Supergiant porphyry Cu deposits are failed large eruptions

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Abstract

Porphyry copper deposits, the principal natural source of Cu and Mo, form at convergent margins. Copper is precipitated from fluids associated with cooling magmas that have formed in the mantle and evolved at variably deep crustal levels, before rising close to the surface where they exsolve fluids and copper. Despite significant advances in the understanding of their formation, there are still underexplored aspects of the genesis of porphyry copper deposits. Here, we address the role played by magma injection rates into the shallow crust on the formation of porphyry copper deposits with different copper endowments. Using a mass balance approach, we show that supergiant porphyry Cu deposits (>10 Mt Cu) require magma volumes and magma injection rates typical of large volcanic eruptions. Because such volcanic events would destroy magmatic-hydrothermal systems or prevent their formation, the largest porphyry Cu deposits can be considered as failed large eruptions and this may be one of the causes of their rarity.

Introduction

The last decades have seen a continuous increase in the understanding of how porphyry Cu deposits form. Several studies have unveiled the different processes that control the formation of porphyry Cu deposits, including, among others, geodynamic setting, tectonics, magma genesis, magma evolution, and fluid chemistry^{1–14}. During the last years there has also been an effort towards a physical understanding of porphyry-related processes through thermodynamic and petrologic modelling^{15–18}. From this point of view, simple mass balance constraints are very useful to set quantitative boundaries within which various processes interplay to form porphyry deposits. Arc magmas are characterized by a narrow range of Cu contents^{19,20} and also fluid-melt partition coefficients for Cu are limited to a relatively restricted range²¹. Thus, purely from mass balance considerations, the main parameter determining the size of a deposit (considering similar precipitation efficiencies from the hydrothermal fluid) is the mass of fluid, which, in turn, is closely associated with the mass of degassing magma^{16,17}.

The mass of magma that can degas to fuel the formation of hydrothermal ore deposits depends on the thermal structure of the crust, as well as the depth and duration of magma accumulation. Thermal and petrological modelling shows that, for long-term average rates of vertical magma injection typical of arc settings (e.g., 5 mm/year; Ref. ²²), the accumulation of the magma masses required for the formation of large ore deposits can only occur if magma is injected into the mid- to lower crust for periods of several Myr¹⁷. However, the accumulation of large magma volumes in mid- to lower crust systems does not guarantee *per se* the formation of a porphyry system. This is confirmed by the absence of a relationship between the duration of magma accumulation at deep crustal levels, which leads to the largest and thus most fertile transcrustal magmatic systems, and the Cu endowments of porphyry deposits (Fig. 1; refs. ^{23–26}).

Magmas in the mid- to lower crust are mostly H₂O-undersaturated, because of the strong pressure dependency of H₂O solubility in silicate melts²⁷. Therefore, the exsolution of mineralising fluids requires

magma ascent to shallower crustal levels. The depth interval (8–17 km) at which deep fertile magmas saturate according to the calculations of ref. ¹⁷ overlaps with the estimated emplacement depths of magma reservoirs feeding the porphyry fingers around which mineralization develops (e.g., ref. ²⁸ and references therein).

We propose that while large magma volumes in the mid- to lower crust are a pre-requisite for the potential formation of large porphyry-Cu deposits, it is the volume of magma transferred to shallower depths that releases the mineralising fluids and, therefore, determines the ultimate Cu endowments of the deposits.

Correlation between Cu endowments and the overall duration of the mineralizing events^{13,17} suggests that the longer lasting is the overall ore-forming process, the larger is the Cu endowment of the deposit (Fig. 2; see also refs. ^{16,29}). Therefore, ultimately the Cu endowments of porphyry deposits depend on the efficiency of transfer of the largest possible magma volumes from the mid-, lower crustal reservoir to the shallow parental magma chamber feeding the porphyry fingers around which ore deposition occurs. This transfer is accompanied by the release of the mineralizing fluids ultimately forming the deposit.

Here, we show that Cu endowments of porphyry deposits increase with the volumes and rates of magma transfer from the mid- and lower-crustal reservoirs to shallower depths. The largest porphyry Cu deposits require magma volumes and injection rates into the upper crust that overlap those leading to large eruptions^{15,38,39}. Because volcanic eruptions are detrimental for magmatic-hydrothermal systems, as they would either destroy them or prevent their formation^{40–42}, the largest porphyry Cu deposits can be considered as failed eruptions.

Model Rationale And Constraints

We used two simple constraints to obtain average magma injection rates from the mid- and lower crust accumulation zone into the upper crustal magma reservoir above which mineralization takes place: (i) the volume of magma required to precipitate a specific Cu mass, with a conservative precipitation efficiency of 50%⁴³; (ii) the time interval within which such magma volume is transferred from the lower- and mid-crustal reservoirs into the upper crust where Cu is precipitated, which is provided by geochronological data. The ratio between these two parameters gives the average magma injection rate corresponding to a specific Cu endowment.

Magma volume and Cu endowments

The point (i) above is constrained by the relationship between potential Cu endowments of transcrustal magmatic systems and the mass (volume) of magma accumulated in the mid-, lower-crust (refs. ^{13,17}; Methods and Table 1). Modelling of ref. ¹⁷ indicates that the largest potential Cu endowments are associated with magma accumulations occurring at pressures higher than 0.4 GPa (> ~ 18 km) and for injection periods longer than 2.5–3.0 Myr.

