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U-Pb AND $^{40}Ar/^{39}Ar$ AGE CONSTRAINTS FOR THE TIMING OF MAGMATISM AND MINERALIZATION IN THE GIANT TOROMOCHO PORPHYRY CU-MO DEPOSIT, CENTRAL PERU

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INTRODUCTION

The evolution of giant porphyry ore deposits commonly results from superposition of multiple magmatic-hydrothermal systems. Such systems are developed in or adjacent to subvolcanic porphyritic intrusions that are apophyses to deeper-seated magma bodies (Dilles and Einaudi, 1992). Geochronological studies have shown that some phases of multistage subvolcanic porphyry intrusions can have ages distinct from associated magmatic–hydrothermal systems or can result from a more prolonged and/or episodic duration of magmatism and ore-formation.

This contribution is focused on the recently re-evaluated giant Toromocho porphyry Cu-Mo deposit in the Morococha district of central Peru, trying to constrain the timing of magmatism and ore formation by U-Pb dating of magmatic zircons and $^{40}Ar/^{39}Ar$ dating of hydrothermal biotite and phlogopite. In addition, whole rock major and trace element geochemistry, as well as in situ zircon trace element and Hf-isotope analyses are used to characterize the geochemical signatures of the Miocene magmatism, genetically related to the ore-formation.

GEOLOGICAL SETTING AND SAMPLING

The Toromocho porphyry Cu-Mo deposit (1.375 billion tones proven and probable reserves, including 22 billion pounds Cu, 758 million pounds Mo and 444 million ounces Ag; Peru Copper Inc. Annual Report-2006) is part of the Miocene polymetallic belt of Peru, hosting several world-class hydrothermal systems such as Yanacocha, Cerro Corona, Alto Chicama, Pierina, Antamina, Cerro de Pasco, and Colquijirca. The Toromocho deposit occupies the central part of the Miocene Morococha district (see also Bendezú et al., this volume), sitting at the eastern border of the Western Cordillera of central Peru and covering an area of about 70 km^2 in the north-western part of the Domo de Yauli complex.

The main regional structure in the area is the Morococha anticlinorium which axis trends roughly NW-SE. The geology of the district consists of continental volcanic rocks and red beds of the Mitu Group (Permian), sedimentary carbonate, volcanic rocks and basalts of the Pucará Group (Triassic-Jurassic), Goyllarisquizga Group, and Chulec, Pariatambo, Jumasha and Celendin Formations (Late Cretaceous), cut by Miocene intrusions with different ages (Eyzaguirre and Montoya 1976; Barrantes 1980; Alvarez, 1999; Fig. 1). The oldest intrusion (14.1 Ma; Beuchat, 2003) covering a large area in the western part of the district is known as Anticona diorite. The Anticona diorite does not show any direct relationship with the Miocene mineralization. The Toromocho magmatic-hydrothermal system is related to multiple porphyritic stocks cropping out in the central part of the district: Quartz-porphyry, Feldspar-porphyry and Granodiorite-porphyry (Fig. 1). The porphyry-related stocks are crosscut by a Dacitic porphyry dyke trending N100-120 which is probably the last magmatic event that took place in the studied area. Being intensively hydrothermally altered the dyke is be interpreted to be pre- to syn-mineralization. We could not find any magmatic body clearly postdating the mineralization at Toromocho. A large porphyritic body, known as Yantac porphyry (8.8 Ma; Beuchat, 2003), crops out in the southern part of the studied area, and more to the west shows crosscutting relationship with the Anticona diorite (Fig. 1). There is no porphyry mineralization or alteration related to the Yantac intrusion. Widespread skarnification and locally massive magnetite skarns are developed along the contacts of the Late-Miocene intrusions. Hydrothermal breccia pipe structures are typical for the central part of the Toromocho system. Part of the latter has been previously interpreted as “collapse-breccias” by Lowell and Alvarez (2005). Epithermal polymetallic veining overprints the porphyry and skarn mineralization, and postdates all Miocene porphyritic intrusions.

