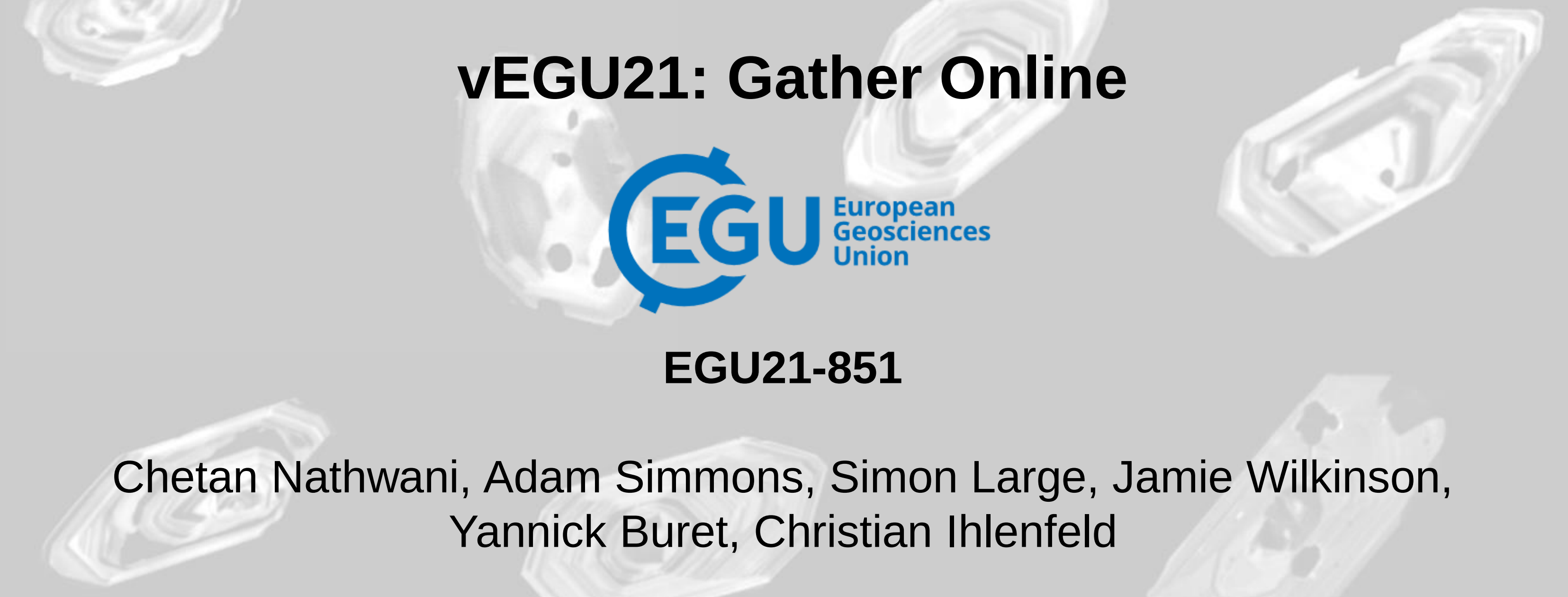
Petrological and zircon chemical record of arc magma evolution from long-lived batholith construction to giant porphyry copper deposit formation



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Introduction

Full paper available at:

Nathwani, C.L., Simmons, A.T., Large, S.J.E. *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* **176,** 12 (2021). https://doi.org/10.1007/s00410-020-01766-1

Outline:

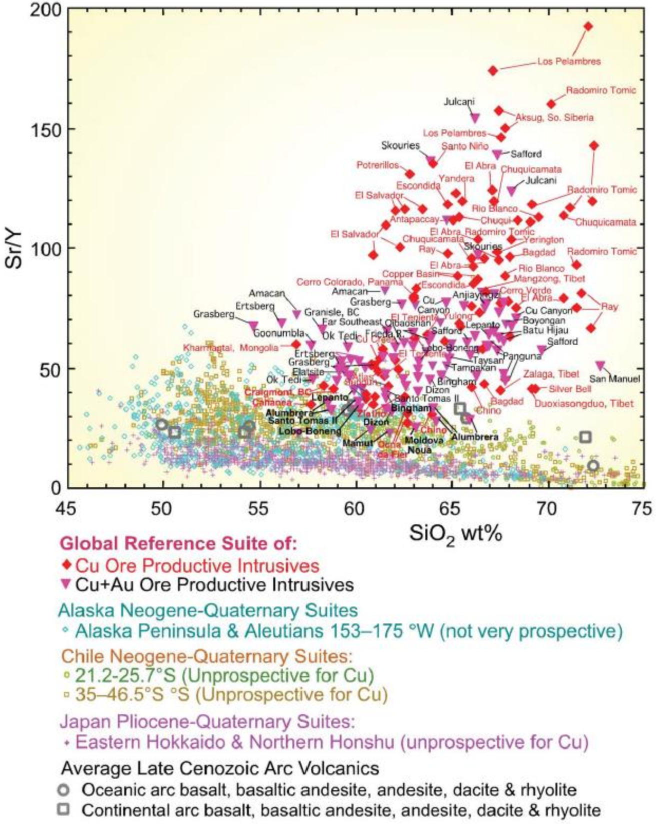
1. Geological background
2. Zircon U-Pb LA ICP-MS geochronology
3. Whole-rock geochemistry
4. Zircon trace element chemistry
5. Numerical modelling of zircon Eu/Eu*

Research motivation

1. Arc magmas forming porphyry Cu deposits have characteristic signatures in whole-rock (e.g. high Sr/Y, high La/Yb) and zircon (e.g. high Eu/Eu*).

