VARIABLE REGIMES IN CENTRAL ANDEAN MAGMA SYSTEMS

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INTRODUCTION

Differentiation and recharge in magma chambers as well as interaction with crust by assimilation affects magma chemistry and occur at a variety of time and spatial scales, especially in continental arcs where crust is thicker and more variable than in oceanic settings. Magmas in the Central Andes traverse c. 70 km of continental crust and their plumbing systems are thus prone to be complex, varied in style with time, and distinct in space, depending on (a) magma composition and supply rate from the mantle, (b) depths of storage, (c) density structure and geothermal gradient in the crust and (d) crustal stress regime (extensional or compressional). These parameters may change spatially as well as temporally as the Andean crust evolves. In addition, local effects due to changing loads by flank collapse of the stratovolcanoes may occur. Apart from hydrothermal weakening and the effect of substrate failure, sector collapses may be particularly frequent in the Central Andes due to the extremely arid climate of the Atacama Desert and very limited erosion during stratovolcano growt. In fact, there are numerous examples of debris avalanche deposits flanking stratovolcanoes between 16° and 26° S in the Central Andes.

We relate petrographic, chemical and isotopic changes spanning the lifetime of three distinct Andean stratovolcanoes (Parinacota, Taapaca, El Misti) and on a field of monogenetic centres (Andagua) in N Chile and S. Peru. The observed compositional changes are related to their magmatic system provide links between eruptive history and magmatic events at depth as well as the (re-) configuration of magmatic systems in the crust, from which magmas? are fed.

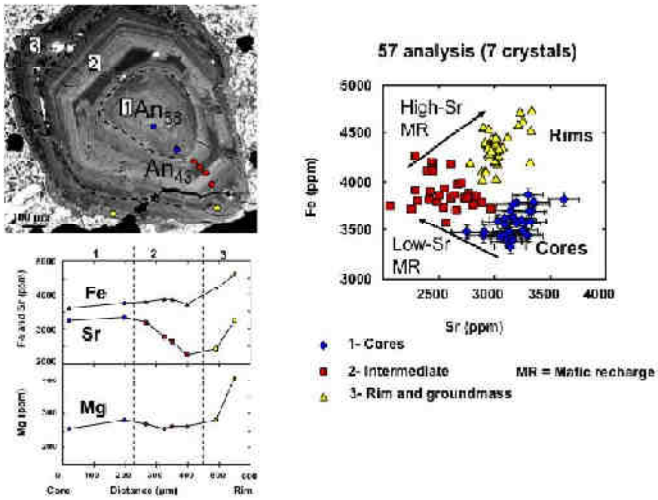
Geochemical, geochronological and mineral chemistry data from distinct stratovolcanoes of the Central Andes are presented here to document contrasting magmatic evolution and plumbing systems.

RESULTS AND DISCUSSION

VOLCÁN PARINACOTA

The 163 ka history, composition and volumetric evolution of **Volcán Parinacota** (18°09'S, 69°08'W, Fig. 1) erupted a large compositional range of basaltic to andesite and rhyolite lavas with a total volume of c. 46 km3. Their composition documents distinct evolutionary phases during the volcano's relatively short evolution at a volume eruption rate of 0,28 km^3 based on newly published 40Ar/39Ar ages (Hora et al., 2007). The history during the last 163 ka spans the construction of an ancestral edifice at Volcán Parinacota, its destruction by sector collapse and subsequent rebuilding of the modern stratocone allows to reconstruct the corresponding sequence of events in the plumbing system. In the „Olde Cone“, which formed prior to the major flank collapse, Parinacota magmas evolve from silicic, porphyritic, and calc-alkaline to mafic, aphanitic, and nearly tholeiitic. This evolution is not simply represented in subsequent eruptions, rather these transitions occur intermittendly and thus apparently do not affect the system uniformly in the early stages of magma system evolution. This indicates that early recharge occurred into, and eruptions were fed from, smaller compartmentalized magma reservoirs in the system when eruptive fluxes were still small. Mixing occurred between different magma batches with highly variable compositions. These separated magma reservoirs evolved into a more homogeneous system after throughput (i.e. recharge and eruption rates) increased through time. This reorganization, however, significantly predates gravitational collapse, implying that mafic magma intruded the system and primed it for high flux that is associated with young cone-building after the old cone collapsed. The changing recharge history is thus changed significantly

Fig. 1 : Volcán Parinacota, N. Chile, with hummocky deposit left from the debris avalanche and sector collapse in the foreground



during the evolution of the magma system during the last 163 ka. This change is not only shown by major and trace elements of erupted magmas but also in the zoning patterns of plagioclase phenocryst in rocks from different stages (Ginibre et al., 2007; Ginibre and Wörner, 2007). Zoning patterns of An content and Fe, Mg and Sr concentrations in plagioclase phenocrysts in andesites from Parinacota volcano reflect recharge events with two chemically distinct mafic magmas throughout its history (Fig. 2). High-Sr plagioclase re-growth after resorption indicates input of Sr-rich mafic magma.

