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DATACION URANIO-PLOMO DE CIRCONES DE LOS PORFIDOS CUPRIFEROS CHUQUICAMATA Y LA ESCONDIDA, CHILE: CIRCONES HEREDADOS CON NUCLEOS DE EDAD PALEOZOICA Y SOBRECRECIMIENTOS TERCIARIOS

URANIUM-LEAD DATING OF ZIRCONS FROM THE CHUQUICAMATA AND LA ESCONDIDA PORPHYRY COPPER DEPOSITS, CHILE: INHERITED ZIRCON CORES OF PALEOZOIC AGE WITH TERTIARY OVERGROWTHS

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INTRODUCTION

Zircon concentrates from samples of porphyritic rocks associated with the porphyry copper deposits of Chuquicamata (22°16'S/68°54'W) and La Escondida (24°16'S/69°04'W), were analyzed at the Royal Ontario Museum, Toronto, Canada, by T.E. Krogh. The samples were collected by V.Maksaev and C.Alpers during their respective thesis studies (Maksaev, 1990 Dalhousie Univ.; Alpers, 1986 Univ. California, Berkeley). We present here the first U-Pb ages on zircons from the two important porphyry copper deposits, and draw preliminary inferences on the unexpected occurrence of inherited zircons with cores of Paleozoic age in samples of porphyritic rocks from both deposits. Two main questions are addressed that remain unresolved: 1) the age and duration of the mineralization process, and 2) the source of the magmas and metals in these major ore deposits.

THE AGE AND DURATION OF THE MINERALIZING PROCESS

Regional geochronology by the K/Ar, $^{40}Ar/^{39}Ar$, and fission track methods suggest that the Domeyko Cordillera was undergoing strong uplift and exhumation at about 40 Ma, preceding the formation of the various porphyry copper deposits of the region, and moderate exhumation during and after their emplacement (Maksaev et al. 1988a; 1988b; Zentilli and Maksaev, 1989; Maksaev, 1990).

The Chuquicamata deposit is hosted by a ca. 31 Ma-old granodiorite porphyry stock (Chuqui Porphyry) 14 km long and 1 km wide. The main orebody occupies an area of about 3 x 1.5 km in the southern end of the complex. To the east the mineralized porphyry intrudes Mesozoic metasediments and Paleozoic igneous and metamorphic rocks (Alvarez and Flores, 1985). The age of the crystalline rocks in the Domeyko Cordillera ranges from Middle Proterozoic (Damm et al., 1986; Tosdal, in press), to Permian and Triassic (Davidson et al., 1985). In the vicinity of the mine, crystalline rocks have K/Ar dates of ca. 250 Ma (Maksaev et al. 1988a; 1988b). To the west, the mineralized body is truncated by a major fault system (Falla Oeste), across which lies the relatively fresh, equigranular, "pre-mineral" Fortuna Granodiorite (Ambrus, 1979), which has been dated by the K/Ar method at 39.5 Ma (Maksaev, 1990), although many K/Ar (Ambrus, 1977, 1979) and $^{40}Ar/^{39}Ar$ ages are somewhat younger, as young as ca. 35 Ma (Maksaev et al., 1988a; Maksaev, 1990). In view of the uncertainty of the magnitude and age of post-mineral strike-slip displacement of the Falla Oeste, it remains to be demonstrated that the Fortuna Granodiorite is genetically related to the Chuqui Porphyry. Potassic alteration accompanied the first pulse of metallic mineralization at Chuquicamata, and its age is about 34.8 to 31.2 Ma on the basis of published K/Ar dates (Ambrus, 1977,1979; Sillitoe, 1988). Maksaev et al. (1988a) obtained (plateau) ages on (potassic alteration) biotite of ca. 32 Ma by the $^{40}Ar/^{39}Ar$ method, and suggested that the older K/Ar ages obtained by different workers might result from excess argon. Most of these dates, unfortunately, were done on minerals with argon blocking temperatures of about 300°C or less, thus the ages could have been partially or totally reset by the main phase of metallic mineralization and pervasive sericitic alteration at Chuquicamata, at ca. 31 Ma (Maksaev, 1990). The coincidence of $^{40}Ar/^{39}Ar$ ages on biotite, K-feldspar, and of fission-track dating in apatite suggest the fast cooling and shallow emplacement of the pluton (Maksaev and Zentilli, 1988), although Sillitoe (1988) referred to a K/Ar age on sericite as young as 28.0 ± 1.1 Ma. An 8-point Rb/Sr isochron of 34.2 ± 4 Ma can be computed from published data (Zentilli et al., 1988b), but the scattered nature of the samples and the analytical uncertainties make this age unreliable.

