HYPOGENE ALTERATION, SULFIDE MINERALOGY, AND METAL DISTRIBUTION AT CERRO YANACOCHA HIGH-SULFIDATION EPITHERMAL DEPOSIT, NORTHERN PERU

by

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APPROVAL BY RESEARCH COMMITTEE

As members of the Research Committee, we recommend that this thesis be accepted as fulfilling the research requirement for the degree of Master of Science.

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Abstract

The Yanacocha district in northern Perú contains clusters of high-sulfidation epithermal deposits, which constitute the most productive group of epithermal deposits in the world. The deposits are hosted by Tertiary volcanic rocks of the Yanacocha volcanic center, consisting of pyroclastic rocks intruded by several generations of breccias and intrusions. Geologic and isotopic evidence indicates that “high-sulfidation” or “acid-sulfate” epithermal deposits have close genetic links to porphyry deposits. This study reports on silicate and sulfide mineralogy, distribution of and time-space relationships of hydrothermal mineral assemblages, and metal zoning at one of those clusters of deposits at Cerro Yanacocha, especially at the deepest levels exposed by drilling. Hydrothermal alteration shows a zoning from a core of massive silica outward to quartz-alunite to quartz-pyrophyllite. At depth, quartz-pyrophyllite hosts a northeast-trending diaspore-bearing zone, and with greater depth diaspore becomes the dominant hydrothermal mineral and is spatially associated with the YpqE intrusive unit. This suggests that the source of heat may have been centered about Crater and toward Los Pinos and Yanacocha Oeste. Outward from the quartz-pyrophyllite zone, Cerro Yanacocha hosts an intermediate argillic alteration assemblage containing illite-smectite, which grades out into propylitic alteration around the diatreme. A zone of muscovite-sericite is observed at depth in two areas, a moderately intense zone close to and right below the margin of the diatreme and a weak zone close to Yanacocha Oeste-Los Pinos-Encajón below the main gold-copper mineralization.
Early pyrite grains contain inclusions of pyrrhotite and chalcopyrite that point to initial low- to intermediate-sulfidation states. Later pyrite contains inclusions of chalcopyrite and bornite, indicating that pyrite continued to be deposited at intermediate to high sulfidation states. Enargite commonly rims pyrite, and covellite rims enargite, recording the transition from high to very high sulfidation states. Late galena, sphalerite, and covellite after sphalerite locally rim pyrite, whereas supergene chalcocite rims and replaces pyrite, enargite, and covellite.

Systematic distribution and zoning of metal contents distribution is apparent in cross section and plan view. Gold distribution is exhibits a northwest-southeast alignment at depth, whereas copper and arsenic contents seem to follow both northeast-southwest and northwest-southeast orientations. Copper grades (>0.5% Cu) are closely related to and are hosted the YPQBx and Bxh breccia units but also occurs along the edge of the diatreme in Yanacocha Oeste and Yanacocha Norte. At Yanacocha Sur, copper seems to be more related to fracturing than brecciation. In turn, lead and zinc seem to be distal relative to the main zone of Cu-As mineralization and generally follow a northeast-southwest trend. Furthermore, two centers of higher molybdenum values are centered in the Encajón area and Los Pinos-Yanacocha Oeste (the connection between Yanacocha–La Quinua) areas.

Most of the alteration-mineralization patterns at Cerro Yanacocha probably are the result of multiple periods of injection of vapor-rich magmatic fluids into the Miocene near-surface environment, with a more recent supergene overprint. Occurrences of massive silica zone may represent the location of the paleo-water table. Kaolinite and dickite are uncommon at Cerro Yanacocha; higher activities of silica in the hydrothermal
fluids at Cerro Yanacocha may have stabilized pyrophyllite relative to kaolinite or dickite, perhaps because of extensive interaction of fluids with originally glassy, permeable, pyroclastic rocks. The diaspore-rich roots to Cerro Yanacocha may mark the main paths of rising magmatic vapor. The highest gold grades and the muscovite-sericite zones may be the products of a rising liquid-rich magmatic fluid, following the permeability channel enhanced by rise of the earlier vapor and perhaps marking the upper levels of an underlying porphyry center.

**Introduction**

Cerro Yanacocha, the focus of this study, is part of a cluster of epithermal deposits that constitute the Yanacocha district in Cajamarca region of northern Perú (Teal and Benavides, 2010) and is the most productive group of epithermal deposits in the world (Longo et al., 2010). The epithermal deposits of the Yanacocha district are classified as “high-sulfidation” or “acid-sulfate” epithermal deposits (e.g., Sillitoe and Hedenquist, 2003; Simmons et al., 2005), thus the epithermal deposits in the Yanacocha district have similarities to other occurrences globally, such as El Indio-Tambo, Chile, Goldfield, Nevada, the Lepanto deposit in the Mankayan district, and Pueblo Viejo, Dominican Republic. Deep drilling in the district has locally intersected porphyry-style Cu-Au mineralization, as at Kupfertal (e.g., Pinto, 2002; Gustafson et al., 2004; Teal and Benavides, 2010).

Geologic and isotopic evidence indicates that such epithermal deposits have close genetic links to porphyry deposits (Hedenquist and Lowenstern, 1994; Arribas et al.,
1995a; Simmons et al., 2005; Seedorff et al., 2005). Nonetheless, direct observation of
the transition from epithermal-style Au mineralization with advanced argillic alteration to
dereper porphyry-style Cu-Au mineralization is well documented at only a few deposits.
Examples of deposits with exposed transitions include Lepanto-Far Southeast,
Philippines (Arribas et al., 1995; Hedenquist et al., 1998), and Wafi, Papua New Guinea
(Tau-Loi and Andrew, 1998). Thus, study of the deeper parts of epithermal Au-Cu
deposits might lead to a better understanding of the epithermal-to-porphyry transition, aid
in solving metallurgical challenges presented by the rocks in this part of the system, and
provide further insight for discovery of porphyry deposits at depth.

Teal and Benavides (2010) and Teal et al. (2010) summarize the history and
advances in geologic understanding of the district, its mineral deposits, and the
Cajamarca region in the last quarter century since discovery of the epithermal gold
deposits in 1985 and inception of modern mining in 1993. Recent research in the district
has focused on the $^{40}$Ar/$^{39}$Ar geochronology and petrology of igneous rocks (e.g., Longo,
2005; Longo et al., 2010; Chambefort et al., 2008) and on characterization of the
Kupfertal porphyry system and at other porphyry systems nearby in the Minas Conga
district (Pinto, 2002; Gustafson et al., 2004; Mendoza, 2010). The ages of hydrothermal
minerals indicates that the epithermal deposits across the Yanacocha district developed in
five stages between 13.6 Ma and 8.2 Ma, that each stage was associated with formation
of several deposits, and that ages of deposits tend to be progressively younger from
southwest to northeast but at the end become focused at Cerro Yanacocha (Longo et al.,
2010). The $^{40}$Ar/$^{39}$Ar geochronology also shows that hydrothermal biotite from the
Kupfertal porphyry system formed during stage three of Longo et al. (2010),
contemporaneous with various dated alunites collected 0.8 to 4 km from Kupfertal, whereas hydrothermal alunite exposed closest to Kupfertal formed during stages four and five. These relationships are consistent with the likelihood of an important lateral, as well as vertical, components of hydrothermal fluid flow at Yanacocha, just as the Lepanto high-sulfidation epithermal deposit is displayed laterally from the cogenetic porphyry system of Far Southeast in the Mankayan district, Philippines (Arribas et al., 1995a).

This study returns to investigating alteration-mineralization at Cerro Yanacocha. The deposits at Cerro Yanacocha formed in the final, fifth stage of hydrothermal activity in the district, which the $^{40}$Ar/$^{39}$Ar geochronology of Longo et al. (2010) suggests can be subdivided into two substages, stage 5A at 9.3-9.1 Ma and stage 5B at 8.8-8.2 Ma. Cerro Yanacocha itself is a cluster of deposits (i.e., a composite of ore bodies such as Yanacocha Norte, Yanacocha Sur, and Yanacocha Oeste), and Cerro Yanacocha contains ~65% of the gold in the district (Longo et al., 2010). This study builds on the earlier work of Harvey et al. (1999), Turner (1999), Loayza Tam (2002), Bell et al. (2004) and recent work by the Yanacocha mine staff, taking advantage of observations from new exposures from mining and drilling, relogs of old drill holes, and an extensive mineralogic and geochemical database. The present study focuses on the distribution of hydrothermal silicate and sulfide minerals as displayed on several cross sections and two levels through Cerro Yanacocha, on time-space relationships of mineral assemblages, and on metal zoning relationships. In particular, this study attempts to extend the understanding of the distribution and timing of alteration-mineralization to greater depths beneath Cerro Yanacocha and to speculate on its relationship to porphyry mineralization.
Location and geologic framework

Location

The Yanacocha district is located 20 km from the city of Cajamarca, in the northwest Andean Orogenic belt of northern Peru, centered on latitude 6°59' 30" S and longitude 78°30' 45" W, at elevations between 3400 and 4200 m above sea level. The district is also located 600 km north of the capital city of Lima and 125 km east of the Pacific Ocean. (Fig. 1).