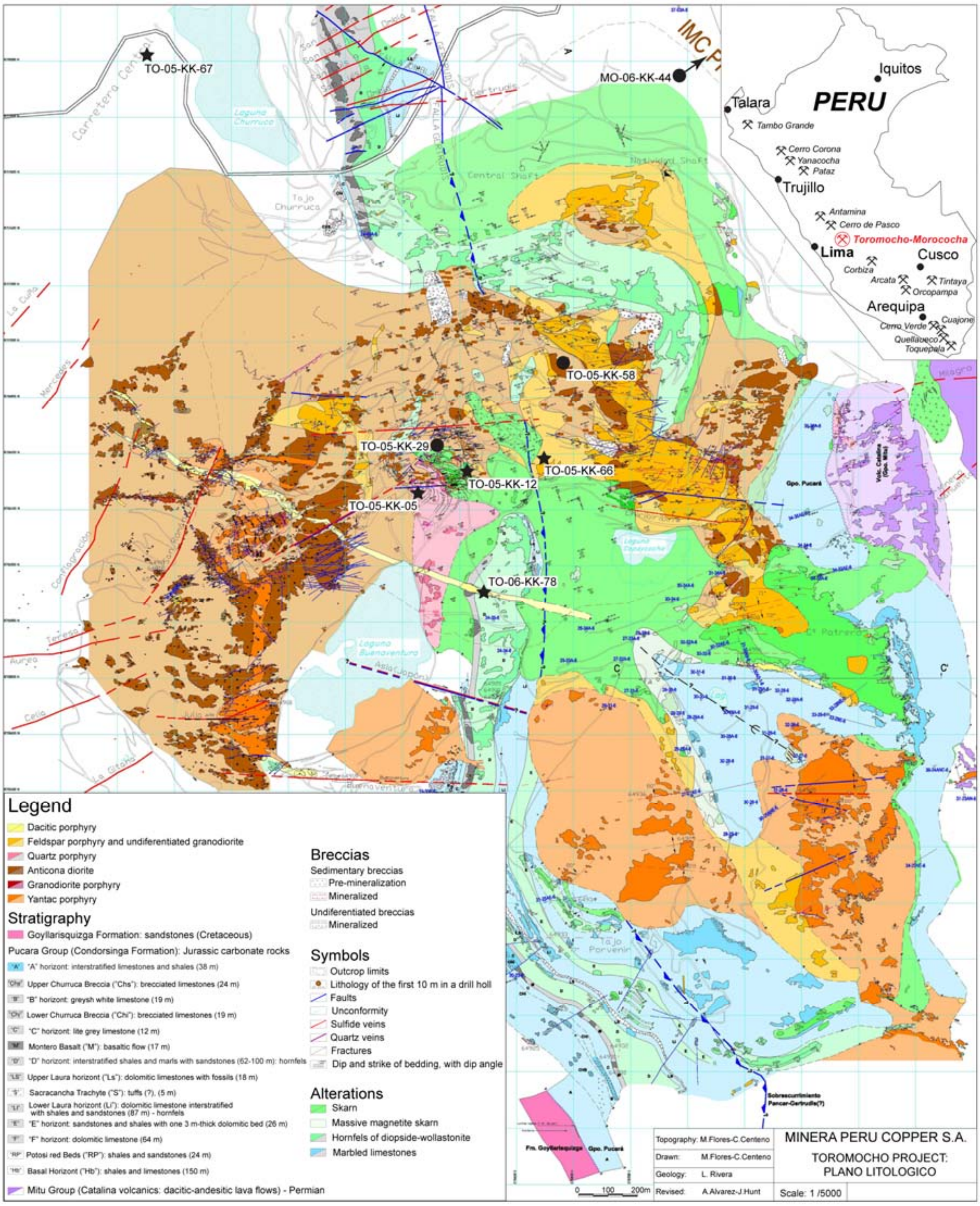

Figure 1 – Geological map of the Toromocho porphyry Cu-Mo (provided by Minera Peru Copper S. A.). Black stars indicate the location of samples used for U-Pb zircon dating, and the black circles – of samples used for Ar/Ar dating.

For the purpose of the present study, the following main Miocene intrusions in the studied area have been sampled for U-Pb dating and whole-rock geochemistry: Anticona diorite, Quartz-porphyry, Feldspar-porphyry, Granodiorite-porphyry and Dacitic porphyry dyke. In addition, three samples of hydrothermal biotite/phlogopite have been chosen for $^{40}Ar/^{39}Ar$ dating: biotite from a quartz-chalcopyrite porphyry vein in the granodiorite porphyry; phlogopite from the hydrothermal matrix of a breccia-pipe exposed in the Toromocho open pit, and phlogopite from a contact skarn, related to the Potosí stock, in the Codiciada area, NE of Toromocho. Location of samples is shown in Figure 1.