2. What magmatic processes are conductive to porphyry Cu formation? Deep magma evolution? High melt H_2O? High melt fO_2?

3. How/why does “normal” arc magmatism transform to “fertile” arc magmatism?

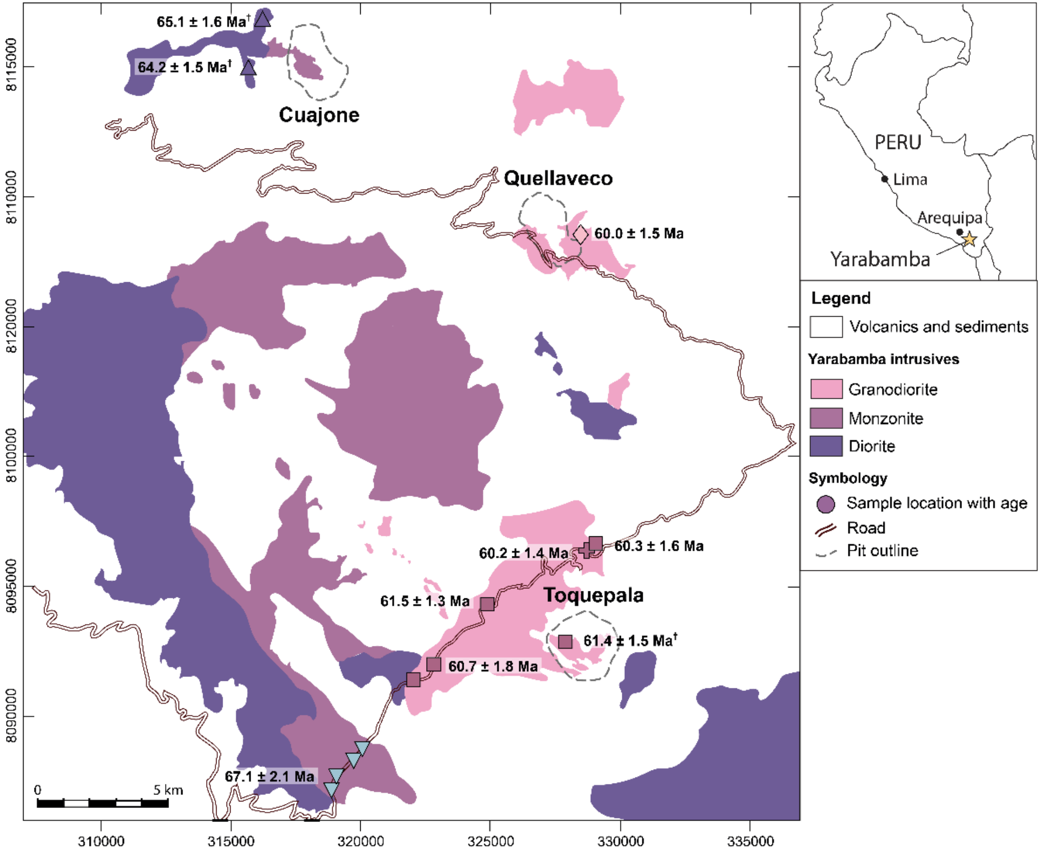


Loucks (2014)

Study area

- Composite Yarabamba Batholith (assembled 69-59 Ma) hosts three, broadly coeval, porphyry Cu deposits (~57-54 Ma): Cuajone, Toquepala and Quellaveco

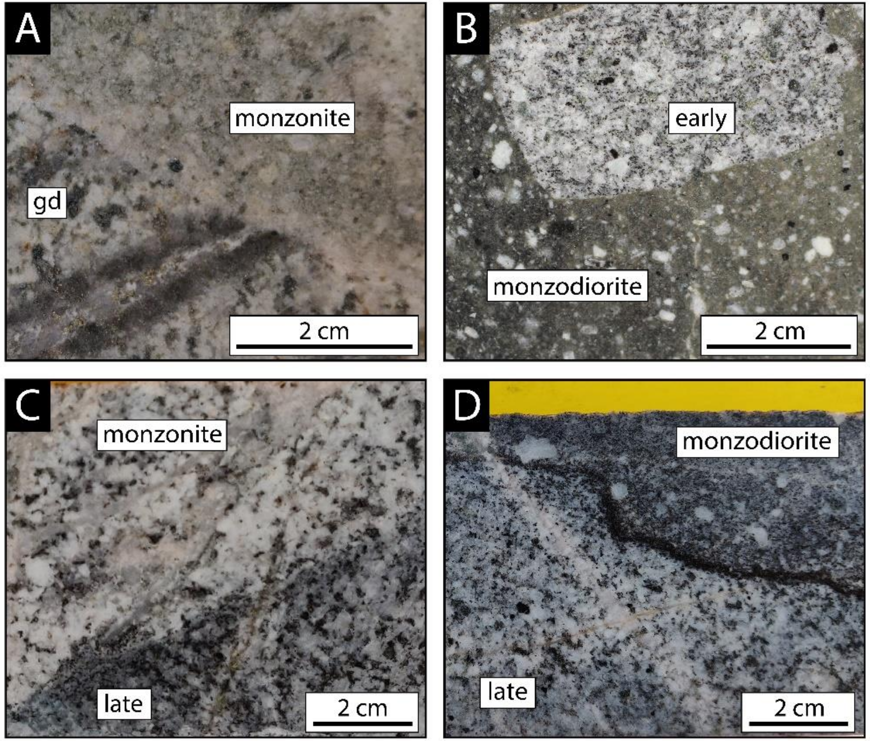
- Samples collected from Yarabamba (see map) and Quellaveco in Spring 2019



