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A unified model for gold mineralisation in accretionary orogens and implications for regional-scale exploration targeting methods

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Abstract

Accretionary orogens are the sites of long-lived convergent margin tectonics, both compressional and extensional. They are also the hosts to the majority of the world's important gold deposits. A very diverse range of deposit types occurs within accretionary orogens, commonly in close proximity in space and time to each other. These include porphyry and associated high-sulfidation Au-Cu-Ag deposits, classic low-sulfidation Au-Ag deposits, low-sulfidation Au deposits centred on alkalic intrusive complexes, Carlin-type Au deposits, Au-rich VHMS deposits, orogenic Au deposits, intrusion-related Au deposits and iron oxide Cu-Au deposits. Empirical patterns of spatial distribution of these deposits suggest there must be fundamental generic controls on gold metallogeny.

Various lines of evidence lead to the proposal that the underlying key generic factor controlling accretionary orogen gold metallogeny is regional-scale, long-term, pre- and syn-subduction heterogeneous fertilisation of the lithospheric mantle that becomes a source of mineralisation-associated arc magma or hydrothermal fluid components. This process provides a gold-enriched reservoir that can be accessed later in a diverse range of tectonomagmatic settings. Based on this concept, a unified model is proposed in which the formation of a major gold deposit of any type requires the conjunction in time and space of three essential factors: a fertile upper-mantle source region; a favourable transient remobilisation event; and favourable lithospheric-scale plumbing structure. This framework provides the basis for a practical regional-scale targeting methodology that is applicable to data-poor regions.

Introduction

Most ore deposit studies are forensic in nature, concentrating on documentation of features at the mineral deposit scale, less commonly district scale, in order to better classify deposit styles into related deposit groups and better understand their genesis. Unfortunately, such studies fail to explain the critical differences between world-class to giant deposits and smaller deposits because their deposit-scale parameters and ore-fluid and isotopic characteristics are generally essentially identical (Groves 2009).They thus fail to provide critical information on the most likely locations of economically significant mineral deposits. Clearly, a more predictive, regional- to terrane- scale approach is required for scientific exploration targeting (Hronsky & Groves 2008) in both semi-mature and greenfields provinces. At this larger, crustal to lithospheric scale, there may also be common links between deposit styles, which have been considered previously to be separate groups on the basis of forensic research, which can aid area selection at the terrane scale.

Outside of the Witwatersrand Basin of South Africa, most gold deposits, including those where gold represents a significant by-product, form in convergent margin or paleo-convergent settings and it is these deposits that are the specific topic of this paper. These deposit types include porphyry and associated high-sulfidation Au-Cu-Ag deposits (e.g., Seedorff et al.2005), classic low-sulfidation Au-Ag deposits (e.g., Simmons et al. 2005), low-sulfidation Au deposits centred on alkalic intrusive complexes (e.g., Sillitoe 2002), Carlin-type Au deposits (e.g. Cline et al. 2005), Au-rich VHMS deposits (e.g., Franklin et al. 2005), orogenic Au deposits(e.g., Goldfarb et al.2005) , intrusion-related Au deposits (e.g., Lang et al.2000) and iron oxide Cu-Au deposits (e.g. Williams et al. 2005; Groves et al. 2010). Each of these deposit types is usually considered to represent a distinctive deposit group with internally common features and a broadly consistent four-dimensional context with respect to the evolution of its host convergent-margin orogen, as discussed further below. The crustal- to lithospheric-scale settings of these deposit groups are examined below in order to better understand what controls the location of the larger examples, particularly critical associations that are common to more than one group.

Importantly in recent years, there have been some major advances in understanding the controls on gold mineralization in these convergent-margin environments. These new concepts, which provide the critical framework for this study, relate to understanding of three major components of the gold systems at the larger scale:

1) The fundamental processes involved in the evolution of accretionary orogens;

2) The central role of upper mantle fertility in controlling gold metallogeny in a broad range of environments within convergent margin settings; and

3) The underpinning factors which allow integration of the observed great diversity of convergent margin gold deposits into a single coherent framework of value to exploration.

This paper systematically explores these concepts.

Accretionary orogens

Orogenic belts may be divided into two end-member types: collisional and accretionary. Collisional orogens form through the relatively simple process of two major continental blocks colliding after closing their previously intervening ocean. Modern examples include the Himalayas and the Alps (Cawood et al. 2009). They might be appropriately alternatively termed “simple orogens”. In contrast, accretionary orogens are much more complex and represent long-lived zones of plate convergence. Effectively, all the modern margins and paleomargins of the Pacific Ocean are of this type.

Accretionary orogens, although long-lived sites of persistent subduction, typically alternate between extensional and compressional states, depending on the relationship between the rate of slab retreat and the rate of advance of the overriding plate. During extensional phases, when slab retreat dominates the margin dynamics, back-arc basins, such as the modern Sea of Japan, typically form. Such accretionary orogens are characterised by broad zones of complex geology, incorporating many distinctive geological domains, including accretionary wedges, island arcs, continental fragments, clastic sedimentary basins and overprinting magmatic belts. These distinctive geological domains have been historically referred to as terranes, and are characterised by lack of correlation of stratigraphy between them.

In the 1980s, it was widely assumed that most terranes represented allochthonous fragments of lithosphere that were successively accreted onto old continental margins and were derived a significant distance away from the margin to which they were eventually accreted (e.g., Monger et al. 1972; Coney et al. 1980). For this reason, they were commonly referred to as exotic or suspect terranes (e.g., Coney et al. 1980). However, this perspective began to change in the early 1990s. LITHOPROBE transects across the Canadian Cordillera revealed the superficial nature of these so-called exotic terranes (Clowes et al. 1995; Cook 1995; Snyder et al. 2002; Cook et al.2004; see Fig. 1). They were mostly recognised to be of North American affinity or origin, rather than derived from the other side of the ocean, to be only 5-15 km thick within a total crustal thickness of >30km, and to be underlain by a broad tapering crustal wedge composed of a mixture of crystalline basement rocks and a sedimentary prism deposited onto the rifted continental margin before the accretionary orogeny began (Snyder et al. 2009).

At about the same time as the LITHOPROBE program, mineral industry geologists gained access for the first time to continental-scale image-processed datasets of gravity data. Patterns in these gravity data strongly suggested that large-scale tectonic fabrics, visible in the adjacent continents, could be traced into the accretionary orogen, presumably underneath the younger accreted rocks. One example of this was the Western Lachlan Fold Belt in Victoria, where more recent seismic surveys have now confirmed the presence of extended Proterozoic basement underlying the orogen at depth (e.g., Willman et al. 2010; Cayley et al. 2011)

Consistent with these observations, recent lithospheric-mantle focused, integrated geophysical and geochemical studies have shown that juvenile arc-related lithosphere is, perhaps surprisingly, not a major component of accretionary orogens (Begg et al. 2009; Belousova et al. 2010; Griffin et al. 2011). The reason for this relates to the fundamental processes of continental lithosphere formation, as summarised by Griffin et al. (2008). There is a sharp dichotomy between the processes that form Archean sub-continental lithospheric mantle (SCLM) and those that form lithospheric mantle in younger terranes. The most essential difference between these two types of lithospheric mantle is that Archean SCLM is depleted in iron and hence strongly buoyant and almost impossible to recycle back into the deep mantle. In contrast, younger lithospheric mantle is not iron depleted and is negatively buoyant once it cools. Therefore, although perhaps present along younger accretionary margins, it has a low long-term survival potential and tends to be readily recycled back into the deep mantle during orogeny (Griffin et al.2003; Groves et al. 2005; Griffin et al. 2008).

Both the above lines of evidence indicate that although terranes dominated by juvenile arc assemblages are common in accretionary orogens, they are likely to largely represent obducted relatively-thin slabs, which tectonically overlie older basement lithosphere. This basement of lower crust and lithospheric mantle must logically comprise two main types of material:

1) Relatively discrete fragments of old continental lithosphere, sometimes termed microcontinents, commonly occurring as elongate ribbons. These mostly formed by rifting off the adjacent continental mass, but commonly represent discrete pre-existing lithospheric subdomains within the continent because convergent margin rifting reactivated older suture zones; and

2) Domains of highly-extended continental lithosphere, which initially formed on the passive margins of the extending continents (Reston 2007; Kuznir and Karner 2007), and were subsequently inverted by the compressional orogenic process. These highly-extended continental margin domains may have their crust totally removed by extensional processes and lithospheric mantle exposed at the sea-floor (e.g., Reston 2007; Begg et al. 2009). The crustal rocks eventually emplaced during orogenic inversion above this extended lithospheric mantle are totally unrelated to their underlying lithospheric mantle basement.

Gold deposit styles and their tectono-magmatic settings within accretionary orogens

A variety of gold (+/- Cu +/-Ag) deposits are formed in accretionary orogens (e.g., Bierlein et al. 2009). Clear associations may be observed where particular types of deposits can be related to a characteristic, broadly consistent tectono-magmatic setting within an evolving accretionary orogen. However, because of the complex history of these orogens, in particular the alternation between retreating and advancing states discussed above, different deposit types, that formed in significantly different settings at different times, can be juxtaposed closely with, or even directly overprint, each other. On the other hand, quite diverse deposit types may form synchronously but spatially separated within the same broad orogen. A good example of this is the Tasmanides, where 440Ma orogenic Au deposits of the West Lachlan province, Victoria, are coeval with porphyry Cu-Au deposits of the Macquarie Arc in Central New South Wales (Squire and Miller 2003).

We have produced a synthesis, based on collective experience and a review of the relevant literature, which relates deposit types to tectono-magmatic setting within accretionary orogens (Table 1). In this synthesis the four main metallogenically important tectonomagmatic environments recognised in accretionary orogens are:

1. Active subduction-related arc magmatism;
2. Superimposed rifting;
3. Inverted retro-arc pericontinental rifts; and
4. Superimposed hot mantle upwellings.

Each one of these broad tectono-magmatic settings includes a range of recognised deposit types. This synthesis indicates some shortcomings with the current published taxonomy of convergent-margin-associated deposits, which has been largely based on observations at the deposit scale. Deposits which have been grouped together in the same class (e.g., porphyry deposits) may form in more than one distinctive tectono-magmatic setting. For example, deposits within Setting 1 are commonly classified as porphyry deposits. However, some deposits that form in Setting 2 (e.g., Ladolam, Lihir) are also commonly classified as porphyry-related (e.g., Carman 2003). This is of great practical significance because, as discussed below, factors relevant to regional exploration targeting relate closely to a large-scale tectono-magmatic context.