In summary, mineralization at Chuquicamata took place between the emplacement of the "pre-mineral" Fortuna Granodiorite at ca. 39 Ma, and 30.2 ± 4.4 Ma, the time of final cooling of the system to ca. 100° C (Maksaev, 1990). The lapse of 4-5 Ma between "precursor" magmatism and early mineralization at Chuquicamata is not unusual (Sillitoe, 1988), but the protracted mineralizing phenomenon of ca. 4-5 Ma duration (Fig.3 in Sillitoe, 1988) is unlikely; these epizonal plutons, interacting with meteoric water, probably cool over few tens of thousands of years (e.g. Cathles,

1981; Maksaev, 1990), and one must consider the hypothesis that at Chuquicamata there could have been two or more discrete pulses of alteration/mineralization.

The geology of the La Escondida porphyry copper was discussed by Alpers (1986) and Alpers and Brimhall (1989), and Alpers and Brimhall (1988) reported several K/Ar dates ranging from 38.3 ± 1.5 Ma to 31.0 ± 1.4 Ma. The authors ascribed biotite K/Ar ages of ca. 33.7 to 32.8 Ma to early hypogene alteration, and sericite K/Ar ages of ca. 31.6 to 31.0 to late hypogene alteration. Hypogene alunites yielded K/Ar ages of 35.7 ± 1.8 and 38.3 ± 1.5 Ma, but were interpreted by Alpers (1986) to be too old, possibly due to excess argon in inclusions in the alunite. Ojeda (1986) reported K/Ar ages from La Escondida that range from 34.6 ± 1.8 to 31.8 ± 1.2 Ma. An older biotite K/Ar of 39.1 ± 1.1 from a biotitized andesite from a deep drillhole was dismissed by this author as "anomalous".

In terms of the age of hypogene mineralization, and considering the uncertainties of sampling and dating methods, Chuquicamata and La Escondida may be considered coeval. It is unclear whether the geochronological techniques used so far can penetrate beyond the "veil" imposed by the last major phase of alteration. Either the emplacement of the porphyries and ensuing potassic alteration occurred a few million years before the last phase of alteration and the K/Ar system was thermally reset, or the late hypogene phase was almost coeval with the intrusion and early hypogene phase. Excess argon could then explain the recurrent older ages. It was hoped that U/Pb dating of zircons would provide reliable ages of intrusion or emplacement for the porphyries.

SOURCE OF THE METALS AND MAGMAS

Zentilli et al. (1988a; 1988b; 1990), and Maksaev (1990) have shown that, despite widely different locations, basement geology, crustal thickness, age of intrusion/mineralization, and age of lithosphere being subducted under their respective locations, ores and rocks from Chilean porphyry coppers have isotopic compositional ranges that are much narrower than those of other ore deposit types or intrusive and volcanic igneous rocks of all ages in the Central Volcanic Zone of the Andes. Within a deposit, isotopic data tend to cluster around the following values, characterized by limited results for Chuquicamata and El Salvador, respectively: $^{143}Nd/^{144}Nd$ (0.51269, 0.51276); ϵNd (+1.3, +2.3); $^{206}Pb/^{204}Pb$ (18.58, 18.51); $^{207}Pb/^{204}Pb$ (15.61, 15.60); $^{208}Pb/^{204}Pb$ (38.53, 38.46), $^{87}Sr/^{86}Sr(i)$ (0.7044, 0.7040); ϵSr (-2, -7). La Escondida is located geographically between El Salvador and Chuquicamata and we would expect comparable values.

