



Mid Cretaceous Cu-Au (Mo) mineralization in the Vallenar district: new Re-Os age constraints from Productora deposit, northern Chile.

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Abstract. Several Cretaceous Iron-apatite, IOCG and Porphyry Copper deposits are known in the Vallenar district of northern Chile, but timing of mineralization has been reported only for a few of them. A new Re-Os age for ore breccia molybdenite from the Productora Project is 128.9 ± 0.6 Ma and interpreted to represent the main sulphide mineralization phase. This age significantly predates previously reported $^{40}\text{Ar}/^{39}\text{Ar}$ determinations for K-feldspar alteration (94 to 88 Ma: Fox, 2000). Furthermore, the new age is close to a U-Pb zircon age of 129.8 ± 0.1 Ma from Cachiyuyito dioritic stock, which crops out 400 m W of the deposit.

The Productora deposit is emplaced within Early Cretaceous volcanoclastic units intruded by coeval and younger mid-Cretaceous intrusive rocks. The subalkaline, low- to high-K plutonic rocks are characterized by metaluminous to weakly peraluminous affinities. Sulphide Cu-Au (Mo) mineralization and hydrothermal alteration are spatially associated with the Productora Fault-Breccia System, which consists of an 8.5 km-long by 0.3 km-wide structural mesh of NS-striking faults dipping 85° - 60°E , subsidiary fault-veins and main hydrothermal breccia. The breccia is mainly characterized by tourmaline-cemented matrix, associated with K-feldspar, epidote, sericite and chlorite alteration.

Keywords: IOCG, Mid Cretaceous, Cu- Au (Mo), Re-Os age, hydrothermal breccia

1 Introduction

The old Vallenar mining district hosts a variety of ore deposit types including: Iron-apatite or Kiruna Type (Los Colorados, Algarrobo, Japonesa), iron poor-sulphide or magnetite-actinolite (-biotite) (Iman, Huanteme), iron rich-sulphide or IOCG (Astilla, Filipina), Cu-Au (Mo) breccia or porphyry systems (Productora, Johanna).

The Cu-Au (Mo) Productora Project (214.3 Mt @ 0.48%Cu, 0.1 g/t Au, 138 ppm Mo) is located 15 km SW of Vallenar city. Productora has been widely regarded as a distinct

IOCG type (Ray and Dick, 2002; Escolme et al., 2015). It contains numerous occurrences of Cu- and Fe-bearing ore bodies and breccias, Na-Ca and K rich alteration mineral assemblages and U-Th-REE anomalies, which among others features, are commonly associated with IOCG mineralization (Fox, 2000; Ray and Dick, 2002; Sillitoe, 2003). This contribution describes and discusses the tectono-magmatic framework of Vallenar district, focusing in the copper-gold-molybdenite mineralization, related alteration, structural features and new Re-Os age result of Productora deposit. Our observations from Productora suggest that it is closely associated with mid Cretaceous porphyry intrusions and hydrothermal breccia systems.

2 Geologic Framework in Vallenar district

The Vallenar district and Productora are emplaced within early cretaceous andesitic and dacitic volcanic and volcanoclastic rocks assigned to Punta del Cobre Group (Upper Jurassic to Valanginian). These are interbedded with calcareous sedimentary rocks of Chanarcillo Group (Upper Valanginian to Lower Aptian: Arévalo and Welkner, 2008; Arévalo et al., 2009; Fox, 2000; Ray and Dick, 2002). Locally the volcano-sedimentary sequences are folded about a NNE- to NS- trending axis (Arevalo et al., 2003), but they commonly dip gently west or east. Volcano-sedimentary rocks are commonly intruded by coeval/younger Mid-Cretaceous large plutonic complexes, stocks, dike swarms and by several dacitic domes or sills.

2.1 Structural setting

Four major fault systems have been recognized in the Vallenar district: Master NNE-striking faults, NS- to NNW-striking secondary faults and, ENE- and NW-striking crosscutting faults. All these systems show evidence of Mesozoic reactivation, a protracted history and are spatially

and temporally related with magmatic and hydrothermal/mineralization processes.

