, plate tectonic processes in the Late Archaean, widespread catastrophic mantle plume events, crustal thickening, accretion–subduction, slab rollback and delamination of subducted oceanic lithosphere and the subduction of spreading ridges resulted in extensive asthenospheric upwelling. This, in turn, triggered and sustained pervasive crustal melting, volcano-intrusive activity and the formation of juvenile crust. The latter appears to be a crucial ingredient in the generation of giant orogenic gold systems as hydrated, mafic (fore-arc to back-arc) crust is far more likely to provide the fluids and metals required to form a giant gold system than pericratonic and felsic igneous rocks. The longevity of crust in the host orogen can be used, in most cases, as an approximate proxy for syn-gold lithosphere thickness, with crustal longevity normally inversely proportional to gold endowment and the presence of giant orogenic gold deposits. Along the edges of older cratons, or in extensional basins within them adjacent to convergent margins, linear orogens that contain primitive crust and record asthenospheric upwelling and thinning of the lithosphere at or just before gold mineralisation are the most likely to contain well-endowed gold provinces and giant gold deposits. Thermal regimes to drive giant hydrothermal systems are fundamental to such scenarios and intrinsically gold-enriched juvenile oceanic rocks may be a consequence of them.

In rare cases, such as the North China Craton, widespread orogenic gold mineralisation may significantly post-date original tectonism in the hosting sequences, locally negating the inverse relationship between crustal longevity and provincial gold endowment. In the case of the North China Craton, the signal for thin lithosphere at the time of gold mineralisation (as determined by detailed geochronology, seismic tomography and SCLM mapping) was rapid delamination of SCLM as a result of an anomalous Jurassic plate configuration involving three penecontemporaneous directions of subduction underneath the craton. Thus, lithospheric thinning was still the controlling process. In other cases such as in the Tien Shan, the site of the giant Muruntau deposit, the major phase of orogenic gold mineralisation appears to have been during a Variscan orogenic event after Caledonian orogeny such that again, the crustal longevity proxy does not function well. It is noticeable that this is a rare case of the involvement of post-Caledonian and pre-Variscan back-arc to continental margin sedimentary sequences in an orogen, implying potential extension and lithospheric thinning before the second, Variscan orogeny, and also providing anomalously gold- and sulphur-enriched local sources in the continental margin sequences.

The actual position of giant gold deposits within a well-endowed province then requires the conjunction of several critical factors that operate at the province scale. These include factors that relate to (1) superior plumbing systems, such as oblique-slip transcontinental fault and shear zones, jogs in these shear zones and traverse faults that splay off or segment these shear zones; (2) ore traps such as reactive host rocks and rheological contrasts between them and (3) seals such as metasedimentary rock sequences or thrust sheets of relatively impermeable rocks overlying structurally permeable and reactive host rocks.

In summary, in the order of descending scale, giant orogenic gold deposits are related to the conjunction of: (1) periods of rapid growth of continental crust and associated lithospheric and resultant asthenospheric instability; (2) intrinsically thin or thinned, preferably primitive, lithosphere just before gold deposit formation to further enhance orogen-scale thermal energy and potentially provide Au-rich source rocks—for most provinces, crustal longevity is a good proxy for lithospheric thickness; (3) suitable, essentially linear geometries with spaced misalignments along crustal-scale structures within permissive, largely low-strain provinces to maximise focused fluid flow and (4) suitably reactive lithostratigraphies with strong rheological contrasts to provide efficient traps and seals for highly focused fluid flux enhanced by the previous factors. The concepts presented in this paper are fundamental to improved conceptual gold exploration, although further research is required to verify the potential interconnectivity of first- and second-order critical factors, and anomalous examples require further critical, integrated research and robust geochronology.

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