WHOLE-ROCK GEOCHEMISTRY

According to major (XRF) and trace element (LA-ICPMS) analyses, the studied magmatic rocks at Toromocho are normal calc-alkaline, medium- to high-K and have mostly dacitic to rhyolitic composition. Incompatible element abundances normalized to the primitive mantle show well expressed depletion in Nb, Ta and Ti, and enrichment in LILE and Pb, characteristic features of subduction-related magmas. Strontium content is usually low and no typical adakitic tendency has been observed. REE patterns of all studied rocks are very similar, except for the Feldspar-porphyry which shows depletion in LREE, most probably due to hornblende and/or apatite fractionation. Studied rocks do not show Eu anomaly.

U-Pb SYSTEMATICS

The U-Pb dating on single zircon grains was performed in the Radiogenic Isotope Laboratory of the University of Geneva using isotope-dilution techniques and measuring isotope ratios on a THERMO TRITON mass spectrometer equipped with a MasCom electron multiplier in ion counting mode. Results are reported in Figure 2. Inherited zircon cores were common in all of the studied samples (Fig. 2f), rendering precise and accurate dating very difficult. In order to minimize the effects of secondary lead loss – the second problem encountered in this study, chemical abrasion technique has been applied to the zircons, consisting of high-temperature annealing followed by a HF leaching step. The latter has been shown to be very effective in removing strongly radiation damaged zircon domains, which underwent lead-loss during post-crystallization fluid-assisted processes.

Five zircon crystals from the Anticona diorite sample are concordant within analytical error and define a weighted mean $^{206}Pb/^{238}Pb$ age of 14.07±0.04 Ma (MSWD=2.8; Fig.2a), which we consider to be the best estimate for the age of this intrusion. Due to common inheritance and lead loss in the analyzed zircons from the Granodiorite-porphyry (Fig. 2b), we could not obtain high-precision age. We estimate 8.21±0.10 Ma to be a maximum age of crystallization for this sample. Due to common lead loss and inheritance, the Feldspar-porphyry and the Quartz-porphyry samples revealed an upper intercept and lower intercept ages of 8.17±0.44 Ma and 7.75±0.13 Ma, respectively (Fig. 2c-d). The Dacitic porphyry dyke, which corresponds to the youngest magmatic event in the district, yields highly imprecise upper intercept age of 8.0±0.1 Ma.

TRACE ELEMENT AND Hf-ISOTOPE SYSTEMATICS OF ZIRCONS

In situ LA-ICPMS trace element and MC-LA-ICPMS Hf-isotope analyses of zircons (von Quadt et al., 2008) were performed at ETH-Zurich. The use of laser-ablation technique for local analysis was imposed by the common presence of inherited cores, thus allowing separate analysis of cores and rims (Fig. 2f). In addition, three to five zircon grains, dated by TIMS, were also analyzed for their Hf isotope ratios using solution MC-ICPMS technique, also at ETH-Zurich.

Zircons from all studied samples show extremely consistent chondrite-normalized REE patterns. A weak Eu anomaly is present in all of them. A slight increase of the Eu/Eu*, Nb/Ta and Th/U ratios has been recorded as a function of the crystallization age of the zircons - from the Mid-Miocene Anticona diorite (14 Ma) to the Late-Miocene porphyries (7-8 Ma), suggesting a slight increase of mantle component of the magmas with time. The positive Ce anomaly of the zircons is considerably higher for the Late-Miocene intrusions, suggesting as well higher oxidation state of the parental magma, which is consistent with the porphyry ore-formation genetically related to these intrusions.

Laser-ablation analyses of zircons allowed quantifying their Ti content and thus applying the Ti-in-zircon geothermometer (Ferry and Watson, 2007). Results are consistent with textural observations as the equigranular Anticona diorite and Granodiorite-porphyry crystallized at higher temperature (650-730°C) than the porphyritic Quartz-porphyry, Feldspar-porphyry and Dacitic porphyry dyke, emplaced in the temperature interval 610-690°C.

