

# Evaluating the role of the mantle as a source of metals for magmatic-hydrothermal ores in arc systems

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**Abstract.** This communication reviews geochemical data on the sub-arc mantle underlying ore-productive arc crust. We highlight that re-fertilization of the subcontinental lithospheric mantle by subduction-related fluids might be a key factor in forming metal-rich domains that contribute to the formation of parental magmas able to generate large metallogenic provinces in the Earth's crust. As noted in several other previous works, the optimal alignment of factors to produce these types of deposits embraces three common features: a mantle source region that has been previously enriched in metals (e.g., Au and Cu), trans-lithospheric faults and a tectonic, possible thermal trigger. The results and interpretations we provide here are a complementary view to current crust-related enrichment models.

## 1 Introduction

Our current view of the Earth's interior dynamics envisions repeated cycles of melt extraction from a convecting fertile mantle, producing a mafic crust (which could differentiate to form continental crust) and a complementary residual depleted mantle (DM). Each crust-formation/depletion episode is followed by a period of recycling, during which the mafic crust is partially or totally mixed back into the convecting mantle or stored deep in the Earth. This scenario, usually taking place during an orogeny, is very favorable for the chemical exchange between different Earth's layers, and therefore for the formation of large ore deposits. These deposits host some of the major mineral wealth in the Earth and provide the largest world resources of copper and gold, plus a significant source of other base (zinc, lead, iron, silver) and critical metals hosted in different styles of the mineralization.

Geoscientists have turned to a number of proxies in an

effort to answer questions such as: when did recycling start, did these cycles operate continually or episodically through time, and how efficient is the convective recycling, particularly at the time to generate those metal-enriched melts. Most of the proxies involved the chemical and isotopic analysis of the ore deposits. However, this only provides an indirect view on the foundational controls able to generate these metal-rich magmas in the convecting mantle. Indeed, the best approach is to study samples representative of the mantle. These samples are nowadays accessible in tectonically uplifted slices and in xenoliths from volcanic rocks.

Perhaps, the highly siderophile elements (including PGE and Au) are the most robust of the geochemical proxies for the study of these metal-rich magmas in the upper mantle. These highly siderophile elements (HSE) have stronger affinity for metal than the chalcophile Se, S, Te and Cu [Luguet and Reisberg 2016]. In the Earth's mantle they are mainly hosted within accessory base-metal minerals (BMM, including sulfides, arsenides and sulfarsenides; [Luguet and Reisberg 2016]) and refractory platinum-group minerals (PGM; [O'Driscoll and González-Jiménez 2016]). Magmatic processes such as partial melting, crystallisation and melt-rock interaction can strongly fractionate HSE, S, Se, Te and Cu. As a result of moderate degrees of mantle melting, the most refractory PGE (IPGE: Os, Ir, Ru) behave as compatible elements, while the less refractory PGE (PPGE: Pt and Pd), Au, Re, S, Se, Te and Cu are more incompatible [Luguet and Reisberg 2016]. Hence, the HSE and chalcophile elements can be used along with lithophile elements to unravel the multistage magmatic history of a mantle domain, and therefore mechanism of mass transference of metals between the different layers of the Earth.

Of particular interest is the potential use of the PGE

and Au as tracers of mantle processes able to generate metal-rich magmas that are eventually involved in the ore forming magmatic-hydrothermal systems in the arc crust. It is well accepted that in arc settings, the oxidation state of primitive melts is directly correlated with the amount of fluids released from the dehydration of the subducting slab (Kelley and Cottrell 2009). At fO<sub>2</sub> conditions typical of an oxidized mantle wedge (FMQ+1 to +3), the dominant sulfur species is S<sup>+6</sup>, and thus sulfur solubility increases significantly from typical mantle concentrations of ~200 ppm (at FMQ<1) to S contents in excess of 1 wt% (Jugo et al. 2010). Empirical and experimental works indicate that S is supplied to the migrating hydrous-oxidizing silicate melts after the removal or pre-existing trace sulfides resident in the peridotites (Hattori et al. 2002). As noted above, these sulfides, together less abundant alloy phases, control the budget of metals such as Au and Cu in the mantle (Luguet and Reisberg 2016). Therefore, the degree of enrichment of metals in S-rich melts in the mantle is associated with the degree of partial melting of the mantle source and its previous history of depletion or re-fertilization. In particular, regional-scale re-fertilization processes by oxidizing subduction-related fluids may have enhance dissolution of sulfides at deep mantle sources and their later precipitation along sizeable (> 100 km) domains at shallower upper mantle. These metasomatic sulfides can be significantly charged in Au, Cu, Co, and other incompatible chalcophile elements (e.g., Wang et al. 2009; Lorand et al. 2013; Hughes et al. 2017; Tassara et al. 2017, 2018).