Table 1

Constraints on the parameters used in the Monte Carlo modelling of magma injection rates.

Parameter	Range of values or value
Magma injection rate in the mid- to lower crust through a circular surface of 15 km diameter	0.0009 km ³ /yr
Duration of magma injection in the mid- to lower crust	0–5 Myr
Pressure at which magma injection occurs in the mid- to lower crust	0.4–1.2 GPa
Potential Cu endowments in mid- to lower crust accumulated magma systems (MtCu)	0-150 Mt Cu
K _D fluid-melt for Cu (K _D)	2-100
Mid- to lower crust magma volumes in the corresponding to a specific Cu endowment (within the random range above 0-150 Mt Cu) (MLC_magmaVol)	$a \cdot \text{MtCu}^b$ (Eq. 1)
Parameter “a” in equation above ¹	60–700
Parameter “b” in equation above ¹	$-0.187767 \cdot \ln(a) + 1.507068$
Number of magma pulses transferring a mid- to lower crust magma accumulation corresponding to a specific Cu endowment to its H ₂ O saturation depth in the shallower crust (N_pulses)	5–20
Duration of magma pulses transferring a mid- to lower crust magma accumulation corresponding to a specific Cu endowment to its H ₂ O saturation depth in the shallower crust (Pulse_duration)	10000–100000 years
Magma volume of each pulse transferring a mid- to lower crust magma accumulation corresponding to a specific Cu endowment to its H ₂ O saturation depth in the shallower crust (Pulse_volume)	MLC_magmaVol / N_pulses
Duration of magma transfer from the mid- to lower crust to the shallow crust	Pulse_duration * N_pulses
Magma injection rate from the mid- to lower crust accumulation reservoir into the shallow crust	Pulse_volume / Pulse_duration
¹ These ranges correspond to enveloping curves enclosing 95% of the data in the correlation between magma volumes accumulated in the mid- to lower crust and their potential Cu endowments exsolvable with fluids at H ₂ O saturation depth with a 50% precipitation efficiency for Cu (Fig. 3).	

The accumulated magmas are characterized by relatively high H₂O contents (6–18 wt.%), yet they are H₂O-undersaturated at depths > 0.4 GPa because of the strong pressure dependence of H₂O solubility in silicate melts²⁷. These magmas can release fluids and potentially lead to the formation of porphyry deposits only if they ascend to depths at which they become H₂O-saturated (~ 8 and 17 km from ref. ¹⁷). Fluid saturation would be achieved at higher depths considering CO₂-bearing magma. However, early excess fluids would be CO₂-rich⁴⁴ and represent a small contribution to the total mass of fluid released²⁷.

For these reasons, in our calculations we simplistically consider that magmas contain exclusively H₂O and that the volumes of magma generated in the lower crust (0.4 to 1.2 GPa), which determine the maximum potential Cu endowment of the porphyry deposits¹⁷ (Fig. 3), are transferred to their H₂O saturation depth. This, in turn, depends on the H₂O content and composition that these magmas acquire at deep crustal levels. At the depth of H₂O saturation, we consider that magmas release the entire amount of H₂O (and associated Cu through the random range, 2 to 100, of K_D values used in the model: Table 1), i.e., we consider that all H₂O is exsolved because of decompression and isobaric crystallization.

Figure 3 shows the expected broadly positive correlation between potential Cu endowments and calculated magma volumes accumulated at mid- to lower crustal levels (i.e., at pressures between 0.4 and 1.2 GPa). The range of variable Cu endowments associated with a specific magma volume depends on: 1) the different depths at which magmas can accumulate in the model (0.4 to 1.2 GPa), which in turn controls the fluid content of the residual melt; 2) the different durations of magma injections (0 to 5 Myr), and, to a lesser extent, the range of K_D fluid-melt values for Cu used in the model (2-100). Since more than 95% of the simulations fall within the two exponential curves of Fig. 3, we have modelled the magma injection rates for the transfer of the magma volumes to the shallow crust comprised within these two curves (Table 1 and Methods). Figure 3 shows that the largest potential Cu endowments (up to a maximum of 150 Mt Cu in the model, for a 50% precipitation efficiency) are associated with volumes of magma accumulated in the lower crust in excess of 2500 km³.

Duration of ore deposition events

The second constraint of the model (ii) is provided by available geochronological data on the overall duration of ore deposition. Geochronological data indicate that the overall ore deposition durations of the largest porphyry deposit formation are < ~ 2 Myr (e.g., Chuquicamata 106 Mt Cu, 1.3 ± 0.36 Myr; El Teniente, 130 Mt Cu, 1.88 ± 0.04 Myr; Rio Blanco, 100.4 Mt Cu, 1.4 ± 0.04 Myr; Fig. 2). This translates into average Cu deposition rates at these deposits of 74 ± 7 t Cu/yr. Taking into account all major porphyry Cu deposits with available geochronological estimation of ore deposition duration¹³, the average rate of Cu deposition for all these deposits is 65 ± 7 t Cu/yr (Fig. 2). We reasonably assume that the overall duration of the mineralizing events constrains the duration of the magma injection into the upper crust. In order to comply with the above figures, in our model we have taken as an upper temporal limit a duration of 2.0 Myr for the transfer into the upper crust of the magma volumes associated with deposition of up to 150 Mt Cu at 50% efficiency.