These isotopic compositions are similar to those of Neogene and Quaternary andesites of the Southern Volcanic Zone (SVZ) of the Andes (e.g. López-Escobar, 1984; Stern, 1988), where the continental crust is thinner, and the age of the subducted slab is younger than at the latitude of Chuquicamata. The remarkable homogeneity of the isotopic signature over thousands of kilometres requires either a surprisingly uniform source, or a most efficient homogenizing mechanism. The REE patterns of Chuquicamata and other porphyries are steep, show no Eu anomaly, and are compatible with low degrees of partial melting in a deep source where garnet was stable. Significant contamination of the porphyry magmas by the relatively radiogenic and hete-

rogeneous upper crust is unlikely. An upper mantle or lower crustal source or contamination by the MASH process (e.g. Hildreth and Moorbath, 1988) is possible. Subduction erosion (e.g. Stern, 1988), and other mechanisms of contamination (e.g. Davidson et al., 1991), accepted for some magmas of variable isotopic signature in the Central Volcanic Zone of the Andes (e.g. Figures 5 and 7 in Zentilli et al., 1988b; see also Tosdal et al., 1994, this issue), appear inconsistent with the remarkably homogeneous ratios of the Chilean porphyries.

ANALYTICAL PROCEDURES

Zircons were dissolved in HF and HNO_3 at 220°C (Krogh, 1973) in the presence of a mixed $^{205}Pb/^{235}U$ tracer (Parrish and Krogh, 1987). Following separation by ion exchange, both Pb and U were loaded on a Re filament in the presence of silica gel and analyzed in sequence in a mass spectrometer. The analyses were corrected for 8 and 0.5 pg of background Pb and U respectively, and an estimated 2 sigma error of 0.5% was applied to both the U-Pb and $^{207}Pb/^{206}Pb$ ratios. The error on the latter ratio was increased by a factor of 3 for analysis 5, which has a higher common lead correction. For a more complete discussion of error considerations for small samples (not merited for this limited data set), see Krogh et al. (1993).

ISOTOPIC RESULTS

The U-Pb results obtained so far (Table 1, Figure 1) yield a remarkably simple data set that indicates that all three samples (from Chuquicamata and La Escondida porphyries) apparently contain a similar inherited component with an age of 291 ± 29 Ma and have a similar age of emplacement, at the precision presently available. For the purpose of this note, we have decided to plot them together in Fig. 1, although it should be noted that one of the samples (ZCAZ-3-3; analyses 5 and 6, Fig. 1) corresponds to a porphyritic ignimbrite (Sample CAZ-321 in Alpers and Brimhall, 1988). Independent lower intercept (intrusion or emplacement) for each body are 32.3 ± 5 Ma for Chuquicamata and 32.6 ± 2 Ma for La Escondida. Combining all the data, a 6-point linear array with a lower intercept at 31.2 +2.1/-2.5 Ma can be computed. Therefore the U-Pb data support the conclusion, already reached with the gas chronology, that the two deposits have essentially the same age.

All analyses have unusually high common lead levels as if some lead was incorporated, possibly as inclusions, at the time of crystallization. However, because we have used the known measured isotopic composition for lead in similar rocks to correct the measured isotopic data (Zentilli et al., 1988b), the effects on the uncertainty of these common lead corrections should be minimal.

DISCUSSION, CONCLUSIONS, AND OUTSTANDING QUESTIONS

The Chuquicamata samples (1, 2, Fig. 1, Table 1), represent the mineralized East Porphyry (open pit, 400 m below pre-mine surface) in potassic alteration (orthoclase, biotite), affected by incipient sericitization. These analyses show the smallest inherited component of the six presented. The same hand sample (ZFT-19, Table 1; FT-19 in Maksaev,