Sampling

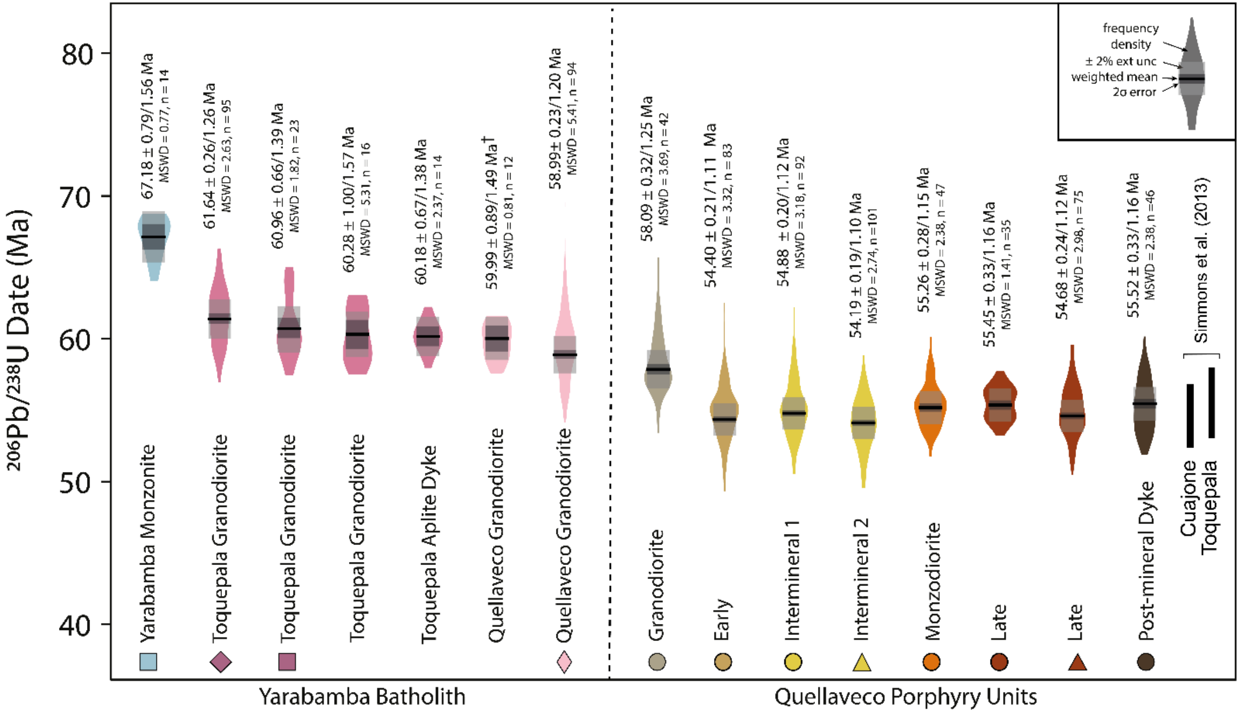
- District-scale sampling of different plutons within the Yarabamba (13 samples)
- Sampling of drill core from the Quellaveco porphyry Cu-Mo deposit – both Yarabamba host rock (7 samples) and porphyry intrusions (51 samples)
- Cross-cutting relationships studied in drill core

Examples of textures and cross-cutting relationships at Quellaveco



U-Pb Geochronology

- Zircon U-Pb LA ICP-MS data indicates sampling of three phases of Yarabamba assembly between 68-58 Ma
- Overlap within uncertainty of Quellaveco porphyries at ~55 Ma, with exception of an older Granodiorite porphyry (~58 Ma)