Magma injection rates

Models based on geological cross-cutting relationships^{29,30}, geochronology^{31–34}, geospeedometry based on element diffusion²⁹, and thermodynamic³⁶ as well as numerical modelling³⁷ suggest that porphyry Cu deposits are formed by multi-step magmatic-hydrothermal pulses, reflecting a variable number of intrusions and fluid release cycles. High-precision dating of both hydrothermal (e.g., molybdenite Re-Os dating) and magmatic activity (U-Pb dating of zircons) suggests that the duration of each pulse may be

as short as a few tens of thousands of years^{31–34}. These results are corroborated also by Ti diffusion in hydrothermal quartz, which indicates timescales of single pulses of magmatic-hydrothermal activity as short as a few thousands of years or even less²⁹. Recent studies on Ti-in-quartz diffusivity^{45,46} suggest slower Ti diffusion rates in quartz (up to two orders of magnitude less than those taken into account in ref. ²⁹). These would result in longer durations of single hydrothermal pulses, which, nonetheless, remain on the order of tens to hundreds of thousand years. Thermodynamic and numerical modelling agrees with timescales determined for individual magmatic-hydrothermal pulses as well^{36,37}.

We allow a random range of 5 to 20 pulses to inject into the upper crust the magma volume required for the deposition of a specific amount of Cu (Fig. 3). We vary randomly the duration of the single magma pulse transfer events between 10000 and 100000 years to comply with the available geochronological data discussed above. In the model, any combination of random numbers of magma pulses (5–20) and durations of pulses (10000–100000 years) is allowed. However, the maximum number of pulses and maximum pulse duration fix the maximum duration of the overall magma transfer to 2.0 Myr (20 pulses at the longest duration of 100 kyr for each pulse), to comply with geochronological data.

The transfer of the magma volume corresponding to a specific Cu endowment from the deep to the shallow reservoir is accomplished through random combinations of fixed magma volume pulses and fixed durations of the magma pulse within the combination of 10000–100000 years pulse duration and 5–20 number of pulses, corresponding to a maximum possible duration of 2.0 Myr and a minimum of 50000 kyr. It follows that each simulation represents an average magma injection rate that results in the transfer of a specific magma volume and associated Cu endowment from the deep to the shallow crustal reservoir. Five hundred thousand simulations were performed (Table 1) using the RStudio script⁴⁷ provided in the Supplementary Material.

Results And Discussion

The average rate of magma injection into the upper crust controls whether magma will freeze and form plutonic intrusions or whether it will accumulate and form variably large reservoirs that eventually may erupt catastrophically^{15,48,49}. Recent studies have started to include magma injection rates in the formation models of porphyry deposits^{15,16,42}. Intuitively, high magma injection rates favor explosive volcanic eruptions^{15,48,49} and are detrimental for the formation of porphyry deposits^{40–42}. This is supported by the occurrence of porphyry-type deposits at the end of variably long periods of precursor volcanic activity and coinciding with periods characterized by the lack of or by very low volcanic activity (e.g., Yanacocha⁵⁰). In contrast, magma injection rates that allow the accumulation of magma at shallow levels without its eruption may eventually result in a magmatic system exsolving fluids and generating a mineralized magmatic-hydrothermal system⁴². However, there are no studies that have addressed quantitatively and on a global scale how and if different rates of magma injection, encompassing the broad range below the threshold of those leading to eruption, control the formation and size of porphyry deposits.

Zircon age distribution modelling¹⁵ and zircon thermometry⁵¹ as well as inversion of hydrothermal and magmatic activity ages¹⁶ suggest a broad range of > 2 orders of magnitude of average magma injection rates ($\sim 0.0001\text{--}0.04\text{ km}^3/\text{yr}$) potentially associated with the formation of porphyry deposits. Ref. ⁴² suggests that magma injection rates higher than $1.3 \times 10^{-3}\text{ km}^3/\text{yr}$ are necessary to form porphyry deposits. Our results allow us to narrow down the ranges of average upper crust magma injection rates associated with porphyry deposits towards the high value side, and to unveil a relationship between magma injection rates and Cu endowments of porphyry deposits.

Figure 4 shows simulations in magma volume versus magma injection rate space. Also shown are the fields corresponding to large porphyry Cu deposits based on zircon age distribution modelling¹⁵, those corresponding to various individual porphyry Cu deposits based on inversion of hydrothermal and magmatic activity ages¹⁶, and the field for Bingham inferred from geochemical and thermal modelling of zircons⁵¹. Our constrained magma injection rates overlap with the variably broad ranges defined by these previous studies, but further constrain the magma injection rates associated with specific porphyry Cu deposits to narrower ranges, especially trimming out the low magma injection rate side (Fig. 4). Figure 4 further shows that increasing Cu endowments require increasing minimum magma injection rates to transfer increasingly larger amounts of magmas and Cu from the deep accumulation zone to shallower levels within the timescales constrained by geochronology. All simulations for the largest possible Cu endowments (> 100 Mt Cu) require magma injection rates $> \sim 0.001\text{ km}^3/\text{yr}$ (Fig. 4). Additionally, the broadly normal density distributions of the simulations for potential Cu endowment intervals (< 10, 10–30, 30–50, 50–70, 70–100, > 100 Mt; Fig. 5) show that all the Cu endowment intervals > 10 Mt Cu (supergiant porphyry Cu deposits according to the nomenclature of ref. ⁵²) require mode values of magma injection rates larger than $0.001\text{ km}^3/\text{yr}$.