## **2 Transfer of metals from subducting slabs to sub-arc mantle**

### **2.1 Dehydration of subduction channel serpentinites**

Subduction zones not only return oceanic lithosphere into the mantle but are also sites where water and other components are transferred from the subducting plate back to the lower/upper crust. During subduction, downgoing oceanic crust that has an important volume of sediments may dehydrate releasing hydrothermal fluids enriched in fluid-mobile elements (e.g., As, Sb, Cs, Pb, Li or Ba). The main dewatering takes place at temperatures between 300 and 600 °C and pressures lower than 15 kb. The upward percolation of these fluids may induce hydration of the overlying peridotite wedge beneath the crust of continental or oceanic arcs. Hydration may produce the partial or total transformation of the peridotite to serpentinites, which act as sponges for a wide suite of elements such as semi-metals (As, Sb, Se), and base (Fe, Zn, Cu) and precious metals (Au, Pd, Pt). The study of some subduction channel serpentinites seems to indicate that anomalously high contents of metals are directly associated with the formation of Ni-As-Sb-S rich minerals, including sulfides, arsenides and sulfarsenides. Particular enrichment of these minerals is observed in serpentinite shear zones, which are interpreted as as a preferential pathway for fluid movement [González-Jiménez et al. 2016].

Continued movement downward of the already hydrated sub-arc lithosphere promotes burial of these serpentinites while they are progressively heated (i.e., prograde metamorphism). As result minerals carrying the metals are destabilized while liberating metal-lead fluids that infiltrate deeper regions of the sub-arc mantle. The subduction channel serpentinite from the Cerro del Almirez in south Spain are good examples of this process of dehydration involving the releasing of metal-rich fluids. Here, antigorite serpentinites of oceanic origin are dehydrated to secondary chlorite harzburgite and both these rock-types crop out in the massif. This is the unique example in the world where the isograde of antigorite breakdown crops out in the Earth's surface. Our systematic study of the bulk-rock abundances of highly siderophile elements (Ir, Ru, Rh, Pt, Pd, Au) in these rocks show significant partitioning of gold towards the fluids released by the dehydration of serpentinites, confirming previous observations subduction-related melts may promote Au enrichment of specific portion of upper mantle (Saunders et al. 2018). Interestingly, the crustal section overlying this portion of mantle infiltrated by these subduction-related fluids charged in Au and other noble metals contain various districts of Au-Ag epithermal deposits.

### **2.2 Mobility of metal-rich serpentinite-related fluids within the sub-arc mantle**

As associated with corner flow may produce the downward movement of the hydrated sub-arc peridotitic rocks. Once heated, these rocks may release fluids enriched in metals. The upward percolation of these fluids through the overlying mantle wedge may produce metasomatism while dissolving pre-existing metal-rich minerals. For example, Hattori et al. (2002) noted that sulfides in peridotite mantle xenoliths that sampled the sub-arc mantle from the Ichinomegata in Japan and Nunivak Island in Alaska have lower contents of As and Sb than sulfides from the primitive mantle. Hattori and co-workers concluded that these lower contents of As and Sb reflect the removal of metasomatic sulfides residing in the mantle during partial melting, consistently with high values in some mantle wedge xenoliths attributed to fluid transport of these elements during mantle metasomatism. Lower contents of As and Sb may also reflect a quick transference of elements by aqueous fluids from the subducting slab/mantle wedge serpentinite to arc magmas without residing long in the mantle. These authors also noted that high abundances of As, Sb and S in arc magmas generally could reflect their enrichment in mantle wedges, although they did not find any evidence of such enrichment in mantle wedges. This suggests that these semimetals were removed from mantle wedges by hydrated arc magmas.

## **3 The metasomatized mantle as a source for the parental melts of Au-rich magmatic-hydrothermal deposits**

### 3.1 Porphyry copper deposits (PCD)

The infiltration of these metal-rich fluids through specific regions of the sub-arc mantle may not only produce dissolution of pre-existing metal-bearing minerals but also deposition of assemblages, giving rise to metal-ferile domains. The size of these domains may range from microns to terranes and are relatively durable until the metal-rich minerals are removed, thus contributing to the formation of metal-rich magmas (e.g., Griffin et al. 2013).

