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METALLOGENY OF THE PACIFIC NORTHWEST: TECTONICS, MAGMATISM AND METALLOGENY OF ACTIVE CONTINENTAL MARGINS

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METALLOGENY OF THE CENTRAL ANDES: GEOTECTONIC FRAMEWORK AND GEOCHEMICAL EVOLUTION OF PORPHYRY SYSTEMS IN BOLIVIA AND CHILE DURING THE LAST 40 MILLION YEARS

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Abstract: The Central Andes is a textbook example of ore formation at an active continental margin. Base metal porphyry systems define short-lived punctuated regional episodes of change in subduction/stress regime on a general background of quasi-continuous subduction. The transition from normal to flat subduction, i.e. lithospheric hydration at very reduced magmatic activity in the outer arc is favorable for the formation of large copper porphyry systems. The oxidized mantle-dominated fluid reservoir with mostly recycled seawater is tapped by deep strike-slip structures which develop in response to changes in plate convergence. Tin porphyries occur in a different inner arc environment during transition from flat to normal subduction, or during subduction rollback, when flow of hot asthenospheric mantle into the expanding mantle wedge leads to melting of the overlying continental crust and subsequent fractional crystallization under reducing conditions of a mostly continental fluid reservoir.

1.INTRODUCTION

The full spectrum of interplay between exogenic (ocean currents, climate) and endogenic processes (tectonics, magmatism, mineralization) is nowhere better exposed than at the Andean margin. Spectacular ore deposits mark time intervals with extreme reaction progress of major petrogenetic processes.

The Central Andes host the largest copper resource in the world and also host some of the historically largest tin and silver deposits. Chile is the top copper producer and provides about one third of the global copper mine production.

The base and precious metal deposits of the Central Andes are controlled by quasi-continuous subduction along the western South American continental margin since at least 200 Ma. The major copper porphyry systems formed in between 31-41 Ma (northern Chile) and 5-10 Ma (central Chile, NW Argentina). Major tin porphyry/granite systems with a silver-rich epithermal superstructure developed in between 25-14 Ma in Andean Bolivia and southernmost Peru. The regional metallogenic zoning pattern and the punctuated nature of major ore formation is a matter of both basic research and great economic importance.

2. GEODYNAMIC SETTING: THE PACIFIC PERSPECTIVE

The geological evolution of the Central Andes is best recorded in the Pacific Ocean. The isochron map of ocean floor ages provides quantitative information on seafloor spreading since about 100 Ma (Müller et al. 1997). The oldest oceanic crust at the trench off the Central Andes is about 45 Ma old; older crust is already subducted (Fig. 1). However, the mirror image of that crust can be observed back to about 100 Ma west of the mid-Pacific ridge. The seafloor age pattern defines an interval of 40-100 Ma with relatively slow subduction rate of 2-4 cm/year. Since 40 Ma, the spreading rate is 8-12 cm/year in the SE Pacific. The seafloor map also indicates relics of old ocean plateau crust in the SW Pacific (Ontong-Java Plateau, and others), which is related to the central Pacific mid-Cretaceous superplume (Larson 1991). This thick oceanic crust must have reached the central part of the South American continental margin at about 40 Ma when a magmatic gap in the volcanic arc system occurs (James and Sacks 1999). The gap is attributed to a change from normal to flat subduction due to greater buoyancy of the oceanic plateau crust which shuts off volcanism by closure of the mantle

