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Origin of selective enrichment of Cu and Au in sulfide deposits formed at immature back-arc ridges: Examples from the Lau and Manus basins

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ABSTRACT

It has long been recognized that magmatic fluids exsolved from the arc-like submarine magmas of immature back-arc basins can directly contribute metals such as Cu and Au to seafloor hydrothermal systems. The extent of this magmatic contribution, however, varies from basin to basin. In order to explain this variation, we make a comparative study of the behavior of Cu during magma differentiation in two immature back-arc ridges: Eastern Ridge (ER) of the Manus Basin and Valu Fa Ridge (VFR) of the Lau Basin. We investigate some of the factors that affect Cu behavior, including oxygen fugacity (fO_2), water content, and crystallization pressure, by means of a geochemical model. Cu abundances show a continuous decreasing trend with magma evolution in the VFR lavas, whereas in the ER lavas Cu increases during the early stage of magma evolution, followed by a rapid decrease. The contrasting Cu behavior for the two lava suites is controlled on the first order by the fO_2 of their primary magmas. The fO_2 values of the primary ER magmas were modeled to be FMQ + 1.2 to FMQ + 1.8, which is sufficiently high to avoid the early sulfide saturation that typically accompanies Cu removal. By comparison, the fO_2 values of the primary VFR magmas range from FMQ to FMQ + 1, falling within the range of mid-ocean ridge basalts. We attribute this difference in fO_2 values between the primary ER and VFR magmas to variable input of sediment melt to their mantle sources. In addition, we show for the first time that Cu content does not increase significantly until the onset of plagioclase crystallization. This finding suggests that both high water contents and high pressure, which suppress plagioclase crystallization, are unfavorable for Cu enrichment in evolved oxidized magmas. We argue that back-arc ridges that develop shallow submarine magma chambers and have a large input of subducted sediment, have a strong potential to support ore-bearing magmatic–hydrothermal systems.

1. Introduction

It has long been recognized that the metal contents, especially Cu and Au, of hydrothermal sulfide deposits formed at back-arc ridges are commonly higher than those formed at mid-ocean ridges (Hannington et al., 2005, and references therein). The enhanced Cu and Au contents in sulfide deposits in back-arc settings have been attributed to the direct contribution of metals from magmatic fluids, in addition to those normally leached from the oceanic crust (e.g., Yang and Scott, 1996, 2002; Moss et al., 2001; Kamenetsky et al., 2001; Sun et al., 2004; de Ronde et al., 2011, 2014; Gruen et al., 2014). In fact, this input from magmatic fluids always occurs at immature back-arc ridges, beneath which arc-like magmas that are hydrous and enriched in volatiles are generated due to the strong influence of subduction (Martinez and Taylor, 2002, 2003). However, not all sulfide deposits hosted by arc-like volcanic rocks are associated with Cu and Au enrichment. For example, the Au contents in sulfide deposits from the Southern Lau Basin are within the range of East Pacific Rise (EPR) sulfide deposits, but an order of magnitude lower than those from the Eastern Manus Basin and Izu–Bonin Arc (Fig. 1a, b). Similarly, sulfide deposits of the Eastern Manus Basin are much more enriched in Cu than those of the Southern Lau Basin (Fig. 1c). The reasons behind these differences remain poorly understood.

Immature back-arc basins are typically floored by lavas that have experienced variable extents of magma differentiation (Tatsumi and Eggins, 1995). During magma differentiation, volatiles such as H_2O, CO_2, HCl, and SO_2 are exsolved once they reach saturation, and are then extracted from the magma as vapor fluid during magma degassing (e.g., Kamenetsky et al., 2002). Several lines of evidence show that magmatic fluids can enter the overlying hydrothermal convection system (Yang and Scott, 1996, 2002), including the anomalously low pH values of hydrothermal fluids (Gamo et al., 1997) and the anomalous H–O–S isotopic compositions of hydrothermal sulfides (Herzig et al., 1998; Roberts et al., 2003; Kim et al., 2004; Hou et al., 2005). Higher metal contents in evolved magmas should mean more efficient formation of metal-rich magmatic fluids. The pre-enrichment of metals in magma

