Oxidized, Water-rich Magmatism in the Hualgayoc Au-Cu Mining Camp, Northern Peruvian Cordillera

M Viala[1], K Hattori[1], P Gomez[2], J Trujillo[3], K Heather[4]

[1]Department of Earth Sciences, University of Ottawa, Ontario, Canada; [2]Gold Fields La Cima, Lima, Peru; [3]Compania de Minas Buenaventura S.A.A., Lima, Peru; [4]Regulus Resources Inc., Lima, Peru

① Introduction

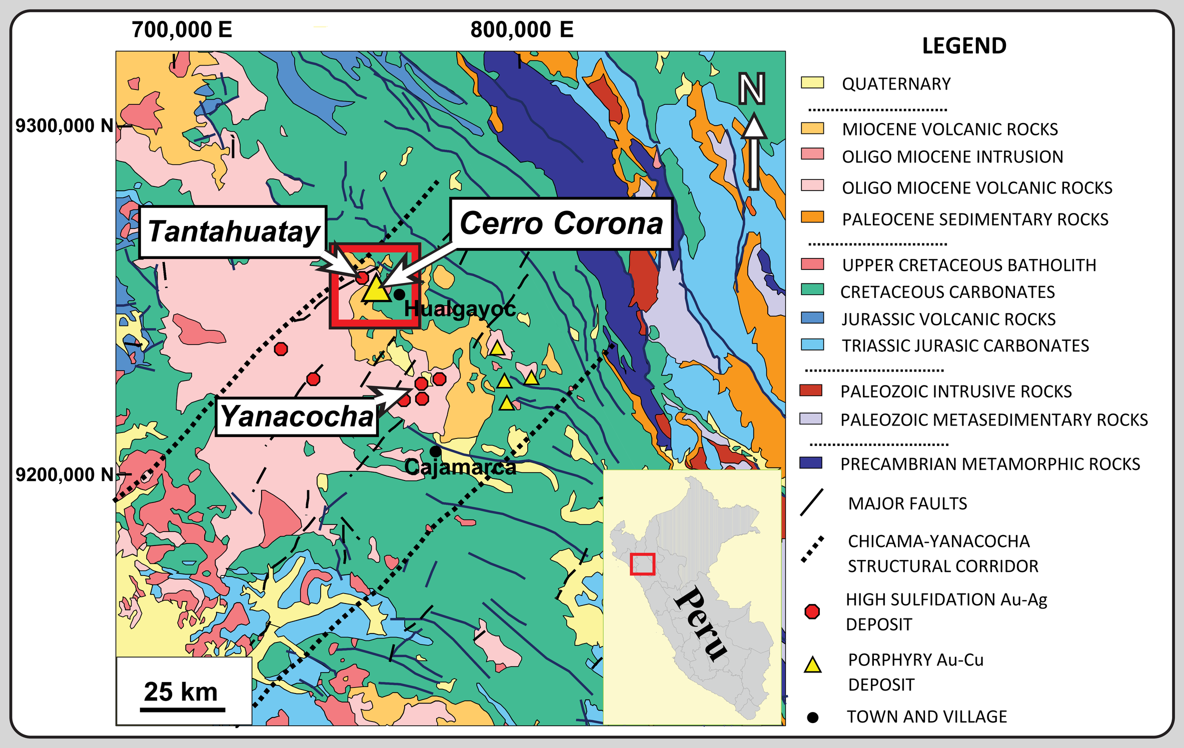


Fig. 1: Regional geological map of the Cajamarca province, from Cerro Corona technical

The Hualgayoc mining district in the Peruvian Cordillera is located 30km north of the Yanacocha high-sulphidation Au deposit. The district hosts numerous Au-Cu deposits.
This study characterizes the igneous rocks in the district to evaluate the features associated with Au-Cu fertile magmas.