Stratigraphy

The regional geology in the Yanacocha area consists of folded and thrust faulted Ordovician to Cretaceous sedimentary basement rocks overlain by Tertiary to Holocene volcanic rocks and Tertiary intermediate to felsic intrusive rocks. Cretaceous sedimentary rocks are referred to the Pulluciana-Quillquiñán Group, in which limestone is the dominant lithology, and the Goyllarisquizga Group, in which quartzite is dominant. Most of the volcanic rocks in the district traditionally have been assigned to the Calipuy Group, although some rocks were correlated with Eocene and Oligocene units. Longo et al. (2010) show that Eocene and Oligocene units are absent in the district and offer a revised stratigraphy of the Miocene rocks, which involves a lower unit consisting of andesitic lahars and dacitic pyroclastic rocks dated at 19.5 to 15.1 Ma that are assigned to the Calipuy Group and an upper unit of andesites and dacites, including several ignimbrites and small domes, dated at 14.5 to 8.4 Ma that are assigned to the Yanacocha Volcanics.
Structural geology and tectonics

The Andean Cordillera has a northwestern structural trend in the Department of Cajamarca, but a major bend in the Cordillera, known as the Cajamarca Curvature (Benavides-Caceres, 1999), deflects the Mesozoic strata into a series of west- and west-northwest–trending fold axes and faults (Fig 2). Incaic II deformation corresponds to a regional scale deflection of earlier, dominant northwest-directed fold and thrust of Incaic I deformation to more west-northwest–to east-west–trending fold axes and thrust faults. The Cretaceous sedimentary rocks underwent two major periods of east-northeast compressive deformation referred to as Incaic I (Paleocene, 59–55 Ma) and Incaic II (mid-Eocene, 43–44 Ma) orogenesis. Volcanism within this orogenic belt began in the early Eocene (45 Ma) following Incaic I deformation and continued intermittently through the next period of Incaic II deformation.

The northeast alignments of faults and fractures of the Yanacocha belt are interpreted to occur along this cross-arc break, referred to by Turner (1997) and Quiroz (1997) as the Chicama-Yanacocha structural corridor.

Geology of the Yanacocha district

The oldest exposed rocks within the Yanacocha district consist of folded and thrust faulted sandstones of the Farrat Formation of the Lower Cretaceous Goyllarisquiza Group, which are exposed in the southwestern part of the district. In the northeastern part of the district, the Yumagual Formation is exposed, which consists of thick-bedded limestone with minor intercalated shale partings and belongs to the regionally extensive Middle Cretaceous Pulluicana Group (Fig. 4). These Mesozoic rocks were subjected to
northeast-directed compressional deformation during the Incaic I and Incaic II orogenies (Rivera, 1980; Wilson, 1985; Benavides-Cáceres, 1999).

The lower andesite sequence is exposed predominantly within the western portion of the district and consists of an intercalated sequence of block and ash flow tuffs, lava flow sequences with rare associated flow domes, and an upper zone dominated by ignimbrites grading upward into a transitional fine-grained, laminated epiclastic horizon. The lower andesite lies unconformably on folded Early Cretaceous basement sedimentary rocks. Longo (2005) dated the sequence using $^{40}\text{Ar}/^{39}\text{Ar}$ between 19.5 and 13.3 Ma. The lower andesite grades upwards into the Yanacocha pyroclastic sequence, which consists of lithic to lithic-crystal tuffs. This sequence is interpreted to include the Maqui Maqui ignimbrite, a distinct fragmental lapilli tuff confined to the western portion of the district. This unit can be constrained to an age range of <13.2 to ~12.4 Ma, based on dating by Longo (2005) of underlying and overlying sequences.

The upper andesite sequence consists of intercalated andesitic to dacitic flows and ignimbrites dominated by multiple flow dome complexes in its upper porion. The unit is subdivided into a lower hornblende porphyry andesite flow (Tupha, 11.8–12.3 Ma), Shascha ignimbrite (Tutx, 11.25 Ma); andesite, porphyry flows (Typ, 11.6–12.3 Ma) and flow-dome complexes (Tud, 11.2–11.6 Ma) (Turner, 1997; Longo, 2005).

The volcanic pile was intruded by multiple phases of late-stage dikes, plugs, and stocks. These consist of two broad suites of early hornblende diorite or andesite to dacite porphyry (Typ- Tsjd) and a dacite-to-rhyolite porphyry (Typq). Ages of these units range from 12.4 to 8.4 Ma (Turner, 1997; Longo, 2005).
**High-sulfidation gold deposits**

The Yanacocha district has several high sulfidation deposits that are aligned along a northeasterly trend (Fig. 6) but also display a secondary northwesterly alignment. Some of the major deposits are Cerro Negro, Quilish, Corimayo-Tapado, the Cerro Yanacocha complex (the subject of this study), Carachugo, San Jose, Chaquicocha, Quecher, and Maqui Maqui (Turner, 1997; Harvey et al., 1999; Longo, 2000; Loayza Tam, 2002; Gómez, 2002; Bell et al., 2004). The Cerro Yanacocha complex is actually a cluster of deposits (i.e., composite of Yanacocha Norte, Yanacocha Sur, Yanacocha Oeste) that contains ~65% of the gold in the district (Longo et al., 2010). The northwesterly trend of high-sulfidation deposits continues outside the Yanacocha district (Fig. 7), to include the Tantahuatay deposit (13.3-8.3 Ma), Sipan, and La Zanja (15.6-11.9 Ma) high-sulfidation gold deposits (Candiotti de los Ríos and Guerrero, 2000; Tanabe and Turner, 2000; Noble et al., 2004; Gustafson et al., 2004; Longo et al., 2010).

**Porphyry systems**

The best characterized porphyry deposit in the Yanacocha district is the Kupfertal Au-Cu deposit (Pinto, 2002; Gustafson et al., 2004), which occurs beneath advance argillic alteration related to the nearby Cerro Yanacocha complex. Several other sulfide Au-Cu occurrences in the district, such as Yanacoche Verde (located beneath the Yanacocha Sur gold deposit), may represent the upper levels of porphyry Au-Cu systems (Teal and Benavides, 2010). About 15 km east of Cerro Yanacocha lies the Minas Congas district, which also has a series of porphyry Au-Cu deposits (~17.3-15.6 Ma; Longo et al., 2010), which include Perol, Amaro, Chailhuagón, and Galeno (Llosa et al., 2000; Gustafson et al., 2004; Mendoza, 2010). Other porphyry deposits near the Yanacocha
district (Figs. 6 and 7) include Michiquillay (20.0-19.8 Ma), Cerro Corona Cu-Au deposit (14.4-13.5 Ma), and La Granja (13.8 Ma) (Long et al, 2010).

*Exotic gold deposits*

The exotic La Quinua deposit is located above the Tapado - Corimayo high-sulfidation deposits (Fig. 6). La Quinua has a resource of 424 Mt at 0.75 g/t containing 10.2 (M oz of gold. La Quinua is hosted by unconsolidated Pleistocene glacial moraine gravel that fills structural basins situated along the western flank of the Yanacocha Sur and Yanacocha Oeste high-sulfidation gold deposits. Gravel fans reach a maximum thickness of 350 m on the downthrown side of the basin-bounding the La Quinua fault. The exotic material at La Quinua was derived by erosion, transport, and deposition of gold particles and mineralized clasts from the top of Cerro Yanacocha, above the Yanacocha Sur and Yanacocha Oeste deposits (Fig. 3), although a portion of the gold might have resulted from chemical mobilization and reprecipitation (Mallett56e et al., 2004).

**Methods**

This results of this project are based on relogging of drill core, whole-rock geochemical analyses, qualitative and quantitative mineralogic determinations, petrography study, and construction of geologic cross sections and level maps.

*Relogging of drill core:* Approximately 18,000 m of core was relogged during 2008 and 2009 by geologists of the Yanacocha Sulfides Team, focusing on lithology, alteration, and sulfide mineralogy. The results of the relogging effort are the basis of the geologic interpretations of the present study.

*Whole rock geochemistry analysis:* ICP-MS analyses
were performed each 2-m core interval in the sulfide zone. Additionally, gold was
analyzed by fire assay, gravimetry, and cyanide digestion; silver and analyzed by atomic
absorption on samples digested with aqua regia, and total copper, acid-soluble copper,
and cyanide-soluble copper assays were performed by atomic absorption on samples
subjected to a triple-acid digestion.

*Mineralogic determinations:* X-ray diffraction (XRD) and Terraspect analysis
were performed on numerous samples for mineralogic identification.