It should be further emphasized that, if the 50% precipitation efficiency of Cu is a realistic one⁴³, the rates of magma transfer to the upper crust obtained here are minimum values, because the overall ore deposit durations considered are maximum values, bracketing the beginning and end of the mineralizing process. If, within these temporal intervals, most of the metals are precipitated within shorter timescales, the transfer rates would be higher than those obtained here. Conversely, for deposits in which there is a higher Cu precipitation efficiency (> 50%), the rates of magma transfer would decrease at equal overall duration of the mineralization. Nonetheless, the broadly linear correlation between Cu endowments and duration of ore deposition for porphyry Cu deposits (Fig. 2) suggests that precipitation efficiencies are probably similar for most porphyry Cu deposits.

Our results show that all deposits fall within magma injection rates between $10^{-2.65}$ and $10^{-3.0}\text{ km}^3/\text{yr}$ (i.e., $\sim 0.0022\text{--}0.001\text{ km}^3/\text{yr}$; Fig. 6). Interestingly, the higher limit of the magma injection rate interval ($\sim 10^{-2.65}\text{ km}^3/\text{yr}$) appropriate for the formation of most porphyry Cu deposits, broadly coincides with magma injection rates into the upper crust that may lead to large eruptions¹⁵. The lower limit ($\sim 10^{-3}\text{ km}^3/\text{yr}$) is the same estimated for the highest possible magma injection rates that may result in the build-

up of non-eruptible large magma bodies at shallow crustal levels¹⁵. However, an important aspect to consider is that there is no fixed threshold of magma injection rate for large eruptions. Protracted magmatic activity results in the long-term modification of the physical properties of the crust and the magma within the plumbing system. For instance, the viscosity of the crust decreases with increasing temperature, and the magma within the plumbing system becomes progressively richer in fluids. Both these phenomena contribute to dampen the pressure developed by magma injection into the shallow portion of the plumbing system^{49,51,53} thus decreasing the probability of volcanic eruptions to occur and generating conditions that are suitable for the formation of porphyry Cu deposits. Such a scenario is consistent with the long-lived precursor magmatic activity recorded for porphyry Cu deposits for which geochronological data are available (Fig. 1).

We suggest that the efficient transfer to upper crustal depths of large volumes of fluid-rich magma that fractionated in the middle-middle-crust is key for the formation of the largest porphyry Cu deposits. Changing stress conditions in the crust^{1,54} could be a likely cause of the modulation of magma volume transfer and injection rates into the upper crust, and control the size of porphyry Cu deposits (Figs. 4–6).

The data here presented and discussed imply that all supergiant porphyry Cu deposits (> 10 Mt Cu) are formed by magma volumes³¹ and average magma injection rates (i.e., > 0.001 km³/yr)^{15,30} into the upper crust that largely overlap those typically leading to large eruptions, supporting similar conclusions on the formation of the Bingham deposit, for which magma injection rates of ≥ 0.0065 km³/yr, based on thermal and geochemical modelling of zircons⁵¹, have been proposed (Fig. 4). Since eruption is obviously detrimental to the formation of porphyry deposits, our results suggest that supergiant porphyry Cu deposits can be considered as failed large eruptions. Our conclusion that high magma injection rates into the upper crust are associated with all supergiant porphyry Cu deposits finds its ultimate explanation in the prolonged magma accumulation occurring at deep crustal levels during long-lived compression, which is an essential condition for the formation of porphyry Cu deposits¹⁷. Such accumulation not only builds up enormous amounts of magma, volatile and metal in the deep crust, but is also responsible for the thermal pre-conditioning of the upper crust that prevents eruption of magmas even when magma injection rates at shallow depth are high⁴⁹.

Methods

The Monte Carlo modelling (500000 simulations) was carried out using the conceptual framework developed in refs. ^{13,17}.

The starting point of the model is the covariation derived from refs. ^{13,17} between potential Cu endowments of magmatic systems (at 50% precipitation efficiency) and magma volumes for the potentially most productive magmatic systems, i.e., those accumulated at pressures of 0.4–1.2 GPa (Fig. 3). Compared to refs. ^{13,17}, where the maximum pressure of magma accumulation was 0.9 GPa, we extended the upper pressure limit to 1.2 GPa. Figure 3 shows > 10000 simulations and their density

distribution. More than 95% of the simulations fall within the two curves of Fig. 3, which are reproduced mathematically by exponential equations of the type

$$\text{Magma Volume} = a * MtCu^b \quad (1)$$

Where parameter “*a*” ranges randomly between 60 and 700, parameter “*b*” = $-0.187767 * \ln(a) + 1.507068$, and “*MtCu*” are the Cu endowments (at 50% precipitation efficiency) that are allowed to vary randomly between 0 and 150 Mt Cu (Table 1).