② Geological setting

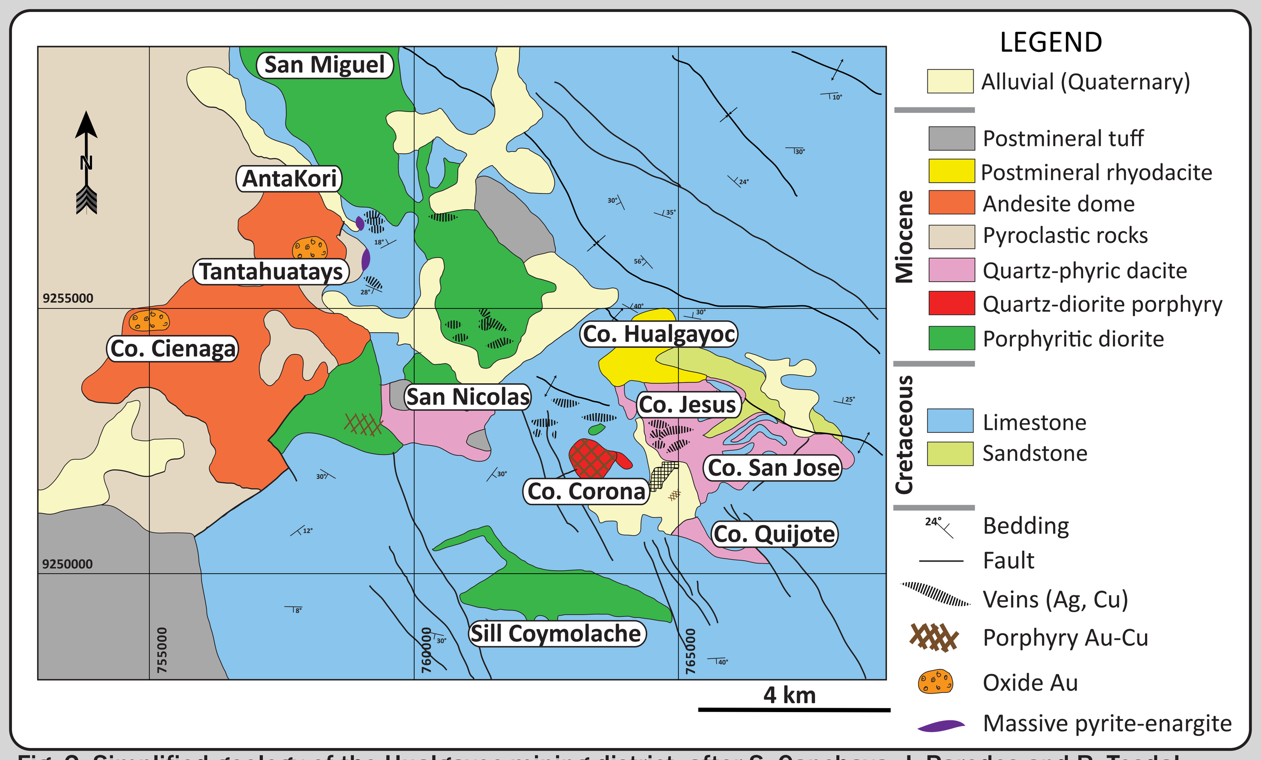
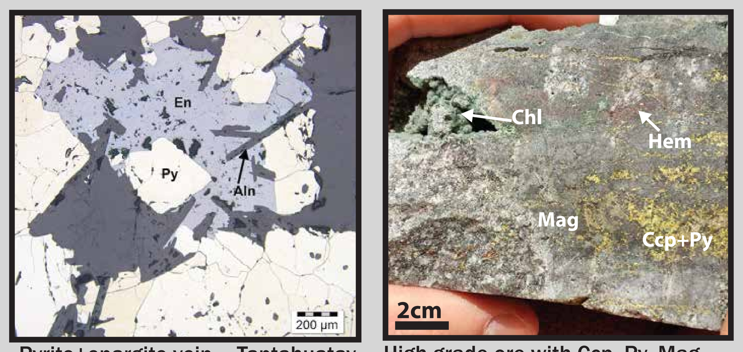


Fig. 2: Simplified geology of the Hualgayoc mining district, after S. Canchaya, J. Paredes and R. Tosdal (1996), cited by Gustafson et al. (2004) and modified.

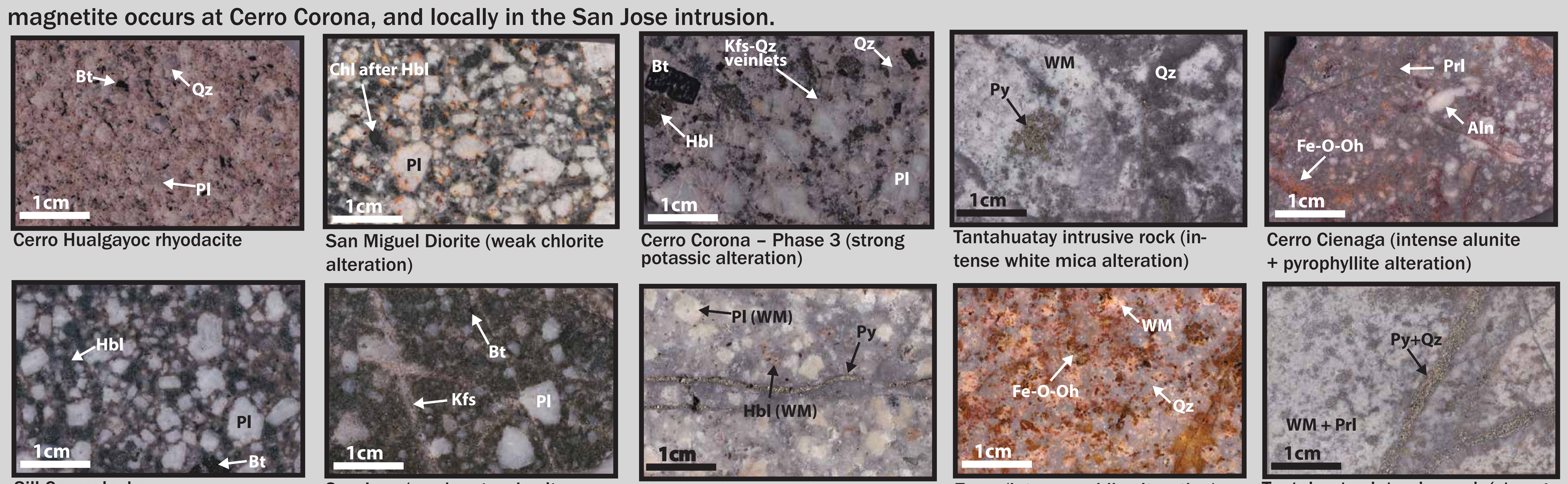
Cretaceous sedimentary rocks were intruded by dioritic rocks, including the Cerro Corona porphyry, and overlaid by andesitic to rhyolitic flows, domes and tuffs. Mineral deposits include the Cerro Corona porphyry Cu-Au mine, Tantahuatay high-sulfidation Au mine, and the AntKori Cu skarn deposit

