How long does it take to make a giant porphyry copper deposit? Advances in high-precision geochronology and modelling of magmatic–hydrothermal processes

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Introduction

Porphyry copper deposits are characterized by multiple phases of magma emplacement alternating with hydrothermal veining, alteration and copper deposition. This geological complexity has contributed to the notion that the formation of the best deposits is a complex process drawn out over an extended time period. Combining the most precise geochronological constraints with microchemical evidence from zircon concur with physical models that the formation of even the biggest deposits is a rapid process lasting a few 10'000 years.

Methods

A workflow of field documentation, zircon petrography using SEM-CL imaging, LA-ICPMS microchemistry including Hf isotopes, and final recovery of the same crystals for chemical-abrasion isotope-dilution thermal-ionization mass spectrometry (CA-ID-TIMS) provides time calibrated information about the evolution of mineralizing magma chambers. These data may be complemented by Re–Os geochronology of molybdenite, whereas in-situ LA-ICPMS U–Pb geochronology and Ar–Ar dating are useful for regional age determination but not for measuring the duration of deposit formation.

Petrochronology

Zircon petrochronology (the combination of U–Pb geochronology with the trace-element geochemistry of zircons, including the estimation of crystallization temperatures from trace-level Ti in solid solution has experienced huge progress over the last decade with regard to analytical precision, accuracy (notably by CA-ID-TIMS) and efficiency of data gathering (by LA-ICPMS). Single crystals of magmatic zircon preserve a record of crystallization age and trace-element content (Szymanowski et al. 2017). Samples of igneous rock typically contain zircon populations with resolvable variations in age and degree of chemical differentiation preceding emplacement and final solidification of the sample. Assuming that the youngest zircon crystals in successively emplaced pre-, inter- and post-mineralization prophyries date the time of emplacement, reliable age brackets on vein and sulfide mineralization ages have been obtained.

Results and discussion

Combining the most decisive case studies carried out at different scales and locations, four major conclusions regarding magma evolution and time scales in porphyry-mineralizing magmatic systems have emerged (Ok Tedi, Papua New Guinea; Koloula, Solomon Island; Batu Hijau, Indonesia; Bajo de la Alumbrera, Argentina; Large et al. 2018; Tapster et al. 2016; Buret et al. 2016, 2017).

(1) The magmatic history of ore-producing districts, typically kilometers to tens of kilometers in scale, is long-lived and typically evolves magma emplacement over several millions of years or more. This long-lived magmatism is driven by lower-crustal magmatic differentiation, fractional crystallization and crustal assimilation, enhancing the initial volatile content of mantle melts. Extrusive volcanism typically stops before porphyry ore formation, but major eruptions may immediately follow and possibly terminate the process of porphyry copper ore formation by catastrophic magma and volatile release.

(2) Hydrothermal ore emplacement in quartz vein stockworks, cutting typically composite porphyry

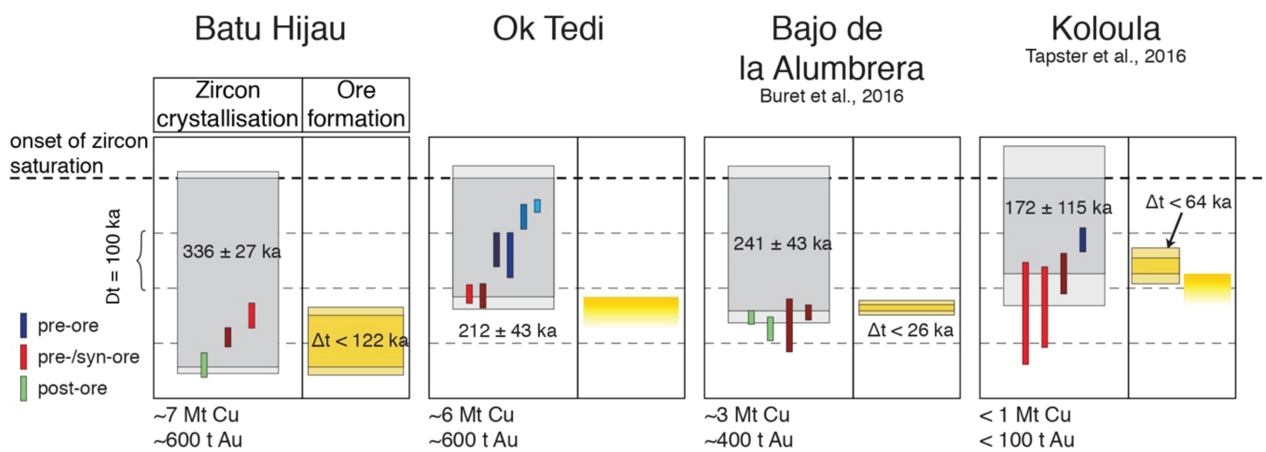

Fig. 1. Summary data comparing deposits of different size, Batu Hijau (Indonesia), Ok Tedi (Papua New Guinea; Large et al. 2018), Bajo de la Alumbrera (Argentina) and Koloula (Solomon Island).

stocks, is bracketed that this process extends over 10'000 to 100'000 years for world-class to giant ore, but not millions of years, by multiple pulses of alternating porphyry emplacement and vein formation documented by contact intersections in the field.

(3) Zircon trace-element compositions show that successive porphyries in a stock are derived from the same magma source and follow a common trend of fractional crystallisation of plagioclase, amphibole and titanite.

(4) Results are consistent with the interpretation that a single upper-crustal magma reservoir at 5–10 km depth acts as the source of fluid making one ore deposit. Antecrysts with geochemical signatures recording upper-crustal fractionation indicate life-times of large crystallizing magma chambers in the upper crust lasting several 100'000 years.

Summary

In summary, economic porphyry copper deposits are not assisted by complexity or by extended duration of superimposed processes. Rather, the largest and richest deposits result from fine-tuning the balance of concurrent processes of fluid production, fluid focussing and heat transfer from the magmatic fluid plume to convecting meteoric water. The thermal lifetime of large upper crustal magma reservoirs as the source of ore fluids and all ore forming components typically lasts a few hundred thousand years, determined by the rate of cooling of the magma chamber. The duration of one or several events of porphyry emplacement and hydrothermal Au–Cu mineralization is much shorter, spanning a range of tens of thousands of years in total, with even shorter durations of individual magma and fluid pulses determined by the rate of fluid extraction from the magma chamber.

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