Because the longest durations of ore precipitations associated with the largest porphyry Cu deposits (i.e., El Teniente 130 Mt Cu, Chuquicamata 106 Mt Cu, Rio Blanco 101 Mt Cu: data from USGS at <https://mrdata.usgs.gov/porcu/>) are < 2.0 Myr (see compilations in refs. ^{13,17}), we have allowed a maximum time of 2 Myr for the transfer of all magma volumes (including those associated with the maximum potential Cu endowments of 150 Mt Cu) from the deep to the shallow reservoirs where fluids exsolve and precipitate Cu with a 50% efficiency.

Additionally, because geological and geochronological evidences indicate that porphyry Cu deposits are formed by repeated magmatic-hydrothermal pulses with durations of few to several tens of kyr, we have allowed in the model that the magma volume transfer from the deep to the shallow crust is accomplished within any random combination of 5 to 20 magmatic pulses, each one varying randomly between 10000 to 100000 years. This means that in our model the transfer of any magma volume from the deep to the shallow crust can occur from a minimum of 50000 years (5 pulses with a 10000 year duration of each pulse) to a maximum of 2 Myr (20 pulses with a 100000 year duration of each pulse). This random temporal variability for the transfer of any magma volume defined by Eq. (1) above translates into broadly different average magma injection rates that are plotted in Figs. 4–6.

The volume of each magma pulse is calculated as the ratio between the accumulated magma volume in the lower crust, that corresponds to a specific Cu endowment and must be transferred to the shallow crust to exsolve fluids and Cu, and the random number of pulses (5–20) through which the deep accumulated volume is transferred. Average magma injection rates from the deep to the shallow crust are then calculated as the ratios between the volume of the magma pulses and the random durations of each pulse in the interval 10000–100000 years that, incrementally (through the random number of pulses), results in the transfer of the overall magma volume associated with a certain Cu endowment (considering a 50% precipitation efficiency).

The duration of the injection of magma from the deep to the shallow crust (which corresponds to the duration of the ore deposition event, since we assume that each pulse results in an “instantaneous” hydrothermal event) is given by the product of the random number of pulses (5–20) and the random duration of pulses (10000–100000 years).

The full RStudio script of the Monte Carlo modelling is provided in the Supplementary Material.

References

1. Tosdal, R. M. & Richards, J. P. Magmatic and Structural Controls on the Development of Porphyry Cu $\pm$ Mo $\pm$ Au Deposits. (2001) doi:10.5382/Rev.14.06.
2. Richards, J. P. Postsubduction porphyry Cu-Au and epithermal Au deposits: Products of remelting of subduction-modified lithosphere. *Geology* <background-color:#FFCC66;bvertical-align:super;>37</background-color:#FFCC66;bvertical-align:super;>, 247–250 (2009).
3. Richards, J. P. A Shake-Up in the Porphyry World? *Economic Geology* <background-color:#FFCC66;bvertical-align:super;>113</background-color:#FFCC66;bvertical-align:super;>, 1225–1233 (2018).
4. Rohrlach, B. D. & Loucks, R. R. Multi-Million-Year Cyclic Ramp-up of Volatiles in a Lower Crustal Magma Reservoir Trapped Below the Tampakan Copper-Gold Deposit by Mio-Pliocene Crustal Compression in the Southern Philippines. in *Super Porphyry Copper & Gold Deposits - A Global Perspective* vol. 2 369–407 (PGC Publishing, 2005).
5. Cooke, D. R., Hollings, P. & Walshe, J. L. Giant Porphyry Deposits: Characteristics, Distribution, and Tectonic Controls. *Economic Geology* <background-color:#FFCC66;bvertical-align:super;>100</background-color:#FFCC66;bvertical-align:super;>, 801–818 (2005).
6. Rosenbaum, G. *et al.* Subduction of the Nazca Ridge and the Inca Plateau: Insights into the formation of ore deposits in Peru. *Earth and Planetary Science Letters* <background-color:#FFCC66;bvertical-align:super;>239</background-color:#FFCC66;bvertical-align:super;>, 18–32 (2005).
7. Zajacz, Z., Seo, J. H., Candela, P. A., Piccoli, P. M. & Tossel, J. A. The solubility of copper in high-temperature magmatic vapors: A quest for the significance of various chloride and sulfide complexes. *Geochimica et Cosmochimica Acta* <background-color:#FFCC66;bvertical-align:super;>75</background-color:#FFCC66;bvertical-align:super;>, 2811–2827 (2011).
8. Richards, J. P. Giant ore deposits formed by optimal alignments and combinations of geological processes. *Nature Geoscience* <background-color:#FFCC66;bvertical-align:super;>6</background-color:#FFCC66;bvertical-align:super;>, 911–916 (2013).
9. Wilkinson, J. J. Triggers for the formation of porphyry ore deposits in magmatic arcs. *Nature Geoscience* <background-color:#FFCC66;bvertical-align:super;>6</background-color:#FFCC66;bvertical-align:super;>, 917–925 (2013).
10. Loucks, R. R. Distinctive composition of copper-ore-forming arc magmas. *Australian Journal of Earth Sciences* <background-color:#FFCC66;bvertical-align:super;>61</background-color:#FFCC66;bvertical-align:super;>, 5–16 (2014).
11. Du, J. & Audétat, A. Early sulfide saturation is not detrimental to porphyry Cu-Au formation. *Geology* <background-color:#FFCC66;bvertical-align:super;>48</background-color:#FFCC66;bvertical-align:super;>, 519–524 (2020).

