Cenozoic magmatism and deformation in the northern and central Chilean Andes: differing paths in the construction of the modern orogen

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Abstract. Processes leading to construction of the modern Chilean Andes have followed different paths along the margin. In the northern region, north of ~27°S, after latest Cretaceous to mid-Eocene Incaic tectonic phase contraction remained continuous until present and the magmatic arc remained approximately at the same location, although with a slight eastward shift. In the central region, after the Incaic phase, in late Eocene to latest Oligocene an extensional event occurred south of ~27°S that caused development of the Abanico basin. Geochemical evidence indicates that whereas continuous crustal thickening occurred in northern Chile, considerable crustal thinning occurred in central Chile during formation of the Abanico basin. Here, contraction resumed in early Miocene causing migration of magmatism and deformation to the east along with a progressive increase in crustal thickness. We propose that the ~25 m.y. long interruption of compression during the development of the Abanico basin in central Chile caused a retard in the mountain uplift and crustal thickening processes relative to the northern region, thus also influencing the timing of other main crustal processes as the formation of the major porphyry copper ore deposits.

Key words: Magmatism, tectonic inversion, tectonic extension, orogen evolution, porphyry copper ore deposits, Chilean Andes.

1 Introduction

The Andes of Chile and Argentina represent the archetypical example of a cordilleran arc orogenic system. They distribute as a continuous mountain range, in a nearly NS belt, along southwestern South America and are a first order result of plate convergence. The latter is given by the eastward subduction of the Nazca oceanic plate beneath the South America continental plate, a convergence setting that has been active uninterruptedly since, at least, Jurassic times (Mpodozis & Ramos, 1989). The tectonic and magmatic processes derived from this plate interaction have modified and shaped the overriding continental lithosphere in leading to the construction of the modern Andean orogen. However, such processes have not been uniform along the South American margin and also neither are the current characteristics of the Andean range along strike.

In this contribution we review the major aspects of the tectonic and magmatic evolution leading to construction of the modern Andes of Chile and Argentina, and particularly focus and compare the northern (17°-27°S) and central regions (33°-36°S). Based on this we discuss on how some of the major differences shown by the Andean orogen among both of them are conditioned by the different evolutive paths these have followed after having a common beginning.

2 Construction of the Modern Andes of Chile and Argentina

2.1 A common beginning: The early Paleogene relief

In northern and central Chile, compressional tectonic events occurred in the early Late Cretaceous (Peruvian orogenic phase) and the mid Eocene. During these events, deformation concentrated mostly along the existing early Late Cretaceous to Eocene arc, probably due to crustal weakening after magmatic advective heat transport into this area. This resulted in formation of a major topographic relief derived from tectonic inversion of the intra-arc, the Incaic relief (Fig. 1). This NNE-SSW-trending relief extended from, at least, southern Peru to central Chile and formed the boundary between two paleogeographical domains. The western domain was mainly characterized by continuous erosion and sedimentation processes along strike throughout Cenozoic. The eastern domain also included significant erosion episodes, but was characterized by different tectonic and paleogeographic evolutions north and south of ~27°S (see Charrier et al., 2007, 2009 and literature therein).

2.2 The Differing Paths for the Northern (~18°-27°S) and Central (33°-36°S) Regions: The Mid-Eocene to Present Tectonic Evolution
The major difference shown by the evolutive paths of the northern and central regions is the occurrence of a ~25 m.y. extensional episode in the latter, during which the Abanico extensional basin was formed (Fig. 1), while the former remained under a contractional regime until today (Charrier et al., 2009, 2013).

The cause of such major difference in the stress regime along a margin under the same tectonic context remains speculative. We hypothesize that the region in northern Chile, southern Peru and western-central Bolivia could have corresponded to a flat-slab subduction segment, as it has been previously proposed (James and Sacks, 1999; Carlotto and Cárdenas, 2004). Such configuration would explain the intense compression associated with rotation in the forearc in the Bolivian orocline in late Paleogene times (Arriagada et al., 2003; Roperch et al., 2006). Moreover, if strongly coupled, such flat-slab could act as an indenter to the margin allowing in turn a mixed regime along the continental margin with strong contractional deformation in the axial zone and extensional deformation towards the margins, similarly to what has been observed at plate scales for the India-Asia collision (e.g., Peltzer and Tapponier, 1988; Fournier et al., 2004).

As mentioned above, following the Incaic event, the region north of ~27ºS remained under a compressional regime since mid-Eocene until today. However, during this time lapse, the paleogeographic configuration evolved from showing magmatic arc activity and contractional deformation along the Incaic relief to a configuration in which the arc shifted slightly to the east. In turn deformation progressively migrated to the east through the Altiplano, the Eastern Cordillera, and the Subandean Belt until reaching the current configuration (Charrier et al., 2009, 2013; Fig. 2a). This shows that after an initial association, magmatism and deformation evolved separately in the Andean margin.