③ Lithology and alteration

The dominant phase of intrusive rocks in the district is hornblende±biotite porphyritic diorite with magnetite micro-phenocrysts, suggesting relatively oxidized parental magmas. Volcanic rocks include rhyodacite domes north of Cerro Corona, and the andesitic to rhyolitic Calipuy formation which partially hosts the Tantahuatay and AntaKori deposits.
Weak to medium chlorite±epidote alteration affects the San Miguel and Cerro Quijote intrusions. Intense white mica alteration occurs in the San Jose and Cerro Jesus intrusion and rocks within the Tantahuatay and AntaKori deposits. Acidic alteration forming pyrophylite±alunite is present in Cerro Cienaga intrusion and within the Tantahuatay and AntaKori deposits. Potassic alteration forms K-feldspar + biotite + magnetite occurs at Cerro Corona, and locally in the San Jose intrusion.



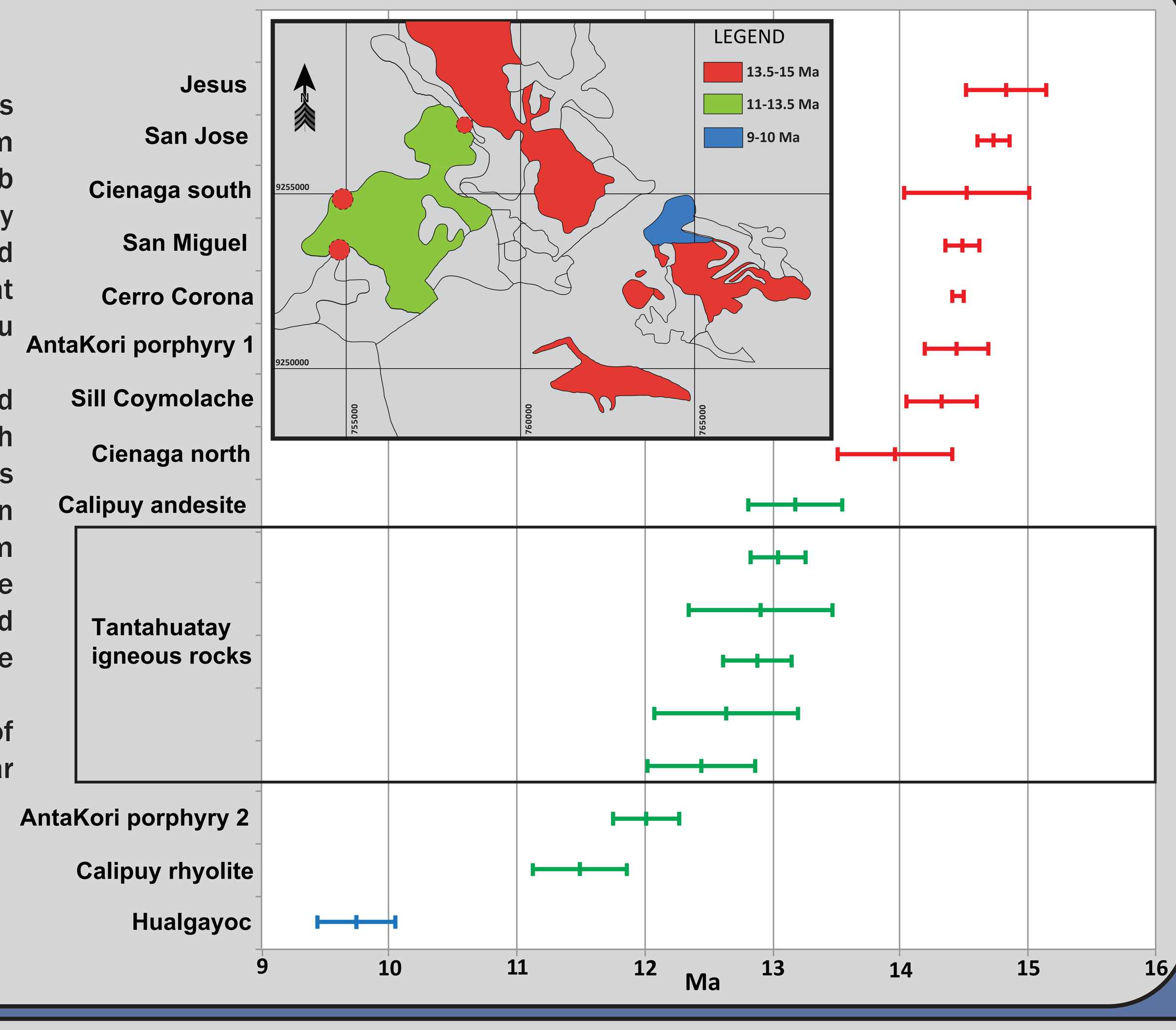
Pyrite+enargite vein – Tantahuatay
High-grade ore with Ccp, Py, Mag and Hem – Cerro Corona.