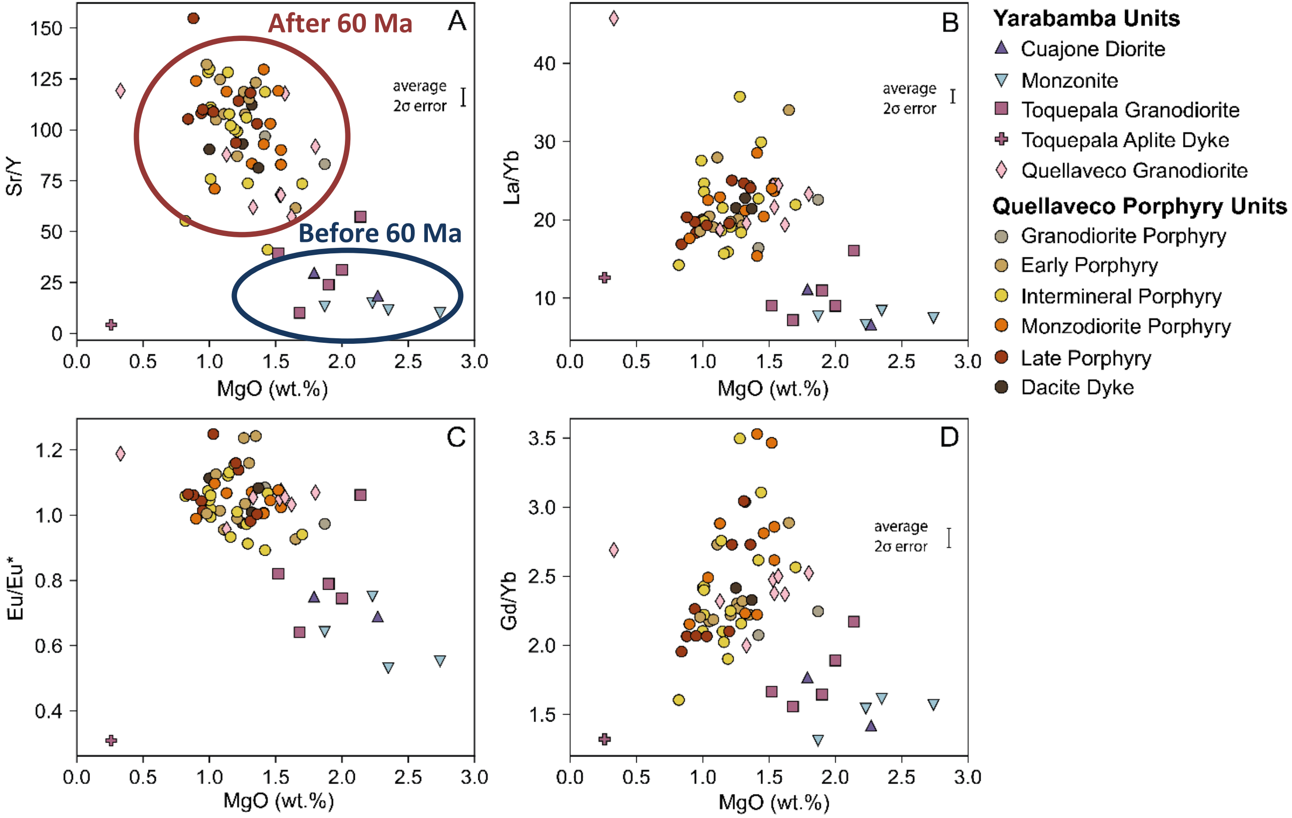

Zircon U-Pb LA ICP-MS data from Yarabamba Batholith and Quellaveco porphyry intrusions

These samples can provide constraints on magma evolution leading up to porphyry Cu mineralisation

Whole-rock geochemistry

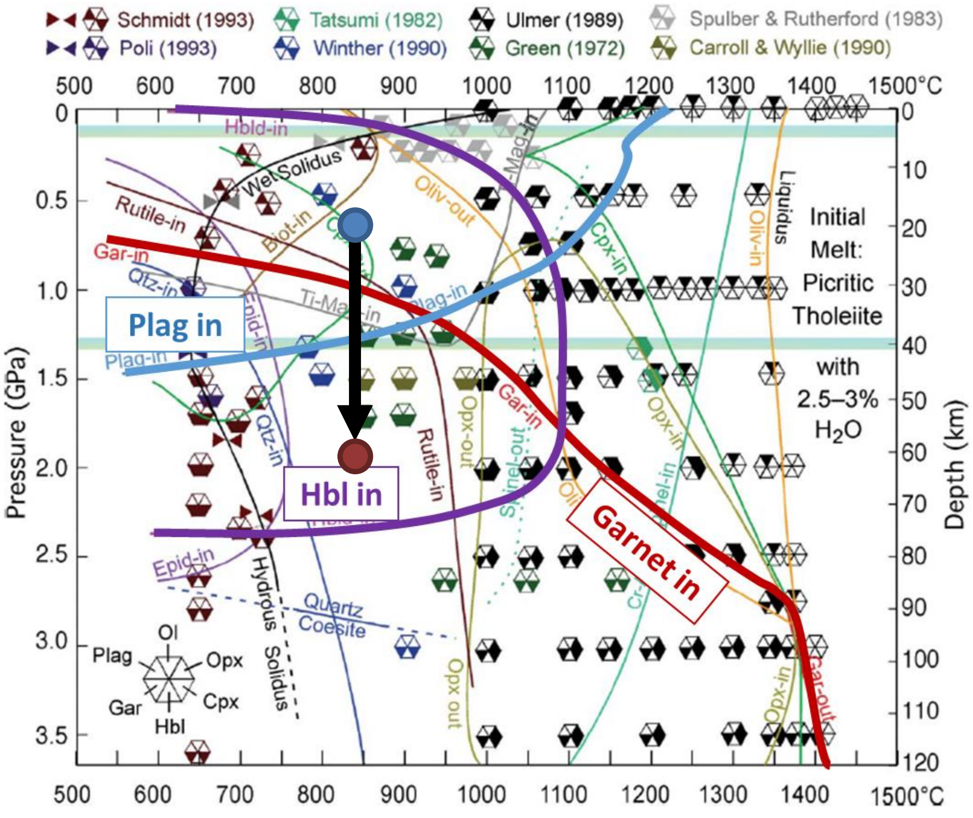
- Clear shift in whole-rock geochemistry to high Sr/Y, high La/Yb, high Eu/Eu* and high Gd/Yb compositions at ~60 Ma

