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Neogene ignimbrites and volcanic edifices in southern Peru: Stratigraphy and time-volume-composition relationships

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Introduction

In the Central Andes of Peru, four volcanic arcs, termed Tacaza, Lower and Upper Barroso, and Frontal arc, have been active over the past 30 Ma (Fig. 1). They form five units between Moquegua and Nazca (14°30–17°15'°S and 70–74°W). The 'Neogene ignimbrites' (<25 Ma) comprise six generations of widespread sheets (>500 km^2 and >20 km^3 each), representing a major crustal melting event, triggered by thickening and advective heat input from the mantle wedge. Also, four generations of edifices (i.e shields, composite cones, and dome clusters) and monogenetic fields mostly overly the ignimbrites based on ages, stratigraphy and mapping.

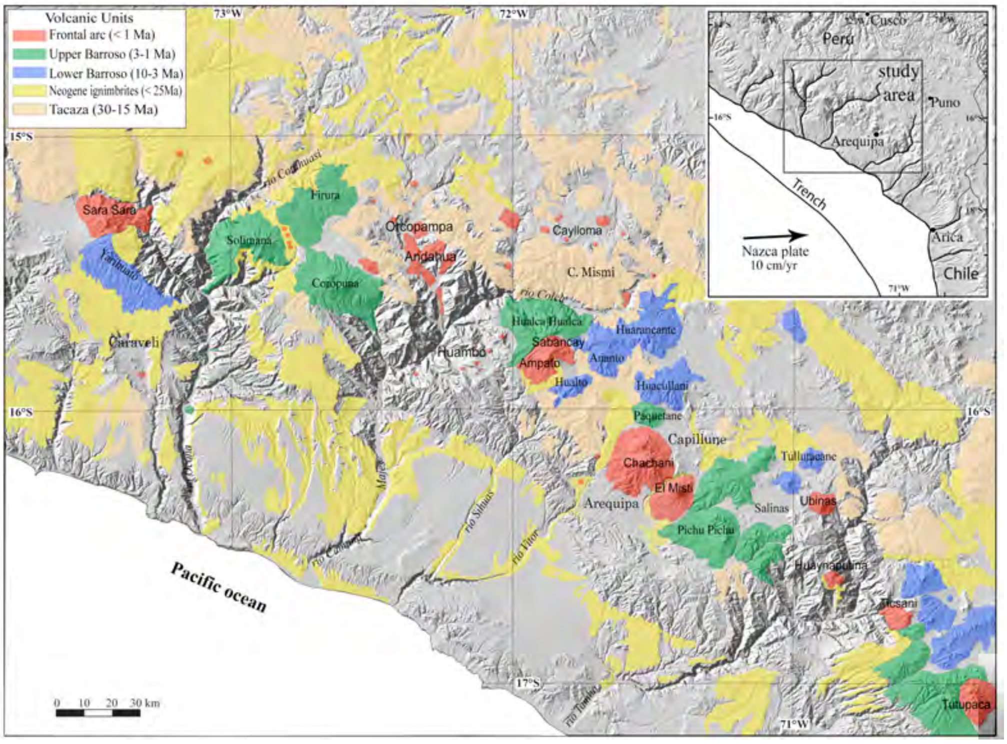

Figure 1. Extent of five volcanic units over the past 30 Ma in southern Peru (Mamani *et al.*, 2008a).

Pre and post-valley incision ignimbrite sheets and western CVZ evolution

Our new stratigraphy (Fig. 2) records changing magma composition, uplift and valley incision of the Central Andes, and the rate of growth and degradation of the Early Miocene to Holocene volcanoes.