Cerro Hualgayoc rhyodacite
San Miguel Diorite (weak chlorite alteration)
Cerro Corona – Phase 3 (strong potassic alteration)
Tantahuatay intrusive rock (intense white mica alteration)
Cerro Cienaga (intense alunite + pyrophyllite alteration)
Sill Coymolache
San Jose (weak potassic alteration)
San Jose (strong white mica alteration)
Zorro (intense acidic alteration)
Tantahuatay intrusive rock (strong white mica+pyrophyllite alteration)

④ U-Pb zircon dates

The igneous activity in the district was previously thought to range from Paleocene to Miocene in age. New U-Pb zircon ages obtained in this study indicate that igneous activity ranged from 14.8Ma to 9.7Ma, similar to that at the Yanacocha high-sulfidation Au deposit.
Most intrusions formed between 14 and 15Ma. Some are associated with mineralization (Cerro Corona) whereas others appear to be barren (Coymolache). Magmatic activity from 13.5 to 11 Ma is focused in the Tantahuatay and AntaKori areas, and consists of porphyritic intrusions and the Calipuy volcanic formation.
Late magmatism at 9-10Ma consists of barren rhyodacite-rhyolite domes near Cerro Corona.



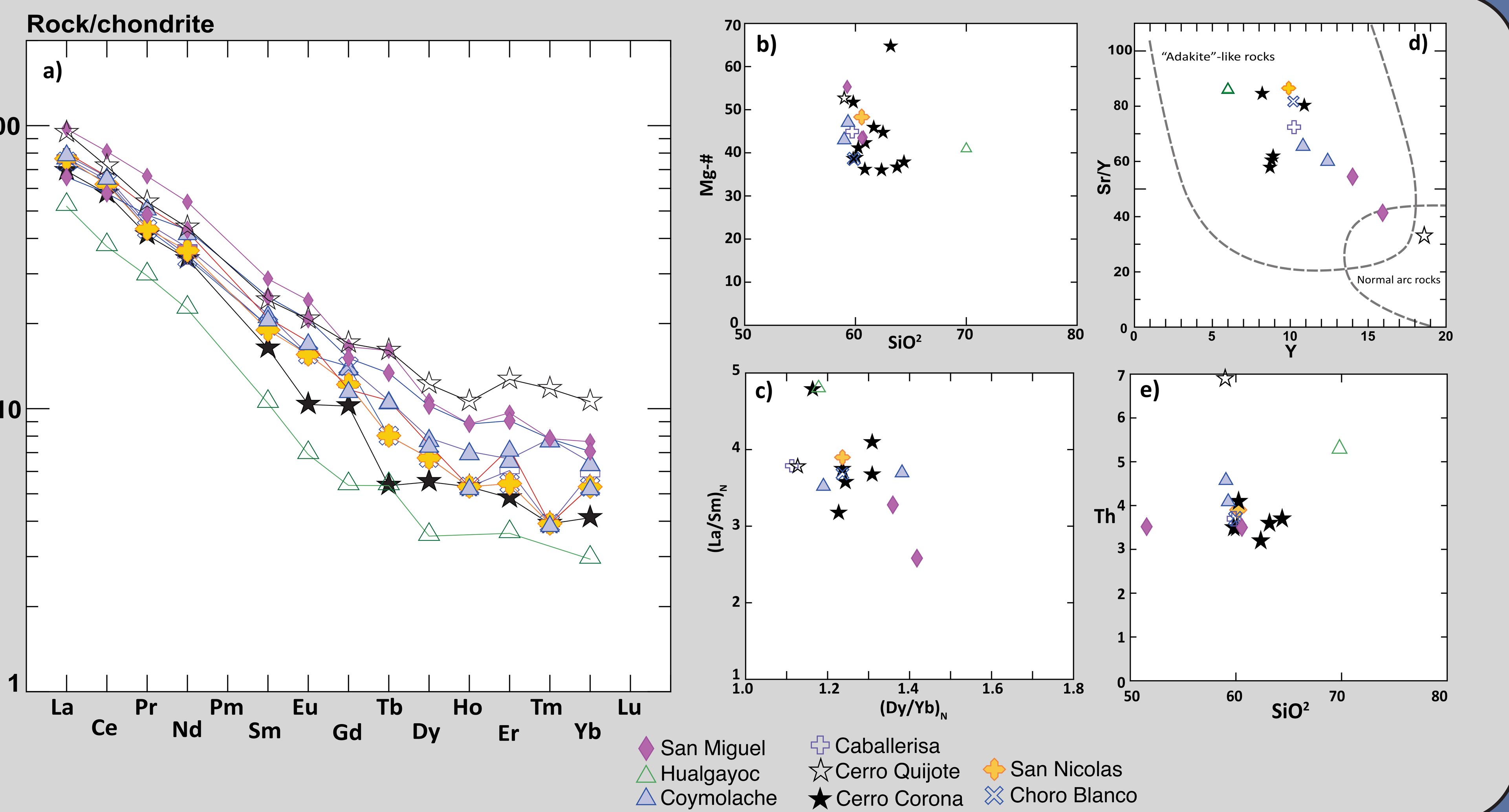
⑤ Bulk rock composition

All the intrusions have similar Mg-# (0.30-0.55) and SiO^2 (59-65 wt%) except the early phase of the Cerro Corona intrusive complex with Mg-# (0.65), and the Cerro Hualgayoc rhyolite which shows high SiO^2 content (70 wt%) (fig.b).