- This changes before emplacement of the Quellaveco Granodiorite (Yarabamba host rock at Quellaveco)



A deepening locus of magma evolution

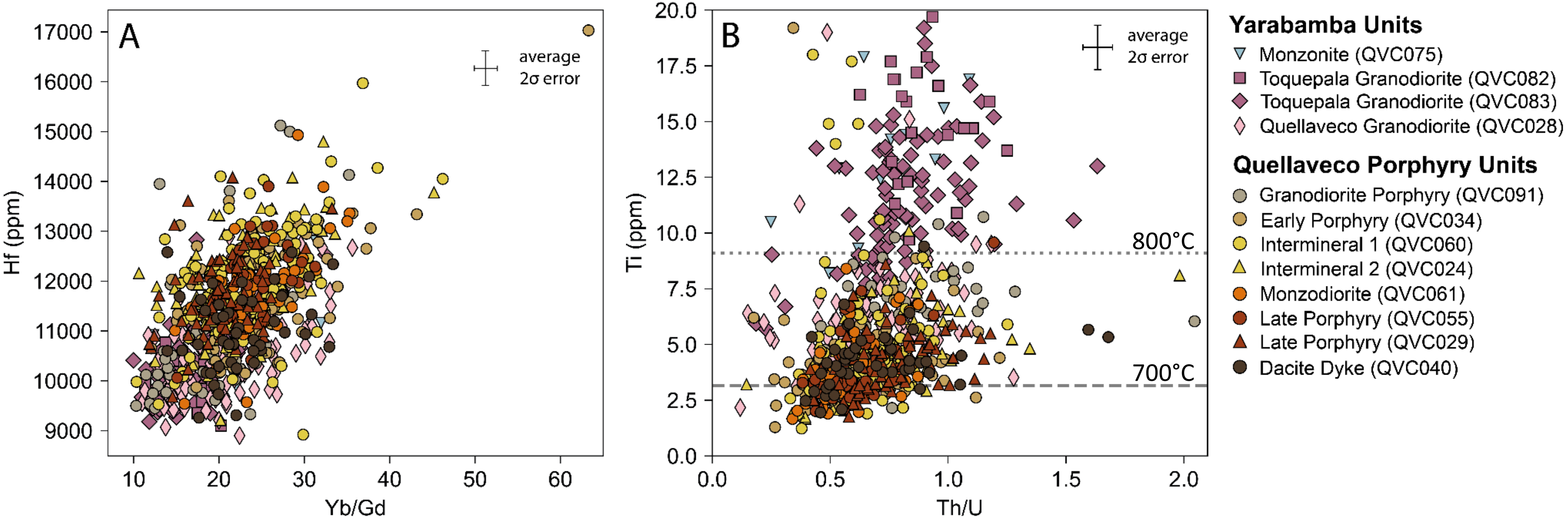
- This ~60 Ma change is consistent with the rotation of convergence of subducting Nazca plate, causing crustal thickening (Incaic orogeny)
- Deepening of magma evolution = amphibole ± garnet stabilised, plagioclase suppressed?
- Higher P = more H_2O soluble = more fluid available for mineralisation?
- 60-57 Ma = assembly of sufficiently large lower crustal magma system?



Loucks (2014)