Mantle xenoliths rapidly brought to the surface by volcanism have provided valuable information about the nature and evolution of this type of processes, particularly in those sections of the upper mantle beneath arc crusts hosting Au-rich porphyry and epithermal deposits. For example, xenoliths of arc-related mantle from near the giant Lihir gold deposit in Melanesia show metasomatic enrichment in Cu and Au. McInnes et al. (1999) reported that the Au ores of this deposit exhibit Os isotopic compositions identical to the metal-enriched peridotite xenoliths. Furthermore, there is a direct relationship between high Cu tonnages in Chilean PCD and their low initial Os ratios (Mathur et al. 2000), suggesting the input of mantle-derived melt. Similarly, xenoliths that have sampled the SCLM beneath the edge of the South China Craton also exhibit anomalously high values of Au in whole rock (14 ppb) and sulfide minerals (5 ppm). These values of gold in the SCLM beneath ore productive crusts are relatively higher than those of both the asthenosphere (about 1 ppb Au) and the non-re-fertilized lithospheric mantle [Griffin et al. 2013 and references therein]. Additionally, Hanley et al. (2010) have documented PGE incorporation into pyrite coincident with Co-Ni enrichment during high-temperature hydrothermal events pre-dating Cu and Au precipitation in porphyry deposits from British Columbia. The formation of these ore deposits is linked with alkaline arc magmas derived probably from an enriched (metasomatized) mantle source.

The enrichment in gold (and other noble and base metals such as PGE and Cu) observed in the SCLM underlying arc crusts hosting PCD could be associated with preferential channeling of primitive mantle melts through zones of weakness that exist between buoyant domains of ancient SCLM [c.f. association of Ni-Cu-PGE deposits with craton margins (Begg et al. 2010, 2017)]. Such enrichment in metals in the SCLM beneath ore-productive crust seems to be associated with modal metasomatism due to migration of melts at decreasing melt-rock ratios, which may result in the modification of the bulk PGE and Au contents of the peridotite via the precipitation/dissolution of PGE- and Au-bearing Ni-Cu-rich sulfides and/or Pt-Pd rich PGMs. The domains of the SCLM enriched in these precious metals may range from microns to kilometers and the mobility of the precious metals can take place in the form of sulfide melts [Tassara et al. 2018], solid metal alloys [O'Driscoll and González-Jiménez 2016] or (supercritical) oxidizing, volatile-rich (C-O-H-S±Cl) fluids of carbonatite-like affinity [Hughes et al. 2017; Tassara et al. 2018]. Griffin et al. (2013) have suggested that such domains of metasomatized SCLM are relatively durable and may

store metals (e.g., Cu and Au) until a later melting event is triggered, leading to episodic formation of ore deposit. Repeated events of melt migration during one or more orogenic cycles may promote multiple episodes of mineralization in the overlying crust.

### 3.2 Epithermal Au± Ag deposits

The ultramafic xenoliths hosted in the alkali basalts from volcanic fields in the back-arc of the Andes and the neighboring Patagonian realm (i.e., Deseado and North Patagonian Massifs) preserve the record of a protracted history of melt depletion and re-fertilization of the SCLM beneath South America. The styles of metasomatism include silicate, silicate-carbonatite and pure carbonatite-like affinities, which have been in some cases attributed to dehydration of subducting slabs. The recent work by Tassara et al. (2017) has revealed the presence of gold minerals in the portion of SCLM beneath the auriferous province of the Desado Massif in the Argentinian Patagonia. This area hosts several Au–Ag epithermal deposits including low and intermediate sulfidation veins associated with calc-alkaline rhyolites, basaltic andesites and basalts from the Chon Aike silicic large igneous province (CA-SLIP) related with the break-up of Gondwana and the subsequent separation of South America and Africa. These results provide the first evidence that link the formation of Au-epithermal deposits in the crust with a mantle source enriched in Au. Tassara and co-workers have suggested that a precursor stage of mantle re-fertilization by plume-derived melts generated a gold-rich mantle source during the Early Jurassic when the aperture of the Atlantic sea separated South American from Africa. The interplay of the enriched mantle domain and subduction-related fluids released during the Middle-Late Jurassic resulted in optimal conditions to produce the ore-forming magmas.

Our preliminary results on the study of mantle xenoliths that have sampled the SCLM beneath the Mesa Central in Mexico also show the presence of several nano-to-micron size particles of gold in metasomatic glasses. This volume of the SCLM enriched in gold is also underlying a back-arc crust with epithermal Au deposits. In this case, metasomatism of the SCLM is related with the infiltration of dehydration fluids released from the subducting Pacific plate.

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