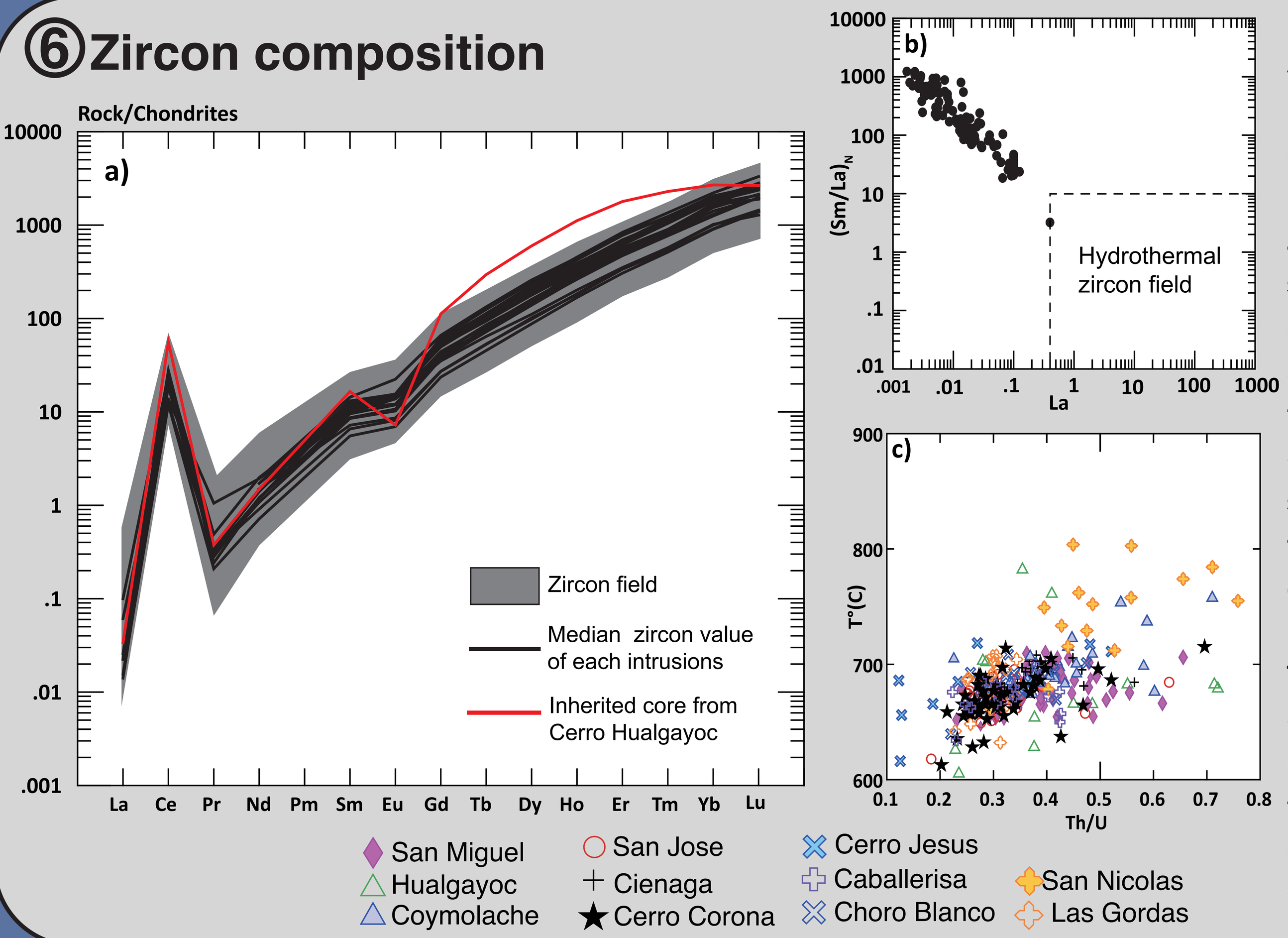
All intrusions show listric-shaped REE pattern (Fig. a), and low $[Dy]n/[Yb]n$ ratio (1.4-1.1) (Fig. c), reflecting preferential retention of middle REEs by amphibole in the source. Intrusions show a weak Eu anomaly (0.8-1.1) reflecting essentially no plagioclase fractionation.

All intrusions except Cerro Quijote show an "adakitic"-like geochemical signature with high Sr/Y ratios (40-90) and low Y (5-16ppm) (Fig. d). High Sr/Y can be explained by high water contents in parental magmas that suppress plagioclase crystallization (Sisson and Grove, 1993). This is consistent with the presence of phenocrysts of biotite and hornblende in most intrusions.

Low Th content in samples (3-7 ppm) indicates essentially no assimilation of siliciclastic rocks during magma ascent through the thick continental crust (Fig. e).



⑥ Zircon composition



Sharp oscillatory zoning and low light REEs concentration in zircons confirm magmatic origin (fig. b).

