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LETTER

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Giant versus small porphyry copper deposits of Cenozoic age in northern Chile: adakitic versus normal calc-alkaline magmatism

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Abstract Cenozoic magmatic activity in northern Chile led to the formation of two contrasting porphyry copper belts: (1) a Paleocene–Early Eocene belt comprising small porphyry copper deposits (e.g., Lomas Bayas) of normal calc-alkaline affinity; and (2) a Late Eocene–Early Oligocene belt hosting huge porphyry copper deposits (e.g., Chuquicamata) of adakitic affinity. Although the first belt comprises both volcanic and plutonic rocks (andesitic–basaltic and rhyolitic lavas and tuffs, and associated sub-volcanic porphyries and felsic stocks), the latter only includes intrusions (mostly granodioritic types, including porphyry copper deposits). We suggest that the Late Eocene–Early Oligocene belt formed when fast and oblique convergence between the South America and Farallon plates led to flat subduction and direct melting of the subducting plate, hence giving rise to plutonic rocks of adakitic affinity. The absence of volcanism, under prevailing compressional conditions, prevented the escape of SO_2 from the adakitic, sulfur-rich, highly oxidized magmas ("closed porphyry system"), which allowed formation of huge mineral deposits. On the contrary, coeval volcanic activity during formation of the Paleocene–Early Eocene calc-alkaline porphyries allowed development of "open systems", hence to outgassing, and therefore, to small mineral deposits.

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Introduction

The northern Chilean porphyry copper deposits (e.g., Sillitoe 1988; Maksaev 1990; Camus and Dilles 2001; among many others) with famous examples such as Chuquicamata (5.8 Gt at 0.55% Cu), La Escondida (2.3 Gt at 1.15% Cu), or El Abra (1.45 Gt at 0.55% Cu) form a N–S-trending metallogenic province of Late Eocene–Early Oligocene age (Sillitoe 1988; Fig. 1). However, there is another copper porphyry belt farther west, of Paleocene–Early Eocene age (Sillitoe 1988), with minor yet productive porphyry copper deposits such as Lomas Bayas (130 Mt at 0.53% Cu), or Spence (400 Mt at 1% Cu; Fig. 1). In this paper we relate the size of the porphyry copper deposits to type of magmatism and plate tectonic setting. Whereas the Paleocene–Early Eocene porphyry copper belt belongs to a rather typical calc-alkaline magmatic province, including both plutonic and volcanic rocks, the Late Eocene–Early Oligocene belt consists only of plutonic rocks, most of them of adakitic affinities, including giant porphyry copper deposits (e.g., Thiéblemont et al. 1997; this work).

Adakitic rocks

The term adakite comes from the island of Adak (Aleutian Islands, Alaska) and was originally defined to describe Cenozoic (<25 Ma) arc-related volcanic rocks with a number of geochemical characteristics, including $SiO_2 \geq 56$ wt%, $Al_2O_3 \geq 5$ wt%, 3 wt% $\leq$ MgO $\leq$ 6 wt%, Y $\leq$ 18 ppm, Sr$\geq$400 ppm (Defant and Drummond 1990). Contrary to normal, arc-related tholeiitic and calc-alkaline rocks that originate in the mantle wedge and later evolve by crystal fractionation or other processes, the adakitic rocks are derived from direct partial melting of a subducting slab (Defant and Drummond 1990). These authors related the magma generation to the melting of hot, young (<25 Ma) subducting lithosphere. Numerical and petrological models (Peacock et al. 1994) restrict the process to even younger subducting lithosphere (<5 Ma) at typically 60–80 km depth. However, this would leave unexplained the important adakitic magmatism recorded in many places around the world, including the Andean chain (e.g., Maury et al. 1996; Thiéblemont et al. 1997; Gutscher et al. 2000; BRGM 2001). In this respect, it has been shown that older oceanic crust (up to 50–60 Ma) can also melt during flat, fast, and/or oblique subduction episodes (Maury et al. 1996; Sajona and Maury 1998; Gutscher et al. 2000). Under such conditions the plate will melt before undergoing dehydration, at the base of the lithosphere (Gutscher et al. 2000). Another key element for slab melting is a high content of water (>10 wt% H_2O) to increase melt percentage, and thus to generate dacitic compositions

