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Distribution of porphyry copper deposits along the western Tethyan and Andean subduction zones: Insights from a paleotectonic approach

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ABSTRACT

Along the western Tethyan and Andean subduction zones the distribution of Cretaceous and Cenozoic porphyry Cu deposits is not random and shows that they were emplaced in distinct regional clusters. To understand the appearance of these clusters within their geodynamical contexts and identify kinematic features which would favor the genesis of porphyry-type ore bodies, we use a paleotectonic approach. Two clusters in the Aegean-Balkan-Carpathian area, which were emplaced in upper Cretaceous and Oligo-Miocene, and two others in the Andes, which were emplaced in late Eocene and Miocene, are sufficiently well constrained to be studied in detail. It appears that they are associated with a specific polyphased kinematic context related to the convergence of tectonic plates. This context is characterized by: 1) a relatively fast convergence rate shortly followed by 2) a drastic decrease of this rate. From these observations, and assuming that the major part of plate convergence is accommodated along subduction zones, we propose a two-phase geodynamic model favoring emplacement of porphyry Cu deposits: 1) a high melt production in the mantle wedge, followed by 2) an extensional regime (or at least relaxation of the compressional stress) in the upper plate, promoting ascension of fertile magmas to the upper crust. Melt production at depth and the following extensional regime, which would be related to variations in convergence rate, are thus associated with variations in plate and trench velocities, themselves being controlled by both plate kinematics at the surface and slab dynamics in the upper mantle. In particular, along-strike folding behavior of the subducting slab may strongly influence trench velocity changes and the location of porphyry Cu deposits. Metallogenic data suggest that periods of slab retreat, which would favor mineralization processes during ~40 Myrs, would be separated by barren periods lasting ~10 to 20 Myrs, corresponding to shorter episodes of trench advance, as observed in laboratory experiments. These results confirm the control of the geodynamic context, and especially subduction dynamics, on the genesis of porphyry Cu deposits. This study also shows that the paleotectonic approach is a promising tool that could help identify geodynamic and tectonic criteria favoring the genesis of various ore deposits.

1. Introduction

Assessing the most favorable areas for mineral prospecting has always been a major concern for exploration geologists. The spatial approach of mineral resources predictivity focuses on the geological context of ore deposits and on distinct parameters that control their distribution, from district to continental scales, defined from geology, tectonic structures, geophysics and geochemistry (*e.g.* Carranza, 2011; Cassard et al., 2008) but also geodynamics and paleogeography (Scotese et al., 2001). It is an upstream phase of prospection campaigns, the goal of which is to guide exploration strategy by predicting *a priori* the most favorable areas.

Porphyry Cu deposits were studied and described by many authors (see the reviews by *e.g.* Seedorff et al., 2005, and Sillitoe, 2010). They are closely linked to their geodynamic surroundings and are most often associated with calc-alkaline and adakitic magmatism in subduction zones (*e.g.* Burnham, 1979; Cline and Bodnar, 1991; Thieblemont et al., 1997). These deposits result from a dual melting process with: 1) an initial melting in the metasomatized mantle wedge, above the subducting oceanic slab, which generates relatively oxidized and sulfur-rich mafic magmas with incompatible chalcophile or siderophile elements (such as Cu or Au), and 2) a secondary melting by injection of dykes and sills in the MASH (Melting, Assimilation, Storage, Homogeneization) zone of the lower crust, yielding a crustal- and mantle-derived hybrid magma, with a high content of volatile and metalliferous elements, and a density that is low enough to allow its upward migration through the crust (Richards, 2003, 2011). They are generally associated with plutonic apexes of granitic bodies (*e.g.* Burnham, 1979; Cloos, 2001; Guillou-Frottier and Burov, 2003; Shinoara and Hedenquist, 1997)

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emplaced in the upper crust of the overriding plate (usually 1–4 km depth). Ore grades are often low, but volumes can be huge, which can possibly make them very large deposits (*e.g.* El Teniente, Chuquicamata or Rio Blanco-Los Bronces, all in Chile, with 78.6, 65.2 and 52.4 Mt of copper respectively; Jébrak and Marcoux, 2008). In addition, porphyry Cu deposits can yield valuable new-technology metals, such as rhenium which is used in strong high-temperature resistant alloys and often produced as by-product of molybdenum (*e.g.* Berzina et al., 2005; Melfos et al., 2001).

For more than 40 years, authors have demonstrated relationships between tectonics and mineralizing processes (*e.g.* Sillitoe, 1972, and compilation by Wright, 1977). The new paradigm of plate tectonics, along with numerous metallogenic studies, allowed proposals of new genetic models linking the lithosphere and mantle dynamics to the occurrence of deposits (*e.g.* Barley et al., 1998; Bierlein et al., 2006; Kerrich et al., 2005; Mitchell and Garson, 1981; Sawkins, 1984; Tosdal and Richards, 2001). Although the close relationship between porphyry Cu deposits and subduction zones is well established, there is, however, no consensus on which subduction parameters primarily control the genesis of porphyry deposits. This is not surprising since, following decades of seismic tomography and modeling studies, distinct modes of lithosphere deformation have been suggested and the number of physical parameters controlling the subduction process has continuously increased (slab density, mantle viscosity, slab to mantle viscosity ratio, *etc.*). The way the subducted lithosphere behaves beneath the overriding plate appears to depend not only on these physical properties but also on plate features at the surface (plate velocity, slab dip angle, amount of retrograde motion, varying ages along trench, *etc.*). Deep subducting lithosphere behavior is also controlled by plate motion and plate layout at the surface (Yamato et al., 2009). One objective of this study, rather than promoting a single parameter as key to ore formation, is to investigate what control a single selected process, subduction dynamics, has on formation of porphyry Cu deposits.

