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THE RED BED-HOSTED TAMBOMACHAY DEPOSIT (CUZCO, PERU): COPPER TRAPPED DURING MIGRATION OF BASINAL FLUIDS BY BACTERIALLY REDUCED SULFUR

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RESUMEN

El yacimiento Tambomachay (región de Cuzco) está compuesto por Cu alojado en grauvacas feldespáticas de las capas rojas de la Formación Kayra (Eoceno Inferior). Bornita, calcopirita, calcocita, covelita, digenita, malaquita y crisocola se presentan diseminadas en lentes estratiformes finos y en vetillas que en parte contienen materia orgánica. La presencia de los minerales de cobre en un horizonte verde, reducido, intercalado en una secuencia de capas rojas, la presencia de materia orgánica en los intersticios entre los sulfuros hipógenos y la composición isotópica del azufre de los sulfuros de cobre (valores $\delta^{34}S$ entre -16.9 y -12.4‰ vs VCDT) señalando un proceso de reducción bacteriana de sulfato, permiten proponer que la mineralización fue causada por fluidos de cuenca salinos transportando cobre que cuando encontraron azufre reducido en un horizonte rico en materia orgánica precipitaron sulfuros de cobre.

ABSTRACT

The Tambomachay ore deposit (Cuzco region) consists of Cu hosted in arkosic red beds of the Kayra Formation (Lower Eocene). Bornite, chalcopyrite, chalcocite, covelite, digenite, malachite, and chrysocolla occur disseminated in thin layers and in veinlets. The occurrence of the copper ores in a green reducing horizon intercalated in the red bed sequence, the presence of organic matter in interstices between the hypogene sulfides, and the sulfur composition of the copper sulfides ($\delta^{34}S$ values between -16.9 and -12.4‰ vs VCDT) pointing to bacterial sulfate reduction, are strong arguments to propose that mineralization was caused by copper-bearing oxidizing saline basinal fluids that precipitate copper sulfides when they meet reduced sulfur in a organic matter rich horizon.

INTRODUCTION

A number of red bed Cu occurrences are known in the Cuzco region in the early Eocene – early Oligocene San Jerónimo Group (Gregory 1916, Carlotto et al. 1996, 2011, Loza et al. 2004). In the past, copper ores were extracted in several small scale mines in the surroundings of Cuzco, including Tambomachay, Tipón, and Zurite in the Cusco province and Ushpa, Guilda, Giovanna, and Langui in the Sicuani Province.

The abandoned Tambomachay Mine (13°28’36.78”S , 71°57’35.98”W, about 6 km to the north of the town of Cuzco (Romero et al. 2015, Salcedo et al. 2017) was chosen as the main site for the present research aimed to better precise the genesis of these copper occurrences. Preliminary results deriving from field work, microscopic characterization of ore and host rock, and sulfur isotope determination suggest that the key factor for the genesis of the copper ores is that copper transported by oxidizing basinal fluids is trapped

by reduced sulfur of bacteriogenic origin located in green horizons intercalated in the red bed sequence.

HOST SEQUENCE AND GEOLOGIC SETTING

The Tambomachay copper ores occur within red arkosic sandstones of the Kayra Formation. At a regional scale, the lower Eocene Kayra Formation and the late Eocene – early Oligocene Soncco Formation consist of mid-coarsely grained, moderately sorted red arkosic sandstone. The combined thickness of both units forming the San Jerónimo Group is more than 6000 m and are interpreted to be deposited in a fluvial environment in a foreland basin of the Western Cordillera of the Central Andes (Carlotto et al. 2011).

