Occurrence of gold in the Far Southeast porphyry copper-gold deposit, Luzon, Philippines

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Introduction

The Far Southeast (FSE) copper-gold (Cu-Au) deposit is located in northern Luzon, Philippines (Fig. 1a). The deposit is being explored by Far Southeast Gold Resources Inc., a joint venture of Gold Fields Switzerland Holdings AG, a subsidiary of Gold Fields Ltd., and the Lepanto Consolidated Mining Company. Porphyry Cu systems are large volumes (10 to >100 km^3) of hydrothermally altered rock centered on shallow porphyry intrusions; in addition to Cu and Au hosted by intrusions, the systems may also contain epithermal base and precious metal mineralization, and other deposit types (Sillitoe, 2010). Porphyry deposits are mainly located in volcanic arc settings; they account for about 70% of the world's Cu production (Sillitoe, 2010). Such deposits are formed as aqueous fluids exsolve from an intrusion, with cooling of the magmatic-hydrothermal system causing alteration of the host rocks and mineral precipitation, including Cu sulfides and Au (Sillitoe, 2010).

The FSE deposit is among the highest Au grade of porphyry Cu deposits in the world, is related to shallow intrusions formed about 1.4 million years ago (Hedenquist et al., 1998). The top of the ore body is located over 900 m below the present surface (Fig. 1b), at an elevation of ~500 m. The host rocks are the Lepanto mafic volcaniclastic unit, the Imbanguila dacite porphyry and the Imbanguila quartz diorite porphyry; the latter two units were intruded shortly before deposit formation. Recent drilling (2010-2013) from the 700 m elevation level underground (Fig. 1c) determined an inferred resource of 892 million tonnes (Mt) at an average grade of 0.7 g/t Au and 0.5 wt% Cu, equivalent to 19.8 Moz Au and 4.6 Mt Cu (Gaibor et al., 2013).

The main purpose of this study was to determine the sulfide minerals related to visible gold, and relate this to the stockwork of quartz and anhydrite veins.

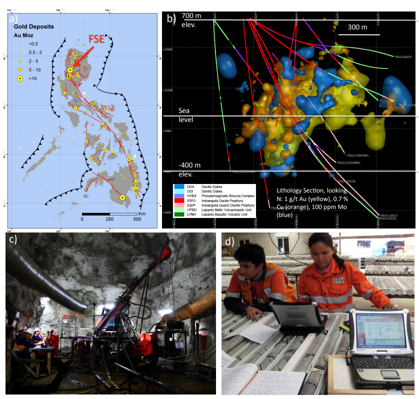

Figure 1 – a) Map of the Philippines and location of the Far Southeast (FSE) deposit in northern Luzon; yellow dots are other porphyry and epithermal-related gold deposits. b) Cross section (W to E, looking N) of the deposit, with collar locations of drillholes on the 700 m elevation level shown. The drill holes studied have their geology along the drill trace (color code listed in the legend of host rocks and intrusions). The metal distribution of copper, gold and molybdenum is shown in a 3D model; the upper limit of the Cu and Au resource is at ~500 m elevation. c) One of the drill platforms in the underground mine on the 700 m elevation level. d) Drill hole samples in the core shed with geologists logging the geology, alteration and mineralization. Diagrams and photographs from Gaibor et al. (2013).

Methods

- Core samples of mineralized rocks were drilled from 700 m elevation (Fig. 1c); over 102,000m of core were drilled in 98 holes from 2010 to 2013. This core was sampled in January 2014 by J.W. Hedenquist.
- Polished thin sections were made from selected core samples at the University of Ottawa.
- Samples were analyzed under petrographic microscope, both transmitted and reflected light (50x to 500x magnification);
- A scanning electron microscope (SEM) was also used for semi-quantitative analyses of sulfide minerals and gold, to help identification and to determine the silver content of the gold.

Results

Veins

After surveying and observing 29 samples under the petrographic microscope, the veins in the samples were separated into different groups. The criteria used were mineralogy and cross-cutting features (Fig. 2). All veins are composed mainly of quartz and anhydrite. Anhydrite is associated with the matrix of the host rock, and is also present in veins where reopened. The veins were divided into 3 groups, A to C. Group A is composed of Chalcopyrite (cp), Bornite (bn), ± Magnetite (mag)/Hematite (hem), locally with bn replaced by Covellite (cv) or Digenite (dg)/ Chalcocite (cc). Group B veins contain Pyrite (py) ± cp ± mag/hem. Group C veins are only hem/mag, and commonly reopen older veins. There can be multiple generation of the same vein type.

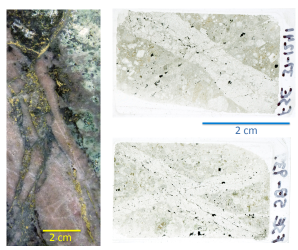

Figure 2 – a) Quartz, chalcopyrite (cp) and bornite (bn) vein in a FSE drillcore sample, 5 cm wide (Gaibor et al., 2013). b) Scanned thin section of sample containing quartz veins with bn, cp and Au (drill hole sample depth in m, 58-939.4 m); see Legend in Figure 6 for abbreviations as well as composition of sulfides. c) Scanned thin section of sample containing a quartz vein with sulfides assemblages (sample 37-1241 m).

