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Unraveling the evolution of southernmost Peru between 100 and 50 Ma through U-Pb geochronology of the Toquepala Group: Implications for exploration of large porphyry copper deposits

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1. Abstract / *Resumen*

Integration of the zircon U-Pb ages available on the Toquepala Group, La Caldera batholith (*s.l.*), and porphyry Cu systems, in combination with geochemical data, unravels the evolution of the magmatic arc of southernmost Peru during the Late Cretaceous and Early Paleogene. Arc magmatic production increased starting ~90 Ma, and culminated between ~74 and ~62 Ma through a flare-up characterized by large plutonic and volcanic (especially ignimbritic) volumes. This long process resulted in the thickening of the arc crust, to a state of overthickening that triggered its extensional collapse, starting diachronously 61–59 Ma, during which giant porphyry Cu systems were emplaced between ~60 and ~53 Ma. Our empirical reconstruction of this protracted evolution provides simple guides for exploration of giant porphyry Cu deposits in southern Peru, as well as a magmato-tectonic theoretical framework.

Aclarando la evolución del extremo sur del Perú entre 100 y 50 Ma mediante la geocronología U-Pb del Grupo Toquepala: Implicancias para la exploración por grandes pórfidos de cobre.

*La integración de las edades U-Pb en zircones disponibles sobre el Grupo Toquepala, batolito de La Caldera (s.l.), y pórfidos de cobre permite aclarar la evolución magmática del arco sur-peruano durante el Cretácico superior y Paleógeno inferior, en combinación con datos geoquímicos. A partir de ~90 Ma la actividad magmática fue creciendo y culminó entre ~74 y 62 Ma por una llamarada (*flare-up*) caracterizada por importantes volúmenes tanto plutónicos como volcánicos (y especialmente ignimbríticos). Este largo proceso resultó en el engrosamiento de la corteza del arco, a tal punto que ésta terminó por sufrir un colapso extensional a partir de 61–59 Ma, durante el cual se emplazaron sistemas porfídicos, incluyendo pórfidos gigantes de cobre, entre ~60 y ~53 Ma. Nuestra reconstrucción empírica de esta evolución proporciona una guía simple para la exploración minera, además de un marco teórico de índole magmato-tectónica.*

2. Introduction

World-class porphyry copper deposits in southernmost Peru (Cuajone, Quellaveco, Toquepala; = CQT hereafter) are related to porphyry intrusions emplaced in a thick succession of volcanic and volcanodetritic strata, referred to as the Toquepala Group (Concha & Valle, 1999; Mattos & Valle, 1999; Martínez & Cervantes, 2003; Acosta, 2006; Martínez et al., 2017). In contrast with the copper deposits, relatively little is known about the geochronology of the Toquepala Group, and this work attempts to fill this gap. Here we outline a chronology based on zircon U-Pb ages that illuminates the magmatic evolution of southernmost Peru and shows that the porphyry copper deposits were emplaced during the final stage of this evolution, a finding that has crucial implications for mining exploration.

We use hereafter '*zUPb*' as an abbreviation for the locution 'zircon U-Pb'.

3. Stratigraphy of the Toquepala Group

The >2 km-thick Toquepala Group is known south of 16.4°S and east of 71.5°W. It generally overlies sedimentary strata of Jurassic to Early Cretaceous age, and is overlain by the forearc sedimentary deposits of the Moquegua Group, the base of which is, at least locally, older than 45 Ma.