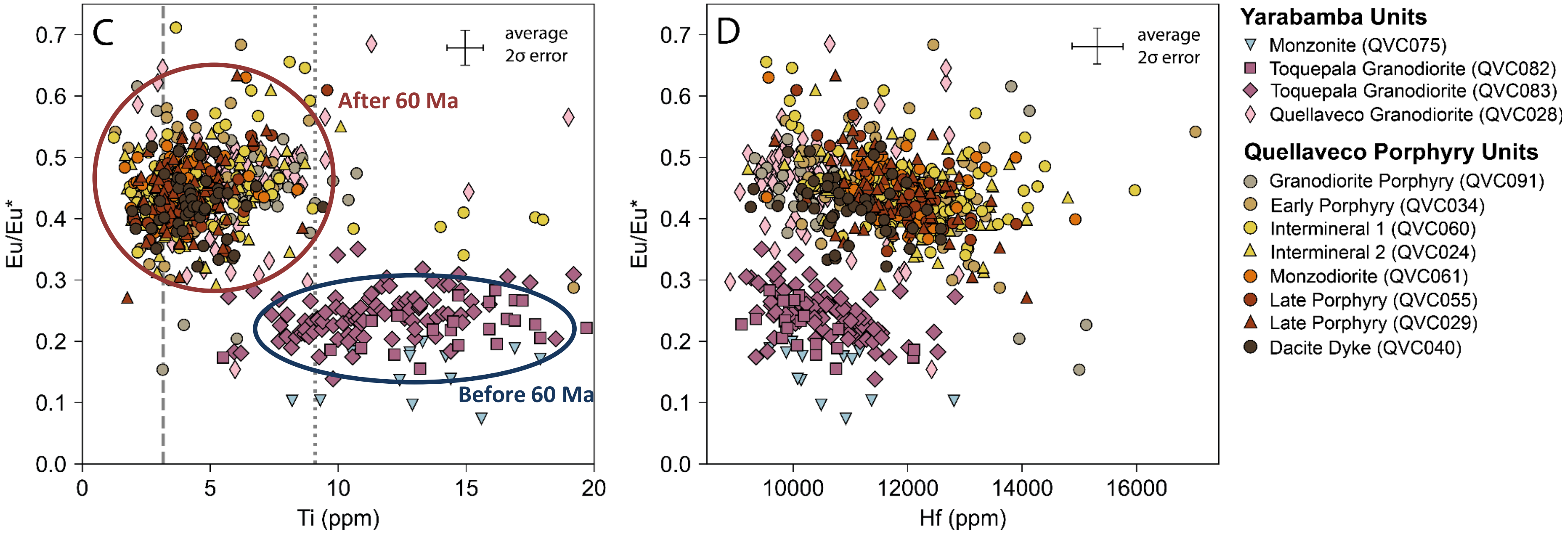
Zircon trace element chemistry

- Zircon trace element LA-ICP-MS data indicate systematic trends within and between samples indicating cooling and crystallisation (decreasing Ti, increasing Hf, decreasing Th/U)



Zircon trace element chemistry

- After ~60 Ma, zircons change to higher Eu/Eu* and lower Ti compositions, consistent with the observed change in whole-rock chemistry

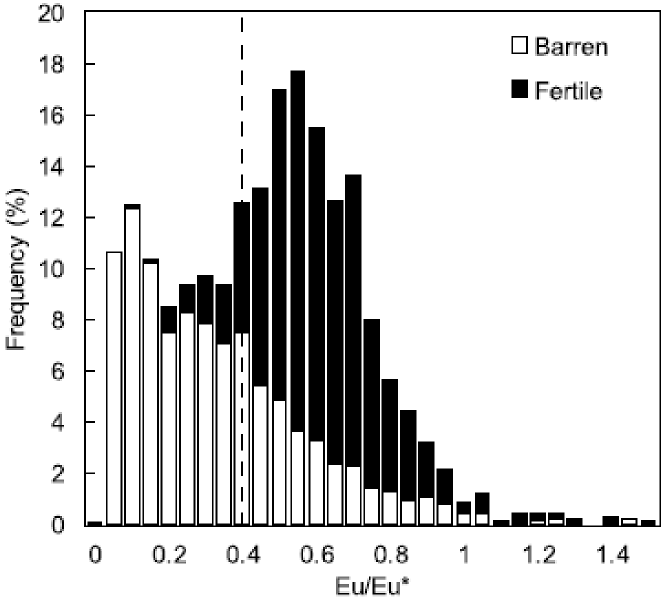


High Eu/Eu* zircons

- These high zircon Eu/Eu* are also observed at the neighbouring Toquepala and Cuajone porphyry Cu deposits (Simmons 2013)

- High Eu/Eu* zircons seems to be characteristic of magmas forming porphyry Cu deposits

- Could reflect:
  1. **High *f*O_2 magmas**
  2. **Higher melt Eu/Eu***



Loader et al. (2017)

Modelling zircon Eu/Eu*

- We can model the influence of melt *f*O2 and melt Eu/Eu* on zircon Eu/Eu* using melt Eu systematics and mineral-melt partitioning theory:

$$D_{Eu(min)} = \frac{D_{Eu^{3+}} + \overset{fO_2}{\boxed{((\frac{Eu^{2+}}{Eu^{3+}})_{melt}}} \times D_{Eu^{2+}})}{(\frac{Eu^{2+}}{Eu^{3+}})_{melt} + 1}$$

Aigner-Torres et al. (2007)