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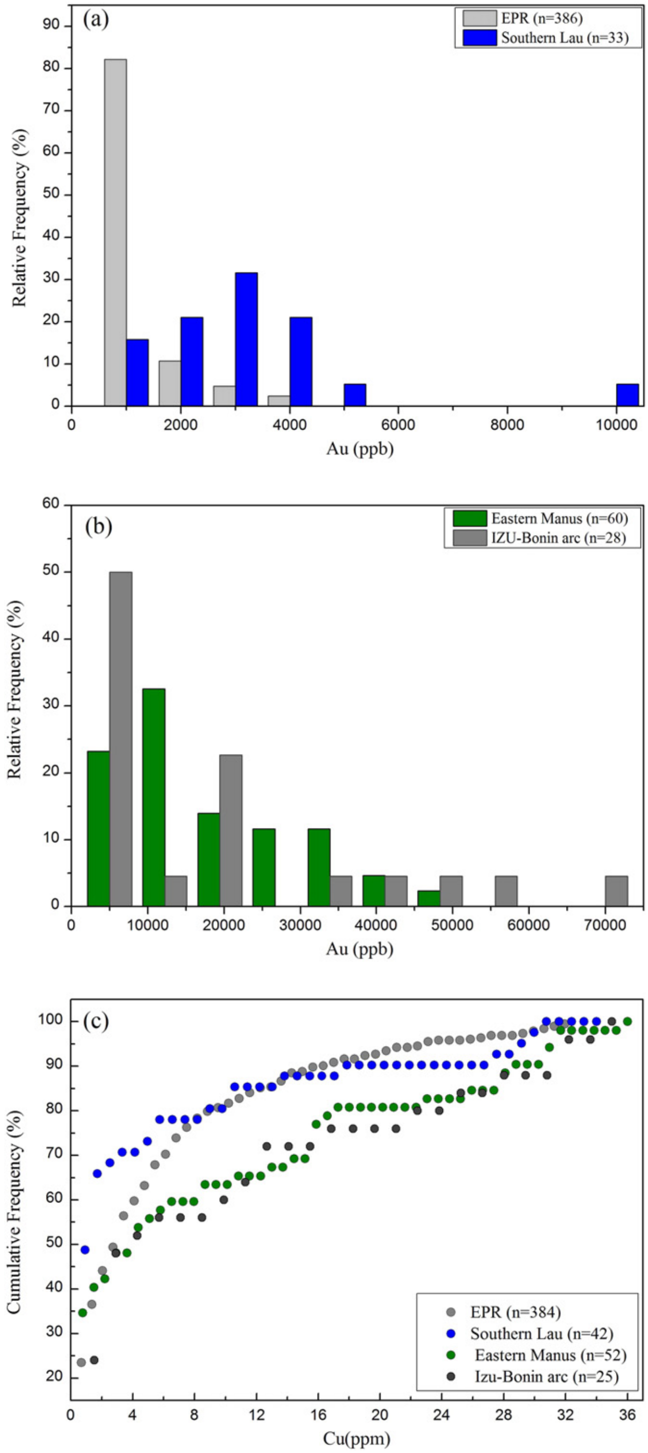

Fig. 1. Compilation of existing data of Au (a, b) and Cu (c) abundances in sulfide deposits from the East Pacific Rise (EPR), Southern Lau Basin, Eastern Manus Basin, and Izu–Bonin Arc. The data are from the database of the International Seabed Authority (http://www.isa.org.jm). The complete source references are not given here because of space constraints.

before large-scale pre-eruptive degassing is thus a crucial step in the generation of an ore-bearing magmatic–hydrothermal system (e.g., Sun et al., 2004; Candela and Piccoli, 2005; Jenner et al., 2010; Richards, 2011).