The Atacama Fault System (AFS) is defined by steeply dipping fault branches of ductile shear zones reworked by left-lateral brittle faults (Brown et al., 1993). Absolute age of ductile coeval left-lateral and dip-slip normal deformation of the AFS in the El Salado Segment occurred at ca. 132 Ma; sinistral displacement at ca. 125 Ma. The AFS was active as a syn-plutonic fault until at least ca. 103 Ma (Dallmeyer et al., 1996; Grocott and Taylor, 2002; Cembrano et al., 2009). In the Vallenar district, three main NNE-striking syn-plutonic fault branches of the AFS have been recognized (Thiele y Pincheira, 1987; Valenzuela, 2002; Arevalo et al., 2003). They recorded an overall similar history: the Infiernillo Shear Zone represents the western branch, the Colorados Fold/Fault System and the Algarrobo Shear Zone constitute the central and eastern branch, respectively, and both host the largest iron deposits in the district.

NS- to NNW-striking fault systems represent subsidiary faults of the AFS. They comprise kilometre-scale steeply dipping faults, cataclastic rocks and hydrothermal/fault breccias commonly related to mineral deposits. Sinistral-dominated displacements have been recognized (eg. Capote vein-faults system, Sosita-Huanteme fault system: Perez et al., 2012; this study). One important but poorly documented NS-striking system is the Productora Breccia-Fault System (PBFS: this study; Escolme et al., 2015): An 8.5 km-long by 0.3 km-wide structural mesh of NS- to NNW-striking splay faults, fault-veins and hydrothermal breccias. Subsidiary, NW-striking vein-faults filled by tourmaline and chlorite (K-feldspar \pm quartz) show sinistral and normal-sinistral kinematic indicators. Master and subsidiary faults dip 85°–60° E. The PBFS is crosscut by younger NW-striking faults (Ray and Dick, 2002; Escolme et al., 2015), which displace and clockwise rotate the PBFS. These NW-trending steep-dipping fault systems occur throughout the district. They are long-lived, margin-oblique, sinistral strike-slip and/or dip-slip normal faults that cut and displace most of the Early Cretaceous rocks and Mesozoic faults systems (Grocott and Taylor, 2002; Cembrano et al., 2009). However, the NW-striking faults partially control dike swarm intrusion, iron poor-sulphide and IOCG mineralization in the Vallenar district.

The ENE-striking system is composed of discrete and discontinuous fracture zones, ductile shear zones and discrete faults with dominant dextral displacements (Thiele y Pincheira, 1987; Perez et al., 2012; this study). Locally, these zones juxtapose intrusive and volcanic Mesozoic rocks, and control part of Iron-apatite and IOCG deposits (eg. Los Colorados, Sosita, Filipina, Elicena-Japonesa).

2.1 Plutonic Rocks

Like several Cretaceous IOCG and iron mineralization deposits in Coastal Cordillera, mineralization in the Vallenar district is temporally and spatially related to plutonic rocks; they can be interpreted to be a potential heat and fluid source for ore formation. For example, in the Candelaria district, geochronological data, petrochemical and isotope composition studies of the Copiapó plutonic complex show that magmatism overlaps with the IOCG mineralization and these magmatic fluids have a genetic link with hydrothermal fluids for Candelaria deposit formation (Marschik and Sollner, 2006; references therein).

Four major NNE-trending, elongated plutonic complexes are recognized in Vallenar district. They lie parallel to both the continental margin and the AFS (Valenzuela, 2002; Arévalo et al., 2009; Grocott et al., 2009). U-Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ ages for these intrusives range from 134 to 93 Ma, with a notable age gap between 120 and 100 Ma (Fig. 1). The Marañón (121 Ma), Ruta 5 (96.1 Ma) plutonic complex and Cachiyuyito Stock (129.8 Ma) crop out in the vicinity of Productora. The oldest, the Cachiyuyito Stock is cross cut by Iron-apatite mineralization of Productora area (Ray and Dick, 2002; this study).

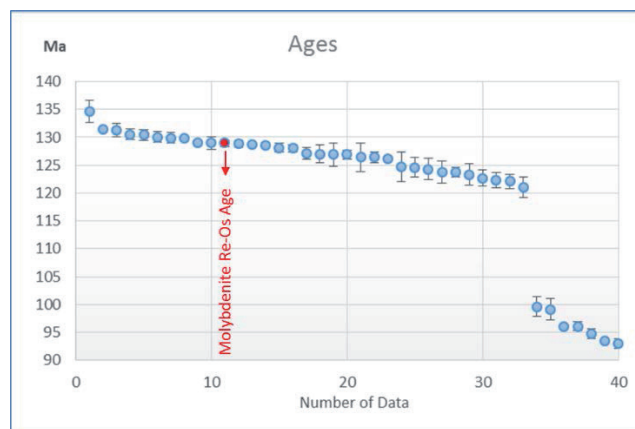


Figure 1. Synthesis of U-Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronological data of plutonic complexes in Vallenar district and the new Re-Os age of Productora sulphide mineralization. (Fox, 2000; Gipson et al., 2003; Hepe, 2008; Arevalo and Welkner, 2008; Arevalo et al., 2009; this study). Notes the gap of magmatic intrusion between 120 to 100 Ma.