The continuous compressional regime in the northern region also controlled the timing of occurrence of major mineralization episodes in the area. This includes both, primary mineralization events as well as secondary supergene enrichment processes. Regarding the first, in this period the late Eocene-Oligocene porphyry copper belt was formed. This belt shows one of largest copper concentrations in the world, which is hosted in numerous world-class deposits. Regarding the second, supergene enrichment processes were also triggered by the paleogeographic configuration and evolution. On the western side of the Incaic relief, the uplifted blocks were subjected to a long exposure to weathering and erosion. This is considered to be the cause for the intense late Eocene to early Oligocene, and late Oligocene to early Miocene supergene enrichment of the porphyry and allied copper deposits developed along the previous arc (Bouzar and Clark, 2002). These two stages of supergene enrichment coincide with periods during which erosion was particularly intense. They correlate to, and thus resulted from, episodes of uplift (middle Eocene) and rejuvenation (Miocene) of the Incaic relief.

Further south, the area between 27º-39ºS evolved differently. Renewed arc activity concentrated to the east of the Incaic relief in the ~80-90 km wide Abanico extensional intra-arc basin (Fig. 2b; Charrier et al., 2002, 2015).

A new tectonic pulse in the latest Paleogene - early Miocene caused rejuvenation of the Incaic relief in northern Chile (Fig. 2a, section D) and inversion of the Abanico basin in central Chile (Fig. 2b, section D). Here, deformation affected again the arc domain, whereas in northern Chile magmatism and deformation were already dissociated. The load caused by the great amount of deposits in the basin and continuous volcanic activity in the basin domain restrained tectonic inversion and new thrust systems developed to the east forming a fold-thrust belt to the east (Pinto et al., 2010; Muñoz-Sáez et al., 2014). Since then the deformation front progressed, like in northern Chile, uninterruptedly towards the east at a higher rate than the eastward shifting of the magmatic arc (Farias et al., 2010; Fig 2b).

2.3 Coeval Magmatic Fingerprint of Major Crustal Tectonic Processes
Cenozoic igneous rocks throughout the Chilean continental margin result from the arc magmatic activity widely developed in the South American plate as a consequence of Nazca plate subduction beneath it (Mpodozis & Ramos, 1989). For these Andean magmas, numerous studies have shown the strong influence exerted by the crustal architecture and evolution over their chemical and compositional characteristics (e.g., Hildreth & Moorbath, 1988; Haschke and Günther, 2003; Kay et al., 2005; Mamani et al., 2010), as well as for arc magmas in general. Among different compositional parameters, the Sm/Yb and La/Yb ratios have shown to be good proxies of crustal thickness as they signal crustal residual mineral assemblages from low-pressure to high-pressure dominated.

Extensive and detailed geochemical studies performed in southern Peru and northernmost Chile, north of ~27º S, show that arc magmas formed since late Cretaceous underwent a systematic increase in the Sm/Yb (Mamani et al., 2010) and in the La/Yb ratios (Haschke and Günther, 2003). These studies show that this situation developed gradually until early Oligocene, coinciding with the formation of porphyry copper deposits. The systematic increase in the Sm/Yb and La/Yb ratios, which has been continuous since late Oligocene, evidences a continuous crustal thickening process that coincided with the continuous compressional regime that dominated this region until present.

Further south, for the area between 27º-39ºS, arc magmas also record as good proxies for the differing evolution respect to the northern region. Here, the extensional regime and crustal thinning throughout evolution of the Abanico basin (Fig. 2, section C) is reflected in the tholeiitic affinity, unfractionated and unradiogenic nature of coeval magmas (Nyström et al., 1993; Charrier et al., 2002; Kay et al., 2005). These also show low La/Yb ratios which systematically increase only from early Miocene and onwards in coincidence with the latest Paleogene tectonic pulse that caused inversion of the Abanico basin in central Chile (Fig. 2, section D) (Kay et al., 2005; Kay and Mpodozis, 2002).

3 Discussion

There is a 25 m.y. time span during which extension and crustal thinning occurred in central Chile, while contractional deformation and crustal thickening occurred since mid-Eocene time without interruption in the north. This might represent an essential factor to explain the differences in the Andean orogen in both regions. The retard in resumption of contraction south of ~27ºS might explain the reduced altitude, width and crustal thickness of the orogen in central Chile relative to northern Chile and Bolivia, and also the 20 m.y. younger age of the porphyry copper ore deposits in the former region. Although both regions show differing evolutions they do show a similar interplay between deformation and magmatism. Deformation zones initially concentrate within the arc domain being probably magmatic-assisted. In time however, evolved contractional deformation overcomes such control to further development subjected to the regional crustal architecture.
Acknowledgements

We acknowledge facilities from Departamento de Geología and Advanced Mining Technology Center (AMCT), Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, and funding from Fondecyt Project No. 1030965, 1120272, and Anillo Project ACT No. 18 (Programa Bicentenario de Ciencia y Tecnología-CONICYT).

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