The magmatic rims of the majority of the studied zircon grains from all samples have εHf values within the large interval -5 to +3, determined by in situ analysis. The Hf isotope values measured from solutions of dated concordant grains, plot within the same range. No significant difference in Hf isotope signatures between Mid-Miocene (Anticona diorite) and Late-Miocene magmas has been recorded. The Hf isotopic composition of Miocene magmatic rocks from Toromocho suggests mixed crustal-mantle origin of the magmas, indicating also significant assimilation of crustal components with various nature as in some of the inherited cores $\varepsilon Hf_{t=0}$ values as low as -25.8 have been measured.

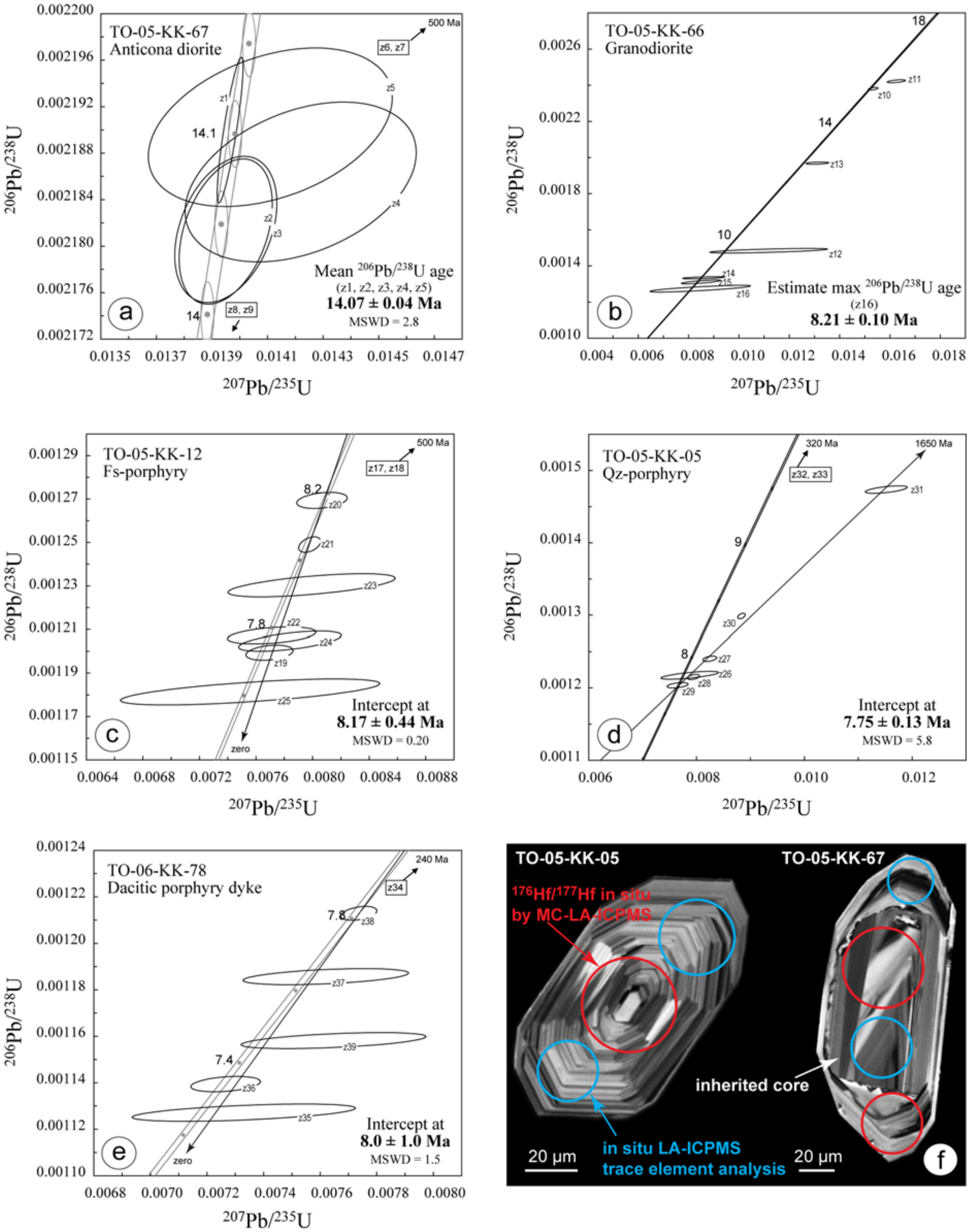

Figure 2 – U-Pb concordia diagrams of the studied samples (a-e) and SEM-CL image of zoned magmatic zircons illustrating in situ $^{176}Hf/^{177}Hf$ MC-LA-ICPMS and trace element LA-ICPMS analysis (f).