12. Lee, C.-T. A. & Tang, M. How to make porphyry copper deposits. *Earth and Planetary Science Letters* <background-color:#FFCC66;bvertical-align:super;>529</background-color:#FFCC66;bvertical-align:super;>, 115868 (2020).
13. Chiaradia, M. Gold endowments of porphyry deposits controlled by precipitation efficiency. *Nature Communications* <background-color:#FFCC66;bvertical-align:super;>11</background-color:#FFCC66;bvertical-align:super;>, 248 (2020).
14. Chiaradia, M. How Much Water in Basaltic Melts Parental to Porphyry Copper Deposits? *Front. Earth Sci.* <background-color:#FFCC66;bvertical-align:super;>8</background-color:#FFCC66;bvertical-align:super;>, (2020).
15. Caricchi, L., Simpson, G. & Schaltegger, U. Zircons reveal magma fluxes in the Earth's crust. *Nature* <background-color:#FFCC66;bvertical-align:super;>511</background-color:#FFCC66;bvertical-align:super;>, 457–461 (2014).
16. Chelle-Michou, C., Rottier, B., Caricchi, L. & Simpson, G. Tempo of magma degassing and the genesis of porphyry copper deposits. *Scientific Reports* <background-color:#FFCC66;bvertical-align:super;>7</background-color:#FFCC66;bvertical-align:super;>, 40566 (2017).
17. Chiaradia, M. & Caricchi, L. Stochastic modelling of deep magmatic controls on porphyry copper deposit endowment. *Scientific Reports* <background-color:#FFCC66;bvertical-align:super;>7</background-color:#FFCC66;bvertical-align:super;>, 44523 (2017).
18. Park, J.-W., Campbell, I. H., Chiaradia, M., Hao, H. & Lee, C.-T. Crustal magmatic controls on the formation of porphyry copper deposits. *Nat Rev Earth Environ* <background-color:#FFCC66;bvertical-align:super;>2</background-color:#FFCC66;bvertical-align:super;>, 542–557 (2021).
19. Lee, C.-T. A. *et al.* Copper Systematics in Arc Magmas and Implications for Crust-Mantle Differentiation. *Science* <background-color:#FFCC66;bvertical-align:super;>336</background-color:#FFCC66;bvertical-align:super;>, 64–68 (2012).
20. Chiaradia, M. Copper enrichment in arc magmas controlled by overriding plate thickness. *Nature Geoscience* <background-color:#FFCC66;bvertical-align:super;>7</background-color:#FFCC66;bvertical-align:super;>, 43–46 (2014).
21. Audétat, A. The Metal Content of Magmatic-Hydrothermal Fluids and Its Relationship to Mineralization Potential. *Economic Geology* <background-color:#FFCC66;bvertical-align:super;>114</background-color:#FFCC66;bvertical-align:super;>, 1033–1056 (2019).
22. Annen, C., Blundy, J. D. & Sparks, R. S. J. The Genesis of Intermediate and Silicic Magmas in Deep Crustal Hot Zones. *Journal of Petrology* <background-color:#FFCC66;bvertical-align:super;>47</background-color:#FFCC66;bvertical-align:super;>, 505–539 (2006).
23. Stern, C. R., Skewes, M. A. & Arévalo, A. Magmatic Evolution of the Giant El Teniente Cu–Mo Deposit, Central Chile. *Journal of Petrology* <background-color:#FFCC66;bvertical-align:super;>52</background-color:#FFCC66;bvertical-align:super;>, 1591–1617 (2011).
24. Reich, M. *et al.* Adakite-like signature of Late Miocene intrusions at the Los Pelambres giant porphyry copper deposit in the Andes of central Chile: metallogenic implications. *Miner Deposita* <background-