Quantitative XRD analysis was performed on pulps (-170 mesh) that weigh
approximately 30-40 g and that are composites of 10-m drill core intervals. Since 2008, a
total of 1869 samples have been analyzed. The samples come from cross sections 14500E
and 14900E, among others, and are systematically spread across the entire deposit,
spaced every 100-150 m along drill holes. Qualitative Terraspect infrared spectrometer
was used to analyze alteration mineralogy on chips of drill core. Measurements were
performed systematically each 20 m and according to geological variability. More than
2400 drill hole samples have been analyzed since 2007 for the Sulfides Project at Cerro
Yanacocha.

*Petrographic studies:* A total of 45 samples were selected from cross sections
14900E 15000E, 14500E, and among other sections spread across the entire deposit.
Polished thin sections were prepared and were studied petrographically in transmitted and
reflected lights.

*Construction of cross sections and levels:* Two cross sections looking to the west
and two plan views were chosen to display lithologic, mineralogic, alteration-
mineralization, and geochemical data obtained from all of the methods described above.
Data were compiled on multiple layers for cross sections 14500 E and 14900 E, and levels at elevations of 3800 m and 3600 m, respectively. Cross section 14500E is a representative section through the deposit and passes through the middle of Cerro Yanacocha (between Yanacocha Oeste and Sur). Cross section 14900E passes through the Yanacocha Sur and Yanacocha Norte pits. The two levels chosen are below the oxide-sulfide boundary in order to evaluate the distribution of features in plan view at relatively shallow and deep levels of the system, in the supergene sulfide and hypogene environments.

**Lithologic Units in the Yanacocha Mine**

The following lithologic units are used to describe the geology of Cerro Yanacocha, including volcanic rocks, intrusions, and breccias.

_Volcanic rocks_

The Lower Andesite Sequence (abbreviated as LPHA, LA) (14.5-13.3 Ma, Atazaico Andesite, Longo, 2005) consists of hornblende to hornblende-biotite andesitic lavas, andesitic crystal tuff, and andesitic crystal-lithic tuffs. This unit has coarse fragments of porphyry and argillite, quartzite, and siltstone from the Cretaceous basement. The Lower Andesite overlies Cretaceous basement rocks and various volcanic rocks (Saderholm et al., 2002).

The Fine Tuff Sequence (Tft) consists of locally laminated rock to a wispy fine tuff with a fine crystal component, to fine crystal-lithic tuff, to reworked volcanic deposits with local laminated lacustrine sediments (Saderholm et al., 2002). Tft commonly overlies the Lower Andesite sequence.
Main Yanacocha Pyroclastic Sequence (TEUT) consists of a sequence of crystal-rich tuff with a noticeable absence of fragments but this unit can contain rare quartzite clast and broken euhedral quartz crystal. Interpreted paleograbens superimposed on the lower sequence.

The Upper Lithic Tuff (ULT, pre-12.4 Ma) includes pyroclastic and heterolithic volcaniclastic rocks. It is a moderately welded, sparsely variable lithic, crystal tuff. That has rare quartz fragments and eyes, and a distinctive eutaxitic texture. The lithic are usually small and many are less than one millimeter. Rocks of intermediate character between tuff and alluvial sediments are represented in the ULT sequence (Saderholm et al., 2002).

The Upper Andesite (Upha) and other isolate rhyolitic domes in the district are dated at 8.4 Ma.

*Intrusive rocks*

_Yananocha porphyry (YP, Cp):*_ The Yp and Cp porphyry intrusions have abundant phenocrysts dominated by plagioclase and hornblende, minor biotite and trace amounts of pyroxene. Ages range from 12.4 to 11.9 Ma (Turner, 1997). SiO$_2$ contents vary from 61 to 64 wt%, consistent with andesitic to slightly dacitic compositions. The Yanacocha Porphyry intrusions are generally pervasively altered to clay The Yp unit is locally exhibits slight patchy alteration (for definition of term, see Gustafson et al., 2004, and Teal and Benavides, 2010).

The Yanacocha Porphyry Cp intrusion has a porphyritic texture with fine grain crystals up to 3 mm. Its name originally was applied to andesite dikes at Carachugo. At Cerro Yanacocha, however, Cp applies to all of the andesite dikes, sills, and lava flows
with small plagioclase phenocrysts that may have been emplaced during several different events. A typical Cp dike has plagioclase phenocrysts with hornblende and minor biotite. The groundmass is very fine grained to aphanitic and green. Where fresh, the rock is always magnetic. The Cp unit is thought to cut the Yp unit.

The Yp unit is subdivided into two distinct subunits, Tp1 and Yp2. Yp1 is an andesite (to dacite) with uniform porphyritic, coarse-grained texture (>5 mm diameter), whereas Yp2 is an andesite (to dacite) porphyry with a bimodal texture. Yp2 is a coarsely crystalline porphyry that occurs as domes, flows and dikes characterized by a bimodal population of plagioclase phenocrysts with glomerophyric plagioclase. Hornblende phenocrysts are abundant and range in size from 1 to 8 mm. The aphanitic groundmass contains plagioclase, K-feldspar, biotite, and hornblende, with rare quartz eyes. In this unit has been observed with weak patchy alteration texture. At its margins, this unit commonly is finely crystalline and may contain numerous autoliths and xenoliths of numerous other older units. Therefore, the margins of Yp form a breccia that in the past was termed Ypbx.

Ypq series (Coriwachay Dacitesm of Longo, 2005): Ypq form the youngest and most silica-rich igneous rocks in the district and includes intrusions and flow domes of dacite to rhyolite (67 to 71 wt% SiO₂). At least four units have been identified at Cerro Yanacocha based on geochronology. Rocks of the Ypq series in the district were dated from 10.8 to 8.4 Ma (Turner, 1997, Longo, 2005; Chiaradia et al., 2009). The dates, from oldest to youngest, are: Corimayo (10.8 Ma), Cerro Yanacocha (9.9 Ma), and Yanacocha Lake (8.4 Ma, Yanacocha Norte). Most of the gold (>47 M oz) was deposited at Yanacocha during the period spanned by the emplacement of these intrusions (Table1).
Ypq-E (Early): This unit exhibits a porphyrytic texture with low to moderate amounts of small quartz eyes (typically <2mm).

Ypq-1; dacite: This unit corresponds to units Ypq-1 as resolved in Cerro Yanacocha logs (Yanacocha Geology Team, 2008). The unit includes a large patchy-altered intrusion of quartz eye tonalite porphyry seen only at depth below the Yanacocha ore bodies (Fig. 9). The unit contains numerous xenoliths of an older Ypq, sedimentsary rocks from the local basement, Lower Andesite, and tuffs. There is a marked increase in xenolith content near the boundaries of this unit. This unit is affected by patchy alteration with abundant pyrite and is thus difficult to identify at Cerro Yanacocha.

Ypq-2; quartz eye porphyry: This unit includes a series of quartz eye porphyry dikes and massive bodies (domes?) that are characterized by large resorbed quartz eyes, 1 to 5 mm in diameter with large (1 to 8 mm) plagioclase phenocrysts with rare glomerophyric plagioclase clusters (Fig.10). It also contains hornblende and rare biotite with a similar groundmass composition that also includes K-feldspar. This unit is not patchy altered and clearly cuts the older Yp, Ypq-E, and YpqBx (phreatomagmatic breccia-diatreme, described below) units. It occasionally has xenoliths of country rock near its contacts. In most of cases, the dikes and other bodies are barren.

Ypq-L (Late): This unit has a porphyritic texture with rare and small resorbed quartz eyes (Fig. 11). This dacitic unit corresponds to Ypq-3 and Ypq-4 as defined in the latest descriptions of Cerro Yanacocha core (Yanacocha Geology Team, 2008). The unit includes a tonalite porphyry dike with rare quartz eyes that cuts both the Ypq-E and Ypq units, as evidenced by and numerous fragments of these and older units. The matrix of
the breccias associated with this unit are favorable for replacement by copper sulfides. The composition of this unit is similar to Ypq but the resorbed quartz eyes are smaller and not as numerous. This unit and other breccias associated with the Ypq series (YpqBx) may in fact be the same (Yanacocha Geology Team, 2008).

**Breccias**

*YpqBx:* Ypq intrusion (phreatomagmatic) breccias that commonly display dike-like forms and may be xenolith-rich Ypq dikes. The fragments are varying quantities of silicified tuff, Lower Andesite and Ypq (Fig. 12). The matrix appears to be similar to Ypq. The upward extension of this unit may be the Bxf unit. The F indicates there are more than 50% fragments and the M indicates there is more than 50% matrix.

*Bhx:* The hydrothermal breccia unit contains rounded to angular clasts in a dominant cryptocrystalline to fine-grained quartz matrix (Fig. 13). In the sulfide environment, the matrix is flooded with quartz, pyrite, alunite, barite and associated with covellite and enargite. These breccias are associated with high gold grades.

*Bxf:* Phreatic Breccias form the most common and volumetrically important type of breccia at Cerro Yanacocha. These units consist of monolithic subangular to subrounded clasts in an abraded sandy matrix (Fig. 14). Fragments and matrix are strongly altered to massive silica.