Fig. 2: Mg -, Sr -, and An – systematics in plagioclase crystals from Parinacota volcano (Young Cone stage after sector collapse): two recharge magmas (high and low Sr) contribute to the resorption – crystallisation patterns.

Recharge of two distinct mafic magma types are thus identified (high-Sr and low-Sr), which must have been present – at increasing recharge rates with time - in the plumbing system throughout the volcanoes history. These magmas are characterized by low and high Sr contents, similar to two recent mafic flank eruptions. One end-member basaltic andesite shows large Sr enrichment and Heavy Rare Earth depletions and thus equilibrated with lower-crustal rocks at depth where plagioclase (high Sr) is unstable and garnet (high HREE, Y) is stable. A second end-member magma is lower in Sr, Ba contents and has REE patterns typical for parent magmas elsewhere in the Central Andes.
The number of recorded recharge events increases after the catastrophic sector collapse and during the subsequent rebuilding of the stratocone. Variations of An, Fe and Mg contents and morphology of plagioclase growth zones suggest also changes in water pressure, including decompression under water under-saturated and water-saturated conditions. Evidence for decompression is more present in post-collapse samples, suggesting that the change in the volcano dynamics involves changes in magma chamber location. This shows the importance of the cone collapse event in the volcano's magmatic evolution. While the magma system has evolved towards a more homogeneous magma reservoir

through time, the magma system has been severely disturbed after the sector collapse resulting in changing rates of eruption and mixing.

VOLCÁN TAAPACA

The nearby **Volcán Taapaca** (18°06'S, 69°30'W, Fig. 3) forms a complex dacitic dome cluster with rare lava flows. It is very different from Volcán Parinacota in having erupted only dacites of surprisingly uniform petrography. Taapaca is also much longer-lived compared to Volcán Parinacota : Ar-Ar ages for Taapaca rocks range from 1,27 Ma at the base to 33 ka for one of the youngest domes. Late Quaternary (< 20 ka) activity is indicated by isolated deposits block - and - ash flows in a distal transverse valley, suggesting descent from the summit over glacier filled valleys no earlier than about 10.000 years ago. The volume of about 60 km^3 translates into an volume eruption rate of only 0,05 km^3/k.y. The volcano is associated with an apron (W and N) and valley - filling (SW) block - and - ash flows resulting from frequent dome collapse. These dome collapse events, however, were of small volumes. Only one major sector collapse occurred, which, however, did not lead to any measurable change in magma composition or eruption rate. The surprisingly uniform magma compositions throughout the volcano's history indicate a steady-state, thermally balanced magma system at 15-20km depth (Al-in-hornblende barometry). Compositional and isotope data suggest a large proportion of crustal melt in the formation of the dacites which, however, occurred at a deeper level of the crust as is evidenced by a strong LREE/HREE fractionation that argues for garnet control during assimilation.

Fig. 3 : Taapaca Dome cluster (N. Chile)

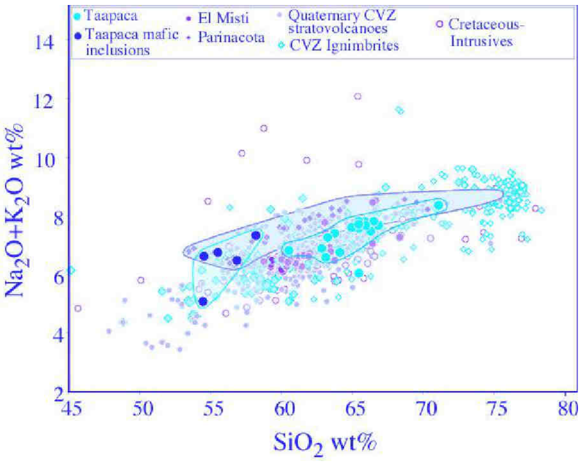


Fig. 4: Compositional variation of Taapaca dacites in comparsion with other stratovolcanoes of the CVZ and the entire CVZ data set (unpubished). Note the most evolved and least evolved data points are from Paleo-Taapaca centers that predate the main dome cluster activity.