- color:#FFCC66;bvertical-align:super;>38</background-color:#FFCC66;bvertical-align:super;>, 876–885 (2003).
25. Rabbia, O. M., Correa, K. J., Hernández, L. B. & Ulrich, T. “Normal” to adakite-like arc magmatism associated with the El Abra porphyry copper deposit, Central Andes, Northern Chile. *Int J Earth Sci (Geol Rundsch)* <background-color:#FFCC66;bvertical-align:super;>106</background-color:#FFCC66;bvertical-align:super;>, 2687–2711 (2017).
 26. Nathwani, C. L. *et al.* From long-lived batholith construction to giant porphyry copper deposit formation: petrological and zircon chemical evolution of the Quellaveco District, Southern Peru. *Contrib Mineral Petrol* <background-color:#FFCC66;bvertical-align:super;>176</background-color:#FFCC66;bvertical-align:super;>, 12 (2021).
 27. S. Newman & J. B. Lowenstern. VolatileCalc: a silicate melt–H₂O–CO₂ solution model written in Visual Basic for excel. *Computers & Geosciences* <background-color:#FFCC66;bvertical-align:super;>28</background-color:#FFCC66;bvertical-align:super;>, 597–604 (2002).
 28. Sillitoe, R. H. Porphyry Copper Systems*. *Economic Geology* <background-color:#FFCC66;bvertical-align:super;>105</background-color:#FFCC66;bvertical-align:super;>, 3–41 (2010).
 29. Mercer, C. N., Reed, M. H. & Mercer, C. M. Time Scales of Porphyry Cu Deposit Formation: Insights from Titanium Diffusion in Quartz. *Economic Geology* <background-color:#FFCC66;bvertical-align:super;>110</background-color:#FFCC66;bvertical-align:super;>, 587–602 (2015).
 30. Annen, C. From plutons to magma chambers: Thermal constraints on the accumulation of eruptible silicic magma in the upper crust. *Earth and Planetary Science Letters* <background-color:#FFCC66;bvertical-align:super;>284</background-color:#FFCC66;bvertical-align:super;>, 409–416 (2009).
 31. Wilson, C. J. N. *et al.* No single model for supersized eruptions and their magma bodies. *Nat Rev Earth Environ* 1–18 (2021) doi:10.1038/s43017-021-00191-7.
 32. Sillitoe, R. H. Cauldron subsidence as a possible inhibitor of porphyry copper formation. *Mining Geol. Spec. Issue* <background-color:#FFCC66;bvertical-align:super;>8</background-color:#FFCC66;bvertical-align:super;>, 85–93 (1980).
 33. Pasteris, J. D. Mount Pinatubo volcano and “negative” porphyry copper deposits. *Geology* <background-color:#FFCC66;bvertical-align:super;>24</background-color:#FFCC66;bvertical-align:super;>, 1075–1078 (1996).
 34. Korges, M., Weis, P. & Andersen, C. The role of incremental magma chamber growth on ore formation in porphyry copper systems. *Earth and Planetary Science Letters* <background-color:#FFCC66;bvertical-align:super;>552</background-color:#FFCC66;bvertical-align:super;>, 116584 (2020).
 35. Cloos, M. Bubbling magma chambers, cupolas, and porphyry copper deposits. *International Geology Review* <background-color:#FFCC66;bvertical-align:super;>43</background-color:#FFCC66;bvertical-align:super;>, 285–311 (2001).

36. Kokh, M. A. *et al.* Combined effect of carbon dioxide and sulfur on vapor–liquid partitioning of metals in hydrothermal systems. *Geochimica et Cosmochimica Acta* <background-color:#FFCC66;bvertical-align:super;>187</background-color:#FFCC66;bvertical-align:super;>, 311–333 (2016).
37. Seedorff, E. & Einaudi, M. T. Henderson porphyry molybdenum system, Colorado I. Sequence and abundance of hydrothermal mineral assemblages, flow paths of evolving fluids, and evolutionary styles. *Economic Geology* <background-color:#FFCC66;bvertical-align:super;>99</background-color:#FFCC66;bvertical-align:super;>, 3–37 (2004).
38. Seedorff, E. & Einaudi, M. T. Henderson porphyry molybdenum system, Colorado II. Decoupling of introduction and deposition of metals during geochemical evolution of hydrothermal fluids. *Economic Geology* <background-color:#FFCC66;bvertical-align:super;>99</background-color:#FFCC66;bvertical-align:super;>, 39–71 (2004).
39. Quad, A. von *et al.* Zircon crystallization and the lifetimes of ore-forming magmatic-hydrothermal systems. *Geology* <background-color:#FFCC66;bvertical-align:super;>39</background-color:#FFCC66;bvertical-align:super;>, 731–734 (2011).
40. Li, Y., Selby, D., Condon, D. & Tapster, S. Cyclic Magmatic-Hydrothermal Evolution in Porphyry Systems: High-Precision U-Pb and Re-Os Geochronology Constraints on the Tibetan Qulong Porphyry Cu-Mo Deposit. *Economic Geology* <background-color:#FFCC66;bvertical-align:super;>112</background-color:#FFCC66;bvertical-align:super;>, 1419–1440 (2017).
41. Buret, Y. *et al.* From a long-lived upper-crustal magma chamber to rapid porphyry copper emplacement: Reading the geochemistry of zircon crystals at Bajo de la Alumbrera (NW Argentina). *Earth and Planetary Science Letters* <background-color:#FFCC66;bvertical-align:super;>450</background-color:#FFCC66;bvertical-align:super;>, 120–131 (2016).
42. Large, S. J. E., Quad, A. von, Wotzlav, J.-F., Guillong, M. & Heinrich, C. A. Magma Evolution Leading to Porphyry Au-Cu Mineralization at the Ok Tedi Deposit, Papua New Guinea: Trace Element Geochemistry and High-Precision Geochronology of Igneous Zircon. *Economic Geology* <background-color:#FFCC66;bvertical-align:super;>113</background-color:#FFCC66;bvertical-align:super;>, 39–61 (2018).
43. Cathles, L., Erendi, A. H. J. & Barrie, C. T. How long can a hydrothermal system be sustained by a single intrusive event? *Economic Geology* <background-color:#FFCC66;bvertical-align:super;>92</background-color:#FFCC66;bvertical-align:super;>, 766–771 (1997).
44. Weis, P., Driesner, T. & Heinrich, C. A. Porphyry-copper ore shells form at stable pressure-temperature fronts within dynamic fluid plumes. *Science* <background-color:#FFCC66;bvertical-align:super;>338</background-color:#FFCC66;bvertical-align:super;>, 1613–1616 (2012).
45. Jollands, M. C., Bloch, E. & Müntener, O. New Ti-in-quartz diffusivities reconcile natural Ti zoning with time scales and temperatures of upper crustal magma reservoirs. *Geology* <background-color:#FFCC66;bvertical-align:super;>48</background-color:#FFCC66;bvertical-align:super;>, 654–657 (2020).