Martínez & Zuloaga (2000) updated the stratigraphy of the Toquepala Group in the Moquegua area and divided it into 4 formations, namely the Huaracane, Inogoya, Paralaque and Quellaveco formations (from base to top). Zircon U-Pb dating of 3 of these units (Simmons, 2013; Fig. 1) however resulted in discrepancies with this stratigraphy, suggesting that the units may have been misidentified, at least in part, during sampling. For instance, samples reportedly from the oldest Huaracane Formation yielded the oldest and *youngest* ages in Simmons' (2013) *zUPb* age dataset: 90.3 ± 0.8 and 68.3 ± 0.7 Ma, respectively. Only one sample assigned to the Paralaque Formation was dated, to 71.4 ± 0.7 Ma, but this age falls in the range of ages obtained by Simmons (2013) reportedly from the Quellaveco Formation; these ages allow to define 4 major eruptions, at 73.8 ± 0.8 Ma (n=1), 72.9 ± 0.6 Ma (n=2), 71.3 ± 0.3 Ma (n=5), and 69.8 ± 0.3 Ma (n=4).

Given these discrepancies, we do not refer hereafter to the stratigraphy and focus instead on absolute *zUPb* ages (Fig. 2).

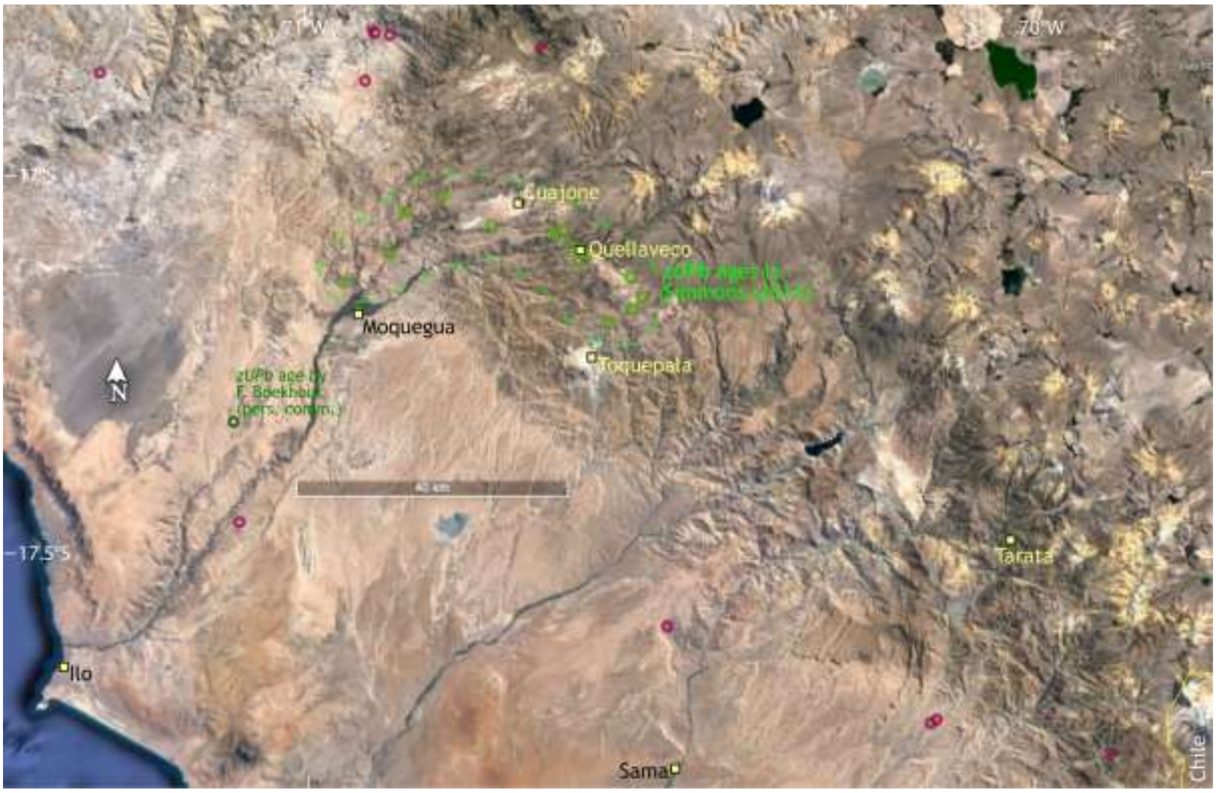

Figure 1. Location of the *zUPb* ages obtained on the Toquepala Group and related units. Circles indicate dated ignimbrites; curved arrows indicate ages on detrital zircons. Red symbols plot ages obtained by Paquette & Sempere (unpublished). The other ages (mainly by Simmons, 2013) are referenced in the figure.