FIGURE CAPTION

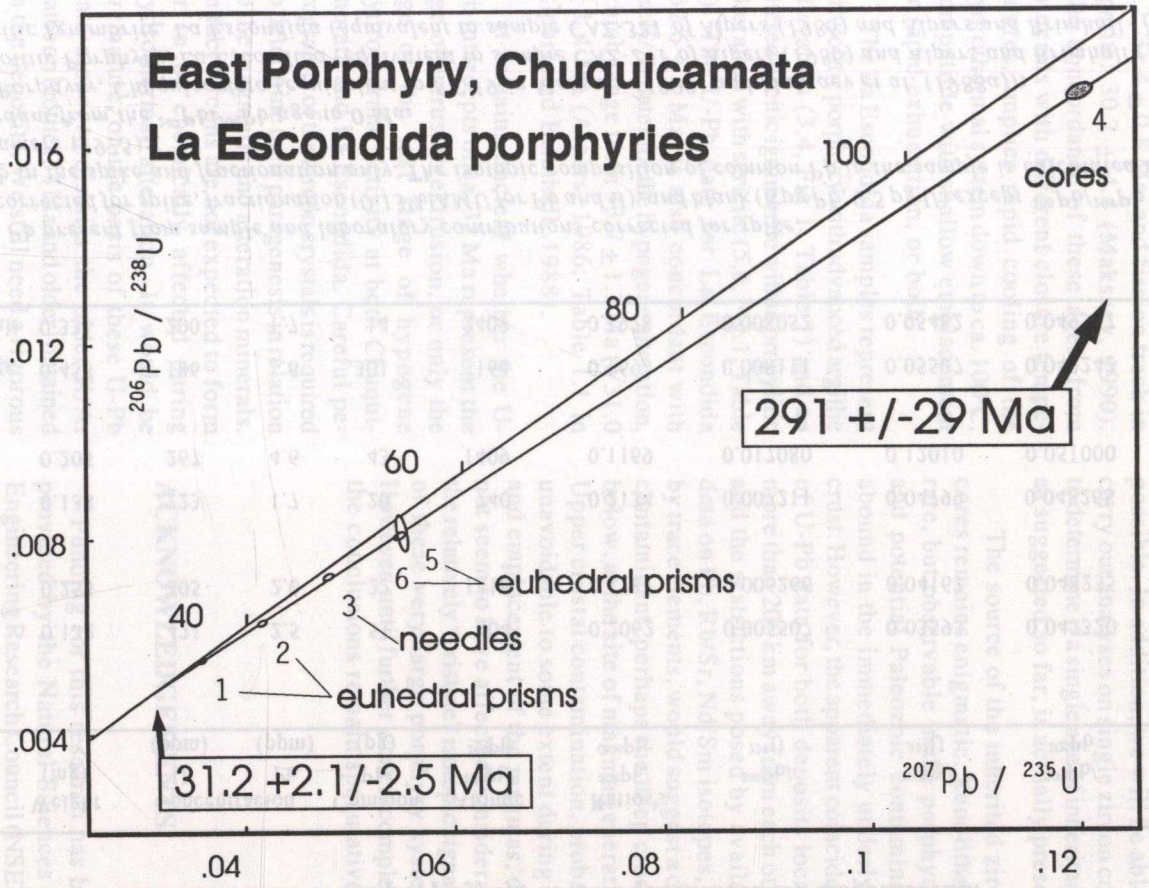

Fig. 1: Concordia plot for zircon samples from Chuquicamata and La Escondida Porphyry Copper Deposits, Chile. Consult text and Table 1 for explanation. Note that analyses 3 - 4, and 5 - 6 represent different rock types (Table 1). Independent lower intercepts are 32.5±5 Ma for Chuquicamata anda 32.6±2 Ma for La Escondida.

TABLE

Table 1. U-Pb zircon data for rocks from porphyries at Chuquicamata La Esconndida.

Description fraction no.	Weight (mg)	Concentración U (ppm)	Pb (ppm)	Common Pb[a] (pg)	Atomic $^{206}Pb/^{204}Pb$	Ratios[b] $^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	Agc (M) $^{207}Pb/^{206}Pb$	% Dic[c]
ZFT-19 [d]											
1. < 0.1 mm	0.132	421	2.5	51	404	0.2062	0.005507	0.03593	0.047320	65.2	46
2. > 0.1 mm	0.255	305	2.0	22	1416	0.1787	0.006266	0.04167	0.048235	lll.0	64
ZCAZ 2-3 [e]											
3. needles	0.138	223	1.7	20	740	0.2134	0.007211	0.04799	0.04826S	112.1	59
4. cores	0.205	267	4.6	43	1409	0.1169	0.017080	0.12010	0.051000	241.0	55
ZCAZ 3-3 [f]											
5. euhedral large	0.453	186	1.6	301	164	0.1693	0.008111	0.05507	0.049242	159.2	68
6. euhedral small	0.331	200	1.7	14	2409	0.1978	0.008052	0.05482	0.049377	166.0	69

