

# Lithospheric footprints of giant orogenic gold systems

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## Abstract

Small orogenic gold deposits have the same deposit-scale geological and geochemical features as those that characterise giant orogenic gold systems (>16 Moz Au). Therefore, a broader-scale approach is needed to identify the critical controls on giant deposits and their disproportionate distribution throughout time and space. Ages of giant gold systems cluster around well-defined periods of lithospheric growth at continental margins, and it is orogen-scale processes during these Late Archaean, Early Proterozoic and Phanerozoic times that determine gold endowment of a province.

A critical factor for giant orogenic gold provinces appears to be asthenospheric upwelling at the time of gold mineralisation to most effectively transfer the thermal energy required to initiate and sustain high hydrothermal fluid flux. The extent of this fluid flux should be related to thickness of the lithosphere beneath a province at the time of gold mineralisation, such that giant gold deposits are much more likely to develop in orogens with oceanic or thinned continental lithosphere. A proxy for the latter is likely to be a short pre-mineralisation crustal history such that thick subcontinental lithospheric mantle was not developed. Conversely, orogens with protracted pre-mineralisation crustal histories are more likely to have a thick subcontinental lithospheric mantle, which 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 be defined by 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 that control fluid conduits, traps, and seals in tectonically and lithospherically suitable terranes within accretionary orogens.

**Keywords:** *orogenic gold, giant gold deposits, metallogeny, tectonics, lithosphere, endowment*

## Introduction

Many orogens contain gold provinces, but only a small percentage of these provinces contain giant deposits (i.e., >500 tonnes or 16 Moz Au). The specific causes for the spatial and temporal imbalance in crustal gold endowment has puzzled explorationists and research geologists for decades. In attempting to resolve this mystery, emphasis has commonly been placed on deposit- to camp-scale investigations. However, given the deposit-scale geological and geochemical commonalities shared by many small and giant systems of the same deposit type (e.g., Cooke & Pongatz, 2002), the recognition of parameters that are critical in the formation of giant gold systems is likely to require a broader-scale approach. Here, such a broader-scale view is taken by considering first-order requirements for the formation of a province that contains at least one giant deposit, rather than those factors that control formation of a giant gold deposit itself. We postulate that the overall endowment of a given gold province, as well as the formation of giant gold deposits within it, is controlled by factors that operate at the orogen- to lithosphere-scale. Via the assessment of broad-scale features that are common to the majority of gold provinces hosting giant ore systems, some of the potential key elements required in the formation of these systems are illustrated. An improved understanding of the critical parameters that define giant ore systems, in turn, aids in the formulation of genetic and exploration models aimed at discriminating between more and less gold-favourable orogens, and parts of orogens.

## The importance of orogen- to lithosphere-scale processes

It is evident that giant orogenic gold deposits, despite broad unifying characteristics, in detail have different types of host structures, depths of formation and ore-fluid oxidation states (e.g., Groves et al., 1998; Goldfarb et al., 2001). Despite these deposit-scale variations, it is terrane- to lithospheric-scale processes that are far more critical in determining which orogens are likely hosts for global giants. Accepting some form of Archaean plate tectonics, all giant orogenic gold deposits are situated in orogens built by the accretion of one or more allochthonous terranes and associated oceanic crust to pre-existing continental margins. In addition, 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 robust geochronological data (summarised in Goldfarb et al., 2001) constrain the formation of giant orogenic gold systems to age clusters in the Late Archaean (2.7 - 2.55 Ga), Palaeoproterozoic (2.1 - 1.8 Ga), late Neoproterozoic (800 - 600 Ma), middle Palaeozoic (455 - 340 Ma), and Permian - Cenozoic (285 - 70 Ma); it is improbable that orogens formed at other times will contain giant deposits.

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., Goldfarb et al., 2001, and references therein). Evidence in support of an association between ore formation and mantle processes comes from the presence of mafic to ultramafic intrusions, including common lamprophyre dykes (Rock & Groves, 1988), along first-order lithospheric, near-vertical fault zones in, or adjacent to, almost all giant gold deposits (Groves et al., 1998; Goldfarb et al., 2001).

High heat flux from the mantle can be linked to lithospheric instabilities that result from (i) thickening of slices of oceanic terranes by terrane underplating during seaward growth of the margin, (ii) mantle plumes bringing hot asthenosphere into contact with shallow crustal rocks, or (iii) erosion or delamination of subducted oceanic lithosphere to enlarge the overlying mantle wedge. Therefore, and in addition to the broader age and lithospheric constraints outlined above, the specific syn- to post-accretionary tectonic history of a terrane is critical in defining whether giant gold deposits are likely to be present.