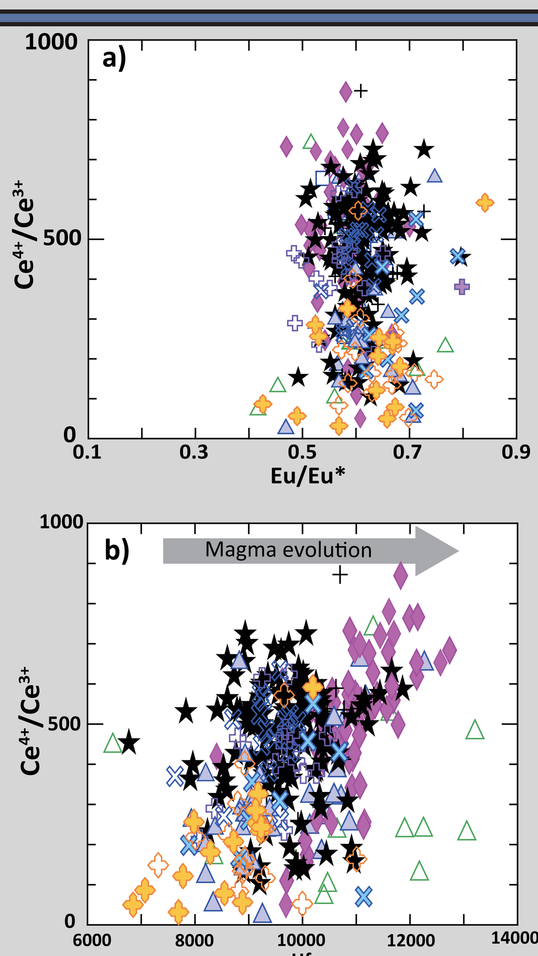
Zircon grains from all intrusions show a similar REE pattern with relatively flat middle to heavy REEs, weak negative Eu anomaly and high Ce anomaly. In contrast, inherited cores show concave-shaped heavy REEs profile and a strong negative Eu anomaly, suggesting the derivation from the basement rocks (fig. a).

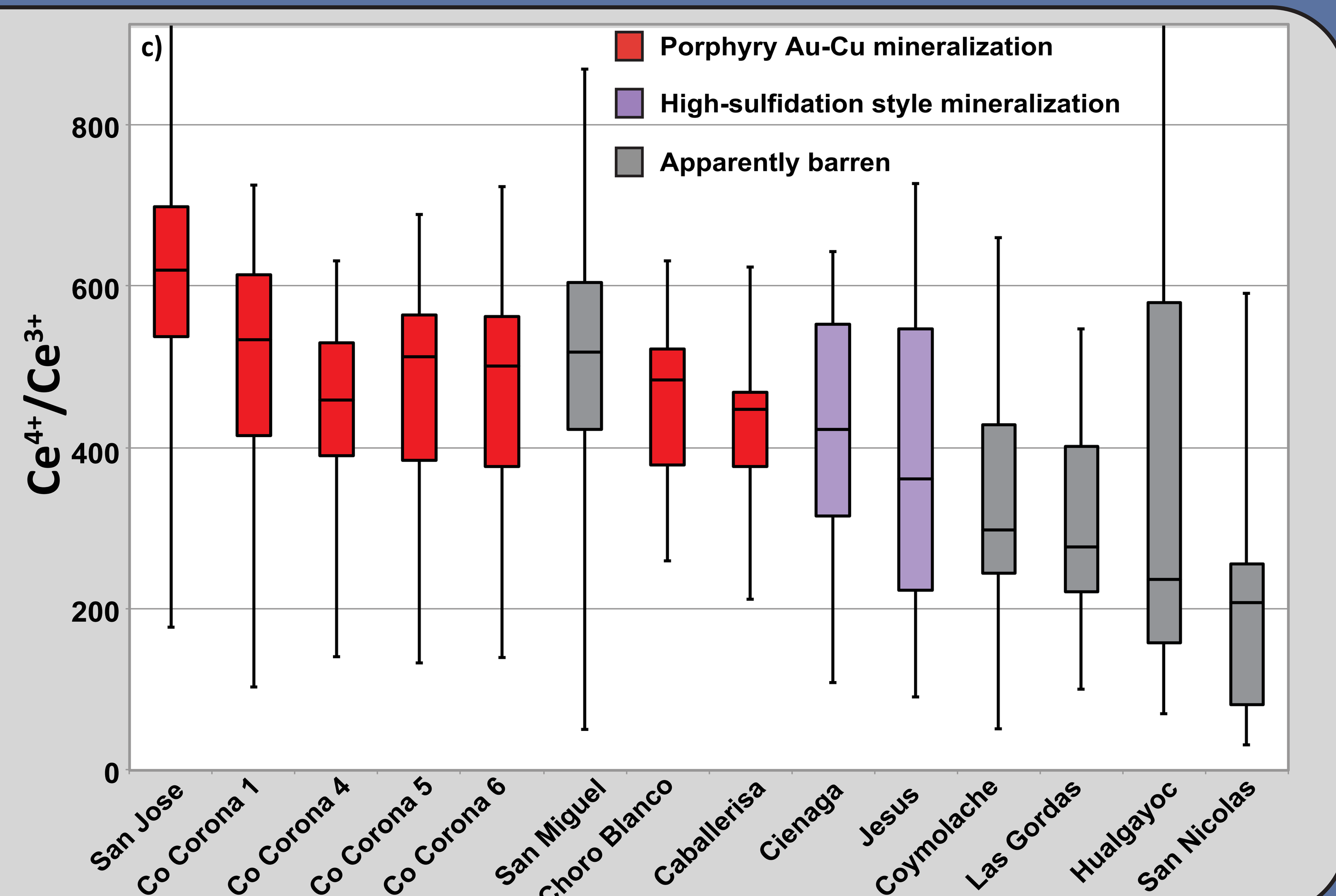
The Ti-in-zircon thermometer yielded crystallization temperatures between 620-720 C° except the San Nicolas intrusion which appears to have crystallized at higher temperature (720-800 C°) (fig.b).