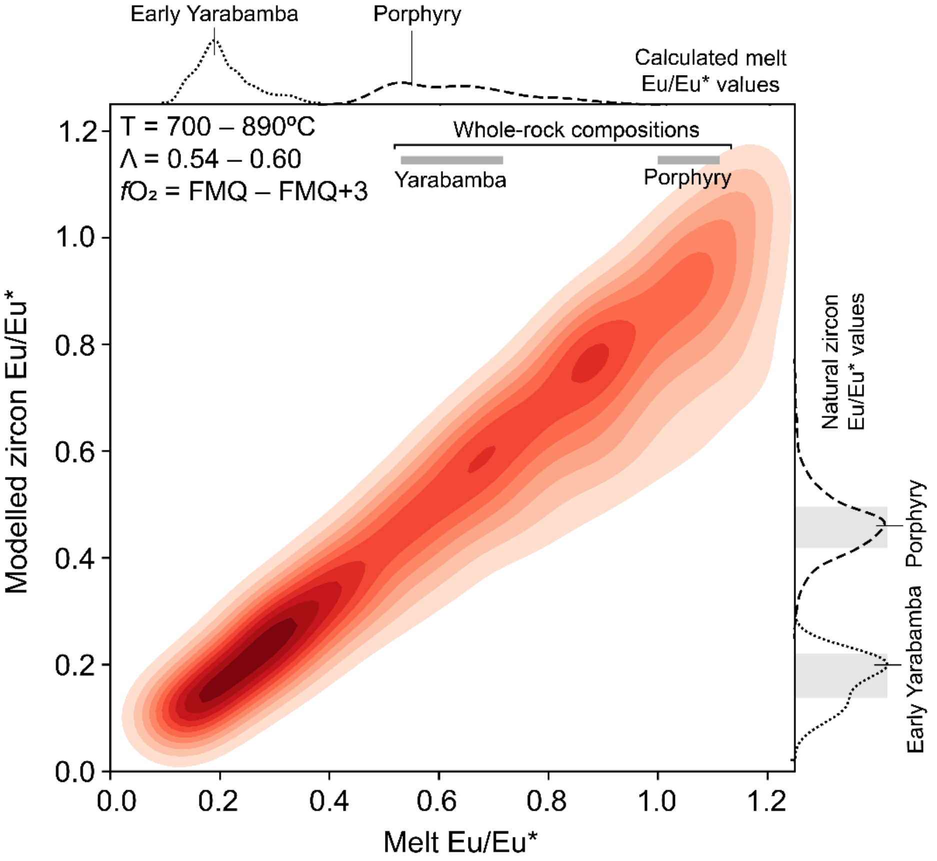
$$\frac{Eu^{3+}}{\Sigma Eu} = \frac{1}{1 + 10^{-0.25 log f O_2 - \frac{6410}{T} - 14.2 \Lambda + 10.1}}$$

Burnham et al. (2015)

- We combine these models, with lattice strain theory, to run Monte Carlo simulations to assess the controls on zircon Eu/Eu*

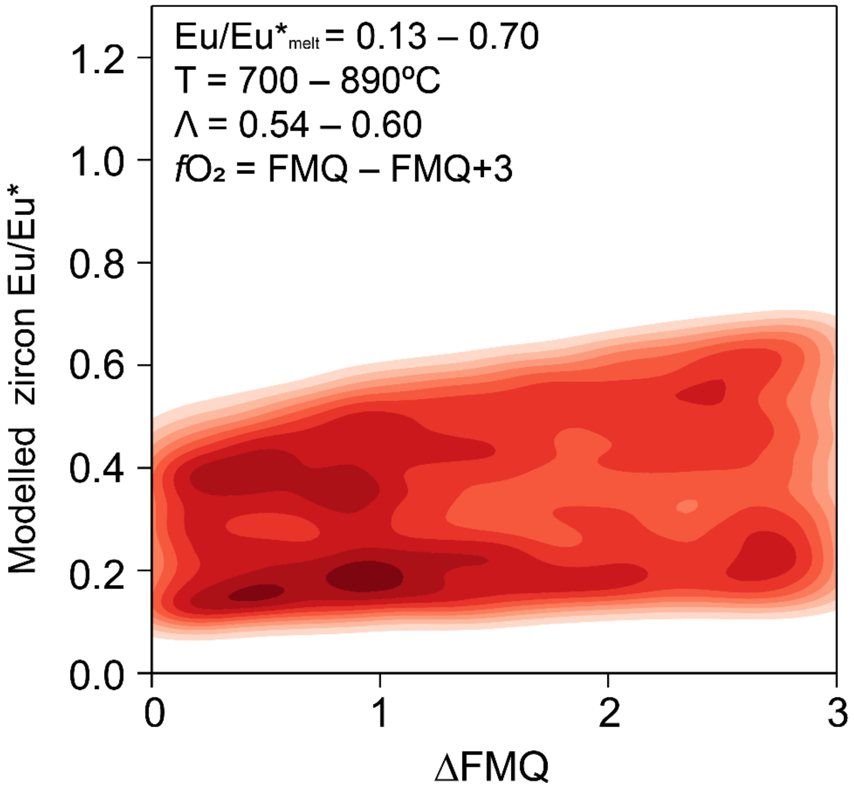
The effect of melt Eu/Eu*

- Strong relationship between melt Eu/Eu* and zircon Eu/Eu* (10,000 simulations)
- Using these results, we can estimate the melt in equilibrium with the natural zircon data (see kernel density plots on top of x-axis).



The effect of melt *f*O_2

- Taking the estimate melt Eu/Eu* for Quellaveco porphyry zircons, we assessed the influence of melt *f*O_2
- Weak influence of melt *f*O_2 on zircon Eu/Eu*
- Considerable scatter indicating stronger control of melt Eu/Eu*

