A Geological Model for the San Cristobal Silver-Zinc-Lead Epithermal Deposit, Potosi, Bolivia

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A GEOLOGICAL MODEL FOR THE SAN CRISTÓBAL SILVER-ZINC-LEAD EPITHERMAL DEPOSIT, POTOSI, BOLIVIA

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INTRODUCTION

This paper presents a geological model for the San Cristobal silver-zinc-lead deposit, Department of Potosi, Bolivia, based on a one day technical visit with a group of geologists organized by the Colegio de Geologos de Bolivia. San Cristobal is the largest zinc deposit in Bolivia and the second largest silver deposit. The deposit is an intermediate sulfidation epithermal deposit of Ag-Zn-Pb, and has a well preserved steam-heated opal cap underlain by kaolinite alteration. This feature indicates that mineralization is epigenetic, and that the top of the hydrothermal system is preserved with little erosion.

GEOLOGY

The San Cristobal volcanic-intrusive center is unconformable on steeply dipping Eocene-Oligocene Potoco Formation red bed sediments, and lies on the NNE-trending San Cristobal Fault, a major, east-verging thrust (Elger, 2003). Magmatism and mineralization post-date the last major phase of thrust deformation of the southern Altiplano which ended at 7-8 Ma (Elger, 2003). Google-Earth images show the center to be a volcano about 12 km in diameter with a low relief of up to 400 m, with flow lobes extending outwards, and a summit depression rimmed by domes. These domes are andesitic to dacitic in composition and have been dated at 8.1 Ma (Phillipson & Romberger (2004).

The central depression is about 4 km in diameter and is filled by up to 300 m thickness of volcaniclastic-lacustrine sediments. The sediments are volcaniclastic, that is reworked volcanic rocks rather than pyroclastic rocks, and are interbedded with red mudstones. The grain size of the volcaniclastic rocks varies from fine grained siltstone to conglomerate, with poorly sorted clasts of porphyritic andesite-dacite, and occasional red mudstone, in a sandy to silty volcaniclastic matrix, which may have graded bedding, or a red mudstone matrix. The depositional environment was alluvial and/or debris flows into a quiescent lake. Clasts of mudstone in some conglomerate beds show there was some tectonic activity and reworking of the sediments.

The basin fill of thick sediments rather than pyroclastic rocks suggests a small graben of tectonic origin, as suggested on sections by Lozano (2014), rather than a volcanic collapse caldera. Phillipson & Romberger (2004) likewise describe this a cauldron, which they define as a tectonic basin in volcanic rocks, rather than a caldera of explosive volcanic origin. The cauldron-fill sedimentary rocks are cross cut by a resurgent rhyodacite dome dated at 7.897 to 7.49 Ma, elongated with 040° strike. This is parallel to the strike of the underlying steep Potoco Formation, which varies from the regional 030° strike. Dilation to focus eruption of the volcanic center, form a small central graben or caldera, as well as late dome emplacement, might be explained by a component of right lateral oblique strike slip movement on the San Cristobal Fault following compression and thrusting.

The volcaniclastic-lacustrine sediments are underlain by the Pyroclastic Unit or Lower Pyroclastic Formation, described as a crystal-lithic tuff up to 200 m thick with welding in the middle member (Phillipson & Romberger, 2004). The clast age is 8.1 to 7.26 Ma (Phillipson & Romberger, 2004). This is part of the main volcanic edifice.

ALTERATION & MINERALIZATION

Mineralization occurs in two forms: hosted by steep fractures and breccias in the peripheral domes/stocks, and as stratiform disseminations in volcaniclastic-lacustrine sediments. The underlying Lower Pyroclastic Formation is generally not mineralized but has some veins, and is at the lower limit of drilling. Mineralization post-dates the late resurgent domes.

Mineralization in the domes/stocks occurs in irregular open space fractures which may form narrow hydrothermal breccias where there are multiple, intersecting fractures. Alteration in the domes/stocks is to pale gray-green colored illite with disseminated pyrite which is an intermediate argillic assemblage. Mineralization is open space fracture- and breccia-fill and is sulfide-rich, coarse grained and often euhedral, comprising pyrite, Fe-rich sphalerite and galena. The galena is argentiferous and is accompanied by

acanthine and native silver (Phillipson & Romberger, 2004). This main stage of simple sulfides was followed by a later stage of Ag-, Pb- and Cu- antimony sulfosalts including jamesonite ($Pb_4FeSb_6S_{14}$), famatinite (Cu_3SbS_4), stromeyerite ($AgCuS$), pyrargyrite (Ag_3SbS_3), polybasite ($(Ag,Cu)_{16}Sb_2S_{11}$), freibergite ($Ag_6[Cu_4Fe_2]Sb_4S_{13-x}$) and boulangerite ($Pb_5Sb_4S_{11}$) (Phillipson & Romberger, 2004; Lozano, 2014). Late stage pale brown, botryoidal smithsonite ($ZnCO_3$) coats sphalerite in vugs. The amount of gangue minerals is low and comprises coarse euhedral barite with a bladed texture, less common prismatic quartz in vugs, and fine grained colloform quartz veins with hematite.