*Bxmf:* This unit consists of phreatomagmatic breccia consisting of rounded to subangular heterolithic clasts in a crystal-rich, feldspathic matrix (Fig. 15). The data compiled and analyzed for this study (see section above on methods) are presented as Figures 16 to 59. Figures 16 to 26 represent multiple layers of data for cross section 14500 E. Likewise, Figures 27 to 37 relate to cross section 14900 E. The multiple layers
Silicate Alteration Assemblages

Numerous silicate mineral assemblages are developed at Cerro Yanacocha, as described below, and their overall distribution in the two cross sections and plan maps are shown as Figures 17, 28, 39, and 50.

Massive silica

In the center of the district, a corridor extends from Cerro Yanacocha through the San José, Carachugo, and Chaquicocha deposits and consists of rock that is altered to massive silica over an area of ~10 km². It occurs in the central part of Cerro Yanacocha (Figs. 17, 28, 39, and 50) and displays a variety of textures that include mainly massive quartz, vuggy quartz, and granular quartz (restricted occurrences at Yanacocha Norte and Yanacocha Oeste). Massive silica does not occur at deep levels. Quartz-rich rock occurs above 3650 m above sea level at Yanacocha Oeste and Yanacocha Sur, and at Yanacocha Norte above 3820 m elevation. These zones have thicknesses of ~200 m at Yanacocha Oeste, up to 400 m at Yanacocha Sur, and reach 300 m at Yanacocha Norte. Massive silica is also present as structurally controlled subvertical bodies. Based on XRD data, massive silica has been modeled as having >80 wt % quartz content, the average quartz content throughout Cerro Yanacocha is 68% quartz. At depth, massive silica alteration exhibits a northwest trend and a slight northeast trend, reaching Yanacocha Norte. At
shallow levels, massive silica is widespread in Yanacocha Oeste, Yanacocha Sur, and Yanacocha Norte. Turner (1997) determined through XRD analyses that granular silica in the Yanacocha district presently consists of $\alpha$-quartz and cristobalite. Silicification is one of the first stages of mineralization as silicified clasts in Bxf and Bx(fm-Diatreme).

Silica-alunite (quartz + alunite ± pyrophyllite)

The silica-alunite zone occurs at the edge of massive silica, both at the bottom and besides (Figs. 17, 28, 39, and 50). Quantitative measurements indicate that alunite can constitute as much as 25 wt % of the rock (average is 6.5 wt % in areas where it is found). It presents a lateral zoning whose envelope could be from 10 to 200 m. at depth and greater than 200 m laterally. XRD data depict that silica alunite assemblages are quartz and alunite mainly, with some of pyrophyllite and very few amounts of kaolinite. Alunite ages show at least four stage of mineralization and therefore different crosscutting events of alunite (Table 2, Fig. X) during approximately 2.6 Ma. at Cerro Yanacocha. This alteration unit can reach 3600m in depth. Alunite occurs in voids, filling fractures and replacing phenocrysts accompanied by pyrophyllite. Alunite also occurs as patches in a texture locally known as patchy silica-alunite and may fill fractures in massive silica in the massive silica alunite texture (e.g., Turner, 1997; Pinto 2002). Based on $^{40}$Ar/$^{39}$Ar ages from hypogene alunite, have been defined five stages of mineralization of which four seems to be related to Cerro Yanacocha.

Silica–pyrophyllite (quartz + pyrophyllite ± alunite ± diaspore ± zunyite)

At Cerro Yanacocha the silica-pyrophyllite alteration zone surrounds the massive silica and silica-alunite alteration zones, extended widely in the deposit both laterally and vertically (Figs. 17, 28, 39, and 50). The vertical range was at least 700 m, from the
present surface at ~3900 m down to an elevation of ~3200 m to. Pyrophyllite occurs in pits, filling fractures and replacing phenocrysts and as patchy alteration at depth, as well. Pyrophyllite reaches a maximum abundance of 34 wt% but the average in areas which it is content generally is around 12 wt %. Pyrophyllite dominant alteration has assemblages of Qtz, pyrophyllite, Alunite and minor Diaspore. Conversely zunyite has been observed in few amount (2 wt %) but still related to pyrophyllite. Dickite and Kaolinite have been observed together rarely in Yanacocha Norte. Dickite amounts do not appear close related to pyrophyllite assemblages.

Silica-diaspore (quartz + diaspore ± pyrophyllite)

The distribution of the silica-diaspore zone is shown in Figures 17, 28, 39, and 50, and further information on the abundance of diaspore is shown in Figures 19, 30, 41, and 52. Diaspore average contains at Yanacocha is 7.5 wt%, enriched zones in which it is dominant can reach values of 18 wt %. Diaspore appears at 3600 m depth and gets increasingly amount up to reach dominance downward apparently related to YpqE. Silica diaspore dominant is seen at depth below silica massive alteration in the main pit and in a SW-NE trend in plain view. At deeper levels diaspore occurs in veinlets along pyrophyllite (alunite traces at depth) with which also fills open spaces. In some places at depth diaspore apparently replaces quartz in patchy alteration.

Diaspore usually is up to 0.4 mm size and exhibits subhedral and euhedral crystals under the microscope. Where this mineral is present quartz is absent, showing an antithetical relationship (Hemley et al., 1980).
Intermediate argillic (illite + smectite ± montmorillonite)

Clay alteration at Cerro Yanacocha of the intermediate argillic type (e.g., definitions of Seedorff et al., 2005) consists of illite-smectite with minor montmorillonite and dickite. Intermediate argillic alteration is restricted to Bxfm-Diatreme in the central part of the deposit (Figs. 17, 28, 39, and 50). Typically this assemblage contains pyrite disseminations and veinlets. Although Turner (1997) recognized the presence of interlayered illite-smectite in the argillic assemblage and the PIMA data available also show the presence of these two minerals accompanied by montmorillonite as well.

Propylitic (chlorite ± calcite ± illite ± smectite)

Propylitic alteration contains chlorite and occurs lateral to the center of the gold deposit (Figs. 17, 28, 39, and 50). In Cerro Yanacocha propylitic alteration is located in the center of Bxfm-Diatreme as a relic of very late intrusion. Propylitic alteration is no well spread at Cerro Yanacocha.

Muscovite-sericite (muscovite/sericite ± chlorite ± dickite ± topaz ± anhydrite ± K-feldspar)

The muscovite-sericite occurs as fine-grained white mica replacing phenocrysts, and it is widespread in the matrix peripheral to the gold mineralization in the high-sulfidation system (Figs. 17, 28, 39, and 50). Muscovite-sericite alteration has been observed at depth in two areas, a moderately intense one right below and beside the diatreme and at Yanacocha Norte, following northeast and north-south trends, respectively. A second, weaker zone has been found below Yanacocha Oeste-Los Pinos and the Encajón zone at the Yanacocha Sur pit. All occurrences seem to have ring-like shape surrounding the pits in Cerro Yanacocha. Where muscovite-sericite is the dominant
alteration type present, it the muscovite-sericite content reaches values greater than 30 wt% and averages 20 wt%. In the areas where it is found, the average chlorite content is 2 wt%; whereas pyrite averages of 7 wt% dickite averages 6 wt %,, and gypsum (probably after anhydrite) averages 4 wt %. Topaz is observed from trace to 1 wt %t, sometimes with traces of anhydrite. K-feldspar can be associated with muscovite at Yanacocha Norte and in some restricted areas close to the diatreme. Muscovite seems to have been the last event in Yanacocha Norte and at the edge of the diatreme. Spatial relationships suggest that these occurrences could mean two different mineralized events in two different places with different intensities (e.g., hole YS-861 at 423 m in Yanacocha Oeste).

**Distribution and Occurrence of Sulfide Minerals**

Figures 20, 31, 42, and 53 show the spatial distribution of sulfide minerals at Cerro Yanacocha in two cross sections and two plan views. Figures 60 to 70 illustrate paragenetic relationships involving sulfide minerals.

Enargite, pyrite and covellite are commonly found together within silica-pyrophyllite alteration and with certain occurrences of silica-alunite. At depth, the same opaque mineral assemblage is observed with silica-diaspore alteration with some occurrences of silica-pyrophyllite as well. Covellite, pyrite, and minor enargite are found in low to intermediate amounts in silica-pyrophyllite alteration outward from the main mineralized body and at the edge of intrusive rock and the diatreme. Small amounts of chalcopyrite occur at depth with silica-diaspore (± pyrophyllite) alteration and in other cases with muscovite-sericite alteration.
Pyrite occurs as anhedral to subhedral crystals. Typically, pyrite fills open spaces especially in vuggy silica, occurs in fractures, or is disseminated in the rock. Pyrite content can reach values of 5-40 wt %. At least two generations of pyrite has been documented. The early one is composed of coarse grained, euhedral pyrite grains, and the late one is fine grained, rimming early coarse pyrite. Small blebs of chalcopyrite, bornite, and pyrrhotite are common in euhedral pyrite, indicating early pyrrhotite deposition could be related to a porphyry system fluids in Yanacocha Oeste, Yanacocha Sur, and toward Crater (e.g., YS-818, 319 m, YS-861, 423.3 m in Yanacocha Oesta; YS-888, in Yanacocha Oeste-Yanacocha Sur; YS-833, 88.25 m in Yanacocha Sur, and CRA-004 in the Crater area). Usually pyrite that occurs at shallower levels lacks inclusions of chalcopyrite and pyrrhotite; deeper samples contain these minerals at levels below 3700 m; the deepest found is 3435 m above sea level. In Yanacocha Norte, four stages of pyrite have been observed. Pyrite commonly is replaced and rimmed by digenite.