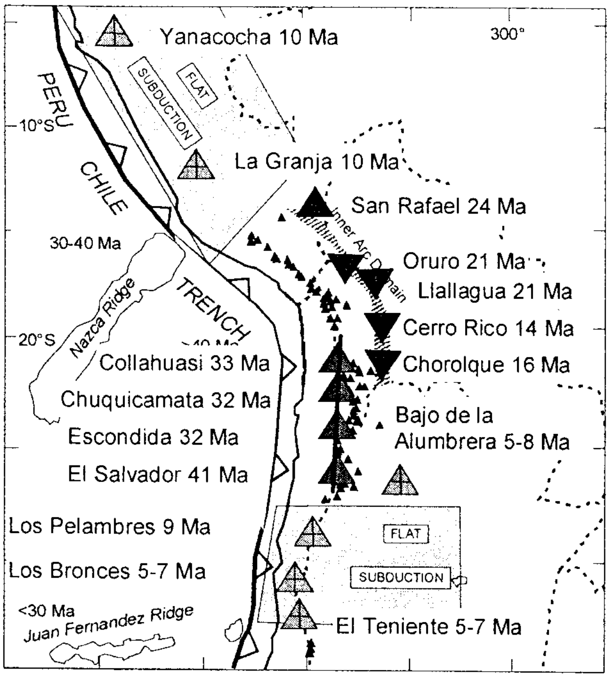

Fig. 1. Giant porphyry/epithermal deposits of the Central Andes and their present-day geotectonic setting. Seafloor age pattern from Müller et al. (1997). Downcast triangle locates tin porphyry/ granite systems (14-25 Ma); upright triangles are for copper porphyry systems of 31-42 Ma and 5-10 Ma intervals. Small solid triangles are recent active volcanoes

wedge. Volcanism sets in again at around 25 Ma in the innermost arc (western Bolivia) with re-establishment of normal subduction. The volcanic zone then broadens westward as hot asthenospheric material flows into the expanding mantle wedge until the present-day position of the volcanic arc is reached at approximately 15 Ma. This reconstruction applies to latitudes 18-27°S, but is different both north and south of this segment. Central Peru and central Chile/NW Argentina have flat subduction during the last 10 Ma (no volcanism) because of subduction of the buoyant Nazca and Juan Fernandez Ridges, respectively. The ages of porphyry systems in these different segments correlate with the corresponding slab regimes.

3. COPPER PORPHYRY SYSTEMS

The giant copper porphyry deposits of northern Chile form a 600 km N-S trending belt controlled by a major strike-slip fault zone (Domeyko fault) (Fig. 1). The ore deposits are associated with multiphase felsic intrusions of the age interval of 31-41 Ma (Sillitoe 1988). Stockwork copper mineralization is located in zones of potassic and phyllic alteration, and is enhanced by supergene enrichment of mostly Miocene age (Mote et al. 2001). The most spectacular example is the Chuquicamata complex (31-35 Ma; Ballard et al. 2001) which is approximately 14 km long and which has a total copper resource of >11 billion tonnes with an average grade of 0.76 % Cu (cutoff at 0.2 %) distributed over several mineralization centers. The production to date totals about 35 million tonnes of copper, i.e. 85 billion USD at current market value.

The porphyry intrusions formed in the beginning and during the flat subduction interval in northern Chile with much reduced magmatism (no volcanic rocks known in between 40 and 25 Ma). They are controlled by the regional strike-slip structure of the arc-parallel Domeyko fault system which reflects the stress field in the plate boundary. Changes in plate convergence (velocity, coupling and obliquity of plate motion) are thought responsible for repeated change in direction of shear movement. The main porphyry pulse around 32 Ma is characterized by a switch from dextral transpression to sinistral transtension (Reutter et al. 1996) allowing tapping of fluids from the hydrated mantle/lower crust.

A second major copper porphyry province is in central Chile and northwesternmost Argentina, with the giant El Teniente, Los Pelambres and Bajo de la Alumbrera copper deposits (Fig. 1). These porphyry systems have an age of 5-10 Ma and occur in a geodynamic setting characterized by present-day flat subduction, probably connected to the buoyant Juan Fernandez Ridge. The change from normal to flat subduction was established at 10-15 Ma, i.e. the copper porphyry formation was during/shortly after establishment of the flat slab regime. A similar situation also applies to the central Peruvian flat slab segment, where several large copper porphyry intrusions formed around 10 Ma, including La Granja and the giant epithermal Yanacocha gold deposit which is probably related to a porphyry system at depth.

The origin of porphyries and metals both in the northern and central Chilean copper porphyry systems is dominantly the mantle with lower crustal contributions as deduced from positive εNd data of 2 ±2, initial $^{87}Sr/^{86}Sr$ ratios around 0.704 and initial $^{187}Os/^{188}Os$ ratios <1 (Maksaev 1990; Mathur et al. 2000; Skewes and Stern 1995). The melt systems were oxidized, as deduced from the general ilmenite-series character (Fe^{2+}/Fe^{3+} <1) of the volcanic-arc sequence and the early potassic alteration (magmatic-hydrothermal fluids) with the magnetite-pyrite-anhydrite mineral assemblage.