## Tectonic and lithospheric constraints on terranes hosting giant orogenic gold systems

Orogens comprising relatively immature terranes of all ages that are characterised by primitive, oceanic crust are generally well endowed and tend to contain giant gold deposits, whereas those with a significant prehistory or pericratonic association may contain gold ores, but not giants. The length of crustal prehistory also acts as an approximate proxy for thickness of subcontinental lithospheric mantle (SCLM) at the time of gold mineralisation; the thinner the lithosphere, for example in oceanic back-arc or strongly rifted arc settings, the greater the potential for high heat flux from asthenospheric upwelling. Conversely, limited and relatively late lithospheric delamination beneath collisional orogens that develop on mature continental crust is unlikely to favour the focused release of fluid volumes and metals required to form giant deposits. Trace element systematics, Sm-Nd and Lu-Hf isotopic fingerprinting of volcano-intrusive successions, SHRIMP U-Pb dating of zircons, and the recognition of inherited zircon populations within these rocks could all provide important clues as to the anatomy of a terrane within an orogen, which, in turn, would determine its relative fertility for containing giant gold systems. The endowment of gold provinces within Archaean orogens is used below to demonstrate these relationships.

### Examples from Archaean greenstone belts

Late 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 inherited zircons, xenocrysts, and Sm-Nd signatures linked to sub-arc mantle melting) at ca. 2.7 Ga, or shows evidence for intra-continental rifting during or just prior to ca. 2.65 Ga gold ore formation. Notably, there is a clear broad inverse relationship between length of crustal prehistory and the occurrence of giant gold deposits in each orogen.

The best endowed Archaean orogen is the southern Abitibi Belt of the Superior Province (e.g., Wyman, 2003), with a recorded production of about 380 Moz Au from, *inter alia*, two giant deposits (McIntyre-Hollinger, Kirkland Lake) and six world-class ( $\approx 3$  Moz Au) deposits. Gold mineralisation is developed in greenstone belts (characterised by very little, if any, xenocrysts and primitive  $\epsilon_{\text{Nd}}$ ) within about 50 m.y. of pre-ore volcanism. The well-endowed Yilgarn Craton (e.g., Barley & Groves, 1990) has produced >165 Moz Au. The giant deposit at Kalgoorlie and numerous world-class deposits lie in one province (e.g., Eastern Goldfields) of the craton in which the dominant greenstone component formed <50-70 m.y. prior to gold deposition, and where there is the least evidence for pre-existing continental basement. Like the Abitibi Belt and the Eastern Goldfields Province, the Dharwar orogen, with a giant gold deposit at Kolar, had a short pre-history prior to gold mineralisation, although this is recorded to occur at ca. 2.55 Ga (Chadwick et al., 2000), rather than at 2.65 Ga as in the other cases. The well-endowed Rio das Velhas Greenstone Belt in Brazil, containing the giant Morro Velho deposit, had a similarly short crustal history prior to gold mineralisation at ca. 2.67 Ga (Lobato et al., 2001). The Sukumaland Greenstone Belt of Tanzania, with two giant deposits (Geita and Bulyanhulu), essentially mirrors the other well-endowed provinces in terms of its crustal evolution (Borg & Krogh, 1999).

The Midlands Greenstone Belt of the Zimbabwe craton, with ca. 2.66 Ga gold deposits (Darbyshire et al., 1996) in greenstone belts with a pre-crustal history at least 500-600 m.y. older, contains no giants despite its significant endowment of 22 Moz of gold. The far less well-endowed belts in the Pilbara (3 Moz Au) and Karelian (1.2 Moz Au) cratons both lack evidence for the addition of substantial oceanic lithosphere via rifting, and instead developed on predominantly continental-character lithosphere that formed at least 200 – 400 m.y. prior to formation of orogenic gold mineralisation (Goldfarb et al., 2001). Similarly, greenstone belt evolution in the Barberton

Province (12 Moz Au) have been constrained to 3.23 Ga, thus predating ~ 3.08 Ga shear zone-hosted gold mineralisation by at least 150 m.y. (de Ronde et al., 1991). Importantly, this was also not a time of major crustal growth (Condie, 2000).

It thus is apparent that the formation of Archaean giant gold systems can be related to the first of a series of episodic periods of major crustal growth and lithospheric instabilities induced by crustal thinning, accretion-subduction, or catastrophic mantle plume events. A similar pattern emerges for the correlation between the presence or absence of giant gold systems, and the crustal history of Palaeoproterozoic and Phanerozoic terranes. An apparent exception is the eastern North China Craton (>200 Moz Au), where Cretaceous orogenic gold (including a giant at Linglong) postdates the cratonisation of the host terrane by >2 b.y. However, this craton is also the only well-defined example of a Precambrian craton that has lost much of its SCLM via lithospheric erosion. This reflects the simultaneous Jurassic subduction of three plates beneath one craton, thus rapidly destabilising the SCLM (e.g., Menzies & Xu, 1998) and producing asthenospheric heating and thermal energy levels approaching those typical of thinned lithosphere. It is significant that the western half of the North China Craton, with its still relatively thick SCLM, lacks Cretaceous gold ores.