Chalcopyrite in veins has been observed at depth, in some cases related to specularite and associated with covellite and with unidentified sulfosalts (YS-911 at 546 m) roughly at 3250 m above sea level. Molybdenite also has been observed rarely at depth in veins.

Enargite occurs as euhedral crystals and as massive aggregates that fill open spaces; it postdates pyrite and is replaced by covellite and sometimes digenite. Covellite occurs as tabular crystals and massive aggregates; it usually fills open spaces, occurs as veins, and is disseminated in the groundmass with the other sulfides. Chalcocite has been observed filling fractures and also as massive aggregates overall at shallow levels. Chalcocite was also observed rimming enargite rarely.
Sphalerite-galena assemblages are observed with pyrophyllite alteration and with illite-smectite alteration. A late assemblage of galena-sphalerite is observed as veinlets mainly peripheral to the main mineralization and usually is seen rimming enargite and rimmed by covellite.

Digenite commonly rims pyrite and some cases covellite, and it definitely rims sphalerite and galena.

On the deposit scale, gold occurs with massive silica alteration, including vuggy silica, and with silica-alunite alteration. High grade gold at Cerro Yanacocha is related to barite and creamy silica. Native gold has not been seen in the studied samples and probably is not visible at the scale of a polarized microscope. Some occurrences of visible gold have been registered at Yanacocha Sur as late veins accompanied by pyrite and alunite following north-south structures. In other deposits, such Chaquicocha, high-grade gold occurs at depth (in some cases visible), related to fine-grained pyrite, covellite (±enargite), and creamy to gray silica. At shallow oxidized levels, gold has been observed with pyrite and creamy silica. The late fine-grained pyrite in the sample could be arsenian and gold bearing (McComb, 2009).

Chalcocite is found at shallow levels as a supergene enrichment blanket associated commonly with silica massive (± alunite ± kaolinite) and pyrophyllite alterations.
Distribution of Metals and Metal Ratios

Gold and silver

Gold is widely distributed at Cerro Yanacocha (Figs. 21, 32, 43, and 54) and displays northwest and northeast trends in plain view at Yanacocha Norte, Sur, and Oeste. It is seen from the surface to depths commonly to the 3600 m elevation level, reaching grades of 0.2 ppm. At the connection of Yanacocha Oeste with Yanacocha Sur, gold has been observed in a feeder that can reach depths of 3400 m.

High grade gold, greater than 1 ppm, is widely distributed and exhibits a north-south trend in Yanacocha Sur and Norte at elevations above 3650 m. Gold in these areas is mostly related to massive silica and at deeper levels with silica-pyrophyllite. The main zone of gold mineralization occurs directly above the copper mineralization, starting at 3600-3650 m, although some gold is related to structures that can persist 200 m deeper.

Silver (not illustrated) exhibits northeast and northwest trends at Cerro Yanacocha and its distribution closely follows gold. Silver grades greater than 50 ppm shows a northwest trend between Yanacocha Sur and Yanacoche Oeste at both shallow and deep levels. At depth, below 3700 m elevation in Yanacocha Oeste and Sur, silver still has feeders with grades of greater than 100 ppm. Conversely, in Yanacocha Norte silver appears to have higher grades at shallow levels, showing grades of >50 ppm, with decreasing grades down below 3800 m, with grades <10 ppm along a northeasterly trend.

Copper

The distribution of copper at Cerro Yanacocha is illustrated in Figures 22, 33, 43, and 54). Low copper grades of 0.2 wt% follow a northeaster trend, starting from Yanacocha Norte to Yanacocha Oeste-Sur toward the Crater area and are both laterally
and vertically continuous. Copper occurs at altitudes of 3250 m as covellite. Locally within the pit, copper has a northwest trend following structures. Copper grades greater than 0.5 wt% are observed close related to YpqBx-Bxh and the intersection with the edge of the diatreme in Yanacocha Oeste and Yanacocha Norte. Another body is well defined at Yanacocha Norte to a depth of 3400 m, implying a thickness of roughly 350 m with an average grade of 0.5 wt% copper. In Yanacocha Norte and Yanacocha Oeste, high grade copper (generally > 1 wt%) is restricted to structures related to the Bxh unit and faults. For instance, a remarkable feeder at Yanacocha Oeste contains > 1% Cu for 300 m to a depth of 3450 m. At Yanacocha Sur, grades greater than 0.5 wt% are associated with the border of the diatreme and with the Teut unit. High grade (>1 wt%) copper mineralization is related to a secondary enrichment zone of chalcocite within the Teut unit. Hypogene enargite and covellite are restricted to Bxh and structures. Copper mineralization in this area occurs at elevations above 3650 m and commonly overlap the high-grade gold mineralization.

Sporadic bodies > 0.5 wt% copper are seen between La Quinua - Yanacocha connections. One body is beside the Los Pinos (100-150 m thickness) area, and the other is at Crater (up to 200 m thick in a structure), both with chalcocite and enargite mineralization.

*Arsenic*

The distribution of arsenic at Cerro Yanacocha is illustrated in Figures 23, 34, 43, and 54, and Cu/As ratios are shown in Figures 24, 35, 46, and 57. Arsenic is widely distributed in all three pits laterally following a main northeast trend, starting from Yanacocha Norte but extending to Los Pinos and the Crater area. A wide, northwestingly...
trend is also observed locally between Yanacocha Oeste and the Yanacocha Sur pit, at both shallow and deep levels. Arsenic generally occurs with copper but extends to higher levels than the copper body. Field observation and microscopic analysis shows that arsenic in oxide zones arsenic occurs as scorodite and in the middle sulfide portion downward as enargite.

Arsenic (>1000 ppm) in Yanacocha Oeste it is found up above 3520 m of altitude, related to YpqBx, Bxh, and associated with feeder structures. At Yanacocha Sur and Yanacocha Norte, its distribution overlaps with Au and Cu, up above 3650 m in elevation.

*Molybdenum*

The distribution of molybdenum at Cerro Yanacocha is illustrated in Figures 25, 36, 47, and 58. At Yanacocha Oeste, molybdenum appears to be better developed than in others areas. Molybdenum appears to occur in two different bodies at depth and at shallow levels. Molybdenum grades of greater than 60 ppm, in some cases reaching 120 ppm, occur distal to the edges of copper shapes of > 0.5 wt% (± arsenic in the central part) persisting to depth as veins. At shallow levels, zones can attain grades >200 ppm Mo. Indeed, at shallow levels in the oxide portion at Los Pinos-Yanacocha Oeste to the Crater area, molybdenum values reach 200 ppm and appears be displaced to the southwest and separate from the main arsenic mineralization in the central part of Yanacocha Oeste. Two consistent areas of ring-shaped Mo anomalies with a radius of 200 m. One is located 150 m below surface at Cerro Los Pinos. Another smaller ring is observed besides the last one between Los Pinos and Encajón area with a 100-m ring radius. In the others pits molybdenum is rare and lacks a defined pattern.
Zinc and lead

The distribution of zinc at Cerro Yanacocha is illustrated in Figures 26, 37, 48, and 59. Zinc has a well defined northeast trend from the central part of Yanacocha Oeste to Yanacocha Norte and beyond along the same trend. In all pits, in cross section and plan view, Zinc is occurs beside and at the edge of arsenic, both laterally and vertically (1000 ppm). Zinc mainly occurs as sphalerite, and the Zn content can reach values of >5000 ppm. Zinc occurs distal to and beneath the main zones of gold mineralization (>0.3 ppm Au). Zinc is seen above and at the edges of the muscovite-sericite zones

Lead (distribution not illustrated) exhibits a northeast trend and seems close related to Zn. Lead has increased values at shallow levels of > 2000 ppm and decreases in abundance with depth. With respect to gold, the distribution of Pb appears lateral to and below the main zones of mineralization (>0.3 ppm Au).