The dominant deposit types that form in Setting 1 are closely associated with porphyry intrusions. As recently summarised by Sillitoe (2010), a diverse array of deposit types may form as part of a broad porphyry-related system, within locations that vary in vertical position and/or distance from the central driving intrusion. These include classic porphyry Cu ± Au deposits, sub-epithermal Zn-Cu-Pb-Ag ± Au veins, high-sulfidation epithermal Cu-Au+/-Ag deposits, proximal Cu-Au skarns, distal Au-Zn-Pb skarns, intermediate sulfidation epithermal disseminated Au ± Ag ± Cu deposits and distal sediment-hosted disseminated Au-As ± Sb ± Hg deposits (Carlin type deposits). With the possible, disputed exception of Carlin type deposits, these all show a close spatial, temporal and genetic relationship to cupolas of porphyritic felsic intrusions. Magmatism varies from calc-alkaline to alkaline. Although gold-rich deposits are not necessarily associated with alkaline magmas, mineralised alkaline intrusions are typically associated with gold-rich deposits. In the case of Carlin type deposits, Ressel and Henry (2006) and Muntean et al. (2011) make a strong case that these deposits are magmatic-hydrothermal and situated above the deep cupolas of intrusions, inferred from gravity data and coeval with late Eocene dykes present in the mined areas. Muntean et al. (2011) proposed that the gold-bearing fluids were released from their parental magmas at a depth of 10-12km below the site of the deposits and that these intrusive sources are not exposed.

A deep lithospheric connection is indicated by the preferential development of porphyry systems adjacent to transform faults or other major deep-seated structures (e.g., Richards 2000). Significant deposits form within anomalous geodynamic settings within the evolution of the accretionary orogen. Two distinct geodynamic settings have been recognised for the deposits that form in Setting 1; transient localised anomalous compression (e.g., Tampakan-Rohrlach and Loucks 2005; Grasberg-Hill et al. 2002; Chinkuashih-Lu et al. 1995), or the transition from a compressional flat slab event to an extensional slab roll back event (e.g., Bingham Canyon; Presnell 1992; and Carlin; Muntean et al. 2011).

The second major metallogenically-important tectono-magmatic setting is where rifting is superimposed on an active convergent margin. This rifting normally occurs as a response to slab roll-back, when the accretionary orogen is in a retreating phase, and may occur either in a back arc position or longitudinally along the main magmatic arc position itself (e.g., the modern Taupo Rift zone and Tonga-Kermadec arc). However, rifting may also occur as a local regime within a complex collisional orogen (e.g., the setting of the Porgera deposit; Richards et al. 1990). A range of gold deposit types occur in Setting 2, including alkalic intrusion-centred low sulfidation epithermal gold deposits (e.g., Porgera; Richards et al. 1990; Cripple Creek, Kelley and Ludington 2002; Lihir; Carman 2003), bimodal rift-associated low sulfidation epithermal gold deposits (e.g., Hishikari; Watanabe 2005), epithermal -VMS hybrid deposits (e.g., Henty; Halley and Roberts 1997; Greens

Creek;Taylor et al. 2008) and gold-rich VMS deposits (e.g., Eskay Creek; Sherlock et al. 1999; Solwara 1; Hannington et al. 2010).

An important control on the type of deposit that forms in this extensional setting appears to be the amount of crustal thinning, which correlates with overlying water depth in a sub-aqueous setting, that had occurred prior to the time of mineralisation. Alkalic intrusion-centred deposits are associated with incipient extension in a sub-aerial environment. For example, Cripple Creek formed near the tip of the Rio Grande Rift (Kelley and Ludington 2002). Bimodal rift-associated low-sulfidation gold deposits are associated with somewhat more developed rifts, still in a dominantly sub-aerial setting. These deposits are lower temperature, with a less direct connection to specific intrusive plutons than the alkalic intrusion-centred deposits. With increasing crustal extension and a transition to a relatively shallow sub-aqueous environment, epithermal-VMS hybrid deposits (e.g., Henty, Eskay Creek) occur. With still more crustal extension and a deep-water sub-aqueous environment, classic VMS deposits form. A good example of the progression from epithermal to VMS-epithermal hybrid to classic VMS mineralisation with increasing crustal thinning and water depth has been documented by Taylor et al. (2008) for the Alexander Triassic Metallogenic Belt in Alaska- British Columbia.

It is emphasised that, although the degree of crustal extension *prior* to mineralisation varies significantly and systematically between this environments, this does not necessarily relate to the amount of extension actually occurring *synchronous* with mineralisation. For example, although the modern gold-rich VMS deposit Solwara 1 occurs in an extended crustal environment at 1600m water depth (Nautilus Minerals website), it is actually spatially associated with the propagating tip of the Manus Basin (Bismarck Sea) back-arc spreading centre (Binns and Scott, 1993; Fig. 2). Therefore, in this regard, its geodynamic setting resembles that of Cripple Creek (Kelley and Ludington 2002). The adjacent, Quaternary alkaline intrusion-centred Ladolam deposit at Lihir is considered by Carman (2003) to also relate to the same incipient extension associated with propagation of the Bismarck Sea spreading centre. This is a good example of two very different deposit types forming associated with a single geodynamic setting. Furthermore, both these deposits occur where this incipient extension intersects the position of the now extinct Outer Melanesian arc (Fig. 2).

The third major metallogenically-important tectono-magmatic setting is associated with the inversion of peri-continental rifts that form in a retro-arc position. These rifts are dominated by primitive sedimentary and/or volcanic sequences, are characterised by relatively high-temperature/low-pressure metamorphic assemblages (in contrast to superficially similar fore-arc accretionary wedge sequences) and typically lie adjacent to continental margins or to the margins of fragments of continental crust. The two most important deposit types in Setting 3 are orogenic Au deposits (e.g., Yakubchuk 2010) and (reduced) intrusion-related Au deposits (IRGD; e.g., Mair et al. 2011). A complexity with this setting is that these host rift zones initially form within Setting 2. Therefore early-formed Setting 2 mineralisation, such as VMS deposits, may be overprinted by later Setting 3 mineralisation such as orogenic Au deposits with resultant genetic controversy (e.g., Groves et al. 2003).

Orogenic Au deposits (e.g., Goldfarb et al.2001,2005) form during compressional to transpressional tectonism late in orogenesis, with strong structural controls among their most distinguishing features, which also include limited vertical alteration zonation as carbonic ore fluids were broadly in equilibrium with wallrocks at depths of 3 to at least 15 km in the crust (Groves 1993).Unlike the porphyry and epithermal deposits, there is no consistent relationship between the orogenic gold deposits and felsic magmatism, which may be pre-,syn or post-gold or even absent altogether in some cases. However, the deposits commonly show a close spatial relationship to small lamprophyre and associated felsic porphyry dykes, sills or plugs (Rock et al. 1987). Even though a precise temporal relationship is rare, this demonstrates a close spatial association of the deposits to deep mantle-tapping structures, probably along lithospheric boundaries (cf., Burke et al.2003).

Intrusion-related Au deposits (IRGD) associated with reduced magmas have many deposit-scale features in common with orogenic deposits(e.g., Lang et al. 2000) and this has caused considerable controversy (e.g., Groves et al.2003). In some cases (e.g., NE Siberia; Goryachev 2008) IRGD and orogenic Au deposits are closely spatially associated. However, in other cases (e.g., Tombstone-Tintina Belt in Alaska and Yukon) they generally occur in provinces previously known for their W-Sn deposits, inboard of orogenic gold deposits in sedimentary basins developed over craton margins. In contrast to orogenic gold deposits, IRGDs show a strong spatial and temporal relationship to magmatism, strong thermal gradients, with high temperature proximal skarns in places, and strongly zoned alteration and mineralisation haloes extending out to Ag-rich haloes. In the case of the Tombstone-Tintina Belt, IRGD mineralisation occurred during post-orogenic extension (Mair et al. 2011) whereas in NE Siberia IRGD deposits predated orogenic deposits that formed during the final stages of rift closure and orogenesis (Goryachev 2008).

The fourth major metallogenically-important tectono-magmatic setting in accretionary orogens is associated with the impingement of hot mantle upwellings: plumes *sensu lato*. This impingement may occur > 100Ma after the cessation of active convergent margin tectonics in the region of the deposit. A well documented, relatively recent example of this process is provided by the mid-Miocene bonanza style low-sulfidation epithermal deposits of Northern Nevada (e.g., Sleeper) which are closely associated in both space and time with the initial crustal impingement of the Yellowstone Hot Spot or re-emergence of the hotspot on the east side of the Juan de Fuca /Cascade subduction zone after the hotspot was over-ridden by south-westward migration of North America (Saunders et al. 2008). A very significant but much older example is provided by the c. 1.59 Ga Olympic IOCG province in South Australia. Although deposits in this province, including the supergiant Olympic Dam deposit, are associated with a major mantle upwelling that generated bimodal volcanism and massive crustal melting centred in the middle of the Gawler Craton (Gawler Range Volcanics and Hiltaba Suite granitoids), they show a strong spatial association with the pre-existing (c.1.7 Ga) Kimban suture zone, occurring in a sub-parallel belt 100-150km inboard of this (Hand et al. 2007).

Regional-scale controls on gold fertility and links to upper mantle enrichment

The observation that large-scale lithospheric structure may correlate with heterogeneity in gold endowment was first made by Titley (2001). Since then it has become increasingly clear that there is strong empirical evidence for continental-scale heterogeneity in gold-endowment that operates at a much larger scale than individual metallogenic belts (e.g., review of gold metallogeny of the North and South American Cordillera by Sillitoe 2008). Geographically-localised zones of gold fertility encompass multiple belts with diverse deposit styles, from orogenic to epithermal deposits, multiple times of formation, and diverse geodynamic settings. As proposed by both Sillitoe (2008) and Richards (2009), the only feasible explanation is the presence of some widespread, long-lived gold-fertile lower-crustal or subcrustal source region. The hypothesis of this paper is that this long-lived gold-fertile region relates to gold-enriched volumes of the upper lithospheric mantle. The main lines of evidence which support this hypothesis are briefly summarised below.