$^{40}Ar/^{39}Ar$ SYSTEMATICS

Incremental heating $^{40}Ar/^{39}Ar$ age spectra for hydrothermal biotite and phlogopite are reported in Figure 3. Ages quoted for each sample are derived from the well defined plateau on the age spectrum. These results indicate different pulses of porphyry ore formation in the district separated in time by about 2 My, as recorded by the Ar/Ar dating of hydrothermal biotite from porphyry vein in the Granodiorite-porphyry (6.81±0.14 Ma; Fig. 3a) and phlogopite from the hydrothermal matrix of a breccia-pipe exposed in the Toromocho open pit (8.98±0.22; Fig. 3b). Skarn formation in the Codiciada area at 8.8 Ma (Fig. 3c), most probably related to the emplacement of the Potosí porphyry stock, is coeval with the first pulse of porphyry ore formation.

DISCUSSION AND CONCLUSIONS

A summary diagram for the timing of magmatism and hydrothermal activity in the Toromocho-Morococha district is presented in Figure 4, summarizing the existing K-Ar, Ar/Ar and U-Pb data (Eyzaguirre et al. 1975; Beuchat, 2003) and the new U-Pb and Ar/Ar dating from the present study.

The Toromocho porphyry Cu-Mo deposit was formed in a multiple intrusion-centered magmatic-hydrothermal system that most probably has been active during more than 2 My. Dating of the different magmatic stocks between 9 and 6.8 Ma, confirmed the relative time relationships observed in the field. Due to the presence of inherited cores in all analyzed zircon grains, it was not possible to precisely determine the crystallization age of the Dacitic dyke, which according to field observations is the youngest magmatic event, related to the Toromocho magmatic-hydrothermal system.

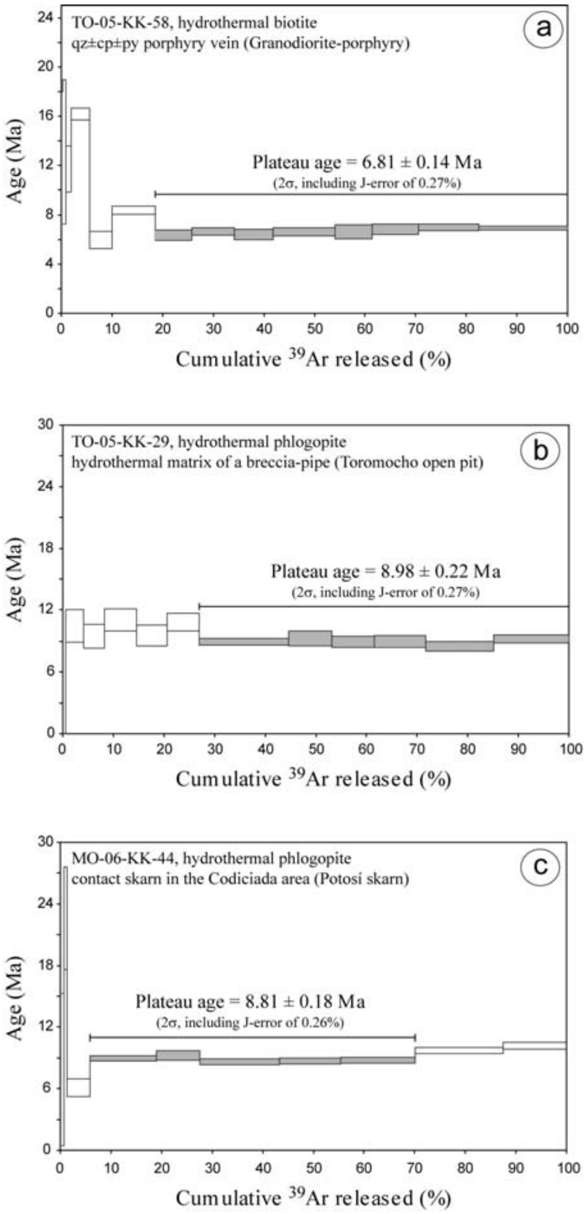

Figure 3 – $^{40}Ar/^{39}Ar$ age spectra of hydrothermal biotite and phlogopite. Plateau ages are calculated with increments colored in gray.