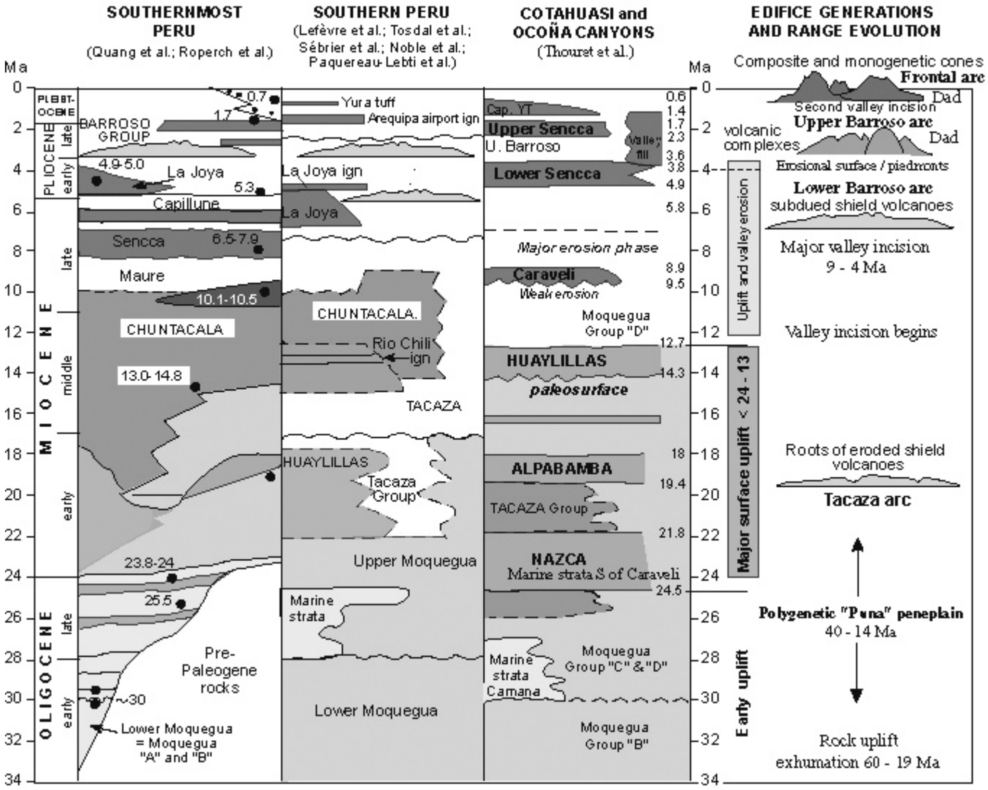

Figure 2. Stratigraphy and chronology of ignimbrites and lava edifices in southern Peru. The evolution of the western Andean range in Peru is also indicated. 'Dad' stands for debris avalanche deposit.

The older ignimbrite sheets pre-date valley incision and are intercalated with voluminous conglomerates that reflect major phases of surface uplift as a response to tectonic phases in a crust weakened by massive crustal melting. 1) The 24.6-21.8 Ma-old, welded Nazca ignimbrite caps extensive plateaus to the N and W of the area as well as further S near Moquegua. 2) The welded, 19.4-18 Ma-old Alpabamba ignimbrite and 3) the 14.3-12.7 Ma-old Huaylillas ignimbrite form extensive plateaus between 4000 and 4500 m S of Coropuna and N of Cotahuasi. They blanket the polygenetic 'Puna' peneplain formed between >40 and 14 Ma (Gunnell *et al.*, 2008). The ignimbrites erupted from calderas (e.g. N of Alca, NW of Oyolo) during growth of the Western Cordillera between 24 and 13 Ma. Distal tuffs of these ignimbrites are interbedded in forearc deposits towards the top of the Moquegua Formation conglomerates (Roperch *et al.*, 2006) in the Majes, Sihuas and Vitor valleys.

The younger, less widespread ignimbrites that filled tectonic basins or were channelled in deep valleys, postdate valley incision. 1) The 9.4-8.8 Ma-old Caraveli ignimbrites fill an irregular topography cut in the Huaylillas ignimbrites and crown small and low plateaus at 3000 m asl. to the W of the area. They were emplaced in shallow wide valleys cut in the peneplain, thus indicating that the fluvial incision had already begun by 9 Ma. 2) The 4.9-3.6 Ma-old non-welded lower Sencca ignimbrites (Lower Barroso equivalents) crop out in conglomeratic piedmonts or are preserved on deep valley flanks. The 4.86 Ma-old La Joya ignimbrite (Paquereau-Lebti *et al.*, 2006) fills the Arequipa depression. 3) The non-welded 2.3-1.4 Ma-old upper Sencca ignimbrites (Upper Barroso equivalents) crop out in similar stratigraphic positions and comprise the non-welded Arequipa Airport ignimbrite (1.63 Ma: Paquereau-Lebti *et al.*, 2007) filling the Arequipa depression. Calderas are not clearly identified but magnetic fabric and AMS measurements (Paquereau-Lebti *et al.*, 2007) indicate that

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Sencca ignimbrites are probably sourced at calderas or crater clusters that are buried beneath younger volcanic complexes such as Chachani, Coropuna, and Ampato. A second phase of valley incision took place after 2.2 Ma (Río Colca valley) or 1.4 Ma, the age of non-welded pumice-flow deposits, which had largely filled the canyon of Río Cotahuasi. Younger ignimbrites exist but none exceeds 200 km^2 and 10 km^3. One such example is the Yura Tuff N and W of Chachani, that may be contemporaneous with the Capillune Formation.

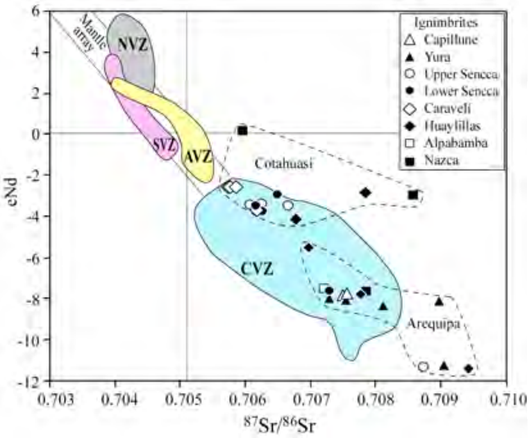

Figure 3. έNd and $^{87}Sr/^{86}Sr$ Plot of ignimbrites of the Cotahuasi and Arequipa areas. Isotope values of igneous rocks support the concept that Andean magmas are controlled by the composition and age of the Andean crust. The Arequipa and the Cotahuasi ignimbrites define a domain that overlaps the average CVZ magma composition domain. The Arequipa ignimbrites eNd is lower than the Cotahuasi ignimbrites eNd. These differences may be the result of the assimilation of crustal materials with different isotopic signatures during magma genesis. Recent geochemical and geophysical data pointed out two distinct crustal domains, termed Cordillera and Arequipa, in southern Peru (Mamani *et al.*, 2008a,b).