In order to elucidate source-region processes that might be involved in gold metallogeny, we reproduce in Table 2 and Figure 3 a compilation by Loucks & Ballard (2003) of published whole-rock analyses of relatively primitive Quaternary arc basalts (6-12 wt. % MgO and Mg # > 60, sulphide-undersaturated) from both gold-mineralised and -unmineralised settings. These data demonstrate that those primitive magmas in gold metallogenic provinces have distinctive geochemical compositions relative to average arc basalts: they are characterised by elevated values of Nb, Th and other highly incompatible lithophile elements, and higher Nb/Y, Th/Yb and Ba/Zr ratios. Significantly, the geochemical data for two sets of shoshonitic lamprophyres, that were directly parental to gold deposits at Laowangzhai in China (Late Eocene) and Hillgrove in Australia (Permian), show very similar geochemical patterns to the gold-fertile primitive magmas in Quaternary gold-ore provinces.

Loucks and Ballard (2003) concluded that these anomalous characteristics of gold-associated magmas do not relate to any anomalous contribution of aqueous fluids or melts from the subducting slab. The possibility of an anomalous contribution of slab-derived fluid is ruled out because the gold-productive magmas, although in absolute terms more enriched in all incompatible elements than barren magmas, showed less *relative* addition (i.e., smaller “spike amplitude” on a spider diagram) of water-soluble incompatible elements (U, K, Pb, Sr, Cs) than comparably primitive basaltic magmas in gold-unproductive arc segments. The possibility of an anomalous contribution from direct slab melting is rejected because the heavy rare-earth elements Y, Ho, Er, Tm, Yb and Lu, which would be expected to be retained in residual garnet in that scenario, show the same flat patterns in Fig. 3 for both gold-productive and non-productive arc tholeiitic parental magmas. Figure 3 also demonstrates that the primitive magmas in Au-ore provinces have substantially higher concentrations of highly incompatible, fluid-insoluble high-field-strength elements (Nb, Ta, Zr) than average N-MORB.

As a result of these tests, Loucks and Ballard (2003) concluded that parental magmas of gold-productive differentiation series represent low-degree partial melts of the subarc mantle. These could relate to either unusually low degrees of partial melting in the asthenospheric mantle wedge or the melting of lithospheric mantle regions that had been pre-enriched in incompatible elements (i.e., fertilised) by the trapping of earlier low-degree partial melts of the deeper mantle. They favoured the latter hypothesis on the basis of the evidence of the existence of a gold-enriched reservoir, which seemed to be persistently available to transient arc magmatism, as discussed below.

There are three more independent lines of evidence in support of this proposition:

(1) A long recognised, although poorly understood, association between alkalic magmas (which, by definition, are enriched in incompatible elements) and gold mineralisation (e.g., Rock et al. 1987; Muller and Groves 1995; Sillitoe 1997; Jensen and Barton 2002; Muller 2002).

(2) Direct evidence for primary gold enrichment in alkalic magmas. Rock et al. (1987) documented significant gold enrichment in Siluro-Devonian lamprophyres from southern Scotland. These rocks were clearly unaltered but nevertheless contained an average of 137 ppb Au. Arima & Kerrich (1988) report Au contents in the range 17-70 ppb in Jurassic kimberlite dikes in Ontario. Studies by Sleep (2009) indicate that low-percentage asthenospheric melts of kimberlitic-lamproitic affinity are principal agents of metasomatic refertilization of sub-continental lithospheric mantle, and similar hydrous, carbonate-rich melts of nephelinitic character are principal agents of metasomatic refertilization of oceanic lithospheric mantle on the periphery of spreading ocean ridges and mantle plumes (Pilet et al. 2011). Gold enrichment in oceanic alkalic magmas has also been demonstrated from Hawaii, where Sisson (2003) documented gold concentrations up to 36 ppb in fresh, early-stage alkalic lavas at Kilauea.

(3) Xenolith studies in the North China Craton (Zheng et al. 2005) provide direct evidence of significant gold enrichment in subduction-refertilised upper mantle peridotite. In the Hebi xenolith locality, peridotite xenoliths are consistently elevated in Au (10.4-13.5ppb)

The clear implication of Loucks and Ballard's (2003) work is that gold must behave as an incompatible element during low to moderate percentages of partial melting of spinel peridotite mantle. This implies that as melting of any particular peridotite progresses, the Au content of the melt is at a maximum at low percentages of partial melting and is diluted as the percentage of partial melting increases. This inference is consistent with the data of Lorand et al. (1999) who showed that, within Pyrenean orogenic peridotites, harzburgites were gold depleted, relative to fertile lherzolites. It is also consistent with the observation that the estimated average crustal abundance of Au is about 3 ppb (Taylor and McLennan, 1985), which is nearly twice the indicated abundance of 1.7 ppb Au in the primitive upper mantle (Fischer-Gödde et al, 2011).

Loucks and Ballard's (2003) infer a bulk partition coefficient melt/peridotite for gold of ≈ 3 to 5. This is similar to the melt/peridotite partition coefficients for Al and heavy REEs such as Yb. This conclusion is consistent with results of Morgan (1986), who showed a 1:1 correlation of Re variations with Au in peridotites variably depleted by melt extraction, and the demonstration by Becker et al (2006) and (Fischer-Gödde et al, 2011) that Re has a melt/peridotite bulk partition coefficient similar to HREE and Al.

Supporting field evidence for this model was provided by McInnes et al. (1999, 2001) in their study of mantle xenoliths erupted from the alkalic Tubaf submarine volcano, located only 14km away from the giant Ladolam gold deposit on nearby Lihir Island. The Ladolam deposit is closely associated with alkaline magmatism and is the youngest known major gold deposit, forming within the last 500 Ka (Carman 2003).

Harzburgite mantle xenoliths from Tubaf were derived from depths of <70km and therefore represent an upper mantle section (McInnes et al. 1999). These xenoliths have been hydrofractured and metasomatised by a high density H_2O-rich fluid, transitional to an alkali aluminosilicate melt, with significant associated carbon and sulfur (McInnes et al. 2001). Importantly, this fluid was also strongly oxidised (about 1.8 -2.0 log units > FMQ). This process was interpreted by McInnes et al. (2001) to represent the net transfer of soluble elements from the lower to upper parts of the mantle wedge. The result was a network of oxidised, metasomatised peridotite, enriched in orthopyroxene, clinopyroxene, phlogopite, amphibole, magnetite and Fe-Ni sulfides. Significantly, the gold contents of metasomatised harzburgite averaged about 20 times that of associated unmetasomatised harzburgite.

McInnes et al. (2001) suggested that preferential melting of these metasomatically-enriched domains could account for the highly oxidised, sulfur and alkalic-rich magmas which form the Tabar-Lihir-Tanga-Feni island chain and host the giant Ladolam deposit. Subsequently, Franz and Romer (2010) demonstrated that the rare earth elements patterns of discrete veins within the metasomatised harzburgite closely matched those of the trachybasalt lavas which had brought these xenoliths to the surface.

In some gold provinces such as Cripple Creek (Kelley and Ludington 2002) and Lihir (Carman 2003), it can also be clearly demonstrated that mantle-derived gold-fertile magmas were emplaced in a geodynamic setting unrelated to active subduction, as a localised response to incipient extension. This provides confirmatory evidence for the existence of a widespread or ubiquitous gold-fertile mantle source region available to be readily remobilised by later tectonic process. Richards (2009) has also argued for the existence of a gold-fertile source region that can be accessed after active subduction has ceased.

In some cases, there is also direct geological and geochemical evidence from gold deposits that implicates a mantle source. In a recent seminal paper, Pettke et al. (2010) directly measured Pb isotopes within fluid inclusions associated with Cu-Au mineralisation at the giant Bingham Canyon porphyry deposit. They conclude that these Pb isotope signatures indicated derivation of Pb, and by analogy Cu and Au, from a lithospheric mantle source that had been metasomatised by a subduction related fluid at about 1.8 Ga. This is consistent with the conclusions of Maughan et al. (2002) who proposed that basic alkaline magmas had played a critical role in providing ore metals to the Bingham deposit via a magma mixing process. They suggested that about ten percent of the monzonitic/latitic magma related to ore formation was derived from a basic alkaline magma. A similar process was invoked by Mair et al. (2011) for the gold deposits of the Tombstone-Tintina

Belt. They clearly demonstrated that the distinctive gold-enriched reduced magmas associated with mineralisation formed via the hybridisation of reduced crustal melts by low-degree partial melts of lithospheric mantle, emplaced during post-orogenic extension. Regional granites emplaced at the same time, but without the signature of hybridisation by mantle melts, generated Sn and W mineralisation but are barren of Au. Similarly, Kelley and Ludington (2002) showed that Sr and Pb isotope compositions of ore-associated magmas at Cripple Creek suggest a subduction-modified subcontinental lithospheric mantle source. Isotopic evidence for the metallogenic importance of a mantle contribution has also been provided by Johnson and McCulloch (1995), who demonstrated from Nd isotopes that the most likely source of REE (and by analogy, Cu and Au) in the Olympic Dam deposit were altered alkaline mafic/ultramafic dykes present within the deposit. More recently, Skirrow et al. (2007) demonstrated that Nd isotopes indicated a much greater mantle contribution in the supergiant Olympic Dam deposit than in minor IOCG deposits within the same province.

In the case of porphyry deposits, some workers (e.g., Kay and Mpodozis 2001; Richards 2009; Shafiei et al. 2009) have suggested an alternative hypothesis to upper mantle enrichment to explain observed patterns of regional-scale metallogenic heterogeneity. They propose that remelting of hydrous mafic (garnet-amphibole) cumulates in the lower crust plays a critical role in the generation of ore-forming magmas. These cumulates are considered to be residual from previous cycles of arc magmatism. The primary evidence in support of this hypothesis appears to be that petrological modelling of melting of these cumulates can reproduce some of the observed distinctive aspects of porphyry-related magmas, such as high Sr/Y and La/Yb ratios (e.g. Richards, 2009).