A stratigraphic column performed in the surroundings of Chincheros, 10 km NE of Tambomachay, yields a minimum thickness of 1500 m for the Kayra Formation (Fig. 1) the upper part of which hosts the Cu ores. It discordantly overlies the Yuncaypata Group that at Chincheros displays the following units (Fig. 1):

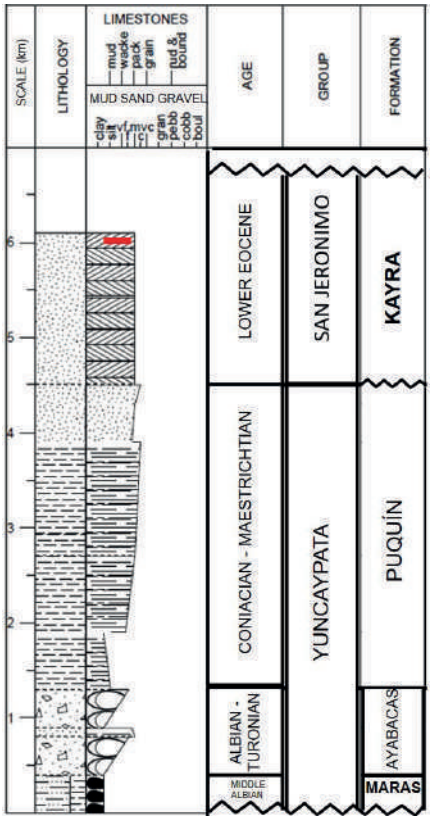

Fig. 1 Composite stratigraphic column near Chincheros (10 km NE of the Tambomachay deposit). Red thick line shows approx. ore body position. Nomenclature and age attribution according Carlotto et al. (1996, 2011)

- 3000 m red and green claystone to the base and well sorted sandstone to the top of the Puquín Formation (Coniacian – Maestrichtian),
- 900 m of mudstone breccias in sandy matrix of the Ayabacas Formation (Albian – Turonian),
- 400 m of claystone, red siltstone, gypsum, and mudstone of the Maras Formation (middle Albian) that is of marine origin in its lower part (Carlotto et al. 2011)

This sequence overlies concordantly sandstones, claystones, and marls of the Paucarbamba Formation of the base of the Yuncaypata Group. Regionally, underlying these, occur rocks of the Lower Cretaceous Huancané Formation, the Lower Cretaceous – Upper Jurassic Huambutío Formation, the Triassic Mitu Group, and of the Paleozoic (Cambrian to Permian) basement (Carlotto et al. 1996).

The NWW-SEE trending "Tambomachay Fault" and other sub-parallel faults, are the main structures in the area and according Carlotto et al. (1996, 2011) faults of this orientation could have already controlled the architecture of the pull apart basins in which deposited the clastic sediments of the San Jerónimo Group that in part could be erosional products of early phases of the Eocene-Oligocene Andahuaylas-Yauri Batholith and of the Anta volcanic arc.

ORE DESCRIPTION

Copper occurs at Tambomachay in a 10- to 90-cm-thick gray-green feldspathic greywacke organic matter-bearing horizon intercalated in the upper part of red beds of the Kayra Formation. The dump size suggests that some thousands of tons of ore were mined.
Primary minerals are bornite and subordinate chalcopyrite (Fig. 2), in part replaced and/or coated by supergene digenite and covelite that are postdated by malachite, chrysocolla, and goethite. The ore occurs predominantly disseminated along bedding planes and filling veinlets. Observations reported by Romero et al. (2015) suggest a structural control of the mineralization. Calcite-bearing veinlets and chloritized feldspars suggest circulation of near neutral fluids. Organic matter occurs interstitially in the host rock and between sulfides. Sulfides of other base metals have not been observed so far but chemical analyses of weakly mineralized samples (Table 1) suggest that sphalerite and galena may occur as traces. The low Zn/Pb ratio may be due to supergene leaching.

Stable isotope determination of sulfide concentrates yields $d^{34}S$ values between -16.8 and

-12.6‰ vs VCDT (Table 2). Because sulfides at Tambomachay are very fine grained (Fig. 2), it was not possible to obtain mono-mineralic separates. However, the mineral composition of the concentrates consists mainly of bornite, digenite, chalcocite, pyrite, chalcopyrite, i.e., minerals with relatively similar sulfur fractionation factors (e.g., Seal 2006), allowing therefore an interpretation in terms of source of the reduced sulfur. Sulfur isotope composition of three gypsum samples contained in the Albian Mara Formation yields $d^{34}S$ values around between 16.1 and 16.4‰ vs VCDT consistent with marine sulfate.

