A geophysical case history of the Yanacocha gold district, northern Peru

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Summary

The Yanacocha district is located in northern Peru and hosts one of the world's largest acid-sulphate gold deposits. The end of 1999 resource/reserve and past production of Minera Yanacocha were reported as 48.9 million ounces of gold.

Several ground and airborne geophysical methods were employed over the district as part of a continuous exploration program. Airborne magnetics/radiometrics, and ground electrical, electromagnetic, and potential field surveys were performed as part of the delineation and discovery of several gold deposits within the district.

The gold resource/reserve is principally contained within oxide ore consisting of silica-altered rock or alluvial material. Ground geophysical techniques that are used to delineate and explore for new deposits primarily consist of resistivity methods.

Resistivity methods that are used most successfully include: Induced Polarization/resistivity (IP/resistivity) surveys, time domain electromagnetic (TDEM) soundings, and controlled source audio-frequency magnetotellurics (CSAMT). Interpretation and quantification of the results are assisted by the use of in-house and commercial inversion programs.

Introduction

The Yanacocha gold district is located in the northern Andes of Peru (Figure 1). The district lies at an elevation of 3400 to 4200 masl, approximately 600 km north of Lima. Newmont Mining Corporation (51%) is the operator of the Minera Yanacocha S.R.L. joint venture with Minas Buenaventura S.R.L. (44%), and the International Finance Corporation (5%). Modern exploration was initiated in 1969, while discovery of the gold deposit occurred in the mid-1980's through systematic rock geochemistry. Several strong gold anomalies were subsequently drilled with success. Initial mine operations and production began in 1993.

Minera Yanacocha is currently the largest gold producer in South America with 1999 production at 1.66 million ounces. The Yanacocha inventory has grown from 1.28 million ounces in 1992 to an end of 1999 resource/reserve and past production total of 48.9 million ounces. A production cash cost of approximately $103/ounce is one of the world's lowest, made possible by near-surface oxide ores, low strip ratio, no crushing or milling, high gold recoveries, and short leach cycles. Average grade is slightly higher than 1g/t.

Figure 1: Yanacocha district location map.

A regional in-house airborne magnetic/radiometric survey was flown in 1994. The survey covered the 120 km^2 Yanacocha concession as well as in excess of 3,400 km^2 in the surrounding area. Since 1997, over 2000 line kilometers of ground magnetics were also completed at Yanacocha to provide detailed coverage over the main exploration target areas.

Approximately 1000 line kilometers of electric and electromagnetic surveys have been completed at Yanacocha since 1997. The results of these surveys have assisted in the delineation and discovery of several gold deposits. The pole-dipole IP/resistivity technique, utilizing 50 to 200 m dipole separations, proved to be an efficient method that has been principally used to define the near surface units of high resistivity that contain the gold mineralization. As oxide targets diminish and deeper sulfide targets are being considered, a multi-spaced gradient IP/resistivity configuration is increasingly being utilized. TDEM sounding surveys are successful for reconnaissance below large areas of conductive ground in search of deeper, buried resistors that may be related to silicification. CSAMT surveys are used in order to provide additional detail of the deep, high resistivity units.

Geology

This large epithermal gold system was developed within a Miocene volcanic center. The volcanic center is characterized by andesitic to dacitic domes, lava flows, pyroclastic/fragmental units, diatremes and dikes developed over a short time span and coincident with the hydrothermal event. Several cells of alteration and gold mineralization were developed in an active, explosive setting with multiple and overlapping magmatic, volcanic, and hydrothermal events. The system is of acid-sulphate/high sulfidation type with the typical alteration and sulphide mineralogy of these occurrences. Alteration is zoned from a silica core outward to alunite, pyrophyllite, kaolinite, montmorillonite, and propylitic alteration. Sulfide minerals include pyrite, enargite, covellite, and chalcocite. (Harvey et al, 1999).

Most of the gold mineralization in the reported inventory is hosted in silica. Significant gold mineralization also occurs in glacial/alluvial deposits located in the topographic lows. The gold tends to fill the fractures and vugs in vuggy silica, massive silica, and iron oxide breccias. Oxidation is prevalent to depths of 400 m

The Yanacocha district exhibits a strong N60E trend that, along with cross cutting NW striking structural zones, control the alignment of the deposits.

Airborne Surveys

In mid-1994 an airborne geophysical survey was completed using the Newmont Airborne Mapping system consisting of a magnetometer and a spectrometer in an Aerospatiale Lama SA 315B helicopter. Regional coverage was at 500 m line separation, while detailed prospect areas such as the 120 km^2 area over the Yanacocha deposits, were surveyed with 250 m line spacing. The survey was flown on east-west lines while maintaining an approximate height of 100 m above the ground. (Wiles, 1994)

Navigation was accomplished by use of both inertial and GPS systems, providing a root mean square positional accuracy of about 20 m. The magnetic information was collected by a GEM GSM-11 Overhauser Proton Precession magnetometer mounted in a towed-bird configuration on the end of a 30 m cable flying approximately 70 m above ground. The resolution of the sensor was 0.2 nT. Diurnal corrections were applied to the data, and a reduction to the pole was performed using an inclination of 10.8° and declination of 0.4°E.