The late stage sulfosalts indicate a change in sulfur fugacity from low sulfidation to intermediate sulfidation, hence the deposit can be classified as intermediate sulfidation epithermal.

Mineralization replaces some of the volcaniclastic-lacustrine sediments, mainly in the lower part of the sequence but also some higher beds to give stacked horizons. The reason for selective replacement is not known but possible causes may be porosity-permeability control, and/or a reactive component in the mineralized sediments, such as carbonate cement, although the unaltered red mudstones tested with acid are non-calcareous.

San Cristobal is distinct in having massive sulfides with little gangue, a common feature of epithermal deposits in Bolivia. The gangue is late stage and comprises mostly barite, indicating high sulfate activity, and minor quartz. Late stage smithsonite indicates late CO_2-rich fluids. The high sulfate activity is a shallow level feature, comparable with near-surface barite in other epithermal deposits in Bolivia such as the upper part of the Tajo Vein at Pulacayo.

Redox front marks alteration and mineralization

There is a distinctive redox front going down drill holes which marks the start of alteration and mineralization. The redox front is marked by color changes from red mudstone and greenish altered volcanic clasts in the volcaniclastic-lacustrine sediments to grey to black due to intermediate argillic alteration and variable amounts of fine grained, disseminated sulfides. Several so-called “black shale” beds are actually intervals with a high percentage of very fine grained sulfides, accompanied by higher than average Ag-Pb-Zn grades, and a high content of smectite or montmorillonite (intermediate argillic alteration). These formed by hydrothermal replacement and are not synsedimentary mineralization or true “black shales”.

Breccias

The San Cristobal deposit has a number of different types of breccias. Magmatic breccias occur in some stocks/domes, with a clasts of one porphyry and a matrix of a different porphyry, indicating multiple intrusive events. In one example seen in core, the igneous matrix of a magmatic breccia is partly replaced by sulfides, giving a magmatic-hydrothermal breccia.

The contact of the Jayula Inferior dome/stock with sediments seen on the east side of the Jayula Pit is outward dipping with bedded sediments dipping off the stock to the south, and appears to have been domed by the intrusion. This pit exposure has a ca 20 m wide breccia in the stock close to the contact, which is probably a tectonic breccia, with slickensides in the adjacent sediments, indicating later fault movement, although it may be reactivation of an earlier igneous contact breccia. The breccia has angular, poorly sorted porphyry clasts, is clast supported and has a fine grained matrix of rock flour, with sulfide mineralization.

Hydrothermal breccias are common over short intervals in the stocks/domes where multiple mineralized fractures intersect, and have a sulfide matrix.

Silica Cap: a steam-heated alteration zone

A silica cap covered a major part of the deposit before mining, with an area of several square kilometers, and has mostly been removed by mining. It is formed of white, low density opal and is underlain by a zone of kaolinite alteration several tens of meters thick (up to 66 m depth in hole JyD486), with minor silicification in the upper part. The intensity of kaolinite decreases downhole and dies out transitionally into unaltered red volcaniclastic-lacustrine sediments. There can be up to 100 m or more of non-mineralized sediments between the opal-kaolinite zone and the start of mineralized sediments.

The opal-kaolinite zone is a zone of steam-heated alteration which marks the palaeo-water table. It is explained by Simmons et al. (2005, p. 494-5) as a zone of low temperature silica deposition, with acid fluid drain-back fluid to give kaolinite alteration. It was formed by the separation of dissolved gas (mainly CO_2 and H_2S) from the hydrothermal fluid due to boiling, and the rise of the gas to the surface along different pathways from the residual liquid. The gases were partially absorbed into cool ground waters at shallow levels, along with condensed water vapor, to form two types of steam-heated waters, CO_2-rich and acid-sulfate. Acid sulfate steam-heated waters are close to 100°C and form in the vadose zone where H_2S comes into atmospheric contact and oxidizes to

H_2SO_4. The pH is ~2 and they contain high levels of sulfate. These waters alter the rocks to an advanced argillic assemblage of opal (cristobalite), alunite, kaolinite and pyrite as the solution is neutralized near the water table.

The silica cap / palaeo-water table is close to the present land surface indicating that very little erosion has taken place since mineralization formed. The silica cap is mostly (entirely?) developed in sediments, considered to be a function of higher porosity and permeability compared to the domes. Some kaolinite vug fill occurs in veins which is interpreted to have been deposited from the drain-back of the steam-heated acid-sulfate water. Cross sections show that the silica cap commonly dips gently off the domes, which is thought to reflect original topographic relief, and probably lateral fluid flow in the sediments.