Although a contribution from lower crustal mafic cumulates is not mutually exclusive of a contribution from an enriched upper mantle, the latter hypothesis is favoured here as the much more important process for gold metallogeny for the following reasons:

(1) There is significant observational evidence that gold is enriched in upper mantle peridotite relative to asthenospheric mantle (e.g., Lorand et al. 1993, Zheng et al. 2005). However, there does not appear to be any similar reports of gold enrichment for lower crustal mafic xenoliths. This is also consistent with the inference that, if gold behaves as an incompatible element (as argued above), it is unlikely to be enriched within a cumulate sequence.
(2) As demonstrated by Sillitoe (2008), large-scale regions of gold fertility are quite localised along extensive convergent margins: in contrast to porphyry copper deposits which are more widely and uniformly distributed. Given the expected ubiquitous development of mafic cumulates at the base of arcs, it is hard to understand why fertile gold-bearing regions are so localised, particularly as this provinciality persists over geological time. This fundamental observation also strongly implies that gold fertility cannot simply be explained by the same process invoked for porphyry copper genesis.
(3) Geochemical data for primitive magmas associated with gold mineralisation (see above) show flat HREE patterns, ruling out the presence of garnet in the source region.

(4) Experimental petrological studies of the melting of fully-hydrated amphibolite (Rushmer, 1991; Wolf and Wyllie, 1994; Rapp and Watson, 1995) show that the resultant melts, although of andesitic bulk composition, have much less water than porphyry-related magmas.
(5) Amphibolite melting has now been shown to be the mechanism for generation of TTG melts (Foley et al. 2002). TTG magmatic rocks are ubiquitous in Archean terranes but have very few associated ore deposits of any type. This would seem to be a compelling empirical argument against an important metallogenic role for magmas related to amphibolite melting.
(6) Even in cases where lower crustal mafic cumulate melting has been proposed as a key process, such as the porphyry province of south-eastern Iran (Shafiei et al, 2009), the supporting isotopic evidence is equivocal. In that particular example, ore-hosting porphyries are reported as showing a narrow range of non-radiogenic Sr isotope ratios.

Therefore, in summary, it appears that previous suprasubduction fertilisation of the upper mantle is an important, if not critical, ingredient in forming large convergent-margin associated gold deposits. Empirically, this gold-fertile mantle enrichment seems to be best developed around the margins of older blocks of continental lithosphere or associated with continental fragments that have undergone double-subduction, with initial subduction under one side switching to later subduction under the opposite side, as first recorded by Solomon (1990). Conceptually, it seems likely that subduction-related metasomatism is best developed along major, lithospheric-domain bounding structural zones. Support for this hypothesis is provided by the North China xenolith study of Zheng et al. (2005), who recorded the strongest Au enrichment in their study from the Hebi locality. This locality occurs very close to the well recognised “North-South Gravity Lineament”, which is highly likely to represent a major lithospheric domain boundary. In this context, it is important to note that most orogenic gold deposits occur in inverted pericontinental basins that form at the transition between the cratonic continent and the back-arc basin (ocean) or at the margins of micro-continental fragments.

Unification of convergent-margin gold metallogeny: First order controls

Convergent margins are characterised by a diverse array of gold- and base metal deposits. In the past, this complexity has hindered the development of a robust predictive framework. However, recognition of the central role of upper-mantle fertility in gold metallogeny provides the key to conceptually unifying the range of deposit styles and the processes that formed them. The essence of this unified model is that the formation of a major convergent-margin gold deposit of *any* type can be considered as the conjunction of three fundamental elements: a fertile upper-mantle source region; a transient remobilisation event that extracts gold-enriched magmas and/or fluids from this source region; and favourable lithosphere-scale architecture that allows the focused flux of these magmas/fluids (Fig. 4). All three of these elements are critical to effective regional-scale predictive targeting and are discussed in more detail below. An example of the application of these concepts to the northern Nevada gold province is shown in Figure 5.

The diversity between individual recognised deposit types is considered to relate to various second-order and third-order controls (e.g., Sillitoe 2010), a detailed discussion of which is beyond the scope of this paper. However, likely important second-order processes include crustal thickness at the time of mineralisation, the nature and amount of crustal magmas that interact with those derived from the fertile mantle source region, the paleodepth of ore emplacement, and the paleodepth of magmatic hydrothermal fluid escape from its parental magma. Likely important third-order processes include spatial relationship to intrusive centre (proximal-distal), local host wallrock composition, local contributions of metals from hosting sequences, and the amount of any meteoric fluid contribution to the ore-fluid.

Fertile upper-mantle source region

This first essential element is a fertile upper-mantle source region. As discussed above, it is emphasised that this fertilisation process relates to the addition of gold-enriched, low-degree partial melts of asthenospheric mantle to the overlying lithospheric mantle. The fertilisation process may relate in part to previous subduction or to veining of the lithospheric mantle during plume activity or rifting events, and there can be a very large (>1 Ga) time gap between the fertilisation process and the process that extracts those melts to the upper crust (e.g., Grainger et al. 2008; Pettke et al. 2010). As demonstrated by Sillitoe (2008), this process of gold enrichment seems to be quite localised within laterally-extensive convergent-margin belts along the North and South American Cordillera. This raises the important question as to the key controls on producing locally enhanced gold-enrichment of the upper mantle.

From first principles, low-angle, so-called “flat” subduction, is conceptually particularly favourable for the process of upper mantle fertilisation described above. There are two reasons for this. First, in this setting subduction-related magma generation is likely to be significantly diminished due to slab-induced refrigeration of the mantle wedge, and any magmas produced are likely to be low-degree partial melts, and therefore gold-enriched (eg Kay et al, 2005). Secondly, low-angle subduction is typically associated with compressional tectonics (Kay et al, 2005; Humphreys, 2009) which inhibits the passage of mantle-derived melts to the surface (e.g. Humphreys, 2009; Finzel et al. 2011). In the modern Earth, all subduction zones with a dip of less than 20 degrees are associated with gaps in arc volcanism (Syracuse and Abers 2006). Both the above factors favour the trapping of incompatible-element-enriched melts from the deeper mantle wedge in the upper mantle. This proposed process is summarised schematically in Figure 6.

Flat subduction is relatively uncommon along convergent margins; only about 6 percent by length of modern subduction zones dip at less than 20 degrees (Syracuse and Abers 2006). Therefore, it is logical to expect that zones which have been exposed to long histories of subduction, possibly at various times throughout geological history, will have a greater probability of being more strongly fertilised. Consistent with this, an increasing number of major gold provinces with a variety of deposit styles throughout the world have been shown to occur at the margins of older, pre-existing cratonic lithospheric domains. These include the Norseman-Wiluna Belt (Cassidy 2006), Abitibi Belt (Faure et al. 2011), Bingham Canyon (Groves et al. 2005), Olympic IOCG province (Hand et al. 2007), NE Siberia gold province

(Nokleberg et al. 2005), New Guinea Highlands (Hill et al. 2002), Stawell, Victoria (Miller et al. 2006) and the Tombstone-Tintina Belt (Mair et al. 2011).

Another factor that may favour the enhancement of this fertilisation process at the margin of pre-existing cratonic lithospheric domains is the role that lithospheric keels play in channelling asthenosphere-derived melts to their margins (eg Sleep, 1996). Recently, Begg et al (2010) have invoked this process as being critical in the formation of nickel sulfide deposits.

Significantly, the spatial extent of the major gold province recognised by Sillitoe (2008) in the western United States correlates broadly with the inferred extent of the c.75 to c. 45 Ma Laramide flat-slab event (Humphreys 2009), which immediately predates the age of most significant gold metallogeny in this region. However this cannot be the complete story here as Pettke et al. (2010) have inferred c.1.8 Ga metasomatic enrichment for the source region of the Bingham Canyon ore magmas. Bingham Canyon is located on a major boundary between two strongly-contrasting lithospheric domains; the Great Basin to the west and the Colorado Plateau to the east (Bennett and De Paolo 1987; Groves et al. 2005). Both of these domains are underlain by lithosphere of at least Paleoproterozoic age (Bennett and De Paolo 1987; Whitmeyer and Karlstrom 2007). It is very plausible that this position represents a long-lived lithospheric boundary that may have been the loci of previous subduction events, including in the Paleoproterozoic (Whitmeyer & Karlstrom, 2007).The northern Nevada region is also very interesting in this regard. If the boundaries of the Archean Grouse Creek craton as mapped by Whitmeyer and Karlstrom (2007) are projected a short distance westward into more extended continental lithosphere, they almost exactly enclose the world-class Carlin gold province (Fig. 5). The Grouse Creek Block is inferred by Whitmeyer and Karlstrom (2007) to represent an older core, flanked by younger Proterozoic-aged domains. These relationships are supportive of the importance of a long paleo-history of subduction. Supporting evidence for a link between multiple subduction events and gold metallogenic fertility is also provided by the Phanerozoic western Pacific margin. Solomon (1990) was the first to point out an empirical association in the SW Pacific between gold-fertility and subduction from more than one direction under the same lithospheric block. Nokleberg (2005) inferred three different directions of subduction beneath the Kolyma-Omolon block in the Jurassic, prior to the major Cretaceous period of gold metallogeny in the region, which was strongly concentrated around the margins of this block.

One important metallogenic implication of the recent advances made in understanding the architecture of accretionary orogens is that extensional processes may result in fragments of ancient continental lithospheric mantle, with potentially a long history of paleo-subduction fertilisation, being locally present within orogens but totally overlain by much younger, syn-orogenic cycle rocks. The margins of these underlying lithospheric blocks may be somewhat cryptic in near-surface geological patterns, but may be metallogenically important, controlling the location of gold deposits which form during the younger orogenic cycle. A good example of this is provided by the giant Bendigo and Ballarat orogenic gold deposits within the Paleozoic Western Lachlan Fold Block of Victoria. These deposits are located above the inferred margins of the Selwyn Block, an underlying older basement domain that occurs locally within the orogen (Miller et al. 2006; Cayley et al. 2011).

Transient remobilisation event

The second essential element in the unified model is the requirement for a transient remobilisation event which remobilises gold-enriched magmas and/or fluids from the upper mantle via selective re-melting of enriched domains (e.g., Begg et al. 2004, 2007; Richards 2009). It is critical that this remobilisation process occurs without major dilution by other melts derived from deeper mantle source regions. The agent of this remobilisation in most cases is likely to be more deeply-derived mantle wedge or asthenospheric melts. Critically, the process will be favoured by situations where only relatively small volumes of these deeper melts are produced and they are strongly focused in their passage into the upper crust. This imposes significant constraints on the range of viable geodynamic scenarios for an effective remobilisation event.

During active subduction, the remobilisation process is likely to be favoured by low-angle subduction, which, as discussed above, will be associated with lower volumes of mantle-wedge derived magmas, or the initial stages of a transition from low-angle subduction to slab roll-back, with resultant asthenospheric upwelling, as at the end of the Laramide Orogeny: see discussion above.