Mineral assemblages and associations

Several sulfide assemblages (minerals in equilibrium) occur in this deposit, inside and outside veins. Minerals such as cv and dg/cc are not part of some assemblages, but typically are a replacement of bn (i.e., an association); dg/cc can be contemporaneous with bn in some assemblages.

1)

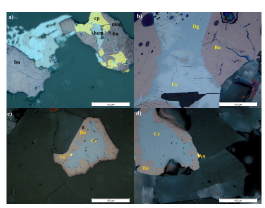

Figure 3 – Photomicrographs in reflected light, scale bar shown. a) Association of bn, cp, hem/mag (sample 3-850.8 m). b) Bn being replaced by dg/cc (sample 58-1000 m) c) Bn with dg/cc replacement containing Au (sample 58-1000m). d) Bn with dg/cc replacement containing Au (sample 58-1000 m).

2)

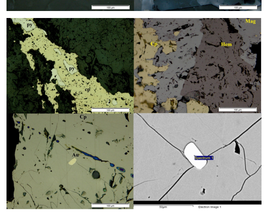

Figure 4 – Photomicrographs in reflected light; scale bar shown. a) Py and cp assemblage (sample 76-878.0m) b) Cp with mag/hem assemblage (sample 3-926.5m) c) Cp crystal enclosing an Au grain (sample 76-878.0m) d) SEM back-scattered electron image containing gold (electrum) grain with 20 at% silver and 80 at% Au in a cp crystal (sample 58-1101.8m).

3)

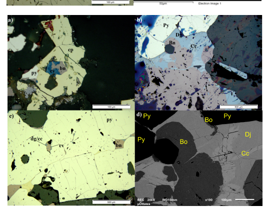

Figure 5 – Photomicrographs in reflected light; scale bar shown. a) Py, cp, bn, cv association, with cv replacement of bn (sample 13-626.3 m) b) Py, bn, dg/cc association, showing dg/cc replacement of bn (sample 58-1000 m) c) Py, bn, cp, dg/cc and cv association; py is the earlier mineral, and cv and dg/cc are a late replacement of bn (sample 10-962.7 m) d) SEM back-scattered electron image containing a py, bn, dg/cc association, with dg/cc shown replacing bn (sample 58-1000 m).

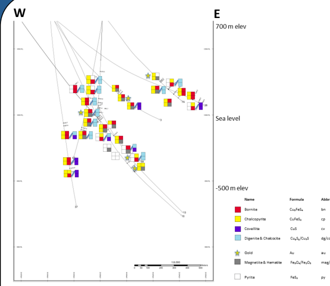

Figure 6 – Cross section W-E, looking N, showing path and depth of drill holes (collared at 700 m elevation level). Sulfide mineral associations are plotted according to drill hole and depth, with relative abundance noted by color proportion; minerals shown after / mark are a replacement. Legend shows the minerals according to color, and their compositions.

Based on Figure 6, the visible Au appears to be central to the main body of the deposit, similar to the overall Au anomaly (Fig. 1b). Gold is almost always associated with the presence of bornite. Pyrite precipitated on the edges of the deposit, and covellite replacement of bornite extends to great depth, particularly along the west side of the deposit.

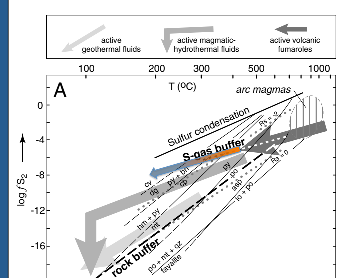

Figure 7 – Diagram of temperature (° C) versus fS_2, showing the relationship between mineral assemblages. A decrease in temperature causes an assemblage of bornite + pyrite to form from chalcopyrite; further cooling causes digenite and finally covellite to form. The observed sulfide associations (Figs. 3-6) are compatible with temperature decrease (but locally there were also episodic periods of temperature increase to account for assemblage repetitions). From Einaudi et al., 2003.

Discussion and conclusions

- Gold-bearing minerals are bornite and chalcopyrite, with gold typically on grain margins; minor visible gold is also in quartz veins.
- Bornite is replaced by both digenite/chalcocite and covellite; the replacement by digenite/chalcocite is more common, whereas covellite is observed at greater depths and on the edges of the deposit. This replacement is caused by cooling (Fig. 7).
- Gold grains observed in bornite are likely the product of exsolution as temperature decreases; bornite and chalcopyrite have a high solubility of gold (up to 2000-4000 ppm) at high temperature, 700° C, whereas decreasing temperature leads to a lower solubility of gold in these minerals, as low as 300 ppm at 500° C (Fraley and Frank, 2014). In addition, the replacement of bornite by digenite/ chalcocite as temperature decreases (Fig. 7) may also lead to formation of gold blebs from that in solid solution in the bornite.
- In some places it appears that pyrite was precipitated earlier than chalcopyrite and bornite.
- The magnetite is both igneous (originally disseminated in the intrusive rocks) and hydrothermal.
- The repetitive assemblages and their order (paragenesis) indicate that cooling was episodic, followed by reheating in pulses (Fig. 7).

References and Acknowledgements

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I acknowledge and thank Dr. Peter Dunkley, project site manager of Far Southeast Gold Resources, for permission to present this work, as well as Alina Gaibor, Glacialle Tiu and Jeffrey Pastoral of Gold Fields Ltd. for assistance with samples plus some figures. I also thank George Mrazek, University of Ottawa for the timely preparation of excellent polished thin sections, as well as Glenn Poirier and Erika Revesz for assistance with SEM work.