Reduction to the pole is an important process to provide an accurate interpretation of the data due to the low angle of the inclination of the earth's magnetic field in the Yanacocha district (10.8°). (Note that a simple sign reversal at this latitude can provide a close approximation).

The radiometric data were acquired using an Explorium GR-820 spectrometer with a 16.7 L downward-looking crystal pack and a 4.2 L upward looking crystal. The radioelement data (K, U, and Th) were corrected for background (cosmic + aircraft), air-absorption, radon and stripping, before conversion to equivalent concentrations.

The main deposit controlling structures (N60E and NW) are clearly evident in the airborne magnetic data (Figure 2). The areas of pervasive hydrothermal alteration can be seen as magnetically "quiet" areas within the typically "noisy" response of unaltered young volcanics. Larger magnetic anomalies, interpreted as intrusives, are seen associated with known porphyry deposits near Yanacocha and similar prospects within the concession boundary.

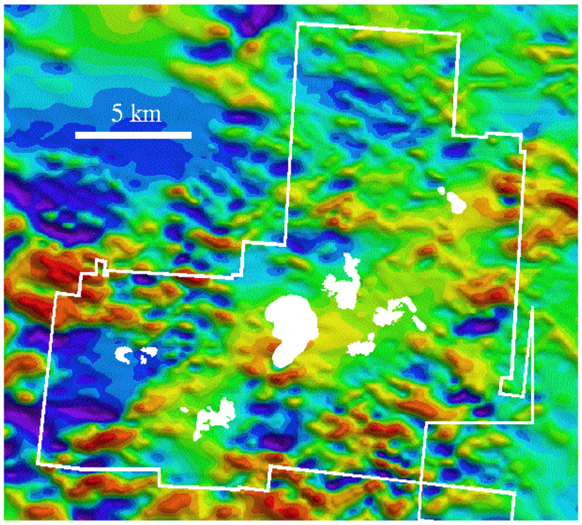

Figure 2: Reduced to pole airborne magnetics showing the Yanacocha concession boundary and the location of the known deposits along the regional structures. The data range is approximately 800 gammas.

The levels of natural radiation in most of the Yanacocha district are generally low. Potassium is the dominant radiometric element at Yanacocha, with the strongest anomalies associated with dacitic intrusives. A low potassium response is interpreted to represent hydrothermally altered outcrop, a result of intense acid leaching. Cretaceous age sediments located along the margins of the Yanacocha volcanic sequence tend to exhibit higher uranium and thorium values.

Ground Surveys

Since 1997, an aggressive exploration campaign at Yanacocha was augmented by a variety of ground geophysical programs. Exploration to date has focused on the delineation of near surface, oxidized silica bodies that contain most of the economic gold. The mapping of silica bodies are successfully achieved with resistivity surveys.

Distinct resistivity contrasts occur that range from 10's of thousands of ohm-m in the most compact silica, to 10's of ohm-m that represent clay and fresh volcanics. Figure 3 shows the ranges of the various types of silica and surrounding rock types.

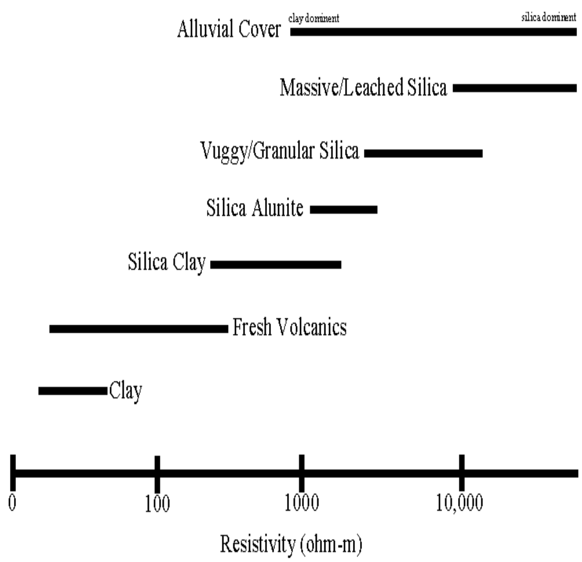

Figure 3: Resistivity ranges of rock types at Yanacocha.

Pole-dipole IP/resistivity, with dipole separation ranging between 50 and 200 m, is the preferred configuration. The resistivity portion of the survey is successful in delineating the lateral and depth extent of the highly resistive silica oxide units of the deposits, if less than 200 m deep. Within the main silica bodies, it is normally possible to distinguish the zonation of the various types of silica - from massive outwards to silica-clay.

The chargeability portion of the IP/resistivity survey is useful in defining the oxide/sulfide boundary and also assists in determining the future sulfide potential of the district.