DEPOSIT FORMATION

Alteration and mineralization at San Cristobal formed from a geothermal, chloride water in a shallow epithermal environment. The fluid source was probably from an intrusion at a depth of possibly 1-2 km below the deposit, and not from the outcropping domes/stocks. The top of the system is preserved in the opal-kaolinite zone (silica cap) which marks the palaeo-water table, and was close to the palaeo-land surface. The system has been drilled to a maximum depth of about 450 m below the palaeo-water table.

Chloride waters are reduced with a near-neutral pH, giving intermediate argillic alteration to illite and smectite. They typically contain 0.1 to >1 wt% Cl, up to 3 wt% CO_2, and 10s to 100s ppm H_2S (Simmons et al., 2005). Silver and base metals are transported as chloride complexes, and Ag possibly also as bisulfide complex. Boiling occurs in the central upflow column down to 1 to 2 km depth, controlled by near-hydrostatic pressure-temperature conditions. Buildup and explosive release of hydrostatic fluid pressure is shown by hydrothermal breccias. Precipitation of minerals was by boiling and cooling in open spaces in subvertical channels in the stocks/domes, and by lateral fluid flow into the adjacent sediments and replacement of sedimentary components to form disseminations and mantos.

The opal-kaolinite zone is a zone of steam-heated alteration which marks the palaeo-water table. Hydrogen sulfide gas condensed at the water table and oxidized to form an acid sulfate fluid which deposited opal, and kaolinite alteration formed by downward acid drain back. The steam-heated alteration did not deposit mineralization as metals cannot be transported in the gas phase. This has important implications for interpretation of surface exploration geochemistry. The steam heated alteration zone can be separated from mineralized sediments by up to 100 m or more of non-mineralized sediments. This indicates that the non-mineralized sediments were in place when mineralization happened, and are not post-mineral.

Phillipson & Romberger (2004) proposed that some mineralization was syngenetic by precipitation in a caldera lake. This was based on the interpretation of beds of sulfide-rich mineralization as “black shales”; however, this mineralization is epigenetic rather than syngenetic. In addition, the steam-heated alteration zone indicates that syngenetic mineralization could not have happened: the presence of a well-developed steam-heated zone and opal cap indicates there was a water table overlain a vadose zone below the land surface when the geothermal system formed, and not a lake.

SUMMARY

1. The San Cristobal volcanic center unconformably overlies steeply dipping Eocene-Oligocene sediments and the San Cristobal steep reverse fault. Magmatism post-dates the last main stage of compressive deformation of the southern Altiplano which ended at 7-8 Ma. The focus of the volcanic center, the central sedimentary basin and the hydrothermal system may be explained by right lateral oblique strike slip movement on a jog in the San Cristobal Fault following thrusting.

2. The mineralized volcaniclastic-lacustrine sediments are interpreted as a lake fill in a central depression about 4 km diameter, which is either a graben or a caldera, above welded and non welded lithic-crystal tuffs (8.1-7.26 Ma). The central depression is surrounded by early domes (8.1 Ma), and the sediments are cut by late rhyodacite domes (7.897-7.49 Ma).

3. Mineralization is epigenetic and post-dates the late rhyodacite domes. Mineralization is preferentially developed in steep fractures in the peripheral domes, and as disseminations and replacement in the lower parts of the volcaniclastic-lacustrine sediments.

4. Alteration and mineralization formed from a geothermal, chloride water in a shallow epithermal environment. The fluid source was probably from an intrusion at a depth of possibly 1-2 km below the deposit.

5. Hydrothermal fluid flow was through steep fractures in the margins of the domes, and by lateral fluid flow into the adjacent sediments.

6. The epithermal system is shallow level and there has been no significant erosion. The opal-kaolin-

ite zone marks the top of the system. The system has been drilled to a maximum depth of about 450 m.

7. Alteration associated with mineralization is intermediate argillic with sulfides. It forms a distinctive redox front in the volcaniclastic-lacustrine sediments.

8. The mineral paragenesis started with simple sulfides of Fe, Pb, Zn and Ag, followed by Ag-Pb-Cu Sb-sulfosalts, and finally late stage Zn carbonate. The gangue is barite and minor quartz.

9. The opal-kaolinite zone is a zone of steam-heated alteration which marks the palaeo-water table. It formed by condensation and oxidation of H_2S gas in the vadose zone to form H_2SO_4 and an acid sulfate fluid. This altered the rocks to an advanced argillic assemblage of opal, kaolinite and pyrite as the waters descended. This alteration did not deposit mineralization as metals cannot be transported in the gas phase. This has important implications for interpretation of surface geochemistry.

10. The presence of a well-developed steam-heated zone indicates there was a water table overlain by a vadose zone when the geothermal system formed, and not a lake. This precludes a model of syngenetic mineralization in a lake. The mineralization is epigenetic.

11. The deposit model is intermediate sulfidation epithermal.

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