The plutonic complexes and stock consist of intermediate to felsic compositions that includes granodioritic, monzodioritic, tonalitic to dioritic rocks. They are coarse-grained and consist of plagioclase, orthoclase, amphibole, pyroxene, biotite, quartz, magnetite and accessory minerals. Each plutonic complex is composed of at least two irregularly-shaped magmatic facies, where either intermediate or felsic compositions can dominate. In most cases, they are interpreted as laccoliths or sill-like sheet intrusions, and some of them, show steeply dipping ductile

shear zones at their margins (Arévalo et al., 2003; Grocott et al., 2009).

The plutonic complexes are classified as subalkaline (Fig. 2), show low- to high-K characteristics and metaluminous to weakly peraluminous affinities. They define a typical calc-alkaline trend in the AFM diagram with near-linear trends of decreasing Fe₂O₃, CaO, MgO, MnO and V₂O₅ with increasing SiO₂. These rocks are compatible with a continental magmatic arc tectonic setting (Fig. 3).

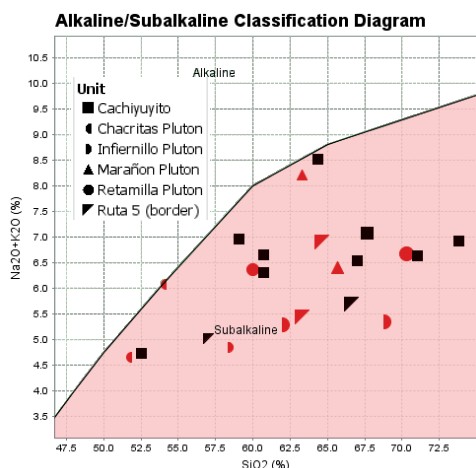


Figure 2. Classification diagram affinities show subalkaline signatures for Infiernillo, Retamilla, Marañón, Cachiyuyito and Ruta 5 plutonic rocks. Geochemical data in red colour are from this study and black symbols are from Fox (2000).

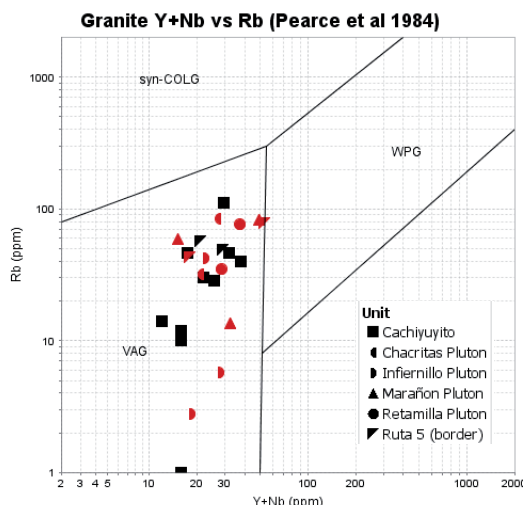


Figure 3. Tectonic discrimination diagram showing volcanic arc granitoids signature. Unaltered and weakly altered rocks of selected plutonic complexes from Vallenar district and Productora area. Geochemical data in red are from this study and black symbols are from Fox (2000).

3 Mineralization and Re-Os Age at Productora

3.1 Mineralization and alteration

Main copper-gold (Mo) mineralization and hydrothermal alteration are spatially closely associated with the NS- to NNW-striking Productora breccia-fault system (PBFS; Fig. 4). The PBFS are hosted in volcanoclastic rocks of the Punta del Cobre Group (Fox, 2000; Dick and Ray, 2002).