### **Tectonic setting and gold-enriched source rocks**

The ultimate source of the gold in the ores remains uncertain and it could be argued that no specific type of source rock is required as long as available gold can be leached and transported effectively to the site of deposition. However, field evidence, isotope patterns, and scarce trace-gold data support the importance of primitive oceanic rocks as favourable gold and sulphur sources for giant orogenic gold deposits (Keays, 1987; Moss et al., 2001; Bierlein et al., 2004). This is because of the generally higher abundance of gold in pyrite in these marine rocks and the relative ease with which the gold and sulphur can be liberated from such during prograde metamorphism. As primitive oceanic crust implies thin lithosphere, there may well be a feedback loop between tectonic setting and lithosphere thickness that controls both thermal energy and the nature of the rock sequences in the thin lithosphere, which includes the enhanced gold source. In addition to metamorphism of underplated, hydrated marine sedimentary rocks, as suggested by the giant Linglong gold deposit where the country rocks themselves would have been long devolatilised, subducted, refrigerated oceanic slabs may also be essential fluid and(or) metal sources required for formation of giant orogenic gold systems.

### **Variations in the gold endowment of the western Lachlan Orogen (Aus) and the Buller Terrane (NZ)**

In accordance with the above, a comparative assessment of the western Lachlan Orogen (85 Moz Au) and the Buller Terrane (6.6 Moz Au) illustrates that certain aspects stand out as potentially playing a more critical role in the generation of a Phanerozoic world-class orogenic gold province (Bierlein et al. 2004). These are: 1) the presence of a hydrated, oceanic-character substrate that can provide a fertile 'source' rock for both fluids and metals, 2) asthenospheric thermal input to trigger and sustain crustal devolatilisation and melting, 3) the existence of a number of near-vertical, deep-seated faults, 4) substantial transcurrent movement, and 5) evolution of an accretionary-subduction system that promotes development of an extensive fore-arc system with prolonged fluid generation and circulation. Unlike the Buller Terrane, the central Victorian gold province fulfils each of the above criteria, and it could be argued that therein lie the principal reasons for why the latter has produced in excess of one order of magnitude of gold more than the former. It is important, however, to bear in mind that even within the central Victorian gold province, significant variations exist with respect to the above parameters and consequently, gold endowment varies dramatically across the province. For example, the Melbourne Zone has been inferred to be underlain by continental-character crust (Cayley et al., 2002), with peak deformation and magmatism there occurring within a far less protracted time interval than in the structural zones to the west.

## Siting of giants within giant-bearing provinces

From GIS-based studies of gold deposit distribution (e.g., Groves et al., 2000) and from studies of giant gold systems themselves (e.g., Kalgoorlie; Phillips et al., 1996), it is apparent that tectonic and lithospheric parameters of orogens dictate whether giant gold deposits may form within them, although the location of these giants will depend on local-scale factors. The localisation of deposits within favourable provinces involves 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). These include a switchover from compressional to transpressional tectonics; a network of long-lived translithospheric oblique-slip faults; fault reactivation; fault geometry, far field orientation and misalignment; strong rheological contrasts promoting strain partitioning; and the nature of displacement and relay zones between fault segments (e.g., Groves et al., 1998; Cox et al., 2001; Goldfarb et al., 2001). The degree of concurrence of these factors, controlled at the province scale, ultimately determines the overall distribution of these deposits, both giants and non-giants, within a given, well-endowed province.

## Conclusions

The formation and distribution of provinces that host giant orogenic gold deposits are defined by first-order controls that operate at the lithosphere scale. At the highest scale, where a given province hosts giant deposits, the timing of ore formation is linked to the occurrence of major lithospheric instabilities that initiated gold-forming events during peak periods of continental growth. Catastrophic mantle plume events, crustal thickening, accretion-subduction, slab roll-back and delamination of subducted oceanic lithosphere, and the subduction of spreading ridges resulted in extensive asthenospheric upwelling, which, 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 crust and overlying carbonaceous marine metasediments are far more likely to provide the fluids and metals required to form a giant gold system than pericratonic and fractionated rocks. The pre-history of the host orogen is clearly important. Linear orogens that contain primitive crust and record asthenospheric upwelling and thinning of the lithosphere at or just prior to gold mineralisation are most likely to contain giant gold deposits. Both the thermal regimes required to drive giant hydrothermal systems and the existence of intrinsically gold-enriched source rocks are fundamental to such scenarios. Consequently, the actual position of giant gold deposits within a well-endowed province requires the conjunction of several critical, more local factors that operate at the province-scale.

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