Interpretations

Hydrothermal mineral assemblages

The spatial distributions of silicate assemblages, sulfide assemblages, and metals provide a basis for speculating on the nature of the “complete” (i.e., silicate + sulfide) hydrothermal mineral assemblages present at Cerro Yanacocha. Given the limited observations available to date involving coupled transmitted and reflected light petrography, the assemblages should be regarded at this time as preliminary interpretations, which are as follows (minor minerals are enclosed in parentheses):

- Massive silica: Quartz + pyrite ± (enargite ± covellite)
- Silica-alunite: Quartz + alunite ± pyrophyllite + pyrite ± (enargite ± covellite)
- Silica-pyrophyllite: Quartz + pyrophyllite ± alunite ± diaspore ± zunyite + pyriteenargite + covellite ± molybdenite ± sphalerite ± galena
- Silica-diaspore: Quartz + diaspore ± pyrophyllite + pyrite + covellite + enargite, with transition at depth to quartz + diaspore ± pyrophyllite + pyrite + (chalcopyrite)
- Intermediate argillic: Illite + smectite ± pyrite ± montmorillonite ± sphalerite ± galena
- Propylitic: Chlorite ± calcite ± illite ± smectite ± pyrite
- Muscovite-sericite: Muscovite-sericite ± chlorite ± dickite ± topaz ± anhydrite ± K-feldspar + pyrite + (covellite) ± molybdenite
- Gold + chalcedony + arsenian pyrite ± barite

As noted above, pyrophyllite is vastly more abundant than either kaolinite or dickite at Cerro Yanacocha. Although temperature is one variable that affects the relative stabilities of these aluminum-silicate minerals (e.g., higher temperatures favor pyrophyllite over kaolinite), the activity of silica also is important (Hemley et al., 1980). One possibility is that hydrothermal fluids at Cerro Yanacocha maintained higher activities of silica, perhaps through extensive interaction with originally glassy pyroclastic rocks during lateral flow along permeable horizons, which would have stabilized pyrophyllite relative to kaolinite, even at temperatures as low as 200°C (Figs. 1 and 3 of Hemley et al., 1980).

Supergene processes

Supergene processes were responsible for formation of the copper enrichment blanket and overlying leached zone with iron oxides. Supergene oxidation of sulfides also
was critical to making the oxide gold ores readily amenable to economical processing via cyanide heap leaching, as noted by others (e.g., Bell et al., 2004). Across the district, this has led to an life-of-mine gold recovery of >70% (Teal and Benavides, 2010).

*Sulfidation states and their evolution through time*

Some pyrite grains contain inclusions of pyrrhotite and chalcopyrite, indicating early low-to intermediate-sulfidation state assemblages. Pyrite also contains inclusions of chalcopyrite and bornite, indicating pyrite continued to be deposited at intermediate to high sulfidation states. Enargite usually rims pyrite, and covellite rims enargite, recording a transition from high to very high sulfidation states. Digenite has being found rimming sphalerite and galena, which suggest that fluid continued evolving to high sulfidation states. Digenite rimming covellite has not being well defined, but its presence indicates a decline to a high sulfidation state.

*Spatial relationship between gold distribution and rock type, alteration, and intrusive events*

Compared with many other deposits of the type (e.g., Arribas et al., 1995a), the deposits in the district tend to be more subhorizontal and tabular in geometry and therefore somewhat less structurally controlled. As noted by earlier workers (e.g., Harvey et al., 1999), this stratabound control of hypogene grades probably results from intense hypogene acid leaching localized by permeable pyroclastic horizons, as is consistent with the distribution of lithologies, alteration, and gold grades (Figs. X – XX)

Copper mineralization is mostly hosted by the YpqBh, BxH, Teut, YpqE, Ypq, YpqL and Yp rock units. High grade copper mineralization occurs in the YpqBh, BxH
and Teut units; intermediate grades occur in the Yp, YpqE and YpqL units. Finally, low grades occur into the Yp, Ypq and YpqL units and in the diatreme.

Gold mineralization occurs mostly in the Teut, Ult, Lpha, Bxh and YpqBx units associated with structures. High-grade gold (greater than 1 ppm) is generally within Teut, Ult and YpqBx-BxH associated with structures (mainly in Yanacocha Oeste), whereas low grade gold occurs in the YpqE, YpqL, Yp, and Lpha units.

Time-space evolution of hydrothermal activity at Cerro Yanacocha

Mineralization in Cerro Yanacocha deposit is the result of the different episodes of magmatic hydrothermal activity. In the district have been recognized five stages of mineralization. Because of spatial rock distribution, alteration occurrences and age dating, four stages of mineralization are recognized at Cerro Yanacocha over a period of 2.6 million years, although the associated crosscutting relationships still are not well documented.

A time-space diagram shows a series of mineralization stages and emplacement of associated intrusive rocks for Cerro Yanacocha (Fig. 71), as a model for how the deposit may have formed. Most of the alteration-mineralization patterns at Cerro Yanacocha probably are the result of multiple periods of injection of vapor-rich magmatic fluids into the Miocene near-surface environment, with a more recent supergene overprint. Formation of massive silica may have occurred at least in part at the paleo-water table. Kaolinite and dickite are uncommon at Cerro Yanacocha; perhaps because higher activities of silica in the hydrothermal fluids at Cerro Yanacocha stabilized pyrophyllite relative to kaolinite or dickite. This could have been caused by extensive interaction of fluids with originally glassy, permeable, pyroclastic rocks. The diaspare-rich roots to
Cerro Yanacocha may mark the main paths of rising magmatic vapor. The highest gold grades and the muscovite-sericite zones may be the products of a rising liquid-rich magmatic fluid, following the permeability channel enhanced by rise of the earlier vapor and perhaps marking the upper levels of an underlying porphyry center. Overall, Cerro Yanacocha reveals a complex series of partially superimposed stages of mineralization, alteration and gold-copper bearing related intrusions.

**DISCUSSION**

The high-sulfidation or acid-sulfate epithermal deposits at Cerro Yanacocha have counterparts in other deposits elsewhere in the Yanacocha district (e.g., Teal and Benavides, 2010; Teal et al., 2010) and have have similarities to other occurrences around the globe, including Chinkuashih, Taiwan (Huang, 1955; Tan, 1991), El Indio-Tambo, Chile (Jannas et al., 1999; Deyell et al., 2004), Goldfield, Nevada (Ransome, 1909; Harvey and Vitaliano, 1964; Vikre, 1989), Lepanto deposit, Mankayan district, Philippines (Garcia, 1991; Arribas et al., 1995a; Hedenquist et al., 1998), Pueblo Viejo, Dominican Republic (Muntean et al., 1990; Vennemann et al., 1993), Rodalquilar, Spain (Arribas et al., 1995b), and Summitville, Colorado (Steven and Ratté, 1960; Stoffregen, 1987; Gray and Coolbaugh, 1994).

Epithermal-style Au mineralization with advanced argillic alteration to deeper porphyry-style Cu-Au mineralization is well documented at remarkably few deposits. Cerro Yanacocha has a great similarity with the Lepanto deposit. The advanced argillic alteration at both deposits is similar. Advanced argillic alteration shows a zoning from massive silica to quartz-alunite to diaspor-pyrophyllite to distal kaolinite-dickite (poorly
developed at Cerro Yanacocha). In both deposits, diaspore occurs right below the massive silica. The main copper-gold mineralization at both Yanacocha and Lepanto deposits are in massive silica related to hydrothermal breccias, but in addition Cerro Yanacocha show a great part of its gold and copper-arsenic mineralization with quartz-pyrophyllite.

**Conclusions**

Yanacocha has the largest amount of gold contained in production, ore reserves, and mineral resources of this deposit type, and the Cerro Yanacocha portion of the district to date has the majority of the known gold production and reserves in the district. The tendency toward stratabound deposit morphologies and the relatively low gold grades are interpreted to be result from intense hypogene acid leaching focused by permeable pyroclastic horizons.

Alteration shows zoning outward from a core of massive silica to a thin ring of silica-alunite, outward to silica-pyrophyllite to intermediate argillic alteration to propylitic alteration and fresh rock. Silica-diaspore occurs at depth, having a southwestern trend in plan view. Sericite-muscovite alteration seems to be at the border of the main copper-gold mineralization and molybdenum anomalies. Patchy alteration as been observed at depth and toward the transition to Muscovite-sericite alteration. Pyrophyllite is vastly more abundant than kaolinite and dickite at Cerro Yanacocha, and higher activities of silica, may have stabilized pyrophyllite relative to kaolinite, even at temperatures <200°C.
Sulfide mineral assemblages indicate that Cerro Yanacocha have evolved from a low-sulfidation state source but later reached very high sulfidation states.

Intrusion of YpqL and associated phreatomagmatic breccia (YpqBX) and hydrothermal breccia (Bxh) at the edges of a diatreme are closely associated with copper grades over 0.5 wt %.

The diaspore-rich roots to Cerro Yanacocha may mark the main paths of rising magmatic vapor. The highest gold grades and the muscovite-sericite zones may be the products of a rising liquid-rich magmatic fluid, following the permeability channel enhanced by rise of the earlier vapor and perhaps marking the upper levels of an underlying porphyry center.
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References


exploración y geología (Volumen Luis Hochschild Plaut): Lima, Instituto de Ingenieros de Minas del Perú, ProEXPLO99, p. 177-195.


Mendoza, N., 2010, Geology, grade distribution, and metal ratios at the Amaro gold-
copper porphyry deposit, Minas Conga district, Cajamarca province, Perú:
Unpublished PSM report, University of Arizona, 73 p.