Re-Os dating of hydrothermal molybdenite at Toromocho (Fig. 4; Beuchat, 2003) yields ages which are slightly older than the host Quartz-porphyry stock (7.75 Ma). We speculate that the Re-Os ages are biased by analytical problems or by complex system behavior in molybdenite.

The barren Yantac intrusion (8.8 Ma; Beuchat, 2003) is about 1 My older than the magmatic stocks in Toromocho. However, the Ar/Ar age (7.14 Ma) of phlogopite from the Porvenir skarn, spatially associated with Yantac, correlates well with the timing of the potassic alteration at Toromocho and postdates by 1.5 My the emplacement of the intrusion itself. Possibly, the skarn formation at Porvenir is not related with the Yantac intrusion, but with younger porphyry intrusion at depth, coeval with the magmatic activity in the nearby Toromocho system.

The obtained Ar/Ar 8.81±0.18 Ma age of the Potosí skarn NE of Toromocho is very close to the U-Pb 8.8 Ma age of the Yantac intrusion and to the U-Pb 9.1 Ma age of the San Francisco porphyry stock in the central part of the district (Beuchat, 2003) and confirms that the magmatic and associated hydrothermal activity in the different parts of the Morococha district took place over a protracted period of at least 2-2.5 My. The spatial superposition of multiple Late-Miocene magmatic and associated hydrothermal events in the Morococha district is most probably responsible for the formation of the giant Toromocho porphyry Cu-Mo deposit in its central part.

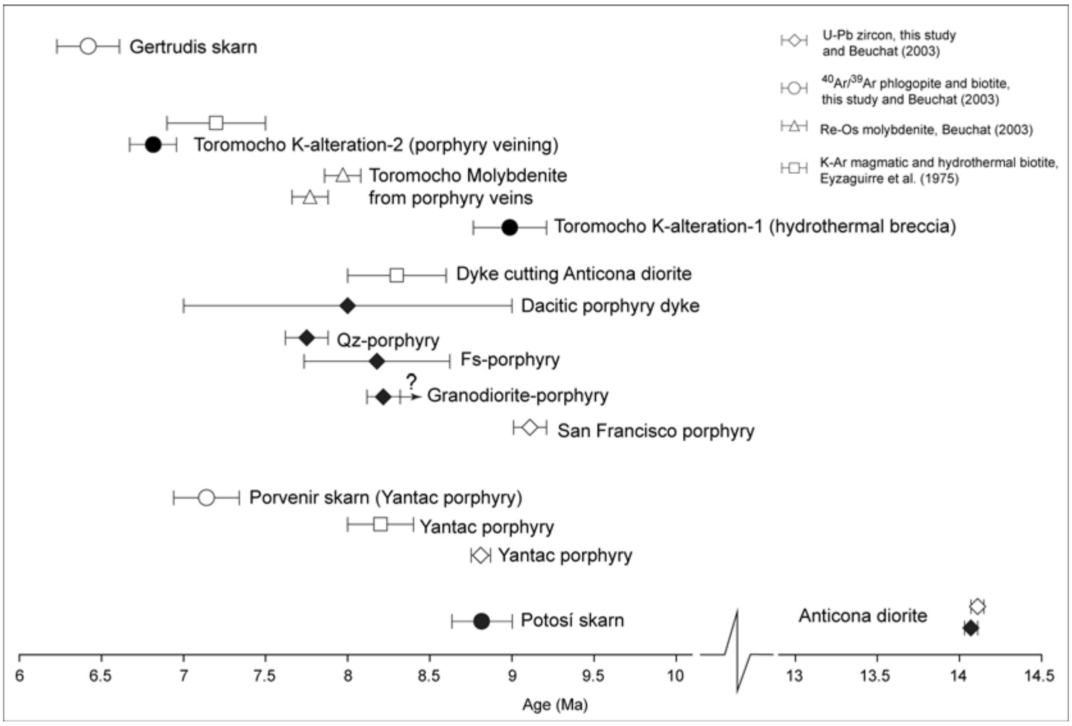

Figure 4 – Summary diagram for the timing of magmatic and hydrothermal events at Toromocho (white symbols – published data; black symbols – this study).

Finally, the new results are in good agreement with the previously reported data by Beuchat (2003) for U-Pb dating of magmatic zircons from the Anticona diorite. This deeply eroded Mid-Miocene magmatic body is the largest Miocene intrusion in the district, but there is no indication of ore bodies genetically related to it.

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