Notes:

[a] Total common Pb present from sample and laboratory contributions corrected for spike;

[b] Atomic ratios corrected for spike, fractionation (0.13%/AMU for Pb and U), and blank (8 pg Pb, 0.5 pg U) except $^{206}Pb/^{204}Pb$ which is corrected for common Pb in the spike and fractionation only. The isotopic composition of common Pb in the sample is calculated using the model of Stacey and Kramers (1975);

[c] Percent discordant from the $^{207}Pb/^{206}Pb$ age to 0 Ma.

[d] ZFT-19, East Porphyry, Chuquicamata (equivalent to FT-19 in Maksaev (1990) and Maksaev et al. (1988a));

[e] ZCAZ 2-3 Rhyolitic Porphyry, La Escondida (equivalent to sample CAZ-241 of Alpers (1986) and Alpers and Brimhall (1988));

[f] ZCAZ 3-3 Dacitic Ignimbrite, La Escondida (equivalent to sample CAZ-321 of Alpers (1986) and Alpers and Brimhall (1988)).

1990) has yielded so far the following age data: U/Pb (lower intercept) in zircon: 32.3 ± 5 Ma (this paper); $^{40}Ar/^{39}Ar$ (plateau age; total-gas age) on biotite: 31.7 ± 0.4; 30.8 ± 1 Ma; $^{40}Ar/^{39}Ar$ (plateau age; total-gas age) on orthoclase: 31.4 ± 0.2; 31.4 ± 0.8 Ma; and fission track in apatite: 30.2 ± 4.4 (Maksaev, 1990). The concordance of these ages, from minerals with different closure temperatures, implies rapid cooling of the hydrothermal system down to ca. 100°C, compatible with shallow emplacement or rapid exhumation, or both.

The La Escondida samples represent a rhyolitic porphyry with advanced argillic alteration (3,4, Fig 1, Table 1) and an altered dacitic ignimbrite within propylitic alteration with sericite (5,6, Fig.1, Table 1). The U-Pb date for La Escondida (32.6 ± 2 Ma) is also concordant with the K/Ar dates for the hypogene alteration, which range from 33.7 ± 1.3 Ma to 31.0 ± 1.4 Ma (Alpers, 1986; Table 1.1 in Alpers and Brimhall, 1988).

It remains unclear whether the U-Pb intercepts of ca. 32 Ma represent the age of intrusion/extrusion, or only the age of the last stage of hypogene hydrothermal activity at both Chuquicamata and La Escondida. Careful petrography of the zircon crystals is required to determine their paragenesis in relation to the magmatic and alteration minerals. In fact zircons are not expected to form or to be chemically affected during hydrothermal alteration. It would be premature, on the basis of these U-Pb data alone, to dismiss the older K/Ar dates on biotite (34 Ma and older) obtained in the deposits. We still need a rigorous test of the hypothesis that these older ages reflect excess argon in the K-Ar system (e.g. Maksaev, 1990).

Dating of carefully selected altered and less-altered samples of the porphyries, detailed petrography, and assessment of analytical uncertainties will hopefully help resolve the question. If inherited components can be successfully avoided in future U-Pb analyses, an age comparison at the 0.1 and 0.3 Ma level should be possible. In addition, we will be able to carry out analyses on single zircon cores to determine if a single age of inheritance, as suggested so far, is actually present.

The source of the inherited zircon cores remains enigmatic. Xenoliths are rare, but observable in the porphyries, and potential Paleozoic contaminants abound in the immediately underlying crust. However, the apparent coincidence of U-Pb data for both deposits located more than 200 km away from each other, and the restrictions posed by available data on Pb, Rb/Sr, Nd/Sm isotopes, and by trace elements, would suggest a deep contaminant, perhaps the deep crust or below, at the site of magma generation. Upper crustal contamination, probably unavoidable to some extent during rise and emplacement of the magmas, does not seem to have affected considerably the relatively "pristine" isotopic signature of these very large porphyry systems. However, until further work is completed, the conclusions remain speculative.

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