Richards (2009) proposed three geodynamic scenarios that might allow the post-subduction remobilisation of previously fertilised and hydrated lithosphere: post-subduction collision; post-subduction lithospheric extension (see Fig. 2); and post-collisional lithospheric mantle delamination. Although his paper was focused on the context of gold-bearing porphyry and epithermal deposits only, there is no reason why these mechanisms should not be more broadly relevant within accretionary orogens. However, a fourth geodynamic scenario not directly related to subduction should be added: the impact of a hot mantle upwelling, possibly related to deep mantle convection processes unrelated to the formation of the convergent margin, on to previously subduction-fertilised lithosphere (e.g., Northern Nevada bonanza epithermal province; Saunders et al. 2008). The requirement that it is necessary to avoid excessive dilution by asthenospheric melts implies a prediction that only the very initial stages of the emplacement of such an upwelling will be prospective, which is what is reflected in the Northern Nevada bonanza epithermal province.

The precise mechanism for remobilisation during post-subduction collision remains unclear. Richards (2009) suggested that lithospheric thickening, followed by thermal rebound, may be the process by which enriched lithospheric domains are remelted and mobilised into the upper crust. An alternative process is that incipient extension occurs within collisional orogens as a consequence of strain heterogeneity during tectonic deformation (e.g. Ratschbacher et al. 1989). In this regard, it is significant that Hill et al. (2002) have shown that the gold-associated syn-orogenic magmas in the New Guinea collisional belt are emplaced along steep-dipping transfer faults and that the age of their emplacement correlates with the in-board progression of the orogenic front. This strongly suggests a much closer, more dynamic relationship between compressional orogenesis and remobilisation of fertile magmas than would be implied by a later thermal-rebound hypothesis.

Compressional orogenesis is also a key geodynamic process in the formation of orogenic gold deposits, all of which are associated with the last phases of orogeny (Groves 1993; Goldfarb et al., 2005). However, because these deposits generally show little or no direct relationship with mantle-derived magmas, the inferred remobilisation process in the context of the model outlined above is less clear.

In some other orogenic gold provinces, there is a clear trend, within the one broad metallogenic event, from early, generally sub-economic gold-enriched alkaline magmatism (± the products of their hybridisation with crustal melts) to later CO_2-rich fluid driven, more economic mineralisation, without any clear links to intrusions. The Laverton District within the Eastern Goldfields province of the Yilgarn Craton of Western Australia is a good example of such a province (Miller et al. 2007, Blewett and Czarnota 2007), as is the Yana-Kolyma orogenic gold belt in North East Russia (Goryachev 2008). In other orogenic gold provinces however (e.g., Sierra Foothills province, California; West Lachlan Fold Belt, Victoria; Macraes Flat district, New Zealand), there is no evidence of any magmatism coeval with the mineralising CO_2-rich fluid event. In these cases, it may be that gold-enriched zones in the upper mantle were remobilised into the crust totally by a CO_2-H_2O fluid, without requiring the agency of a silicate magma. Dasgupta and Hirschmann (2006) have concluded that incipient melting of carbonated upper mantle is likely to produce low volumes of carbonatite melts, which are very strongly enriched in incompatible elements and therefore an abundant source of metasomatic fluids. It is speculated that, at upper mantle conditions, the transition between a CO_2-H_2O fluid and a carbonatite magma may be gradational. The coexistence of carbonatite and late carbonate-chalcopyrite-magnetite veins at Phalabowra (Palabora) in South Africa may be such an example (e.g., Groves and Vielreicher 2001).

Despite the above uncertainties, there is increasing evidence that orogenic Au deposits are an integral part of the spectrum of accretionary orogen gold metallogeny and subject to the same general large-scale controls. For example, the major orogenic gold deposits of the West Lachlan Fold Belt, which have no recognised magmatic association, still show a similar large-scale lithospheric architectural context: that is, proximity to old cratonic margins and/or the margins of buried old lithospheric blocks (Miller et al. 2006) to other gold deposit types with a clearer magmatic association. Furthermore, these deposits formed at exactly the same time (440 Ma) as world-class porphyry Cu-Au deposits (e.g., Cadia) developed in the eastern part of the belt (Squire and Miller 2003). This implies that the same geodynamic event produced porphyry-type deposits proximal to the subduction zone position at that time and, simultaneously, orogenic Au deposits in a more distal position, within an inverted pericontinental basin (Squire and Miller 2003). The remobilisation of fertile lithosphere in two widely separated settings by a single transient compressional orogenic event seems a likely explanatory hypothesis. Further evidence for a link between orogenic and magmatic deposit classes is provided by the giant, gold-enriched super-province in the western USA recognised by Sillitoe (2008), which includes both types.

Lithosphere-scale structures

The third essential element in the unified model is the requirement for the presence of lithosphere-scale structures, which are vital to allow the focused transport of fertile magmas/fluids to the upper crust. It has long been realised that most significant mineral deposits in convergent margin settings are closely associated with crustal to lithosphere-scale structures and, in particular, the intersection of orogen-parallel structures of this type with transfer or accommodation structures at a high-angle to the orogen trend (e.g., Billingsley and Locke 1935, 1941; O'Driscoll 1986; Richards 2000; Richards et al. 2001). Such intersection zones are likely to provide a highly permeable pipe-like connection between the mantle and the upper crust. Both sets of structures can commonly be demonstrated to have had a long prehistory and to have propagated from major older structures in the adjacent continental basement, or to be parallel to such structures (e.g., Padilla et al. 2001; Crafford and Grauch 2002; Grauch et al. 2003). Similar fundamental structural controls apply to all deposit types because they require the common process of a concentration of advective fluid and/or magma flux.

As discussed above, extensional processes during accretionary orogen development can result in a basement of older lithospheric mantle $\pm$ lower crust underlying much younger rocks. This provides a mechanism by which older lithospheric-scale structures on the retro-arc side of the orogen can be extended laterally and vertically into younger syn-orogenic cycle rocks through growth and reactivation, and negates previous criticisms concerning the erection of crustal-scale lineaments that cross time boundaries (e.g., O'Driscoll 1986).

Methodology for application to regional targeting

Based on the concepts discussed above, it is possible to develop a systematic methodology for regional -scale gold metallogenic analysis and targeting in convergent margin orogens. The key steps in this methodology are:

1) Define the underlying lithospheric architecture: This is the first-order regional control on gold metallogeny within any convergent margin orogen and provides the basic underlying framework for the analysis. In many cases, this architecture will be cryptic in existing geological mapping. Defining it requires the integration and synthesis of available geophysical and geological datasets with an emphasis on those features likely to be proxies for basement architecture. Patterns in structural data (such as platform- rift transitions), the spatial distribution of mantle-derived magmatic products, gravity data and high resolution seismic tomography are particularly useful.

2) Identify the major metallogenic events in space and time: In most regions, an apparent confusing plethora of mineralisation events and styles can usually be reduced to a small number of major events, which significantly aids the development of metallogenic understanding. Mapping out the spatial distribution of intrusions in time and space is an important component of this process.

3) Relate each metallogenic event to the underlying lithospheric architectural framework: The endowment within any major metallogenic event is invariably extremely heterogeneous in spatial distribution. It is the collective experience that this endowment heterogeneity can be empirically related at the regional scale to patterns in the lithospheric architecture (e.g., see Fig. 5). In the future, it is hoped that it will be possible to develop techniques to map, either directly or via proxy, zones of fertilised upper mantle, independent of the known distribution of gold deposits.

4) Delineate gold provinces: These are defined on the basis of the above relationships to delineate areas of broadly uniform mineralisation potential at the regional scale. It is important to note, however, that at a more detailed scale within a province, endowment potential can be related to proximity to fundamental, orogen-parallel, trans-lithospheric structural corridors, and in particular areas where they intersect similar-scale, approximately orthogonal transfer structures.

5) Identify camp-scale targets: These are defined based on positions where there is coincidence between areas of major trans-lithospheric structural-corridor intersection with other targeting elements of relevance to the gold deposit sub-type being targeted. For example, in the case of orogenic gold deposits, major antiformal culminations are a very important targeting ingredient. In the case of magmatic deposit types, areas of focused magma emplacement, particularly with multiple types of differentiated magmatic rocks, are important. For all deposit types, clusters of alkaline, mantle-derived intrusions are an important targeting ingredient, irrespective of their direct relationship with ore-formation, as they indicate well-developed lithosphere-scale permeability.

Conclusions

Successful exploration for the next generation of major gold deposits is likely to require a greater emphasis on covered terranes. Therefore, regional-scale predictive targeting capability will become more important than in the past, when empirical exploration methods dominated. Such predictive capability cannot be derived from knowledge of deposit scale geology and rather requires the development of a generic, regional-scale understanding of the patterns of gold metallogeny and their controls.

This paper argues that the critical fundamental control on gold metallogeny is the presence of a gold-enriched upper mantle region. There are a number of lines of evidence in support of this hypothesis which are summarised above. The fundamental enrichment process is considered to be the progressive transfer of gold, which behaves as an incompatible element in this setting, in low-degree partial melts from the convecting mantle wedge to the non-convecting upper lithospheric mantle, where it can become concentrated over geological time. This concept allows the unification of the genetic models for all gold deposits within accretionary orogens into a simple framework where the formation of a major gold deposit of any type requires the conjunction in time and space of three essential factors: a fertile upper-mantle source region, a favourable transient remobilisation event and favourable lithospheric-scale structure. Based on this concept, it is possible to apply a practical regional-scale targeting methodology.