3. Late Cretaceous – Early Paleogene zircon U-Pb age spectrum

The oldest *zUPb* age obtained so far on the Toquepala Group is from a laminated ignimbrite intercalated in andesite flows ~34 km NE of Ilo, which yielded a late Cenomanian age (~94.1 Ma; Paquette & Sempere, unpublished). This ignimbrite occurs ~1 km above the base of a very thick volcanic succession mapped as the Toquepala Group, which overlies volcano-sedimentary strata that yielded Callovian ammonites (Bellido & Guevara, 1963). The youngest age, ~63.4 Ma (Danian), is from a deformed ignimbrite sampled ~34 km NNE of the city of Tacna (Paquette & Sempere, unpublished).

Figure 2 displays most of the available *zUPb* ages concerning southernmost Peru: porphyry and plutonic rocks from the CQT deposits and area, and ignimbrites from the Toquepala Group (Fig. 1). A clear continuity of *zUPb* ages is observed between the main ignimbrite field, the dated plutons in the CQT area, and the CQT porphyry systems, as well as the known range of *zUPb* ages obtained on the La Caldera batholith (*sensu lato*, *i.e.* from the Arequipa region to the border with Chile; Mukasa, 1986; Demouy et al., 2012; Noury, 2014; Paquette & Sempere, unpublished). In addition, porphyry Cu systems in the Arequipa area (where the Toquepala Group is unknown; Núñez et al., 2000) intrude the La Caldera batholith (and, tangentially, the Precambrian basement) but have only slightly older ages (~60-59 Ma; Mukasa, 1986).

The continuous age distribution observed in Fig. 2 indicates that porphyry emplacements in the late Paleocene and earliest Eocene occured near the end of one single protracted evolution that had started in the mid-Cretaceous or even earlier.