Main alteration paragenesis associated with Cu-Au (Mo) mineralization within the PBFS consists of intense K-feldspar that affected previously albite (\pm silica) altered porphyritic volcanic/intrusive clasts cemented by latest black tourmaline (Fig. 4). These hydrothermal breccias are overprinted by sulphide mineralization that comprises disseminations and veinlets of chalcopyrite and pyrite, and slightly later molybdenite. Spatially restricted to sulphide mineralization, it is common to find epidote (\pm allanite) and less commonly sericite \pm chlorite (this study; Ray and Dick, 2002; Escolme et al., 2015). Chlorite \pm K-feldspar (\pm sericite \pm epidote \pm magnetite/hematite) as pervasive or selective alteration, also occurs marginally around the PBFS. Cutting the previous alteration are chlorite-quartz (\pm sericite) and tourmaline (\pm chlorite \pm magnetite) assemblage vein-faults and veinlets. Locally phyllic and advanced argillic alteration assemblages have also been recognized by other authors to the east margin of the deposit (Escolme et al., 2015). Later calcite veins are present along the PBFS.

To the west and north margin of the described mineralization/alteration association of PBFS is a widespread early actinolite-magnetite-albite (\pm biotite) alteration, cut by massive silica alteration and quartz cemented breccia. This early alteration assemblage is associated with Iron-apatite deposits (eg. Elicena). These pre-date the PBFS and are spatially associated with Cachiyuyito Stock (Ray and Dick, 2002; this study).

Recently new Cu-Au-Mo mineralization related with intense potassic-altered tonalitic porphyry intrusion is described on this western margin, at 700 m of the PBFS. The porphyry mineralization comprises disseminated chalcopyrite and pyrite and several veins such massive quartz, quartz \pm sulphide, anhydrite, chlorite and calcite (Escolme et al., 2015),

3.2 Molybdenite Re-Os Age

Molybdenite within the PBFS was collected from one drill hole (PRD-0011) that intercepts the main Cu-Au (Mo) mineralization phase. The molybdenite sample yields a model age of 128.9 ± 0.6 Ma (Fig. 1). This sample is characterized by fine-grained molybdenite disseminated within a tourmaline-rich cement surrounding sub-rounded to angular volcanic clasts. These are pervasively altered to

K-feldspar, locally epidote and chalcopyrite and disseminated pyrite (Fig. 4-a). Molybdenite veins and disseminations in the PBFS overlapped and immediately post-date the described alteration and sulphide mineralization (Fig. 4-b).

This new Re-Os age significantly predates previously reported K-feldspar $^{40}\text{Ar}/^{39}\text{Ar}$ ages ranging from 94 to 88 Ma interpreted to represent the age of Cu-Au mineralization (Fox, 2000).

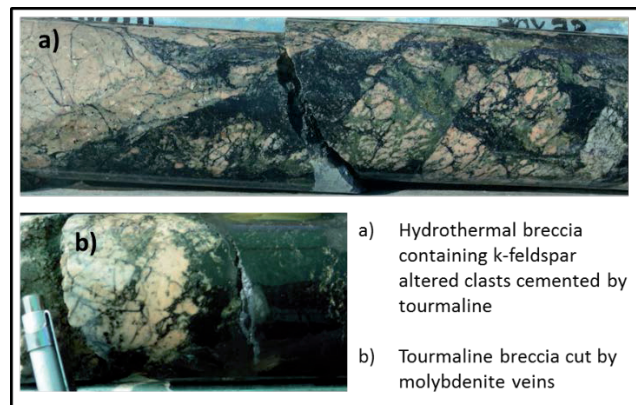


Figure 4. Photographs of Productora hydrothermal breccia-fault system containing K-feldspar (remnants of early albite-silica) altered clasts, cemented by tourmaline (a). Later epidote alteration and Chalcopyrite>>Pyrite overprinted by molybdenite dissemination and veins (b).

4 Discussion and conclusion

The new molybdenite Re-Os age of 128.9 ± 0.6 Ma is interpreted as the main sulphide mineralization age of Productora deposit. This age shows that Cu-Au (Mo) mineralization of the PBFS slightly postdates the 129.8 ± 0.1 Ma Cachiuyito Stock and related Iron-apatite mineralization by ca. 1 Ma. Further, we suggest that the previously hydrothermal K-feldspar $^{40}\text{Ar}/^{39}\text{Ar}$ age determinations were actually reset, and may represent the intrusion age of the Ruta 5 granitic Pluton emplacement at ca. 96 Ma.

Our observations and data suggest that at ca. 130 Ma dioritic magmas may have been related to Iron-apatite mineralization and early Na-Ca alteration and soon thereafter, breccia-hosted porphyry-style Cu-Au (Mo) mineralization was emplaced at Productora. This rapid change may be related to a tectonic change and exhumation. However, the emplacement of the hydrothermal breccia and sulphide Cu-Au (Mo) at Productora occurred under a dominated left-lateral to normal oblique-slip kinematic setting.

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