(Prouteau et al. 1999). A good example of modern adakites is provided by the 1991 anhydrite-rich dacitic pumice of Mount Pinatubo, Philippines; this volcanic eruption led to massive outgassing of about 20 Mt of SO_2. Anhydrite is an important mineral in porphyry copper systems: it can be up to half of the total sulfur budget (Hunt 1991). Porphyry copper deposits can, in turn, be regarded as the plutonic equivalents to Pinatubo-type volcanic rocks (Pasteris 1996). Porphyry copper deposits are derived from sulfur-rich, highly oxidized magmatic systems, with oxygen fugacities (fO_2) between the nickel–nickel oxide and hematite–magnetite oxygen buffers (Imai et al. 1993; Pasteris 1996). High water contents, high fO_2, and adakitic magmatism are closely related phenomena. The first two are connected via the equilibrium reaction: $H_2O = H_2 + 1/2\ O_2$. Given the high diffusivity of H_2, fO_2 increases to maintain equilibrium, and concomitant with this increase, the ratio SO_2/H_2S increases 1,000 times or more, which eventually results in almost complete extraction of sulfur from the melt (Burnham 1979). In an open system, this sulfur will be outgassed to the atmosphere via volcanic activity. On the other hand, water in excess (>10 wt%) of that structurally bound in minerals plays a vital role in achieving direct slab melts, i.e., adakitic magmatism (Prouteau et al. 1999).

Oxygen fugacity and sulfur species: the importance of closed systems

Isotopic data from porphyry copper deposits suggest isotopic equilibrium between oxidized and reduced species of sulfur (both in fluids and minerals), and a magmatic source for this element (e.g., Ohmoto and Rye 1979). The fO_2–T data are consistent with an origin related to highly oxidized I-type (Ishihara 1981) magmas (Fig. 2). However, can we consider that the fluid exsolved from such magmas cools down in a closed system without being decompressed? Above 650 °C (at $P_T = 1$ Kb), the fluid is SO_2 rich and the system is buffered between the hematite and pyrrhotite stability fields (Fig. 2). In the pyrite stability field, below 650 °C, the fO_2 is not buffered by iron oxide–sulfide reactions, but is controlled by sulfide–sulfate equilibria. If the system is suddenly decompressed (path A of Fig. 2), the fluid becomes SO_2 rich (Gerlach 1993; Rye 1993). As most of the sulfur can be discharged into the atmosphere, the system is open to sulfur. If decompression occurs at temperatures above the stability field of pyrite (e.g., Mount Pinatubo; Imai et al. 1996), the dominant sulfur mineral phase would be anhydrite, with minor (unstable) associated pyrrhotite. Because the sulfur content in oxidized silicate systems is high, a re-equilibration of the remaining fluid to $H_2S = SO_2$ at lower temperatures takes place. This mechanism of decompression and discharge of SO_2 in extensional–transtensional regimes is related to magmatic systems that are "open" to the surface via volcanic activity. On the other hand, closed systems must be related to internally buffered systems at the H_2S–SO_2 boundary (path B of Fig. 2; Rye 1993). As we will show, the giant northern Chilean porphyry copper deposits are related to fluids derived from magmas of adakitic affinities (i.e., highly oxidized, water- and sulfur-rich) that would have evolved in a closed or near-closed system because no coeval volcanic activity (e.g., Davidson and Mpodozis 1991) leading to major decompression took place.