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Figures

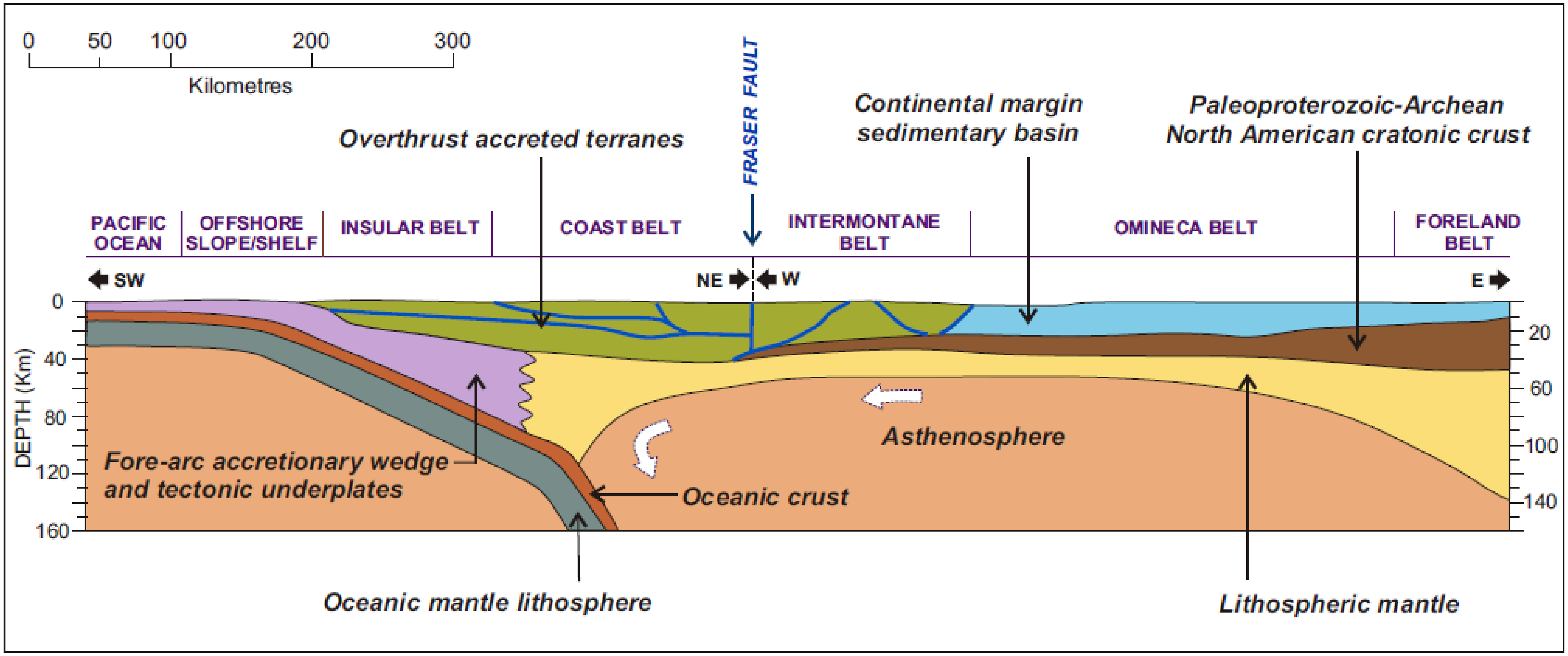

Figure 1: Simplified section through the Canadian Cordillera based on LITHOPROBE data (modified from Clowes et al. 1995). The Canadian Cordillera represents a good example of an accretionary orogen. The critical observation is that the accretionary terranes of the Cordillera are underlain by attenuated older continental lithosphere.

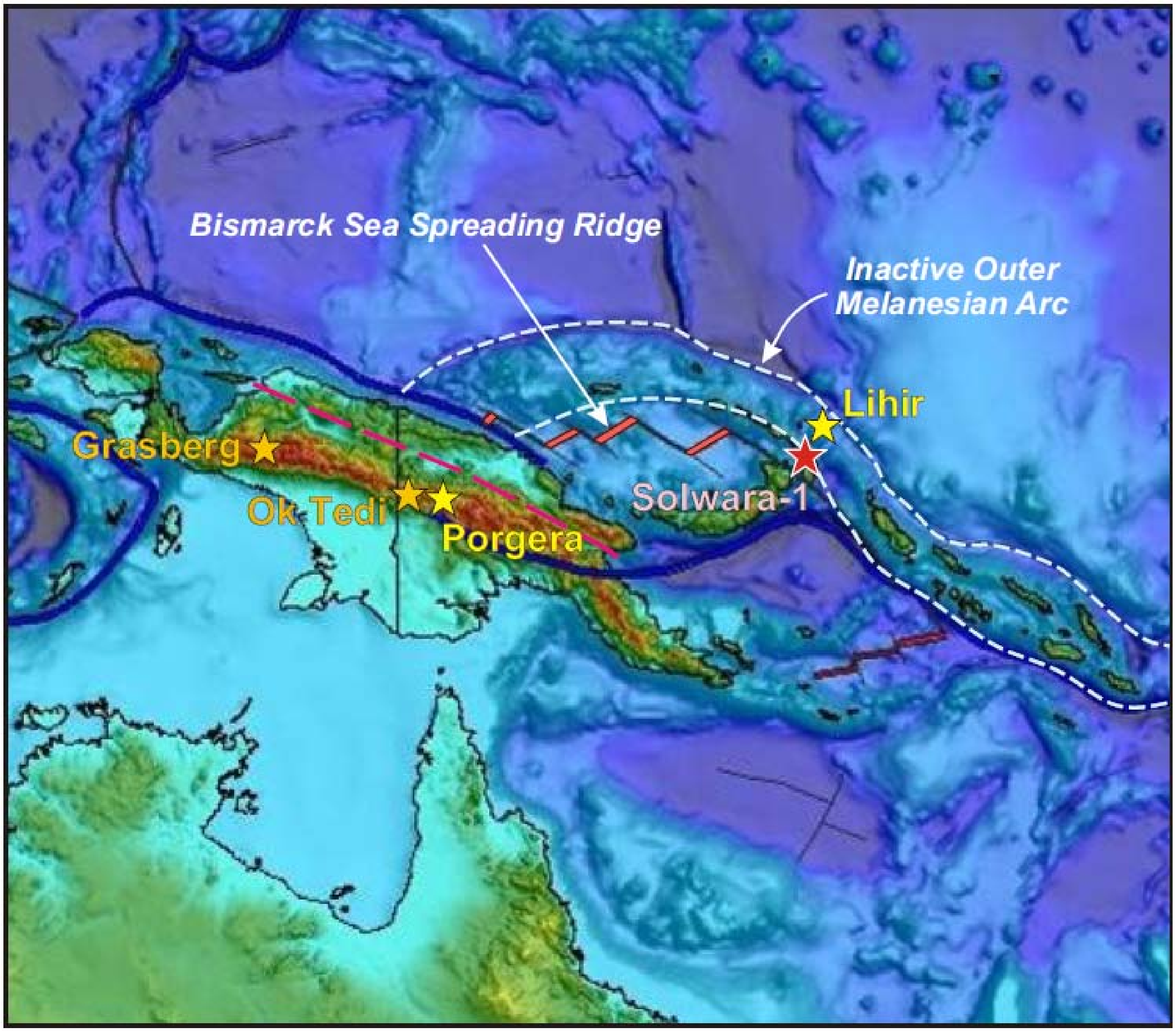

Figure 2: Location of the modern gold-rich sea-floor VMS deposit, Solwara-1 where the Bismarck Sea Back-arc spreading centre propagates into the position of the now extinct Outer Melanesian Arc. Solwara-1 is located relatively close to Quaternary-aged Lihir alkalic-intrusion associated epithermal Au deposit, the emplacement of which is also considered by Carman (2003) to relate to incipient extension related to Bismarck Sea spreading. Significantly, both these deposits, although of completely different deposit type, are associated with the same broad geodynamic context and are both plausibly associated with the remobilisation of components from the previously fertilised mantle lithosphere beneath the Outer Melanesian Arc.

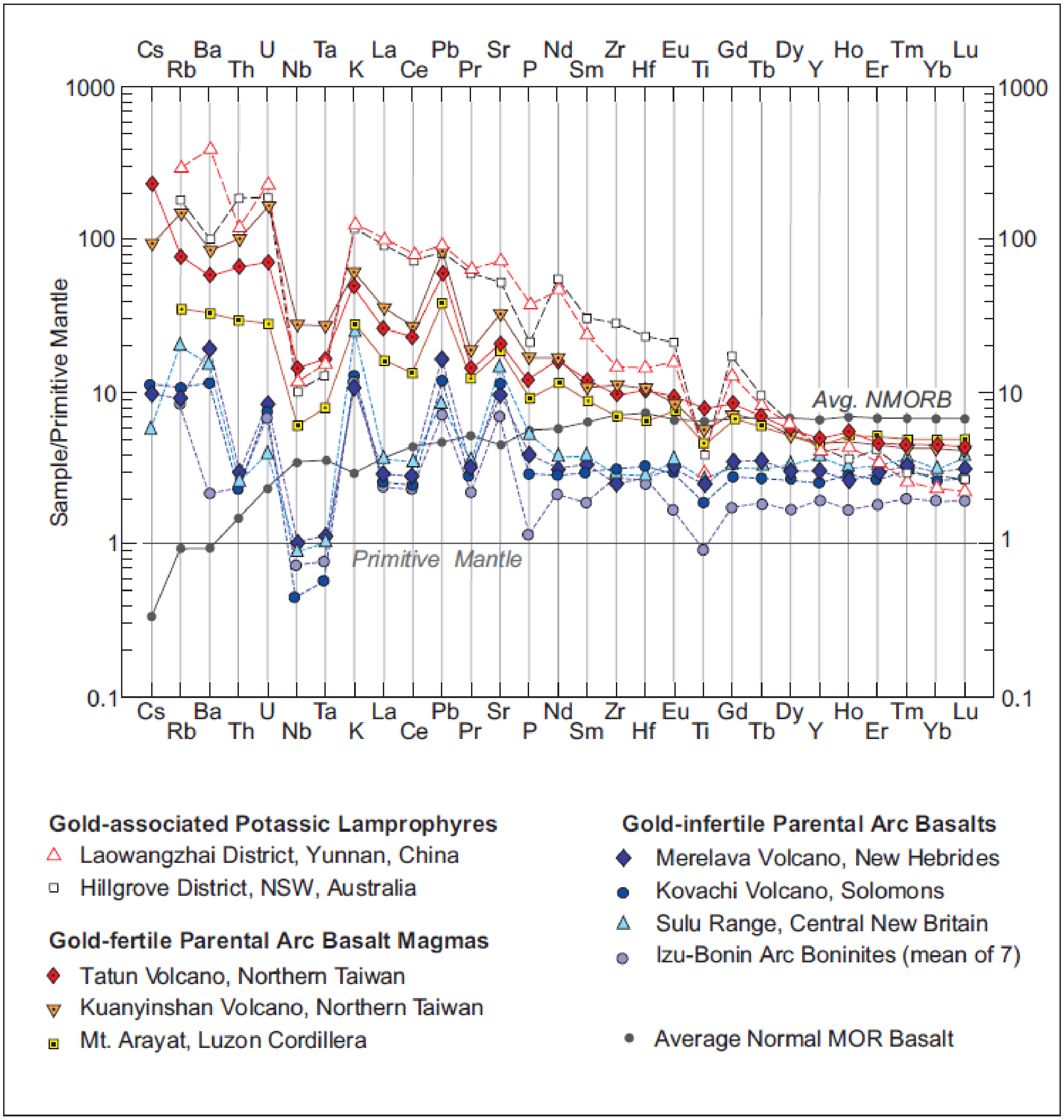

Figure 3: Incompatible, lithophile trace-element geochemistry for relatively primitive Quaternary arc basalts, comparing samples from arc segments lacking known gold mineralisation with samples closely associated with Quaternary magmatic-hydrothermal gold deposits. The plot also shows data from two sets of lamprophyres of Eocene and Permian age closely associated with gold mineralisation. Data and sources are listed in Table 2. First presented in Loucks and Ballard (2003).