We attribute the contrasting behaviour between Taapaca and Parinacota to result from the depth of magma emplacement within the crust, the size and temporal evolution of individual reservoirs. Both, Taapaca and Parinacota magmas are affected by deep crustal assimilation processes. However, Parinacota established above this level a series of distinct magmas reservoirs at a relatively shallow depth, which emerged into one more homogeneous magma system with time. By contrast, Taapaca had evolved earlier and for a longer time into a stable steady state magma reservoir at intermediate crustal depth. Because of the deeper reservoir and smaller collapse volumes, the Taapaca magma system is less sensitive to unloading by sector collapse.

EL MISTI STRATOVOLCANO

El Misti stratovolcano (16°17,8'S, 71°24,5'W; 5822 m) near the city of Arequipa has been active for the past 112ka (Thouret et al., 2001; Fig. 5) and erupted mosty andesites, more rarely dacites (e.g. "the" 2000 a ignimbrite) and produced only one rhyolite deposit (Chiguata Surge). Thus, it represents the same compositional range as e.g. Parinacota or Ubinas, the most active stratovolcano in Peru (Thouret et al., 2005). However, its lavas very rarely contain (xenocrystic) amphiboles and eruption rates have been much higher than for all other volcanoes (0,71 km^3/k.y.), i.e. about 15 times more than at Taapaca and 2.5 times more than at Parinacota.

Plagioclase zonation patterns and electron microprobe major and trace element analysis, in particular, Fe concentration in plagioclase reveal valuable information within a magmatic system to explore the dominance of closed- vs. open-system processes. Large and correlated Anorthite - Fe contrasts at resorption zones identify compositional mixing related to recharge. Subhorizontal An-Fe variations record thermal or water-induced effects. El Misti volcano, a large but still relatively youthful stratovolcano, is dominated during most of its approx. 110 ka history by closed-system effects during its evolution. Recharge and mixing mostly occurred cryptically as it is not recorded in drastic compositional changes in magmas or their phenocrysts (Fig. 6).

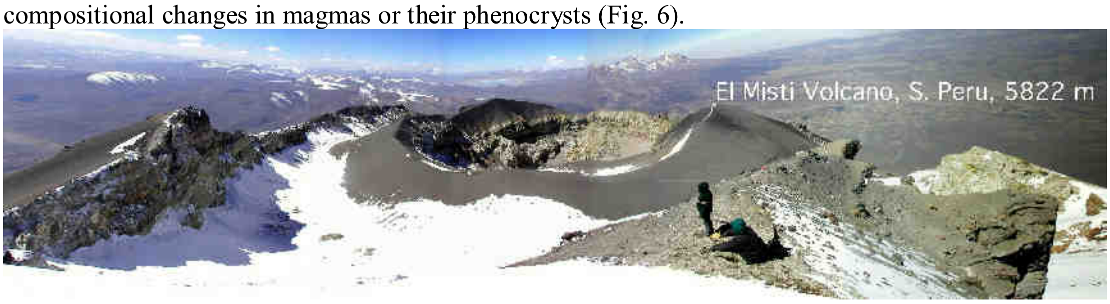


Fig. 5 : Summit Crater of El Misti Volcano (S. Peru)

For the El Misti magma reservoir, resorption events caused by thermal effects or magma ascent are more frequent in comparison to the actual eruption frequencies. Many cycles of closed-system evolution (heat transfer and decompression) therefore occurred without resulting in an eruption.

Apparently, the magma system was well-buffered with respect to volume and temperature as new recharge did not lead to eruption triggering events. However, this magmatic regime may have changed rather recently in the history of the volcano: The steaming plug that presently fills the crater of El Misti volcano (Fig. 5) has very different zonation patterns in their plagioclases compared to all other studied lavas from the stratovolcano (Fig. 6). It only represents a very small volume erupted at El Misti, however, it is affected by strong open-system behaviour as reflected in strongly correlated variations in An and Fe contents of plagioclase compositions.

Its crystal population is texturally and chemically are in fact very similar to lavas of the monogenetic cinder cones of the Andahua Volcanic Field (Fig. 5), which represents a series of small volume eruptions probably fed from deep reservoirs (Fig. 7). This may indicate, that El Misti has entered a new and different magma regime recently and eruption history and frequency may change in the future compared to the geological past. This conclusion in fact is similar to Ubinas volcano, that also pears to have change its magmatic regime in relatively recent times (Thouret et al., 2005).

It is difficult to reason by what process this change is caused and what its implications may be for hazard mitigation. However, in considering future hazards from these volcanoes, these observations need to be considered.