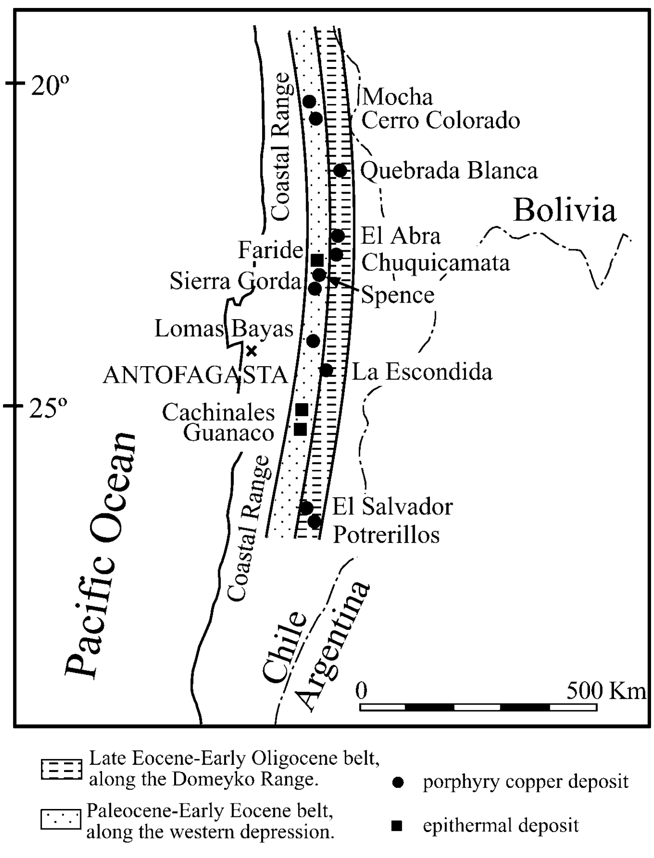

Fig. 1 Porphyry copper belts (including selected epithermal deposits) in northern Chile (porphyry copper belts after Sillitoe 1988; Maksaev 1990; Camus and Dilles 2001)

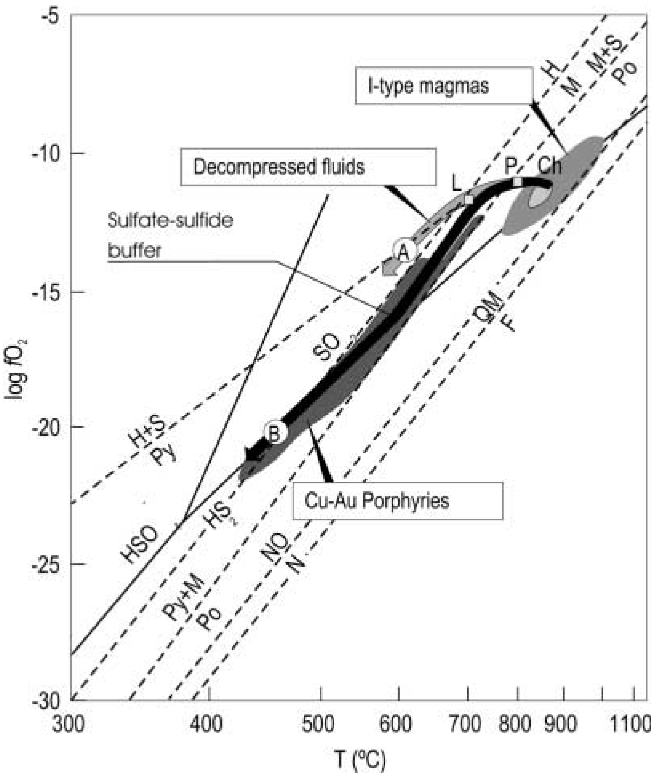

Fig. 2 Log fO_2–T diagram illustrating the redox conditions (at P = 1 Kb) of adakitic magmas and related hydrothermal fluid. Hypothetical paths of hydrothermal fluid after exsolution from adakitic magma: *path A*, degassing magma (open system); *path B*, large porphyry copper deposits (closed system). Based on Ohmoto (1986); Rye (1993); Imai et al. (1996). *L* Luzon porphyries; *P* Mount Pinatubo; *Ch* El Chichón; *H* hematite; *S* sulfur; *M* magnetite, *Po* pyrrhotite; *Py* pyrite; *Q* quartz; *F* fayalite, *NO* nickel oxide; *N* nickel