Previous studies have suggested that the abundance of chalcophile elements, such as Cu and Au, in magma depends mainly on the sulfur content and speciation (Jugo et al., 2005, 2010; Jugo, 2009). These metals behave incompatibly when sulfate is the dominant sulfur species in an oxidized magma, and become compatible after the conversion of S^{6+} to S^{2-} due to magma reduction (e.g., Sun et al., 2004, 2011, 2012, 2013, 2015; Liang et al., 2006, 2009; Jenner et al., 2010). However, the most favorable oxygen fugacity (fO_2) for Cu–Au enrichment remains unclear. In addition, the influence of other factors (e.g., water content and crystallization pressure) on the behavior of Cu and Au has received little attention.

We base our study on a dataset compiled from the literature, and restrict our investigation to Cu, which behaves similarly to Au during magma evolution (Moss et al., 2001; Sun et al., 2004), because precise Au data for volcanic rocks are rare. We investigate several of the factors influencing Cu behavior, including fO_2, water content, and crystallization pressure (P), by constructing a geochemical model using the Petrolog3 software package (Danyushevsky and Plechov, 2011). The aims of this study are (1) to investigate how these controlling factors (fO_2–H_2O–P) affect Cu behavior, (2) to determine the conditions favorable for Cu enrichment during magma evolution, and (3) to shed light on the origin of selective enrichment of Cu and Au in hydrothermal sulfide deposits that form at immature back-arc ridges in general. Two immature back-arc ridges in the Manus and Lau basins, were selected for this purpose, because they both possess a complete magmatic suite with a variable extent of differentiation (Jenner et al., 1987; Pearce et al., 1994; Sinton et al., 2003), and active hydrothermal venting as well as sulfide deposits occur at the ridge axes (Fouquet et al., 1991, 1993; Binns and Scott, 1993).

2. Geological background

The Manus Basin was formed by the extension of pre-existing crust (the Bismark Plate) associated with the subduction of the Solomon Sea Plate at the New Britain Trench (Fig. 2a). Two linked spreading segments formed between the Willaumez (WIT) and Djaul (DT) Transforms: the Manus Spreading Center (MSC) in the east and the Extensional Transform Zone (ETZ) in the west. To the east of the MSC, there is broadly distributed irregular strike-slip motion and extension, including in the Southern Rift (SR) and en echelon Eastern Ridge (ER; Martinez and Taylor, 1996). The ER is a shallow pull-apart basin with dispersed and irregularly distributed volcanism, but enhanced magmatism due to a strong subduction influence (Martinez and Taylor, 1996). The lavas range in composition from basalt to highly evolved rhyodacite (Sinton et al., 2003). Three active hydrothermal fields occur at the ER: PACMANUS, Susu Knolls, and Desmos. The former two are associated with extensive sulfide mineralization and are hosted exclusively by felsic rocks such as dacite and rhyodacite (Binns and Scott, 1993).

The Lau Basin, located between the Tonga Ridge (an active arc) and the Lau Ridge (an inactive arc), is a triangular back-arc basin with a maximum width of 500 km in the north (Fig. 2b). It consists of attenuated original island arc crust and crust formed at propagating spreading centers (Hawkins, 1995). The Eastern Lau Spreading Center (ELSC) started opening at 17°S at 6 Ma and progressively propagated southward to produce the Valu Fa Ridge (VFR). The Central Lau Spreading Center (CLSC) formed later by ridge jump of the northern ELSC, forming a 'relay' called the intermediate Lau Spreading Center (ILSC), located between the two (Hawkins, 1995). The northern end of the CLSC links the Lau Extensional Transform Zone and the Peggy Ridge (PR), which is located in the most northwestern part of the basin. From the CLSC and ELSC to the VFR, the lavas change in composition from normal mid-ocean ridge basalt (N-MORB)-type to arc-type, as the subduction zone is approached (Pearce et al., 1994; Martinez and Taylor, 2002). Notably, the VFR lavas are the most vesicular, fractionated, and enriched in slab-derived components (Jenner et al., 1987; Escrig et al., 2009; Li et al., 2015). In addition, widespread hydrothermal activity occurs at this most inflated ridge (e.g., Baker et al., 2006), and three major sulfide deposits