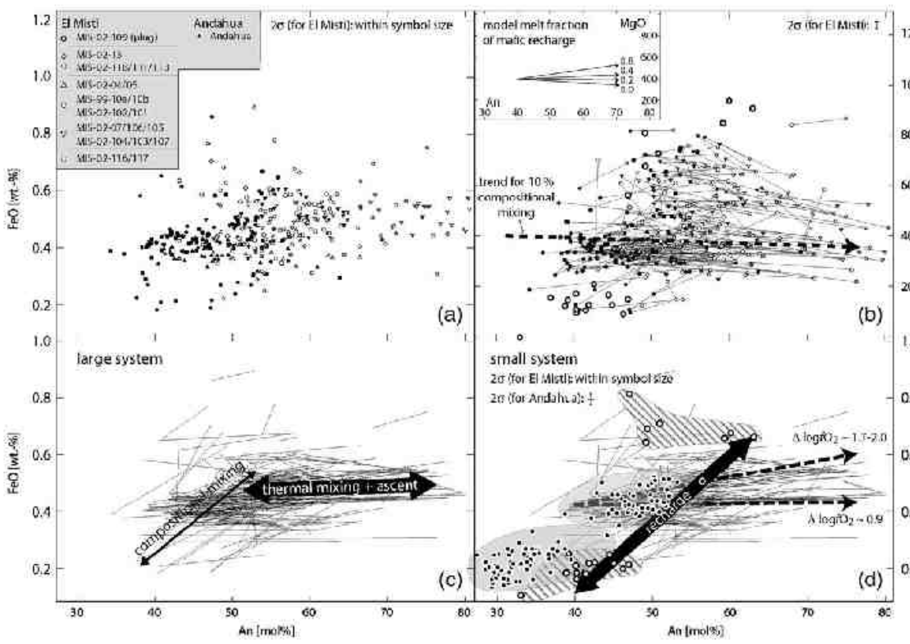


Fig. 6: Fe-An systematics of feldspar zonations at El Misti Volcano. Note the distinct trends: a) large variations in An with no Fe variation (flat trends) indicate "thermal mixing", i.e. changes in T due to magma recharge and underplating without changes in composition (no mixing) or (b) An–Fe changes correlated trends indicating chemical disturbance and compositional mixing of new magma.

ANDAHUA-ORCOPAMPA AND HUAMBO MINOR CENTERS

Minor centres in the Central Volcanic Zone (CVZ) of the Andes occur in different places and are essential to understand the processes leading to the composite volcano formation. The Andahua-Orcopampa (Fig. 7) and Huambo monogenetic centres are located in a unique tectonic setting, in and close to a deep valley, which is oblique to the NW-SE-trend of the CVZ, and between two composite volcanoes; the Nevado Coropuna to the east and the Nevado Sabancaya to the west. Structural analysis of these volcanic areas, based on SPOT satellite image, indicates four main groups of faults, which may have controlled magma ascent and the distribution of the centres in this deep valley. Morphometric criteria and ^{14}C age dating attest to four main periods of Quaternary activity: Late Pleistocene, Early to Middle Holocene, Late Holocene and Historic (Delacour et al., 2007). The two most interesting features of these cones are their wide compositional range (52.1 to 68.1 wt% SiO_2) and the unusual occurrence of mafic lavas (olivine-rich basaltic andesites and basaltic andesites). The occurrence of such minor volcanic centres and mafic magmas in the CVZ may indicate that larger crustal magma systems at intermediate depths are bypassed (or do not form) and thus these centers provide clues on deep crustal magma reservoirs.

This is confirmed by the observation that plagioclase zonation patterns are very distinct from almost all lavas eruption in Andean stratovolcanoes. Zonation patterns are simple and show only one major resorption event with a distinct overgrowth of contrasting composition.

This overgrowth suggests mixing between magmas of very distinct compositions and thus the lack of any volume - buffer such as observed in the large systems. Magmas erupted from minor centers do not stagnate, evolve and mix in shallow magma reservoirs during their ascent. This is distinct from lavas that are produced by the composite volcanoes and that are strongly affected by shallow processes, which mask the deeper processes. However, the major, trace, and rare earth elements, as well as isotope data obtained on the high-K calc-alkaline lavas of the Andahua-Orcopampa and Huambo volcanic fields of minor centers display a range of bulk compositions which is surprisingly similar to that of the CVZ composite volcanoes. Therefore, the main compositional characteristics of Andean magmas evolve at relatively deep levels in the crust while further development only changes the bulk major element compositions by differentiation at shallow depth, this implies that isotopic and trace element signatures remain unmodified by these shallow processes.

Fig. 7 : Satellite image of Andagua valley with minor mafic centers.

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