⑦ Ce and Eu anomaly in zircon

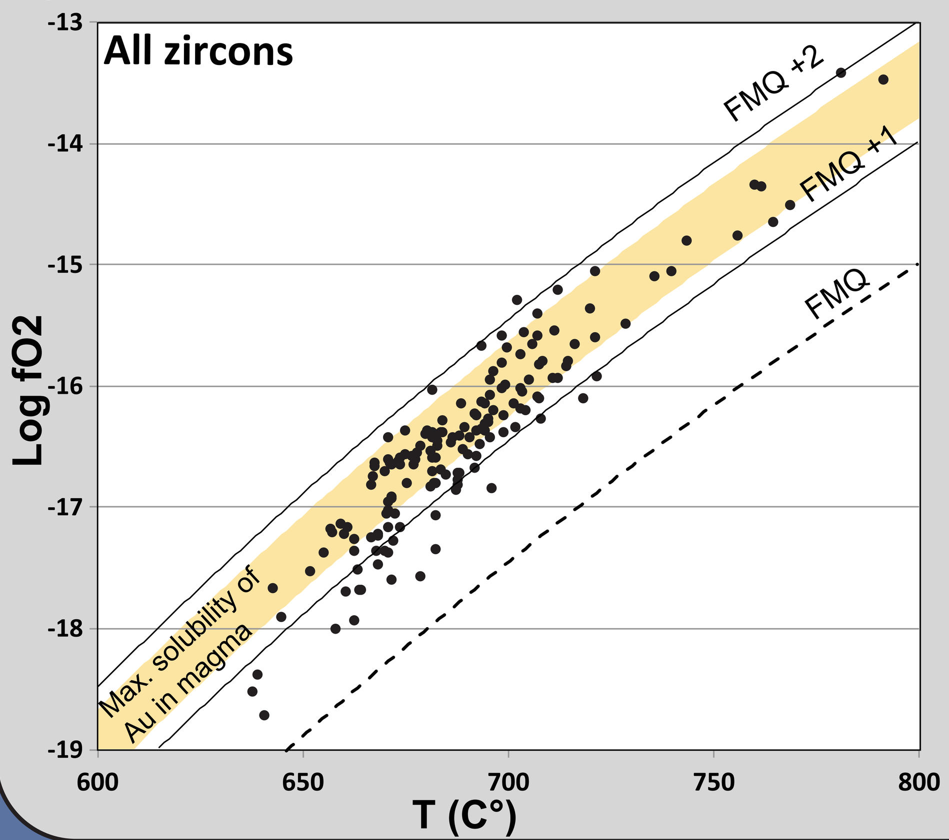
REEs are mostly +3, but Ce can be +4 under oxidized conditions and Eu +2 under reduced conditions. Zircon readily incorporates Ce^{4+} into the Zr^{4+} site. Therefore, the Ce and Eu anomaly in zircon may be used to evaluate magmatic redox state. All zircons have consistently low anomalies of Eu (Eu/Eu^*=0.5-0.7) (Fig. a) and variable Ce^{4+}/Ce^{3+} (10-900). Ce^{4+}/Ce^{3+} appears to increase with magma evolution (fig.b).

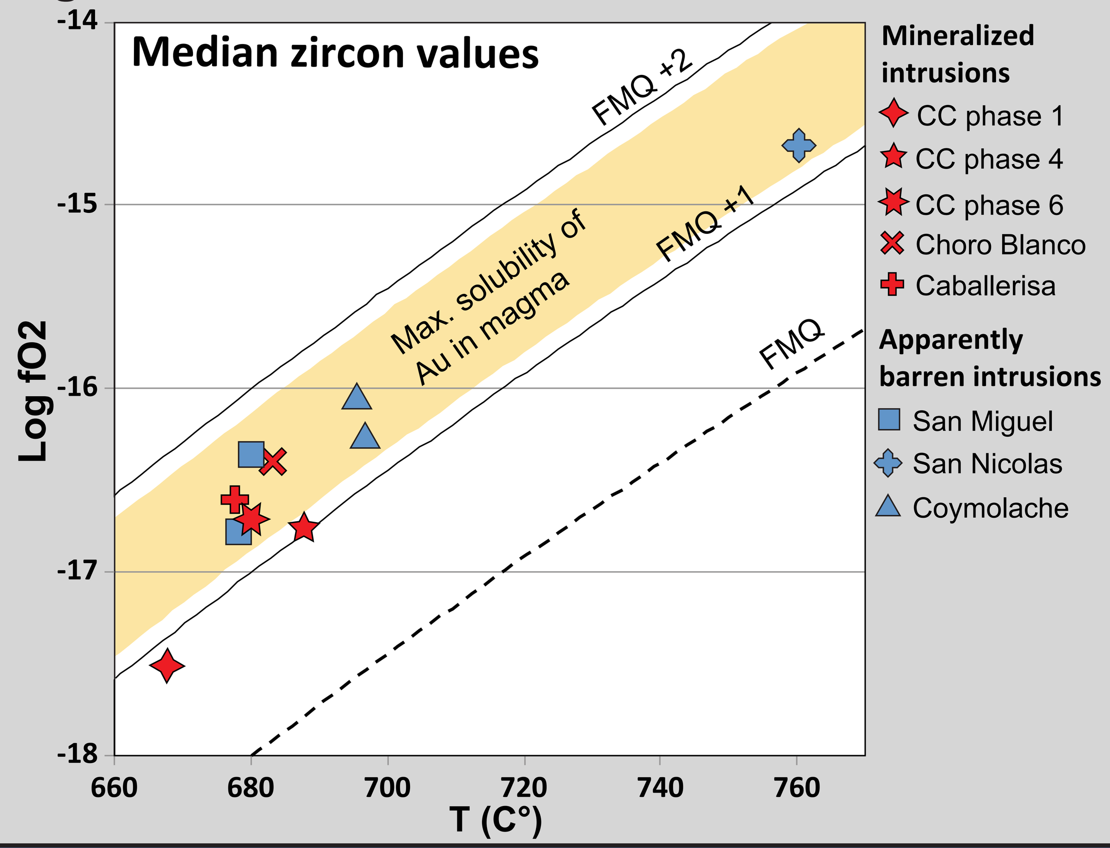
All mineralized intrusions including the Cerro Corona porphyry have high median Ce^{4+}/Ce^{3+} values (360-625) while all apparently barren intrusion have low median Ce^{4+}/Ce^{3+} values (200-290), except the San Miguel intrusion (~ 500) (Fig. c).