The obtained sulfur isotopic signatures of the sulfides is typical for bacterial sulfate reduction. A thermochemical sulfate reduction of sulfates of the Mara Formation, another possible reduction taking in account the presence of organic matter at Tambomachay, can be discarded as a main source of the reduced sulfur.

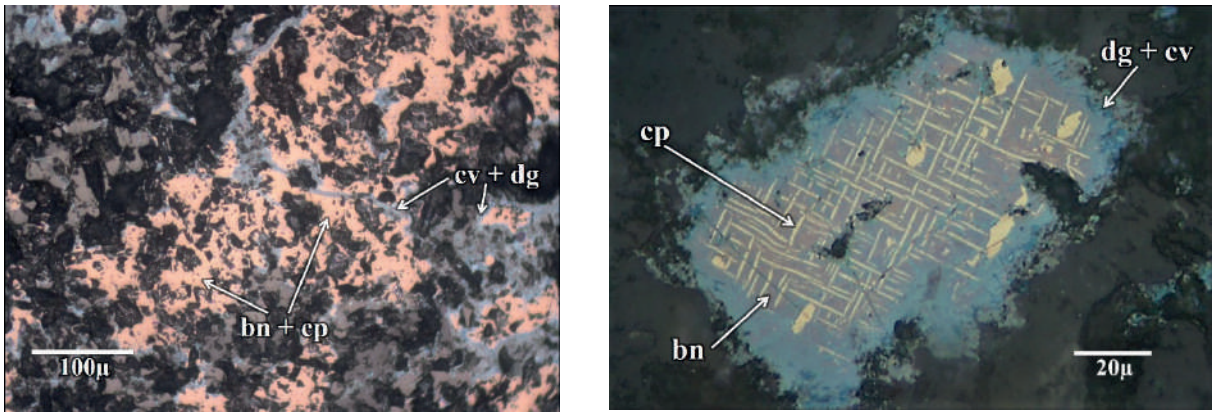

Fig. 2 Left: Bornite (bn) and chalcopyrite (cp) coated and cross-cut by digenite (dg) and covelite (cv). Right: Bornite intergrown with chalcopyrite, partly as spindles along (100) of the host bornite, both coated and partly replaced by digenite and covelite, whereby chalcopyrite is slightly better preserved.

Table 1 Analysis of three samples of the Tambomachay deposit. The low Zn/Pb ratio suggests significant leaching by oxidation (values in ppm, four acid digestion, ICM40B SGS Callao)

Sample	Cu	Zn	Pb	Ag	Co	Ni	Mo	As	Sb
PUCP2	3382	227	1871	6	12	8	65	21	0.6
PUCP5	293	163	1935	2	10	7	51	17	0.4
PUCP7	3124	245	706	5	11	8	24	8	0.3
Detection Limit	0.5	1	0.5	0.02	0.1	0.5	0.05	1	0.05

Table 2 Sulfur isotope analyses of sulfides disseminated and in veinlets in the ore-bearing greenish greywacke in the Tambomachay mine and of an evaporitic gypsum sample of the Maras Formation (Stable Isotope and Organic Geochemistry Laboratories – IDYST – University of Lausanne)

Sample	$d^{34}S$ (‰ vs VCDT)*			Description
SR-S2	-16.7	-16.9		Sulfide concentrate (bornite, digenite, chalcocite, pyrite, chalcopyrite).
SR-S3	-12.4	-12.9		Sulfide concentrate (50%, bornite, digenite, chalcocite, pyrite, chalcopyrite. The rest are mainly host rock silicates)
SR-S4	-15.0	-15.0		Sulfide concentrate (20%, bornite, digenite, chalcocite, pyrite, chalcopyrite. The rest are mainly silicates of the host rock)
Yeso -1	16.1	16.4	16.2	Gypsum intercalated in claystones of the Albian Maras Formation