4. TIN PORPHYRY/GRANITE SYSTEMS

The inner arc (about 300 km east of the present-day volcanic arc; Fig. 1) from southermost Peru to northernmost Argentina hosts the Andean tin belt with two of the largest hard-rock tin deposits in the world with about 1 Mt Sn resource each, i.e. Llallagua (high-grade veins mined out, now low-grade porphyry-style with 0.5 % Sn; Ahlfeld and Schneider-Scherbina 1964) and San Rafael (high-grade vein style with current reserves of 14 Mt @) 5.3 wt% Sn + 0.16 % Cu; Mlynarczyk et al. 2003). San Rafael is associated with a 25-Ma-old peraluminous leucogranite porphyry stock (600 x 900 m large), Llallagua is in a 21-Ma-old rhyodacite porphyry (700 x 1000 m in size). There are a number of other major tin systems within the time bracket of 14-25 Ma, some with an epithermal volcanic suprastructure partly preserved such as the 14-Ma-old Cerro Rico de Potosi which grades from a tin porphyry in deeper parts to a giant high-sulfidation epithermal silver deposit in the upper part (historic production of about 50,000 t Ag, and remaining resource of 142 Mt @ 174 g/t Ag; Min J, Apr 4, 1997, p. 276). The tin belt is within a more than 10-km-thick Lower Paleozoic shale-sandstone sequence overlying unexposed Precambrian gneiss basement.

An intriguing feature of the Bolivian tin porphyry deposits is the fact that they are not in highly evolved felsic rocks, as typical for tin deposits in general (Lehmann 1990), but in subvolcanic rhyodacite stocks. However, melt-inclusion studies have shown that the tin porphyries are the result of mixing of andesitic to basaltic melt and highly evolved silicic melt (Dietrich et al. 2000). All tin deposits in the Andean tin belt have strong quartz-sericite-tourmaline alteration, and hydrothermal boron enrichment is a diagnostic feature. The vein systems also have early pyrrhotite (commonly altered into pyrite), and the unaltered igneous rocks have ilmenite-series affinity, i.e. reflect a relatively reduced melt environment. The neodymium isotope composition of the por-phyry intrusions (εNd –5 to –11) indicates an origin from the continental crust with a variable mantle component (Lehmann et al. 2000).

5. REGIONAL METAL ZONING: FROM GEOTECTONICS TO MELT INCLUSIONS

The above geodynamic and metallogenic review can be condensed to:

(1) The transition from normal to flat subduction seems to be favorable for the formation of large copper porphyry systems. Reduced magmatic activity during ongoing fast subduction allows large-scale lithospheric hydration and oxidation by slab-derived fluids. Oxidation of the mantle wedge or lower crust to values of $\log fO_2$ >FMQ+2 appears to be required to provide a sulfide-free environment with then mobile Cu, Au, Mo (Mungall 2002). This reservoir can be tapped by suitable stress fields, such as margin-parallel shear-zones from oblique convergence. The build-up of a mantle/lower crustal fluid reservoir by slab dehydra-tion will lead to metal enrichment of those components soluble in oxidized highly saline high-T aqueous fluids, such as Cu, Zn and Au.

(2) The transition from flat to normal subduction, i.e. flow of hot asthenospheric mantle into the expanding mantle wedge with melting of the overlying continental crust in the inner arc and subsequent intracrustal fractionation, is favorable for the formation of large tin porphyry/granite systems. The main ingredients for the formation of tin deposits are extended fractional crystallization under reducing melt conditions (Lehmann 1990). Reducing melt conditions are given for peraluminous ilmenite-series granites, which develop from partial melting of

thick sedimentary sequences with organic carbon (Takagi and Tsukumura 1997).

The two scenarios have different end-member composition of their source rocks/fluids, although mantle energy is the driving force behind both settings. The subduction input is clearly visible in the outer arc systems whereas the inner arc systems are a mixture of continental crust with variable mantle input. Reconnaissance boron isotope data on melt inclusions show a recycled seawater signature in the Chilean copper porphyry systems (positive $\delta^{11}B$), whereas the Bolivian tin porphyry systems have melt inclusions with a distinctly upper crustal fluid source (negative $\delta^{11}B$) (Lehmann, Wallianos, Wiedenbeck, Wittenbrink; unpubl. data). These results are in line with across-arc variations in Japan (Ishikawa and Nakamura 1994) and with data on Miocene ignimbrites from NW Argentina (Schmitt et al. 2002).

Microanalysis of melt inclusions in magmatic quartz phenocrysts also gives direct information on trace elements in porphyry systems prior to solidification and hydrothermal overprint. The distribution of copper for Chilean copper porphyries and Bolivian tin porphyries is shown in Fig. 2. Several important conclusions can be derived:

(1) Copper in bulk-rock samples is high in copper porphyry systems, and low in tin porphyry systems, as expected. However, the copper distribution in melt inclusions from both environments is very similar and reaches close to the percent range.