The northern Chilean porphyry copper deposits

Porphyry copper mineralization in northern Chile is associated with two main magmatic pulses: Paleocene–Early Eocene and Late Eocene–Early Oligocene (e.g., Sillitoe 1988). In the first event, a large N–S trending volcanic field developed along the so-called western depression, now bound by the present-day Coastal and Domeyko ranges (Fig. 1). Volcanism consisted of andesitic–basaltic and rhyolitic lavas and tuffs, and associated sub-volcanic porphyries and felsic stocks. The chemistry of these rocks (Maksaev 1990; Williams 1992) indicates that they are typical arc, calc-alkaline rocks (Fig. 3). This tectonomagmatic event gave rise to deposits of both epithermal and porphyry type. The epithermal mineralizations include deposits such as Faride, Guanaco, and Cachinales (Rivera and Stephens 1988; Davidson and Mpodozis 1991). Examples of porphyry copper mineralization include Mocha, Sierra Gorda (breccia pipe), Lomas Bayas, and Spence (Sillitoe 1988; Maksaev 1990; Camus and Dilles 2001; Fig. 1). After the Incaic compression (Late Eocene; Maksaev 1979, 1990) magmatic activity recommenced, but was restricted to the intrusion of plutonic rocks, including large porphyry copper deposits (e.g., Chuquicamata) during Late Eocene–Early Oligocene times (Rivera and Stephens 1988; Sillitoe 1988; Davidson and Mpodozis 1991) (Fig. 1). The decrease in magmatic activity was largely caused by the fast, flat, and oblique subduction of the Farallon plate beneath the Chilean margin (Davidson and Mpodozis 1991; James and Sacks 1999). The Late Eocene–Early Oligocene rocks are of adakitic affinity (Fig. 3). Fast, flat, and oblique subduction does not necessarily prevent magma generation (Maury et al. 1996; Gutscher et al. 2000), which can be achieved by direct melting of the subducting plate (Prouteau et al. 1999; Gutscher et al. 2000). A direct consequence of this process is the generation of adakitic magmatism, which in the northern Chilean case is shown by the character of the Late Eocene–Early Oligocene Chilean porphyry copper deposits and associated plutonic rocks (e.g., Thiéblemont et al. 1997; this work; Fig. 3). We thus envisage two well-differentiated periods of porphyry copper generation, which relate to different plate tectonic settings (Fig. 4): (1) Paleocene–Early Eocene, a magmatic arc comprising widespread normal calc-alkaline magmatism (volcanic and plutonic rocks) under mostly extensional conditions; and (2) Late Eocene–Early Oligocene, increased stress, wrench tectonics, adakitic magmatic activity in the form of granodioritic intrusions. In the first case, a vertical connection between porphyries and volcanic centers seems plausible, e.g., the classical model of Sillitoe (1973), with a volcano sitting on top of a porphyry system. A vertical connection of such a kind will lead at least to partial outgassing of sulfur (open system, path A of Fig. 2) in the form of SO_2, hence to what Pasteris (1996) terms "negative porphyry coppers". Thus, it should not be surprising that, despite the huge amount of calc-alkaline magmatic activity recorded during the Paleocene–Early Eocene, with the sole exception of Spence, only minor porphyry copper deposits formed in northern Chile. On the contrary, the Late Eocene–Early Oligocene plutonic belt, with no clear volcanic connections, led to closed, highly oxidized adakitic magmatic systems retaining sulfur and, hence, to huge concentrations of hydrothermal sulfides and anhydrite (path B of Fig. 2). These porphyries are about ten times larger than their Paleocene–Early Eocene counterparts. Adakitic magmatism in flat subduction settings has a transient character, flourishing during the initiation of flat subduction (Gutscher et al. 2000). This would explain the lack of porphyry copper deposits after 30 Ma in northern Chile (Fig. 4), despite continued oblique and fast subduction (Hartley et al. 2000).