* 2 to 3 different aliquots

GENETIC MODEL

The features described at the Tambomachay are typical for "sedimentary rock-hosted stratiform copper deposits" (e.g., Hitzman et al. 2005, 2010). It is well known that copper and other base metals are mobile under oxidizing conditions at low temperatures in saline fluids even in near-neutral environments but that copper precipitates in presence of reduced sulfur (e.g., Fontboté et al., 2017). Already the occurrence of the Tambomachay copper ores in a green reducing horizon intercalated in a red bed sequence suggests that the ore forms at a redox boundary. The presence of organic matter in interstices between the hypogene sulfides and the sulfur composition of the copper sulfides pointing to bacterial sulfate reduction, are additional strong arguments to propose that copper-bearing oxidizing saline basinal fluids precipitated copper sulfides when they met reduced sulfur in the organic matter rich horizon. The scarcity of sphalerite or galena indicates further that availability of reduced sulfur was low and so precipitation of the very chalcophile copper was privileged and Zn, Pb, and other elements mostly remained in solution.

The structural control of the mineralization reported by Romero et al. (2015) at Tambomachay and the redox control described above do not favor an early diagenetic timing as proposed by Loza et al. (2004) for similar deposits in the Cusco region. An epigenetic origin appears more likely. The "Falla Tambomachay" and other regional structural elements described by Carlotto et al. (1996, 2011), could have acted as feeders for oxidizing basinal copper-bearing fluids that precipitated copper sulfides in reduced horizons inside the Kayra Formation. Fluid migration was probably driven by tectonically-induced topography gradient.

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BIBLIOGRAPHY

CARLOTTO, V.; GIL, W.; CÁRDENAS, J. and CHÁVEZ, R. (1996). Geología de los cuadrángulos de Urubamba y Calca: INGEMMET. Bol N° 65. Serie A. 247 p.

CARLOTTO, V.; CÁRDENAS, J. and CARLIER, G. (2011) Geología del cuadrángulo de Cuzco. INGEMMET. Boletín N° 138. Serie A. 255 p.

FONTBOTÉ, L.; KOUZMANOV, K.; CHIARADIA, M. and POKROVSKI, G.S. (2017) Sulfide minerals in hydrothermal deposits. Elements. V. 13, p. 97-103.

GREGORY, W. (1916). Geologic reconnaissance of the Cuzco Valley, Peru. American Journal of Science. Fourth series, Vol. 41, p. 1-100.

HITZMAN, M.; KIRKHAM, R.; BROUGHTON, D.; THORSON, J. and SELLEY, D. (2005). The sediment hosted stratiform copper ore system: Economic Geology. V. 100. p. 609-642.

HITZMAN, M.; SELLEY, D. and BULL, S. (2010). Formation of sedimentary rock hosted stratiform copper deposits through Earth history: Economic Geology. V. 105. p. 627-639.

LOZA, M.; SARMIENTO, J.C.; CARLOTTO, V. and CÁRDENAS, J. (2004) Los yacimientos estratoligados de cobre de las Capas Rojas de Cusco y Sicuani (Eoceno – Oligoceno): Mineralización, relación tectónica, sedimentación y metalogenia: XII Congreso Peruano de Geología. Resúmenes extendidos, p. 671-674.

ROMERO, M.; LÓPEZ, W. and CÓRDOVA, A. (2015) Estudio estructural y sedimentológico preliminar del depósito estratoligado de cobre de Tambomachay – Cuzco. ProExplo 2015, resúmenes, 4 p.

SALCEDO, C., ROBLES, M. and ROSAS, S. (2017) Stratiform copper deposits in the San Jerónimo Group, Cusco Area, Peru: Petromineralogical and genetic case study of the Tambomachay Deposit. SEG 2017 Conference – Pekín , Abstracts, 1 p.

SEAL, R. (2006) Sulfur isotope geochemistry of sulfide minerals. Reviews in Mineralogy & Geochemistry. Vol. 61, p. 633-677.