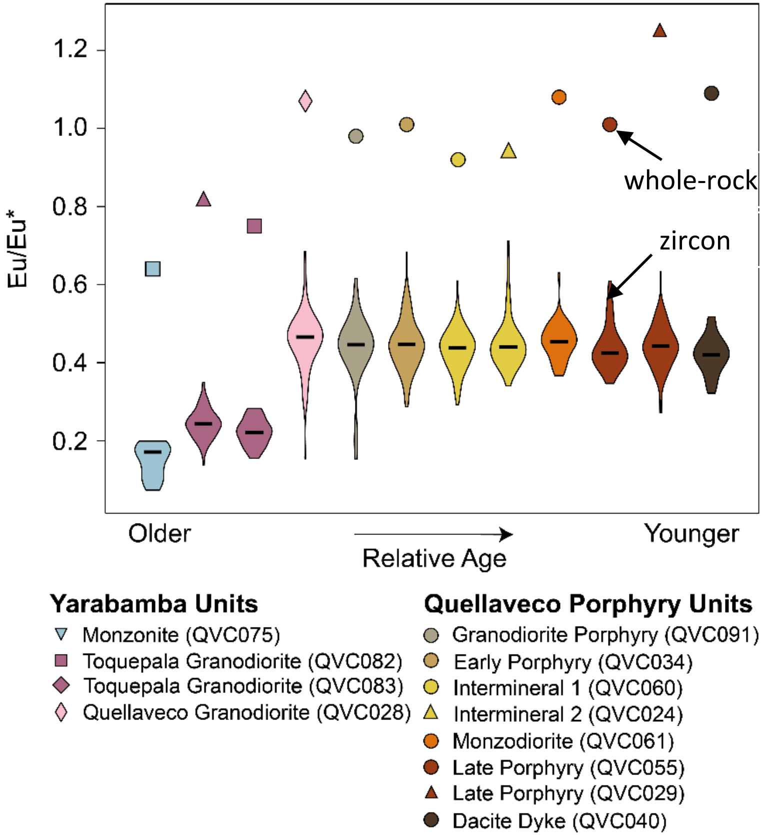


Zircon Eu/Eu* tracks melt Eu/Eu*

- The melt Eu/Eu* control on zircon Eu/Eu* is consistent with the observation that WR + zircon Eu/Eu* show a commensurate increase at ~60 Ma

- Zircon inherits the melt Eu/Eu* signature of deep magma evolution, upon its saturation in the shallow crust

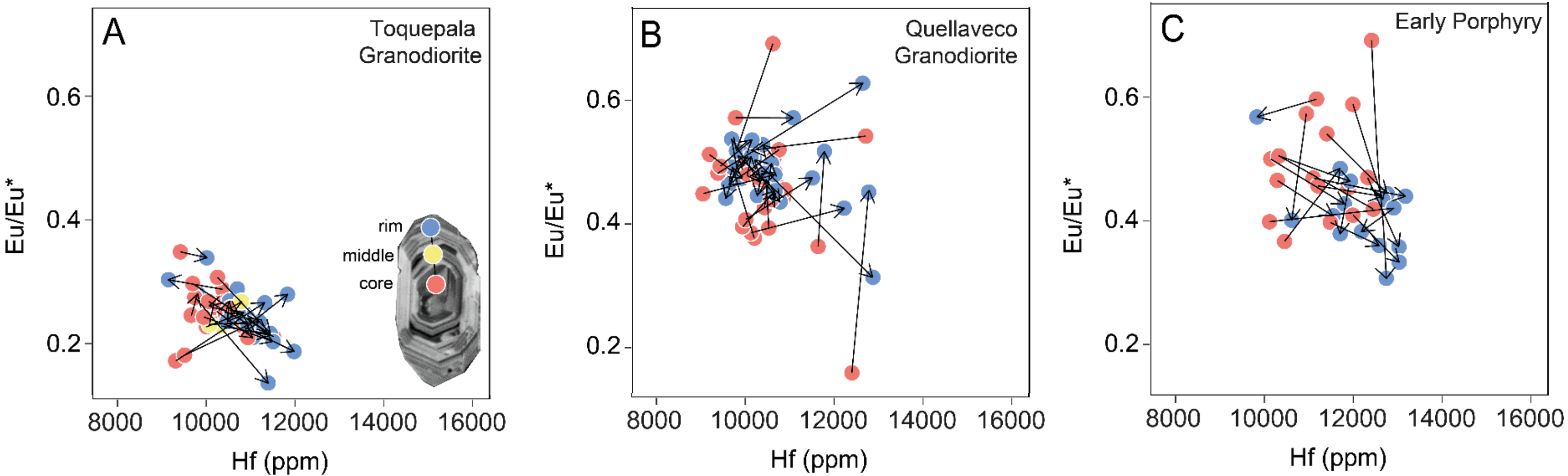
- A melt *f*O_2 control would only have an influence on zircon Eu/Eu* and not whole-rock Eu/Eu*



Shallow crustal controls on zircon Eu/Eu*

- Core-rim systematics indicate high Eu/Eu* signature changes during zircon crystallisation, likely due to plagioclase crystallisation (decreasing Eu/Eu*) and magma recharge (increasing Eu/Eu*)

- Paucity of increasing core-rim Eu/Eu* indicates high Eu/Eu* signature acquired prior to zircon saturation (i.e. in deep crust)



Summary and conclusions

1. In Southern Peru, the locus of lower crustal magma evolution deepened at ~60 Ma, 2-3 Myr before district-scale mineralistion at Quellaveco, Cuajone and Toquepala, as a result of crustal thickening

2. Such magma compositions were favourable (e.g. higher water content) to mineralisation, which likely occurred once a large enough volume of melt accumulated in the deep crust

3. Zircons record this deepening of magma evolution through Eu anomalies, with a subordinate role of melt fO_2 on controlling zircon Eu/Eu*