Concluding statement

Although a connection between porphyry copper deposits and volcanic activity existed during the Paleocene–Early Eocene, magmatic activity had no or little volcanic expression during the Late Eocene–Early Oligocene (compressional conditions; Fig. 4). The geologic setting of the Paleocene–Early Eocene magmatic belt provided multiple paths for sulfur escape from porphyry systems via volcanic activity (path A in Fig. 2). On the contrary, most of the highly oxidized sulfur contained in the adakitic porphyry facies of the Late Eocene–Early Oligocene remained within "closed porphyry systems", and thus was available to generate huge concentrations of sulfides and anhydrite (path B in Fig. 2). The

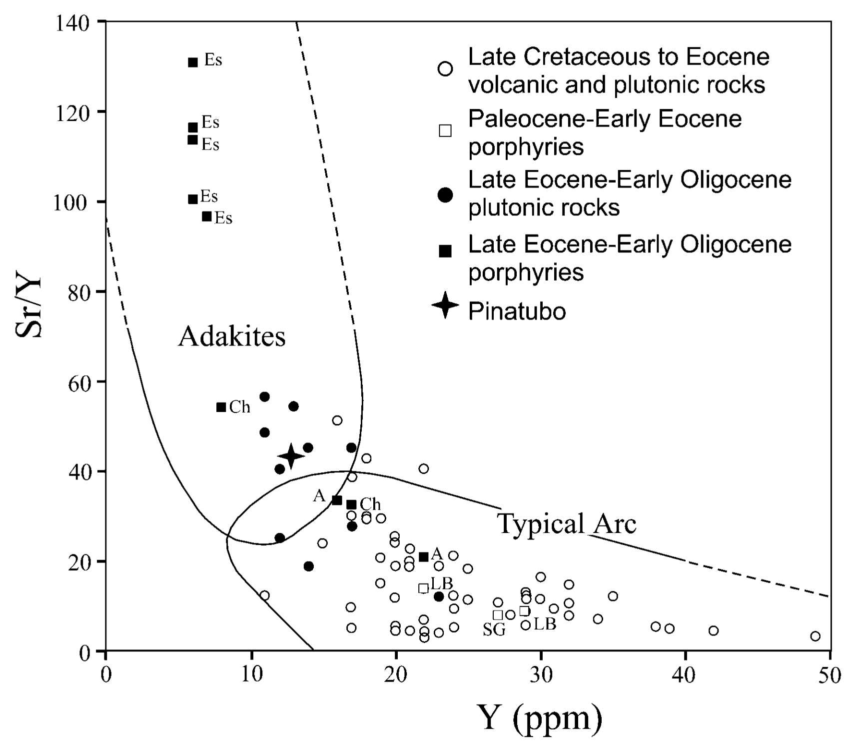

Fig. 3 Y versus Sr/Y diagram for samples of plutonic and volcanic rocks from northern Chile (data from Baldwin and Pearce 1982; Maksaev 1990; Williams 1992). *A* El Abra; *Ch* Chuquicamata; *ES* El Salvador; *LB* Lomas Bayas; *SG* Sierra Gorda. Mount Pinatubo: average 1991 pumice (after Bernard et al. 1996). Fields after Defant and Drummond (1990)