In the Tethys belt it is widely accepted that the genesis of many types of mineralization is closely linked to the geodynamic context (*e.g.* de Boorder et al., 1998; Lescuyer and Lips, 2004; Lips, 2007). Neubauer et al. (2005) and Loiselet et al. (2010a) have shown the strong impact of the geometry and dynamics of the eastern Mediterranean subduction on the distribution of porphyry and epithermal deposits in the Carpathian and Aegean regions. Similarly, in the Andes numerous studies have suggested specific relationships between subduction parameters and the occurrence of porphyry Cu deposits: conditions of flat-slab subduction (Billa et al., 2004; Kay and Mpodozis, 2001), stress relaxation and transtensional structures (Richards et al., 2001). In particular, the convergence configuration between the subducting and the overriding plates (velocities and obliquity) would dictate how mineralized bodies emplace in the shallow crust (Tosdal and Richards, 2001). Rosenbaum et al. (2005) have suggested that subduction of topographic anomalies (ridges and plateaus) triggered the formation of ore deposits. According to Cooke et al. (2005), topographic and thermal anomalies on the subducting slab could trigger the formation of giant porphyry deposits. All these studies clearly show that past subduction history and, in particular, the convergence parameters have to be accounted for when genesis of porphyry Cu deposits is studied.

To identify relationships between mineralization and geodynamic processes, it is, thus, necessary to place the mineralization within the geodynamic framework that prevailed at the time of its genesis. It is a necessary step to better understand the relationships between the mineralization itself and its environment (plate boundaries, tectonic structures, stress and strain regimes, geology, *etc.*). This would, in turn, help identify criteria that are favorable to its genesis. The present study aims at better understanding of the geodynamic parameters, in terms of plate kinematics and slab dynamics, that could favor the genesis of porphyry Cu deposits in subduction contexts. For this, we have focused our analysis on two mineralized subduction zones: the western Tethyan suture and the Andean subduction zone. We have adopted a paleotectonic approach, which has been little used so far in the field of metallogeny, to study past geodynamic contexts and plate kinematic patterns. This approach is coupled with results from laboratory experiments to assess the 3D slab dynamics and its possible relationships with plate kinematics and deposit genesis.

2. Subduction dynamics and convergence rates

2.1. Dynamics and deformation of the subducting lithosphere

Dynamics of subduction zones is governed by the balance between driving forces (*i.e.* slab pull, ridge push), resisting forces (*i.e.* viscous shear and viscous resistance in the mantle) and other external forces due to the large-scale mantle flow or to density contrasts created by phase transitions in the mantle (*e.g.* Billen, 2008; Heuret and Lallemand, 2005; Husson, 2012). Relative magnitude of these forces determines surface plate kinematics, including the possibility of trench retreat or advance episodes. Variations in plate velocity at the surface are one consequence of the deformation of the subducting lithosphere in the mantle. In the particular case of trench retrograde motion, trench curvature is one of the surface signatures of the longitudinal plate deformation that results from the interaction between subducting lithosphere and surrounding mantle flow (Funiciello et al., 2006; Loiselet et al., 2009; Morra et al., 2006; Schellart, 2004). The various observed plate curvatures (Fig. 1) are mainly due to plate physical properties (*i.e.* density, viscosity), dimensions (Dvorkin et al., 1993), and internal heterogeneities (Morra et al., 2006). Longitudinal plate deformation can also be inferred from laterally varying slab dips within the same plate (*e.g.* Hayes et al., 2012). Furthermore, deformation of the subducting lithosphere along the mantle transition zone at 660 km depth has been suggested to control trench kinematics (Goes et al., 2008).

At greater depth, thanks to more than two decades of seismic tomography studies, different deformation modes of the subducted lithosphere have been suggested (Fukao et al., 1992; van der Hilst et al., 1991). The 660 km mantle discontinuity (phase transition zone) imposes a viscosity contrast between the upper and lower mantles, creates a resisting force preventing the subducted slab to penetrate straightly into the lower mantle (Kincaid and Olson, 1987), and induces viscous slab deformation along the interface. Tomography images have illustrated horizontally spreading slabs above the mantle transition zone (*e.g.* Japan subduction zone, Sandwich subduction zone) but also thickening and vertically sinking slabs into the lower mantle (*e.g.* Marianas subduction zone). Intermediate deformation modes involving thickened pile of buoyant material around the transition zone (*e.g.* Java subduction zone) have been successfully reproduced by laboratory and numerical experiments (Christensen, 1996; Griffiths et al., 1995; Guillou-Frottier et al., 1995; Houseman and Gubbins, 1997). In particular, the folding mode allows the accumulation of dense subducted folded lithosphere together with light upper mantle material trapped in between folds. This folding behavior has been increasingly invoked to explain tomography images of thick blue zones near the mantle transition zone (Ribe et al., 2007), and to interpret seismic data on focal mechanisms (Myhill, 2013).

When the folding regime is described, the 3D character due to along-strike — and not only down-dip — undulations (hereafter considered as "buckling" behavior) is rarely invoked. However, a few recent studies suggested that the slab buckling process may be more common than previously thought. This dynamic mechanism would occur in many subducting plates and would be a natural consequence of the Earth sphericity (Morra et al., 2012; Stegman et al., 2010). According to Schettino and Tassi (2012), lateral deformation of the subducting lithosphere is directly related to plate bending along an arcuate trench, but the mantle transition zone would also play a key role on the 3D deformation of slabs (Loiselet et al., 2010b). Although recent 3D numerical models investigated the temporal evolution of the subducting