Negro acid sulfate Au-Ag deposit, Pueblo Viejo, Dominican Republic: Important
factors in grade development: Economic Geology, v. 85, p. 1738-1758.

relationships of some porphyry Cu-Au, epithermal Au, and other magmatic-
related mineral deposits in northern Peru: Society of Economic Geologists Special
Publication 11, p. 313-318.

Pinto A., R. M., 2002, Transición de un sistema de alta sulfuración a un sistema porfírico
de alto nivel en Kupfertal, distrito minero de Yanacocha, Cajamarca, Perú:
Nacional Mayor de San Marcos, 89 p.

Quiroz, A., 1997, El corredor estructural Chicama-Yanacocha y su importancia en la
metalogenia del norte del Perú [extended abs.]: Congreso Peruano de Geología,


Rivera, L., 1980, Mapa geológico del cuadrángulo de Cajamarca: Sector Energía y
Minas, Instituto Geológico Minero y Metalúrgico, República del Perú, Bulletin
no. 31, 67 p.


Tanabe, H., and Turner, S. J., 2000, La Zanja prospecto epitermal de oro-plata en la franja de volcánicos terciarios del norte peruano [abs.], Congreso Peruano de
Geología, 11th, Lima, 2000, Resúmenes Extendidos: Sociedad Geologica del Perú
Publicación Especial No. 2, p. 92.


Williams, S.A., 2000, Description of samples from the central part of the Yanacocha district: Unpublished Newmont memorandum, 18 p.

### Table 1. Summary of ages Ar-Ar for Intrusives, Yanacocha

<table>
<thead>
<tr>
<th>Rock name (symbol)</th>
<th>Previous names</th>
<th>Composition rock type</th>
<th>SiO2 (wt %)</th>
<th>Phenocryst proportion</th>
<th>Textures</th>
<th>Ar-Ar age(s)</th>
<th>Name</th>
</tr>
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<tbody>
<tr>
<td>Quilish dacite Tod</td>
<td>Early dacite ?</td>
<td>Sactite (intrusions)</td>
<td>68-64</td>
<td>PlHbQzA5&gt;B10qq</td>
<td>Porphyry, plagioporphyric</td>
<td>no radiometric age</td>
<td>Longo</td>
</tr>
<tr>
<td>Yanacocha porphyry Yp and Cp</td>
<td></td>
<td>Andesite to dacite porphyry dikes, plugs, lavas</td>
<td>61-61.6</td>
<td>PlHb=AF Trace Qz=B1Ag1Qpx</td>
<td>Int crossly porphyritic (e.g., DN=77, S LT-2); Lavas are trachytic-textured, and flow-foliated (e.g., YS=378); common feldspar</td>
<td>12.39±10.12 to 11.90±0.11 to 12.39±0.12</td>
<td>Turner</td>
</tr>
<tr>
<td>Lower San Jose Ignimbrite Ths</td>
<td></td>
<td>Dacite, andesite minor, trachydacite, trachyandesite ignimbrite</td>
<td>62-64.2</td>
<td>PlHb=Qpx+Op+Sp</td>
<td>Estalitic to non-welded, broken phenocrysts, fines depleted</td>
<td>11.79±0.14 to 11.34±0.09 to 11.43±0.06 to 11.34±0.10</td>
<td>Turner</td>
</tr>
<tr>
<td>Corinayo dacite Tod</td>
<td></td>
<td>Dacite</td>
<td>67-69</td>
<td>PlHb=Ab</td>
<td>Broken phenocrysts with stuff</td>
<td>10.78±0.05 to 11.06±0.02 to 10.62±0.155</td>
<td>Longo</td>
</tr>
<tr>
<td>Co. Yanacocha dacite porphyry Typq</td>
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<td>Dacite</td>
<td>68</td>
<td>PlHb=Ab</td>
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<td>9.93±0.04 to 9.92±0.05</td>
<td>Turner</td>
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<td>Yanacocha lake rhyolite dikes Tryr</td>
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<td>Rhyolite</td>
<td>70.6</td>
<td>PlHb=Ab</td>
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<td>8.40±0.06 to 8.59±0.14</td>
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<td>Name and location</td>
<td>Material</td>
<td>Ma preferred age</td>
<td>± 2σ</td>
<td>δ18OUnit</td>
<td>Au (ppm)</td>
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<tr>
<td>ON-1 Vuggly Cerro 2</td>
<td>Coarse Alunite</td>
<td>13.56 ± 0.24</td>
<td>20.8</td>
<td>0.81</td>
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<td>CCQ-37 110m</td>
<td>Alunite breccia</td>
<td>13.48 ± 0.64</td>
<td>25.3</td>
<td>3.2</td>
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<tr>
<td>QN-1 Vuggly</td>
<td>Coarse Alunite</td>
<td>12.64 ± 0.61</td>
<td>21.8</td>
<td>0.5</td>
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<tr>
<td>CLL-1 dacite tuff</td>
<td>Alunite</td>
<td>11.41 ± 0.89</td>
<td>18.8</td>
<td>0.03</td>
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<td>Baul-1</td>
<td>Alunite vein</td>
<td>11.01 ± 0.09</td>
<td>17.9</td>
<td>0.01</td>
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<tr>
<td>MM-314 259.7m</td>
<td>Alunite breccia</td>
<td>10.81 ± 0.10</td>
<td>11.4</td>
<td>0.38</td>
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<tr>
<td>Maqui Maqui 43-50m</td>
<td>Alunite breccia</td>
<td>10.74 ± 0.13</td>
<td>16.5</td>
<td>0.005</td>
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<tr>
<td>Punta Negra dacite</td>
<td>Alunite</td>
<td>10.74 ± 0.16</td>
<td>16.8</td>
<td>0.06</td>
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<td>COR-3 39213m</td>
<td>Alunite</td>
<td>10.76 ± 0.17</td>
<td>14.5</td>
<td>1.5</td>
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<tr>
<td>Corimayo</td>
<td>Alunite vein</td>
<td>10.73 ± 0.17</td>
<td>19</td>
<td>0.02</td>
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<tr>
<td>CLL-2 Colotan Angelita</td>
<td>Alunite breccia</td>
<td>10.73 ± 0.10</td>
<td>16.4</td>
<td>0.06</td>
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<td>LBQ-40 441.2m</td>
<td>Alunite</td>
<td>10.74 ± 0.13</td>
<td>16.5</td>
<td>0.005</td>
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<tr>
<td>SJS-1 Yp bottom</td>
<td>Alunite</td>
<td>10.73 ± 0.10</td>
<td>16.4</td>
<td>0.06</td>
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<tr>
<td>Puna Dacite tuff</td>
<td>Alunite breccia</td>
<td>10.29 ± 0.31</td>
<td>15.9</td>
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<td>MM-46177</td>
<td>Alunite breccia</td>
<td>10.26 ± 0.22</td>
<td>15.9</td>
<td>0.04</td>
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<td>Cerro Sugares</td>
<td>Alunite</td>
<td>10.24 ± 0.14</td>
<td>15.8</td>
<td>0.1</td>
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<tr>
<td>Tapado</td>
<td>Alunite breccia</td>
<td>9.95 ± 0.14</td>
<td>20</td>
<td>0.13</td>
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<tr>
<td>SJS-3 andesite</td>
<td>Alunite</td>
<td>9.25 ± 0.10</td>
<td>15.9</td>
<td>0.01</td>
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<tr>
<td>YN-105 85.7m</td>
<td>Alunite breccia</td>
<td>9.12 ± 0.32</td>
<td>16</td>
<td>0.11</td>
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<td>YBNK breccia</td>
<td>Alunite breccia</td>
<td>8.82 ± 0.01</td>
<td>19</td>
<td>0.2</td>
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<td>Yanacocha Norte</td>
<td>Alunite breccia</td>
<td>8.45 ± 0.32</td>
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<td>0.36</td>
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<tr>
<td>ENC-6 137.5m at Encagon</td>
<td>Alunite breccia</td>
<td>8.22 ± 0.46</td>
<td>16.8</td>
<td>0.23</td>
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<tr>
<td>KUP-3 571m</td>
<td>Hydrothermal</td>
<td>10.73 ± 0.05</td>
<td>18.8</td>
<td>0.5</td>
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Modified table from Longo 2010.
Au was determined in hole rock assay.
Kup-3 571m. Is from and elevation of 3250m above sea level.
Kup-3 54m comes from ~450m above kupfertal hydrothermal biotite (3712 m above sea level) from the same hole DDH KUP-3.
FIGURE CAPTIONS

Fig 1: Schematic map showing the geology of Peru and general location of the Yanacocha mining district (from Teal and Benavides, 2010).

