Reaction, deformation and fluid flow during porphyry copper formation

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Project Highlights:

You will answer the following key research questions using the El Teniente Porphyry Copper deposit

- What are the reaction thermodynamics and kinetics of ore formation?
- What do mineralogies and bulk compositions tell us about fluid fluxes?
- What are the links between observed vein geometries and predicted fluid fluxes?

Overview:

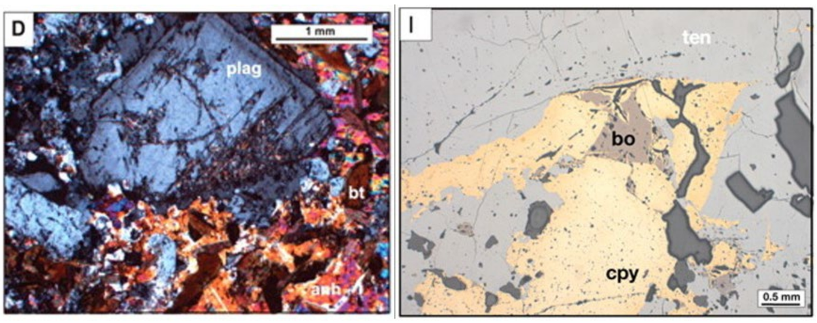

Figure 1: Minerals from El Teniente. Left: Anhydrite replacing plagioclase. Right: Cu minerals (Vry et al., 2010)

Cu is a critical element because it is needed for the clean energy transition. Porphyry copper ore minerals form from reaction between fluids exsolved from calc-alkaline magma and various host rocks (trigger 4 of Wilkinson (2013)). There are three incompletely understood aspects focussed on here, which will provide novel insights into porphyry copper formation. We will target the El Teniente porphyry copper, Chile, one of the world's largest, with a wealth of material to investigate.

1) Driving forces and rates of **reaction** are key controls on ore formation, otherwise Cu remains in the fluid. El Teniente shows varied Cu ore relationships (Skewes et al., 2005), for example, associated with magmatic and/or hydrothermal anhydrite. Henley et al. (2022) show breakdown of plagioclase to anhydrite is a key part of sulphide depositional. Because this involves silicates, and not just sulphide precipitation from fluid, a holistic approach to understanding reactions is needed. You will unravel the reaction/precipitation story using petrographic and chemical data from entire assemblages including all reactant and product and precipitated minerals.

2) Focused **fluid flow** and highly efficient precipitation are needed to transport, deposit, remobilise and redeposit Cu for high grade (Cu rich). One conceptual model involves a rock reacting with pulses of fluid, each characterised by "fluid/rock ratio", and sequestering Cu from each pulse. Another model involves gradual precipitation during flow along a temperature gradient making "time integrated fluid flux" the appropriate description (Ferry and Dipple, 1991). You will apply thermodynamic models to understand conditions of ore formation and will construct mathematical models to quantify fluid flow.

3) Fluid flow needs fracture networks, recorded when filled as **veins**. The microstructure of veins provides information about mineral precipitation and fluid-rock interaction. The evolving geometry of fracture networks must be linked to the timescales of porphyry copper formation and the fluid fluxes inferred from chemical arguments. You will undertake this via petrography and hand specimen characterisation constrained in a 3D sample framework.

You will synthesise these three themes - reaction, brittle deformation and fluid flow – in their km-scale geological context to provide new insights into porphyry copper formation.

Methodology:

1) Petrography (optical microscopy, SEM backscatter) will provide the fundamental textural data to constrain **reactions**. A Zeiss Axio will provide full section high resolution optical mapping. Chemical data will be obtained via EDS on SEM; automated SEM (TESCAN TIMA) will provide context for LA-ICP-MS. Electron Backscatter Diffraction will provide insights into reaction mechanism.
2) Thermodynamic models such as CHIM-XPT (Reed et al., 2013) will allow theoretical predictions of ore forming reactions for fluid compositions constrained by existing fluid inclusion LA-ICP-MS data. Mathematical models will constrain the time-integrated **fluid fluxes**, or fluid/rock ratios, required for bulk composition changes.
3) **Vein** characterization at the sample and microscopic scale (shape, relative orientation, spatial distribution, mineralogy). We will first look for empirical links between veins, metasomatism and reaction. Vein distribution will be heterogeneous so we will explore a variety of upscaled models to constrain large scale permeability and link it to fluid flux interpretations.