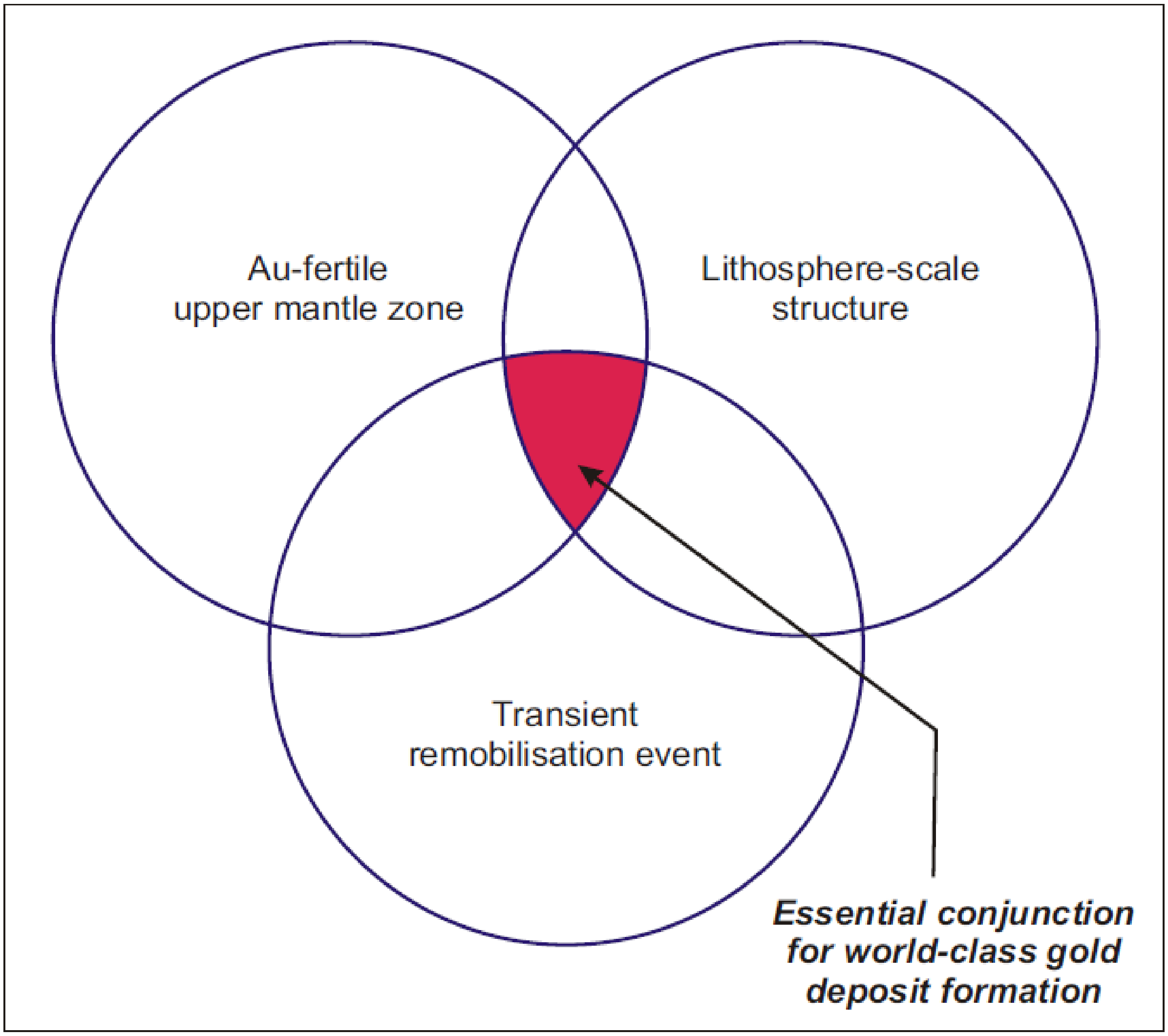

Figure 4: Schematic illustration of the conjunction of three independent parameters required to form a world-class gold deposit (of any deposit type) within an accretionary orogen

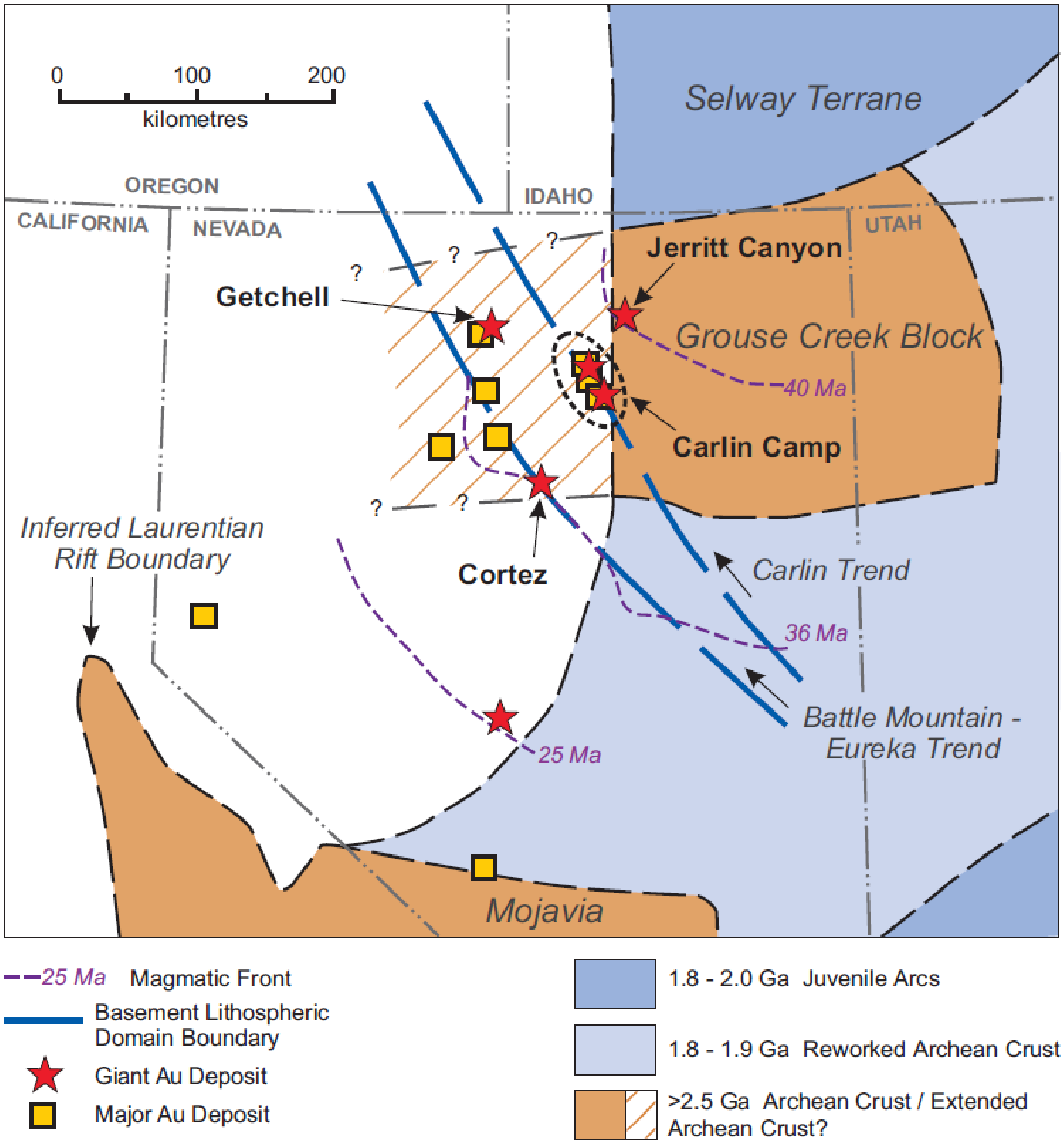

Figure 5: A diagrammatic summary of the first-order elements which control the highly-endowed Northern Nevada gold province, modified after Whitmeyer and Karlstrom (2007) and Muntean et al. (2011). This is a real example that illustrates the conjunction of the three fundamental parameters proposed in the paper to form a giant gold province. The close spatial association of large gold deposits with the extrapolated extent of the Archean Grouse Creek Block into the extended margin of Laurentia suggests pre-fertilisation of the old lithosphere underlying this block was a critical factor. The strong spatial association of large deposits with the Carlin and Battle Mountain-Eureka trends reflects the requirement for proximity to major, trans-lithospheric structures (e.g., Grauch et al. 2003). These deposits also show a close association in time with the position of mid-Tertiary magmatic fronts which progressively retreated south-westward at that time, reflecting slab roll-back at the end of the Laramide Orogeny. This is considered to represent the favourable transient remobilisation event required in the unified model. For example (as summarised by Muntean et al, 2011), the age of magmatism at Jerritt Canyon is 39-42Ma and mineralisation is < 41Ma; at the Carlin camp, both magmatism and mineralisation occur at 37-41 Ma; at Getchell mineralisation occurs at 37-42Ma; and at Cortez, magmatism occurs at 33-36 Ma and mineralisation at 34-35 Ma.