As the potential to discover near surface silica-oxide type drill targets diminishes, electrical methods that provide a larger depth of investigation than dipole IP are to be used more frequently. The main objective of these techniques is to detect and delineate deeper resistors that could be caused by silicification.

TDEM soundings provide improved depth of investigation over the pole-dipole electric approach. The soundings proved to be a rapid, inexpensive method, able to penetrate conductive cover effectively enough to detect deep (+200 m) resistors. Subsequent drilling confirmed the presence of silicification under clay.

CSAMT surveys are used to assist drill targeting by improving the resolution of the resistivity data collected with pole-dipole IP/resistivity and TDEM methods. Figure 4 shows a typical resistivity response over a known deposit.

A multi-spaced gradient IP/resistivity array is being tested in order to provide improved depth of investigation and lateral resolution over the pole-dipole method. This method also provided the chargeability data that is lacking from the CSAMT and TDEM surveys.

Self potential (SP) data collected at Yanacocha provided noteworthy results. Negative anomalies in the order of several volts are routinely recorded, and are related to the exposed high resistivity zones associated with the silica units. The highest SP responses correlate well with the highest resistivity and largest silica bodies. The largest SP anomaly, (–10 volt) was recorded over a large, compact silica body with the deepest oxidation.

In addition to the above-mentioned surveys and techniques, gravity surveys (to determine depth to cretaceous limestone basement), ground magnetics (for structural interpretations), and gradient array IP/resistivity surveys (to search for covered porphyry targets), are increasingly being used to evaluate the potential of the Yanacocha district.

Conclusions

At Yanacocha, airborne and ground geophysical surveys have been performed to assist in the mapping of the silica-altered rock that contains most of the oxide ore.

Extreme resistivity contrasts between the deposits and surrounding rock have made electric and electromagnetic methods the techniques of choice in the delineation and discovery of new deposits at Yanacocha.

Acknowledgments

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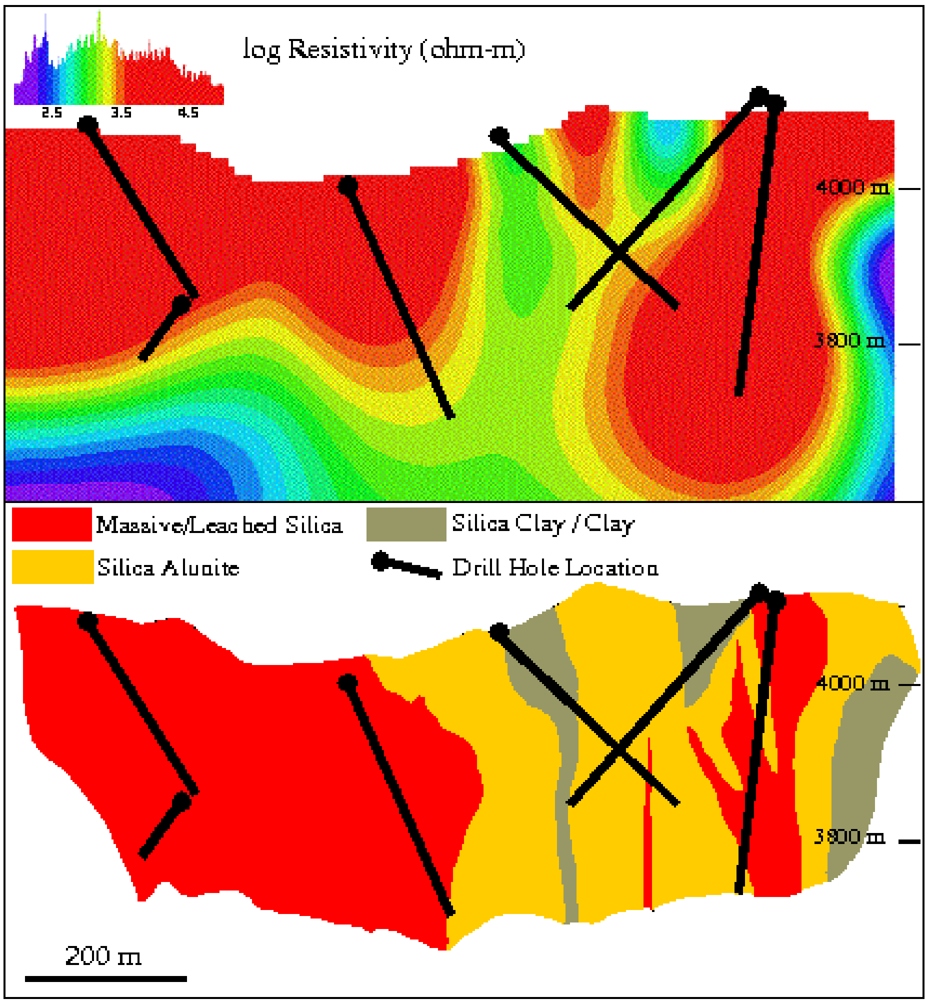

Figure 4: A typical example of the resistivity response at Yanacocha showing a 2D model inversion of CSAMT compared with a geologic section.