46. Audétat, A., Miyajima, N., Wiesner, D. & Audinot, J.-N. Confirmation of slow Ti diffusion in quartz by diffusion couple experiments and evidence from natural samples. *Geology* (2021) doi:10.1130/G48785.1.
47. R Core Team. *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. (2013).
48. Schöpa, A. & Annen, C. The effects of magma flux variations on the formation and lifetime of large silicic magma chambers. *Journal of Geophysical Research: Solid Earth* <background-color:#FFCC66;bvertical-align:super;>118</background-color:#FFCC66;bvertical-align:super;>, 926–942 (2013).
49. Karakas, O., Degruyter, W., Bachmann, O. & Dufek, J. Lifetime and size of shallow magma bodies controlled by crustal-scale magmatism. *Nature Geoscience* <background-color:#FFCC66;bvertical-align:super;>10</background-color:#FFCC66;bvertical-align:super;>, 446–450 (2017).
50. Longo, A. A., Dilles, J. H., Grunder, A. L. & Duncan, R. Evolution of Calc-Alkaline Volcanism and Associated Hydrothermal Gold Deposits at Yanacocha, Peru. *Economic Geology* <background-color:#FFCC66;bvertical-align:super;>105</background-color:#FFCC66;bvertical-align:super;>, 1191–1241 (2010).
51. Large, S. J. E. *et al.* Copper-mineralised porphyries sample the evolution of a large-volume silicic magma reservoir from rapid assembly to solidification. *Earth and Planetary Science Letters* <background-color:#FFCC66;bvertical-align:super;>563</background-color:#FFCC66;bvertical-align:super;>, 116877 (2021).
52. Clark, A. H. Are outsize porphyry copper deposits either anatomically or environmentally distinctive? *Society of Economic Geologists Special Publication* <background-color:#FFCC66;bvertical-align:super;>2</background-color:#FFCC66;bvertical-align:super;>, 213–283 (1993).
53. Caricchi, L., Townsend, M., Rivalta, E. & Namiki, A. The build-up and triggers of volcanic eruptions. *Nat Rev Earth Environ* <background-color:#FFCC66;bvertical-align:super;>2</background-color:#FFCC66;bvertical-align:super;>, 458–476 (2021).
54. Bertrand, G., Guillou-Frottier, L. & Loiselet, C. Distribution of porphyry copper deposits along the western Tethyan and Andean subduction zones: Insights from a paleotectonic approach. *Ore Geology Reviews* <background-color:#FFCC66;bvertical-align:super;>60</background-color:#FFCC66;bvertical-align:super;>, 174–190 (2014).

Figures

Figure 1

Cu endowments (Mt) versus duration of magma injection into the crust. Colored dots are 50% precipitation efficiency simulations from ref. 17 and different colors indicate the volumes of the magma accumulated. The black dots are porphyry Cu deposits for which data are available for Cu endowments and duration of magmatic activity. Abbreviations: ET = El Teniente; Chu = Chuquicamata; RB = Rio Blanco; Es= Escondida; LP = Los Pelambres; ES = El Salvador; Cc= Corocchohuayco; Tk = Tampakan; Ju = Junin; EA = El Abra; Qv = Quellaveco; Ay = Antapaccay; Ch = Chaucha.

Figure 2

Correlation between the overall duration of ore period (Myr) and Cu endowments (Mt) from ref. 13. The uncertainties reported for a and b are 1 standard deviations.

Figure 3

Plot of magma volumes versus potential Cu endowments at 50% precipitation efficiency for magmatic systems accumulated at depths corresponding to pressures of 0.4-1.2 GPa. Over 10000 simulations are reported from the algorithm of refs. 13,17. Density distribution is shown on top of the data as different color shades. More than 95% of the simulations fall within the two exponential curves, as discussed in the Methods.

Figure 4

Monte Carlo simulations of magma volumes versus injection rates subdivided by color codes indicating different intervals of potential Cu endowments. The blue fields and associated blue labels correspond to individual porphyry Cu deposits determined by ref. 16 from inversion of hydrothermal and magmatic activity ages of the deposits, the field enclosed by the blue dashed line is the field of large porphyry Cu deposits defined by ref. 15 using zircon age distribution modelling, and the Bingham (Bh) value is from ref. 51. The black bars (and associated black labels) correspond to the magma volumes and magma injection rate intervals constrained by the present study on the basis of Monte Carlo simulations for the same individual deposits of refs. 16,51. Abbreviations: ET = El Teniente; RD = Reko Diq; RB = Rio Blanco; Es = Escondida; LP = Los Pelambres; Gr = Grasberg; PCD = porphyry Cu deposits.

Figure 5

Probability curves of Monte Carlo simulations of log₁₀[magma injection rates] for different Cu endowment intervals.

Figure 6

Monte Carlo simulations of duration of ore deposition (=duration of magma injection into the upper crust) versus Cu endowments subdivided by color codes indicating different intervals of magma injection rates. The plot shows that all deposits fall within the interval of magma injection rates (~ -3

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