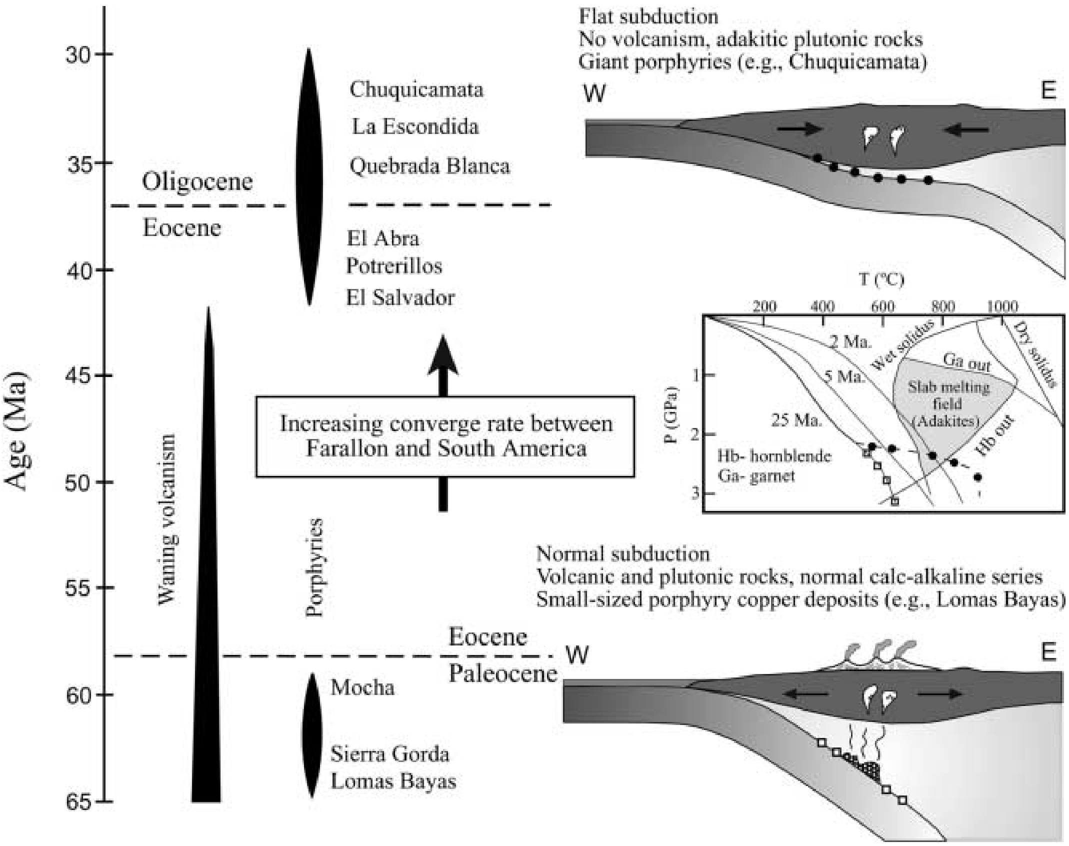

Fig. 4 Evolution in time of volcanism, porphyry emplacement, and plate tectonic setting. Age of porphyries after Maksaev (1990). *Inset* P–T metamorphic and melting reactions diagram displaying P–T–t paths for 2-, 5-, and 25-Ma-old subducting plates. Note that only the 2-Ma plate will directly melt. The 25-Ma plate will melt directly if flat subduction occurs (*solid dots*; see also upper plate tectonic scheme). *Open squares* (see also *bottom plate tectonics scheme*) show the normal trajectory of a 25-Ma-old subducting plate undergoing dehydration (Hb out) at greater depth. Based on Gutscher et al. (2000)

differences in size derived from the contrasting plate tectonic settings were enormous, with the mineralization of the late porphyry copper deposits being up to ten times larger than the early ones. The magmatic character of the porphyries (adakitic versus normal calc-alkaline) coupled with the understanding of the specific plate tectonic setting in which the porphyry copper deposits were emplaced, may provide a useful tool to assess the economic potential of porphyry copper belts.

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