Four generations of edifices and time-volume-composition relationships

Dated lava flows and pyroclastic deposits indicate that four generations of composite and monogenetic edifices have crowned the Western Cordillera and mostly overlie the ignimbrites (Fig. 2). 1) Although the Tacaza arc is deeply eroded, roots of hydrothermally-altered edifices remain in the Caylloma area 60 km N of the Frontal arc. 2) The 9 to 4 Ma-old Lower Barroso edifices are moderately eroded, subdued shields with a core of 6-4 Ma-old basaltic andesite and andesite lava flows (e.g. near Cora Cora and Laguna Salinas); 3) The Upper Barroso 3-1 Ma-old stratovolcanoes and dome complexes, with a wider range of composition from mafic andesites to rhyolites, have been carved by glacial erosion and abundant scars of flank failures (e.g. Pichu Pichu and Chachani); 4) The Pleistocene – Holocene volcanoes are composite cones such as El Misti, Ubinas, and domes on caldera edges such as Ticsani. Most of these composite cones are younger than 0.8-0.6 Ma (Thouret *et al.*, 2001, 2005). The frontal arc includes coeval monogenetic fields like the Andahua-Orcopampa-Huambo field, where strombolian cones and lava flows formed between 0.5 Ma and historic times (Delacour *et al.*, 2007).

The $^{40}Ar/^{39}Ar$ chronology combined with volumes of composite cones allow eruption rate estimation, which are minimums because of glacier erosion and explosive destructions. Eruption rate is apparently lower during the first phase of the growth of stratovolcanoes over a long period (400 – 800 ka) and apparently accelerates during maturation and growth of the summit cones: 0.6 km^3/ky at Misti over 110 ka and 0.22 km^3/ky at Ubinas over 250 ka. Eruption rates fluctuate between 0.1 and 1 km^3/ky according on the time span considered and with respect to magma composition and eruptive style (mafic effusive vs. evolved and pyroclastic). Composite cones have changed between Plinian eruptions that form summit calderas (Misti 13-11 ka; Ubinas 25-9 ka). Large debris avalanches occurred at composite cones and dome complexes during the last 0.5 Ma. The largest collapse at Ticsani produced a 20 km^3 debris-avalanche deposit but smaller, recurring debris avalanches as young as middle-late Holocene have also occurred at the Ubinas cone and Tutupaca.

The $^{40}Ar/^{39}Ar$ chronology and petrology of lava flows and pyroclastic deposits allow us to estimate the magmatic evolution through time (Fig. 3). Andesite and mafic andesite magmatism forms the base of stratovolcanoes beneath summit cones and are present in monogenetic compound lava flow fields throughout the region, mostly along deep-seated, normal N80-trending faults (e.g. Ichupampa Fault). The monogenetic field of Andahua-Orcopampa-Huambo has 25-50 km^3 of lava, with an eruption rate of 0.09-0.18 km^3/ky. The ascent of magma producing coeval compound lava fields has bypassed the reservoirs of composite cones in the upper crust: the magma genesis is attributed to partial melts of the lowermost part of the thick Andean continental crust added to mantle-derived arc magmas in a high pressure MASH zone (Delacour *et al.*, 2007).

Conclusion: implications on eruption frequency and hazards

From the chronostratigraphy, large-scale ignimbrite sheets (>20 km^3) have erupted on intervals of 5 Ma but many individual smaller ignimbrites have also occurred. Each of the four generations of composite and shield volcanoes has lasted between 1 and 4 My but this belies the rapid growth of short-lived (<0.8 My) composite cones, which have erupted at a rate of 0.2–1 km^3/ky on average over the past 250 ka.

A 50 ka-long record of identified and dated tephra and lava flows is linked to 10 volcanic edifices and monogenetic fields between Nevado Sara Sara and Yucumane. The record of the Frontal arc displays at least 50 events, i.e one eruption every kyr over the past 50 ka, including 12 large Plinian-type eruptions with >1 km^3 of tephra. If the more complete 15 kyr-old tephra record is taken at face value, the eruption frequency increases to 3 events per kyr, comprising two moderate-sized ashfalls every kyr and one voluminous Plinian pumice fall on a 2400–3600 yr interval. Very large eruptions such as the Huaynaputina AD1600 event potentially would have a large effect on southern Peru, western Bolivia, and northernmost Chile. Such eruption could occur in the area comprised between Huaynaputina, Ticsani and Tutupaca (Fig. 1): in this region, a long volcanic history and recent eruptions of silicic magma suggest that similar vigorous eruptions may occur in the near geological future. In addition, debris avalanches and landslides from from ignimbrites cliffs and from hydrothermally-altered composite cones, even without any eruption, and subsequent debris flows pose serious threats to the population.

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