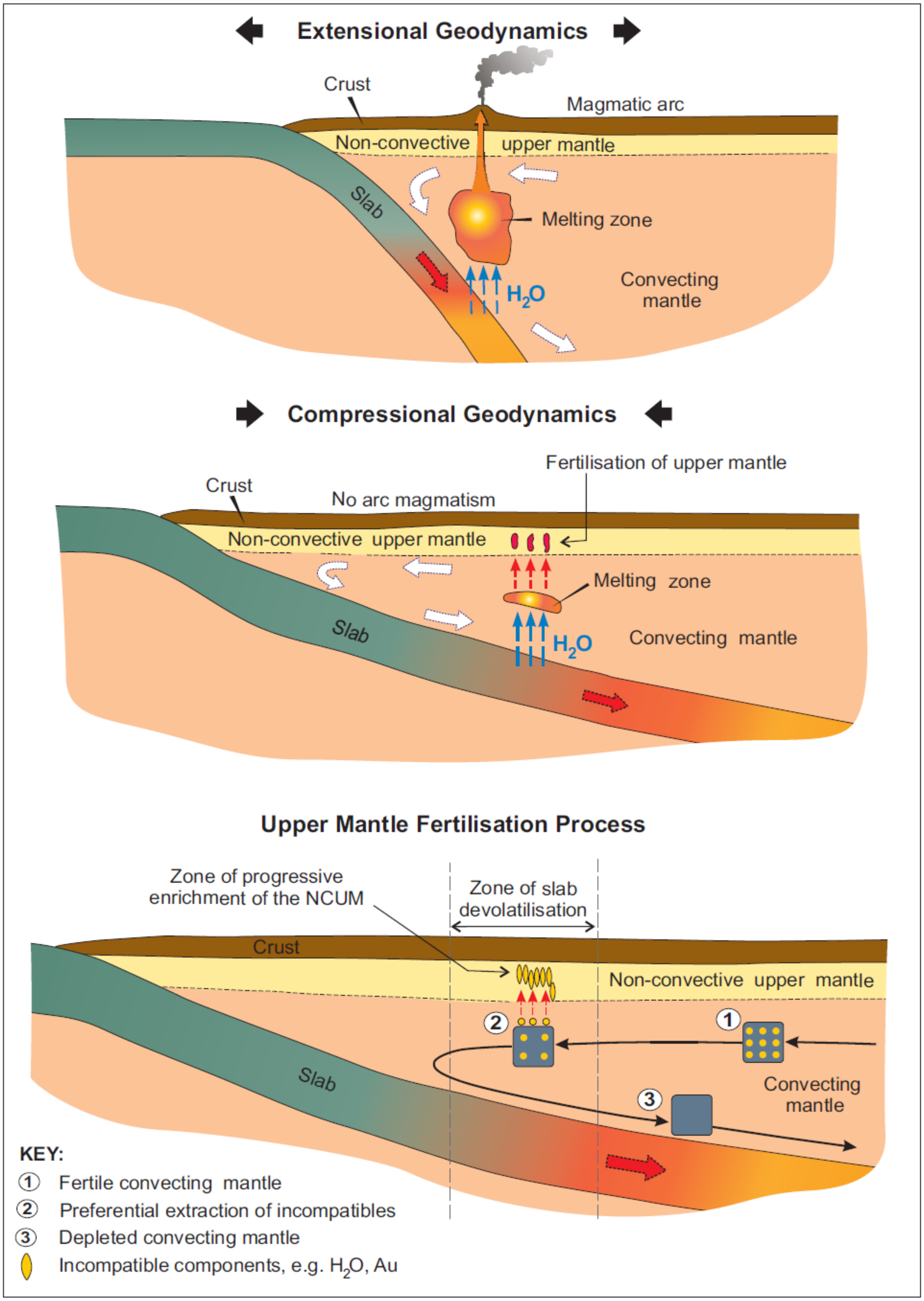

Figure 6: A diagrammatic summary of the conceptual model proposed in this paper for the supra-subduction associated gold fertilisation of lithospheric upper mantle.

Tables

Table 1: Diversity of Accretionary Orogen Au (± Base Metal) Metallogeny
A summary of the major metallogenically important tectono-magmatic settings within accretionary orogens and their associated deposit types.

Major Tectono-magmatic Setting	Deposit Types	Specific Favourable Geodynamic Regimes	Comments	Major Examples
1. Active Subduction-Related Arc Magmatism	Porphyry and related deposits (e.g., High-Sulfidation Epithermal Au deposits)	• Transient anomalous compression • Transition from flat-slab compression to extensional slab roll back	Diversity of deposits depending on proximal – distal spatial relationship with magmatic centre	Tampakan Bingham Canyon Carlin? Grasberg
2. Superimposed Rifting	Alkalic Intrusion Low-Sulfidation Epithermal Au; Bimodal Rift-Associated Low-Sulfidation Epithermal Au; VMS and VMS-epithermal hybrids	• Incipient extension associated with slab roll-back ,either in the arc or back-arc position • Local extension within a collisional setting	Deposit type strongly dependent on degree of extension/water depth at time of mineralisation	Ladolam,Lihir Cripple Creek Porgera Henty Eskay Creek
3. Inversion of Retro-Arc Pericontinental Rifts	IRG and Orogenic Au deposits	• Terminal stage of collisional inversion • Minor post-orogenic extension	Significant crustal magmatic contribution in this setting (a petrogenetically fertile environment) dominates mantle-derived component	Donlin Creek Kalgoorlie Muruntau Ashanti Bendigo
4. Superimposed Impingement of a Hot Mantle Upwelling	Olympic Dam-type IOCG deposits Sleeper-style Low-Sulfidation Epithermal deposits	• Initial stages of hotspot impact on crust	Mineralisation may occur >100s my after cessation of active local subduction	Olympic Dam Sleeper

Locality Sample[Ref]	NMORB Global Average[1]	Izu-Bonin Boninites Avg of 7[2]	Merelava Vanuatu MLM7[3]	Sulu Range New Britain 3039B[4]	Kavachi Solomons KK4342[5]	Tutun TaiwanA-129[6]	Kuanyinshan TaiwanK-64[6]	Mt. Arayat Luzon AY55[7]	Laowangzhai China YK-1[8]	Hillgrove Australia R64067[9]
SiO_2	50.45	52.67	51.37	55	52.52	49.27	50.42	49.29	51.81	56.7
Al_2O_3	15.26	13.04	12.63	15.7	15.83	17.38	14.85	14.58	13.69	13.17
FeOt	10.43	7.55	8.30	8.20	7.93	8.58	7.50	9.75	6.33	5.20
MnO	-	0.15	0.16	0.16	0.16	0.17	0.15	0.19	0.12	0.08
MgO	7.58	13.06	11.65	7.05	7.90	5.95	8.40	9.07	10.87	7.16
CaO	11.30	8.24	12.36	10.00	11.25	10.64	10.43	12.46	9.25	5.93
Na_2O	2.68	1.61	1.68	2.10	2.13	2.23	2.17	2.23	1.53	2.72
P	0.051	0.010	0.035	0.026	0.048	0.109	0.148	0.083	0.336	0.205
K	0.070	0.290	0.290	0.299	0.614	1.179	1.428	0.664	2.947	3.055
Ti	0.760	0.111	0.300	0.228	0.348	0.923	0.642	0.576	0.348	0.504
Rb	0.56	5.12	5.3	6.2	12.4	45.3	85.2	21.0	177	117
Ba	6.3	14.0	126	75	103	388	539	216	2547	692
Nb	2.33	0.467	0.680	0.302	0.600	9.44	17.80	4.00	7.68	7.00
Sr	90	134	203	225	304	404	630	381	1459	1097
Zr	74	28	25	32	32	103	113	75	154	315
La	2.50	1.83	1.91	1.67	2.47	16.8	22.5	10.4	63.9	63.0
Ce	7.50	4.15	4.50	4.19	5.82	37.5	43.0	22.4	133.9	134.0
Pr	1.32	0.54	0.72	0.69	0.89	-	-	3.13	15.7	17.0
Nd	7.30	2.64	3.85	3.58	4.84	20.6	20.3	14.7	59.0	73.0
Sm	2.63	0.75	1.43	1.18	1.60	4.66	4.14	3.64	9.95	13.00
Eu	1.02	0.26	0.48	0.45	0.57	1.44	1.26	1.22	2.45	3.50
Gd	3.68	0.94	1.82	1.53	1.92	4.52	3.87	3.80	6.93	9.80
Tb	0.67	0.18	0.35	0.27	0.34	0.68	0.59	0.62	0.81	1.00
Dy	4.55	1.14	2.04	1.82	2.33	3.86	3.48	3.77	3.87	4.40
Ho	1.01	0.25	0.40	0.41	0.51	0.80	0.71	0.79	0.66	0.60
Er	2.97	0.78	1.30	1.18	1.46	2.23	1.99	2.29	1.49	2.00
Tm	0.46	0.13	0.22	-	0.26	0.32	0.30	0.33	0.18	0.20
Yb	3.05	0.86	1.38	1.19	1.44	1.96	1.89	2.15	1.06	1.40
Lu	0.46	0.13	0.21	0.18	0.27	0.30	0.29	0.33	0.15	0.20
Y	28	8.4	12.9	11	17	21.2	20.7	19	17.8	19
Sc	41	29	47	37	34	34	49	45	28	15
Ni	150	230	118	44	73	23	94	73	279	195
Cu	75	63	99	95	131	93	92	-	22	53
Pb	0.70	1.06	2.47	1.77	1.30	8.87	12.1	-	-	14
Cs	0.007	-	0.21	0.22	0.12	4.85	1.95	-	-	-
Th	0.12	0.185	0.23	0.18	0.23	5.26	7.9	2.37	9.83	16
U	0.047	0.152	0.17	0.15	0.08	1.42	3.39	0.58	4.61	4
Ta	0.132	0.028	0.042	0.021	0.04	0.60	0.99	-	0.58	-
Hf	2.05	0.78	0.79	0.89	0.86	2.93	2.90	1.89	3.97	-

Table 2: List of data for Figure 2; all major element oxides as per cent, all other data in ppm

First presented in Loucks and Ballard (2003). Data sources: 1. Sun and McDonough (1989) for minor and trace elements, Hoffmann (1988) for major element oxides, 2. Arculus et al. (1992), Pearce et al. (1992), 3. Peate et al. (1997), 4. Woodhead et al.(1998), 5. Johnson et al. (1987), 6. Wang et al. (1999), 7. Bau and Knittel (1993), 8. Huang et al. (2002), 9. Ashley et al. (1994).