Fig. 2: Regional geology of northern Peru showing principal northwestern, northeastern, and west-northwest alignments (from Longo, 2005). Key locations are the porphyry Cu-Au and other Au and base metal deposits that define a northwest trend from the Michiquillay and Minas Congas porphyry Cu-Au deposits, to the Tantahuatay high-sulfidation gold deposit and possibly to La Granja porphyry Cu deposit. The Yanacocha mining district is in the Yanacocha Volcanic Field (YVF).

Fig. 3: Location map for Cerro Yanacocha on an aerial photograph of the district.

Fig. 4: Tectonic framework of the northern Peruvian Andes (modified from Davies, 2002).

Fig. 5: Stratigraphic column for the Yanacocha district, showing mineralized horizons. (from the Yanacocha geologic team).

Fig. 6: Simplified geologic map of the Yanacocha district, including location of the high-sulfidation gold deposits outlined in red (from Longo, 2005).

Fig. 7: The locations and ages of mineral deposits in the structural corridor defined by the Cajamarca and La Zanja-Antahuatay lineaments (gray dots). Geologic map of northern Peru in the vicinity of Yanacocha and Minas Congas. (modified from Longo et.al, 2010)

Fig. 8: Yp, phenocrysts dominated by plagioclase and hornblende with minor biotite and pyroxene in traces or absent.
Fig. 9: YpqE, Porphyritic texture with presence of few to moderately little quartz eyes. It includes a large patchy altered intrusion of quartz eye tonalite porphyry seen only at depth.

Fig. 10: Ypq, a series of quartz eye porphyry dikes and massive bodies are characterized by large resorbed quartz eyes 1 to 5 mm and large plagioclase phenocrysts from 1 to 8 mm with rare glomerophyric plagioclase clusters.

Fig. 11: YpqL, Porphyrytic texture with rare and little quartz eyes – Dacite

Fig. 12: An Ypq intrusive breccia that often has a dike-like form and may in fact be xenoliths rich Ypq dikes. It is showing Covellite-Enargite-Pyrite min.

Fig. 13: Bxh with silicic massive alteration and sulfide mineralogy filling spaces.

Fig. 14: Bxf, Phreatic Breccia, rounded fragment s to sub angular fragments, monolite . Matrix very fine frained.

Fig. 15: BxFm, phreatomagmatic breccia diatreme. It is observed with angular fragments in a porphyritic matrix.

Fig. 16: Cross section 14500, lithology.

Fig. 17: Cross section 14500, general distribution of alteration.

Fig. 18: Cross section 14500, distribution of muscovite-sericite.

Fig. 19: Cross section 14500, distribution of diaspore.

Fig. 20: Cross section 14500, distribution of sulfide minerals.

Fig. 21: Cross section 14500, distribution of gold.

Fig. 22: Cross section 14500, distribution of copper.

Fig. 23: Cross section 14500, distribution of arsenic.

Fig. 24: Cross section 14500, distribution of copper/arsenic ratio.
Fig. 25: Cross section 14500, distribution of molybdenum.

Fig. 26: Cross section 14500, distribution of zinc.

Fig. 27: Cross section 14900, lithology.

Fig. 28: Cross section 14900, general distribution of alteration.

Fig. 29: Cross section 14900, distribution of muscovite-sericite.

Fig. 30: Cross section 14900, distribution of diaspore.

Fig. 31: Cross section 14900, distribution of sulfide minerals.

Fig. 32: Cross section 14900, distribution of gold.

Fig. 33: Cross section 14900, distribution of copper.

Fig. 34: Cross section 14900, distribution of arsenic.

Fig. 35: Cross section 14900, distribution of copper/arsenic ratio.

Fig. 36: Cross section 14900, distribution of molybdenum.

Fig. 37: Cross section 14900, distribution of zinc.

Fig. 38: Level map of 3800 m elevation, lithology.

Fig. 39: Level map of 3800 m elevation, general distribution of alteration.

Fig. 40: Level map of 3800 m elevation, distribution of muscovite-sericite.

Fig. 41: Level map of 3800 m elevation, distribution of diaspore.

Fig. 42: Level map of 3800 m elevation, distribution of sulfide minerals.

Fig. 43: Level map of 3800 m elevation, distribution of gold.

Fig. 44: Level map of 3800 m elevation, distribution of copper.

Fig. 45: Level map of 3800 m elevation, distribution of arsenic.

Fig. 46: Level map of 3800 m elevation, distribution of copper/arsenic ratio.

Fig. 47: Level map of 3800 m elevation, distribution of molybdenum.
Fig. 48: Level map of 3800 m elevation, distribution of zinc.

Fig. 49: Level map of 3600 m elevation, lithology.

Fig. 50: Level map of 3600 m elevation, general distribution of alteration.

Fig. 51: Level map of 3600 m elevation, distribution of muscovite-sericite.

Fig. 52: Level map of 3600 m elevation, distribution of diaspore.

Fig. 53: Level map of 3600 m elevation, distribution of sulfide minerals.

Fig. 54: Level map of 3600 m elevation, distribution of gold.

Fig. 55: Level map of 3600 m elevation, distribution of copper.

Fig. 56: Level map of 3600 m elevation, distribution of arsenic.

Fig. 57: Level map of 3600 m elevation, distribution of copper/arsenic ratio.

Fig. 58: Level map of 3600 m elevation, distribution of molybdenum.

Fig. 59: Level map of 3600 m elevation, distribution of zinc.

Fig. 60: YS-869, 68.85 m, pyrite sometimes has inclusions of chalcopyrite and pyrrhotite. This represents an early low to intermediate sulfidation state. Reflected light (altitude 3729 m).

Fig. 61: YS-888, 89.95 m, 50, chalcopyrite rimming and replacing pyrite. Some chalcopyrite inclusions also are observed in pyrite. Reflected light (elevation 3766 m).

Fig. 62: YS-895, 259.00 m, pyrite locally contains inclusions of chalcopyrite and bornite, indicating a transition from intermediate to high sulfidation state. Reflected light (elevation 3598 m).

Fig. 63: YS-869, 162.35 m, 10X. Enargite, galena coating the walls and filling a vug, with late covellite filling open space. Reflected light (elevation 3642 m).
Fig. 64: YS-869, 162.35 m, 10X. Enargite being replaced by covellite reflects the shift to a very high sulfidation state. Enargite rims coarse pyritel. Reflected light.

Fig. 65: YS-869, 162.35 m. 50X. Enargite being replaced by covellite reflects the shift to a very high sulfidation state. Some galena is shown between enargite and covellite. Euhedral quartz is growing at the wall. Reflected light.

Fig. 66: YS-810, 254-258 m, covellite and digenite rims on pyrite. Enargite contains Sn and V. MLA scan image.

Fig. 67: YS-810, 172-176 m, enargite filling open spaces within quartz- pyrophyllite alteration at intermediate levels in the deposit. MLA scan image.

Fig. 68: YS-810, 94-98 m, 10X150, quartz-pyrophyllite alteration at shallow levels, right below the massive silica alteration. Enargite, covellite and pyrite specimens are present.

Fig. 69: YS-810, 74-78 m, 10X150, diaspore alteration predominance close to massive silica alteration, Diaspore coexists with pyrophyllite, kaolinite, and traces of zunyite. Covellite, enargite and pyrite are related to this type of alteration.

Fig. 70: YS-810, 348-352 m, 10X150, quartz-diaspore alteration at depth, diaspore also is replaces quartz. Considerable sericite appears at that level, which is located above a body with abundant sericite.

Fig. 71: Time-space diagram, showing the sequence of events in Cerro Yanacocha epithermal deposit, several stages of mineralization are observed related to a complex of intrusions. Superimposition of events is expected together with destruction of earlier alteration. Abundant diaspore is present at depth. Muscovite-sericite alteration seems to be last alteration event.
Fig. 1

General Geology of Peru

- **Intrusive Rocks** (Various ages)
- **Volcanic Rocks** (Miocene-Cretaceous)
- **Sedimentary Rocks** (Mesozoic)
- **Sedimentary Rocks** (Paleozoic-Precambrian)
Fig. 2

Fig. 3
Fig. 4

Fig. 5
Fig. 6

Fig. 7
Fig. 8

Fig. 9
Fig. 12

Fig. 13
Fig. 16

Fig. 17
Fig. 18

Fig. 19
Fig. 24

CROSS SECTION 14500  Cu/As Distribution

Fig. 25

CROSS SECTION 14500  Mo Distribution
Fig. 26

Fig. 27
Fig. 30

Fig. 31
Fig. 32

CROSS SECTION 149000  Au Distribution

EXPLANATION
- 0.2 ppm
- 0.5 ppm
- 1.0 ppm
- 2.5 ppm

Diatreme  Bxh + YPQ 8x  Fault  Current Pit

200m

Fig. 33

CROSS SECTION 149000  Cu Distribution

EXPLANATION
- 0.1 wt %
- 0.5 wt %
- 1.0 wt %

Diatreme  Bxh + YPQ 8x  Fault  Current Pit

200m
Fig. 34

Fig. 35
Fig. 36

Fig. 37
Fig. 60

Fig. 61
Fig. 68

Fig. 69

87
Fig. 70