Possible Timeline

Year 1: literature review, selection of initial samples to study based on literature, starting in most altered (potassic) zone with some focus on anhydrite occurrence. Petrography, basic SEM and chemical characterisation to address aspect (1) and (3).
Year 2: Advanced chemical characterisation, Electron Backscatter Diffraction; thermodynamic modelling for aspect (2). Depending on the level of detail the student and team decides is appropriate, investigation of samples from phyllic and propylitic alteration zones.
Year 3: Final data gathering, thermodynamic modelling, fluid flux modelling, synthesis, paper and thesis writing.

Training and skills:

TARGET researchers will participate in a minimum of 40 days training over the 3.5 years of study composed of:

- an annual one-week workshop dedicated to their year group, and tailored to that cohort's needs in terms of skills development – *for the first three years of their study*;
- an annual all-TARGET workshop with cross-year interactions, advanced training and opportunities to specialise in particular areas – *all years of study*;
- a number of one-day workshops;
- additional online events and in-person workshops attached to relevant conferences.

<u>Specific training</u>
Petrography from ore mineralogy, metamorphic and igneous perspectives, using optical and SEM imaging. Microstructural development including gathering EBSD data and interpreting it using various quantitative methods. Quantitative chemistry of major and trace elements; interpretations in terms of qualitative processes. Measurements and interpretation of veins and fractures. Quantitative

modelling using thermodynamic packages; generation of simple reactive fluid flow models. Synthesis of various types of geological information.

Partners and collaboration (including CASE):

The student will interact with **Wheeler** and **Mcnamara** who are skilled in microstructural and microchemical analysis. Frequent visits to London will allow the student to benefit from **Wilkinson's** porphyry copper expertise and from advanced chemical analysis equipment. **Morata** and **Arancibia** will help train the student in generic and specific Chilean aspects of porphyry copper deposits. **Bonson** has a broad background consulting for mineral extraction industries (https://tektonik.co.uk/) and has specific experience studying the role of anhydrite in the precipitation of metals in copper deposits. He will advise based on his scientific expertise and his understanding of industrial imperatives.

Further reading:

Ferry, J. M. and Dipple, G. M. (1991) 'Fluid flow, mineral reactions and metasomatism', *Geology,* 19, pp. 211-214.

Henley, R. W., Mernagh, T., Leys, C., Troitzsch, U., Bevitt, J., Brink, F., Gardner, J., Knuefing, L., Wheeler, J., Limaye, A., Turner, M. and Zhang, Y. (2022) 'Potassium silicate alteration in porphyry copper-gold deposits: a case study at the giant maar-diatreme hosted Grasberg deposit, Indonesia', *Journal of Volcanology and Geothermal Research,* 432, pp. 107710. DOI: https://doi.org/10.1016/j.jvolgeores.2022.107710.

Reed, M., Rusk, B. and Palandri, J. (2013) 'The Butte Magmatic-Hydrothermal System: One Fluid Yields All Alteration and Veins', *Economic Geology,* 108(6), pp. 1379-1396. DOI: 10.2113/econgeo.108.6.1379.

Skewes, M. A., Arévalo, A., Floddy, R., Zuñiga, P. and Stern, C. R. (2005) 'The El Teniente Megabreccia deposit, the world's largest copper deposit', in Porter, T.M. (ed.) *Super Porphyry Copper and Gold Deposit - A Global Perspective*. Adelaide, Australia: PGC Publishing, pp. 83-114.

Vry, V. H., Wilkinson, J. J., Seguel, J. and Millán, J. (2010) 'Multistage Intrusion, Brecciation, and Veining at El Teniente, Evolution of a Nested Porphyry System', *Economic Geology,* 105(1), pp. 119-153. DOI: 10.2113/gsecongeo.105.1.119.

Wilkinson, J. J. (2013) 'Triggers for the formation of porphyry ore deposits in magmatic arcs', *Nature Geoscience,* 6(11), pp. 917-925. DOI: 10.1038/ngeo1940.

Further details:

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