⑧ Magma oxygen fugacity estimated using Ce^{4+}/Ce^{3+} in zircon





The magmatic oxygen fugacity of the intrusions calculated following the method of Smythe and Brenan (2016) show moderately oxidized values, FMQ +0.5 to +2, independent of the association with mineralization. Mineralized Cerro Corona porphyry intrusions appear to be less oxidized with median value of FMQ +0.8 to +1.3.
Experimental data shows maximum solubility of Au in andesitic melt at around FMQ +1.5 and decreases at higher and lower fO_2 (Botcharnikov et al. 2010). In contrast, the solubility of Cu in melt increases with increasing oxidation conditions (Zajacz et al. 2012). The median fO_2 value of magmas from the Hualgayoc mining district, FMQ +1.28, correspond to the condition for relatively high Au solubility and appears to be consistent with the abundant Au mineralization in the district with relatively high Au/Cu ratio, ~1.7 x10-4, of the Cerro Corona deposit.

⑨ Implication for exploration

Zircon grains from mineralized intrusions have higher Ce^{4+}/Ce^{3+} than most zircon grains from barren intrusions. This suggests that the Ce anomaly in zircon can be used to identify intrusions that may be potentially Au-Cu fertile within a district.
Our results also suggest that Au-fertile districts are characterized by moderate magma oxidation conditions (FMQ +1 to +2). This may be useful to identify potentially fertile districts.

⑩ Summary and on-going work

Au-Cu mineralization in the district is associated with hydrous, moderately oxidized magmas that originate from amphibole-bearing source rocks, with little to no crustal assimilation. Contemporaneous emplacement of mineralized and barren intrusions in the district suggest that oxidized magma do not necessarily produced Cu and Au mineralization. The mineralization requires other factors including focused injections of magmas and hydrothermal activity to concentrate the metals to economic values.
On-going work includes more U-Pb zircon dating, and trace element analysis of zircon and bulk rocks to evaluate any differences for magmas associated with high-sulfidation Au deposits, skarn and porphyry Au-Cu deposits.

References

- Botcharnikov, R. E., Linnen, R. L., Wilke, M., Holtz, F., Jugo, P. J., & Berndt, J. (2011). High gold concentrations in sulphide-bearing magma under oxidizing conditions. Nature Geoscience, 4(2), 112.
- Gustafson, L. B., Vidal, C. E., Pinto, R., & Noble, D. C. (2004). Porphyry-epithermal transition, Cajamarca region, northern Peru. Society of Economic Geologists, 11, 279-299.
- Sisson, T. W., & Grove, T. L. (1993). Experimental investigations of the role of H_2O in calc-alkaline differentiation and subduction zone magmatism. Contributions to mineralogy and petrology, 113(2), 143-166.
- Smythe, D. J., & Brenan, J. M. (2016). Magmatic oxygen fugacity estimated using zircon-melt partitioning of cerium. Earth and Planetary Science Letters, 453, 260-266.
- Zajacz, Z., Candela, P. A., Piccoli, P. M., Wälle, M., & Sanchez-Valle, C. (2012). Gold and copper in volatile saturated mafic to intermediate magmas: Solubilities, partitioning, and implications for ore deposit formation. Geochimica et Cosmochimica Acta, 91, 140-159.

Aknowledgements

We thank Gold Fields Cerro Corona mine staff for their logistic support during our field work; Buenaventura and Regulus Resources Inc. for their help with sampling; Samuel Morfin, Glenn Poirier and Alain Mauviel for their analytical assistance; and Jeffrey Hedenquist for his advice on the project. The project was supported by Natural Science and Engineering Council of Canada Discovery Grant to K.H.