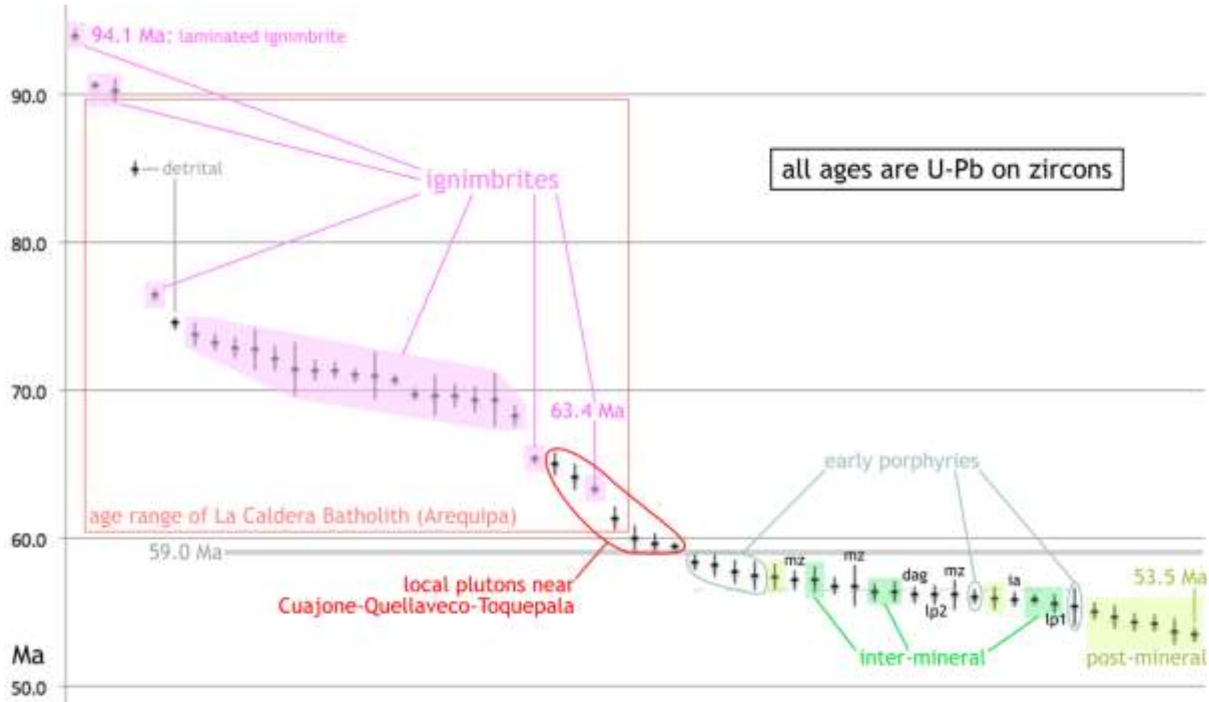

Figure 2. Spectrum of *zUPb* ages relative to the area shown in Figure 1, evidencing the time continuity between the overall evolution of the magmatic arc and the giant porphyry systems. Most age data are derived from Sillitoe & Mortensen (2010), Simmons (2013), Simmons et al. (2013), and Paquette & Sempere (unpublished). The *zUPb* age range of the La Caldera batholith in the Arequipa region is also shown (Mukasa, 1986; Demouy et al., 2012).

4. Magmatic (over)thickening of the arc crust

The La Caldera arc was established at ~90 Ma along what is now the homonymous horst, and underwent a magmatic growth reflected by increasingly voluminous plutonic masses (Demouy et al., 2012). This growth culminated between ~74 and 62 Ma by a magmatic flare-up involving very large plutonic and volcanic volumes, with thick ignimbrites erupted every 1–2 Myr (Fig. 2; Simmons, 2013; Noury, 2014; this work).

The available geochemical data strongly suggest that this growth resulted in an anomalous thickening of the arc crust (Martínez et al., 2017, 2018; Marchena, 2019; Marchena et al., 2019): the “precursor” plutons shortly predating the porphyry systems (Fig. 2) display indeed high Sr/Y ratios reflecting that the coeval crust was overthickened at that time. This signature commonly results from high Sr implying the inhibition of plagioclase crystallization by high lithostatic pressure at depths >50 km, and/or from low Y reflecting that the lower crust included stable garnet and was thus anomalously thick.

5. Extensional collapse and coeval emplacement of porphyry systems

Confirming a now classical concept, the overthickened arc crust ended up undergoing a major extensional collapse, which resulted in the uplift and exhumation of specific areas. The *zUPb* dataset reveals that the collapse was initiated diachronously between 61 Ma (Arequipa longitude) and 59 Ma (Quellaveco longitude). In agreement, nearly all faults observed in the area of interest are normal, and the most important have km-size offsets that define large blocks. In particular, the La

Caldera horst was structured and exhumed during the collapse. Thermochronological ages in the area (Noury, 2014; Noury et al., 2017) are compatible with a collapse-driven exhumation and cooling during the ~60-55 Ma interval. Hydrothermal muscovite crystallized in a normal fault zone 40 km NNE of Tacna yielded an ^{40}Ar-^{39}Ar age of 61.4 ± 0.3 Ma (Sempere et al., 2018).

Because the porphyry systems that host the giant Cu deposits of southernmost Peru yielded *zUPb* ages between ~60 and ~53 Ma (Mukasa, 1986; Sillitoe & Mortensen, 2010; Simmons et al., 2013; Fig. 2), our work implies that they were emplaced during the extensional collapse.

6. Conclusions

The world-class porphyry Cu systems of southern Peru were emplaced during a short (<7 Myr) time span that coincided with the extensional collapse of the previously overthickened arc crust.

This empirical finding provides a simple guide for exploration, and also suggests a theoretical framework that stresses the importance of tectonic phenomena driven by arc magmatism.

Acknowledgments

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