(2) The copper distributions for both bulk-rock samples and melt inclusions are scatter distributions. Scatter is expected for the bulk-rock sample set with strong hydrothermal behavior. However, the melt inclusions also display the same degree of scatter, only at lower Ti content which corresponds to the more evolved melt inclusion system compared to the bulk rock (early crystallization of Ti-bearing mineral phases). The scatter in copper abundance of the melt inclusions also must reflect open-system behavior, i.e. early exsolution of copper-rich fluids concomitant with trapping of melt inclusions. This distribution pattern is different from most other elements which show systematic enrichment and depletion, i.e. closed-system behavior (Dietrich et al. 2000, Lehmann et al. 2000).

The high copper content in the melt inclusions from the Bolivian tin porphyries is intriguing because their bulk-rock copper content is so low (Fig. 2). However, there is copper bound to a number of complex base-metal sulfides in the vein systems, and there is also copper in the outer part of the hydrothermal tin systems. The giant San Rafael mine started out as a copper producer until the deeper high-grade tin veins were discovered. Copper in the Bolivian tin systems was obviously more mobile than in the Chilean copper porphyries where Cu is fixed close to central parts of the systems. The solubility of Cu is dependent on oxygen fugacity. Tin porphyry systems are about 4 log-units lower in fO_2 than copper porphyry systems, as deduced from mineral assemblages (Lehmann

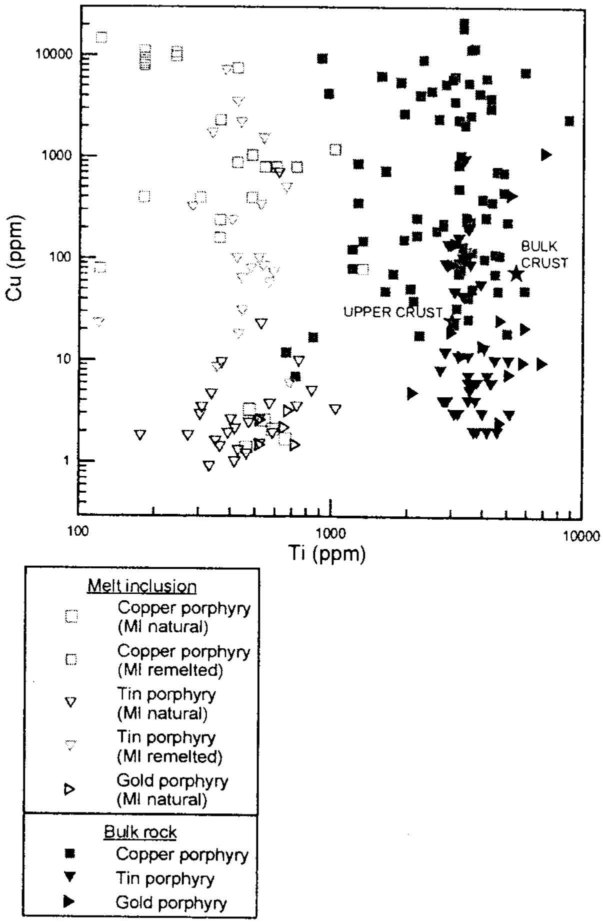

Fig. 2. Ti versus Cu in whole-rock samples and in quartz-hosted melt inclusions from copper and tin porphyry systems. Data from Campos et al. (2002), Dietrich (1999), Ulrich (1999). Titanium is used here as an indicator of degree of magmatic evolution.

1990). This difference translates into control by Cl-complexing in copper porphyries, whereas copper in tin porphyry systems would be dominantly transported as sulfide complexes (Barnes 1979).

The large scatter in the melt-inclusion Cu data does not allow to draw a conclusion if there is a significant difference in Cu level in between both copper and tin porphyry systems. The limited data sets presently available overlap (3800 ±4600 ppm Cu in Zaldivar Cu porphyry; 1333 ±2034 in several Bolivian Sn porphyries). But the data clearly corroborate that the formation of ore deposits is not only controlled by metal supply but also by the efficiency of ore mineral precipitation. A large amount of metals is simply flushed through the system, such as Pb and Zn in copper porphyry systems, which are in equal or higher amounts than copper in the fluid system (Ulrich et al. 2001).

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