

Cronoestratigrafía del volcanismo con énfasis en ignimbritas desde hace 25 Ma en el SO del Perú – Implicaciones para la evolución de los Andes centrales

Jean-Claude Thouret¹, Brian Jicha², Jean-Louis Paquette¹, con la colaboración de la DGR, INGEMMET³

¹ Université Clermont-Auvergne, CNRS OPGC et IRD, Laboratoire Magmas et Volcans, F-63000 Clermont-Ferrand, France – J-claude.thouret@uca.fr

² Department of Geoscience, University of Wisconsin-Madison, Madison WI 53706 USA

³ DGR, Ingemmet, Dirección de Geología Regional, Av. Canadá, San Borja, Lima, Perú

Palabras clave: estratigrafía, cronología, volcanismo, ignimbritas, Central Andes.

Resumen corto

El sur del Perú representa el segundo campo ignimbrítico de los Andes con un área que sobrepasa los 25 000 km² y volúmenes de casi 5000 km³. Se presenta la extensión, la estratigrafía y la cronología de 12 ignimbritas que afloran en el área de los cañones profundos de los Ríos Ocoña–Cotahuasi–Marán y Colca (OCMC). La cronología de las ignimbritas a lo largo de los últimos 25 Myr está basada en 74 dataciones ⁴⁰Ar/³⁹Ar and U/Pb. Antes de 9 Ma, ocho ignimbritas con gran volumen fueron producidas cada 2.4 Myr. Después de 9 Ma, el periodo de reposo entre cada ignimbrita de volumen pequeño a moderado ha disminuido hasta 0.85 Myr. Esta cronología de las ignimbritas y de las lavas del Neogeno y Cuaternario ayuda a revisar la nomenclatura de las formaciones volcánicas utilizadas para la Carta Geológica Nacional. Además las unidades volcánicas identificadas son herramientas para reconstruir la evolución geológica del flanco occidental de los Andes Centrales durante su levantamiento desde hace 25 Ma. Junto con la cronoestratigrafía de estas unidades, datos geomorfológicos obtenidos en las cuencas y sobre otros depósitos de los cañones OCMC ayudan a precisar la historia de la incisión del flanco occidental de los Andes Centrales desde hace 25 Ma. Finalmente la cronología de depósitos de avalancha de escombros y de terrazas rocosas basada en cosmogénicos (Be¹⁰) permite precisar la evolución de los cañones durante el Pleistoceno y el Holoceno.

Introduction

With an area exceeding 25,000 km² and volumes c. 5000 km³, south Peru hosts the Andes’ second largest Neogene ignimbrite field. We document the extent, stratigraphy and chronology of 12 ignimbrite sheets in the Río Ocoña–Cotahuasi–Marán (OCM) and Colca deep canyons (Fig. 1). Based on 74 ⁴⁰Ar/³⁹Ar and U/Pb age determinations, ignimbrite-forming episodes span 25 Myr. Prior to 9 Ma, eight large-volume ignimbrites were produced every 2.4 Myr. After 9 Ma, average lulls between small- to moderate-

volume ignimbrites decreased to 0.85 Myr (Thouret et al., 2016, 2017).

The ⁴⁰Ar/³⁹Ar geochronology was determined using pumice from 54 ignimbrites and crystals from 22 lava flows at WiscAr Lab in Madison (Wisconsin, USA). U–Pb geochronology was determined by laser ablation inductively coupled plasma mass spectrometry using 280 U/Pb analyses of zircons from 10 ignimbrite units at LMV in Clermont-Ferrand (France).

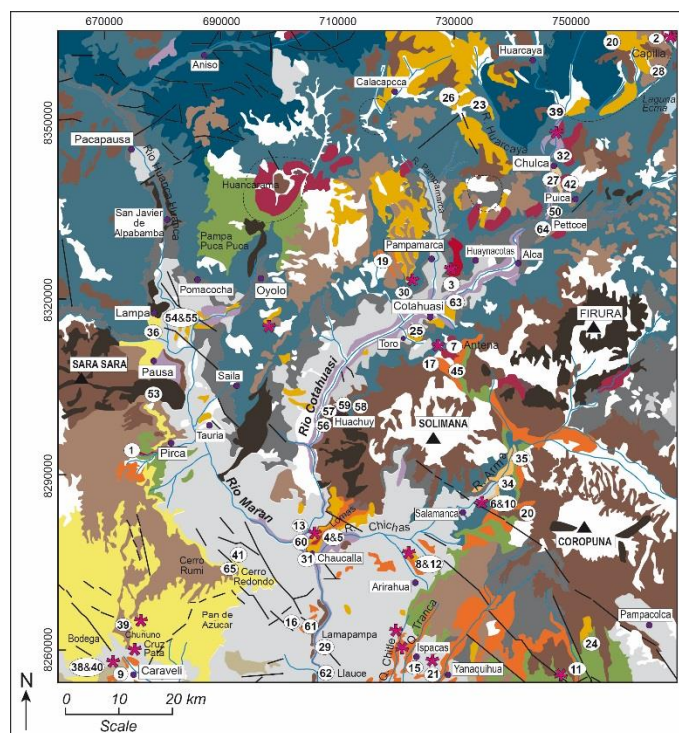


Fig. 1A – Two geological maps, (a) north and (b) south of the OCM region, draped on the NASA SRTM DEM, highlighting the 12 ignimbrites and PDC deposits together with the Late Miocene to Pleistocene lava flows. The legend for the geological maps is shown in (c) Fig. 1B. Non-volcanic bedrock has been simplified. Sites of principal logs and dated samples are indicated. (d) OCM ignimbrites in a total alkali v. silica diagram.

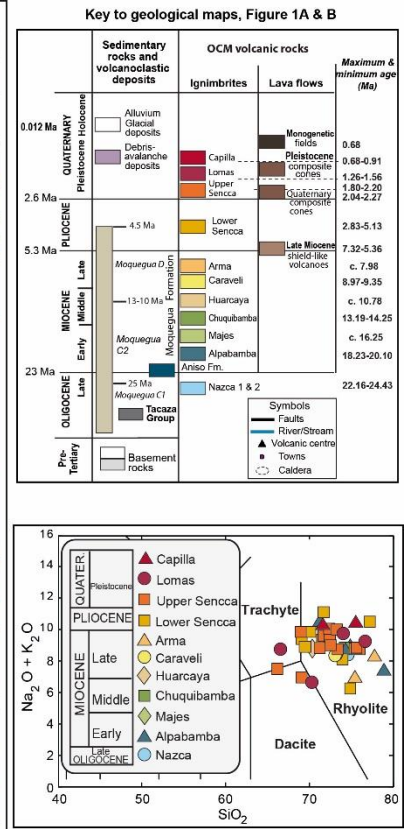
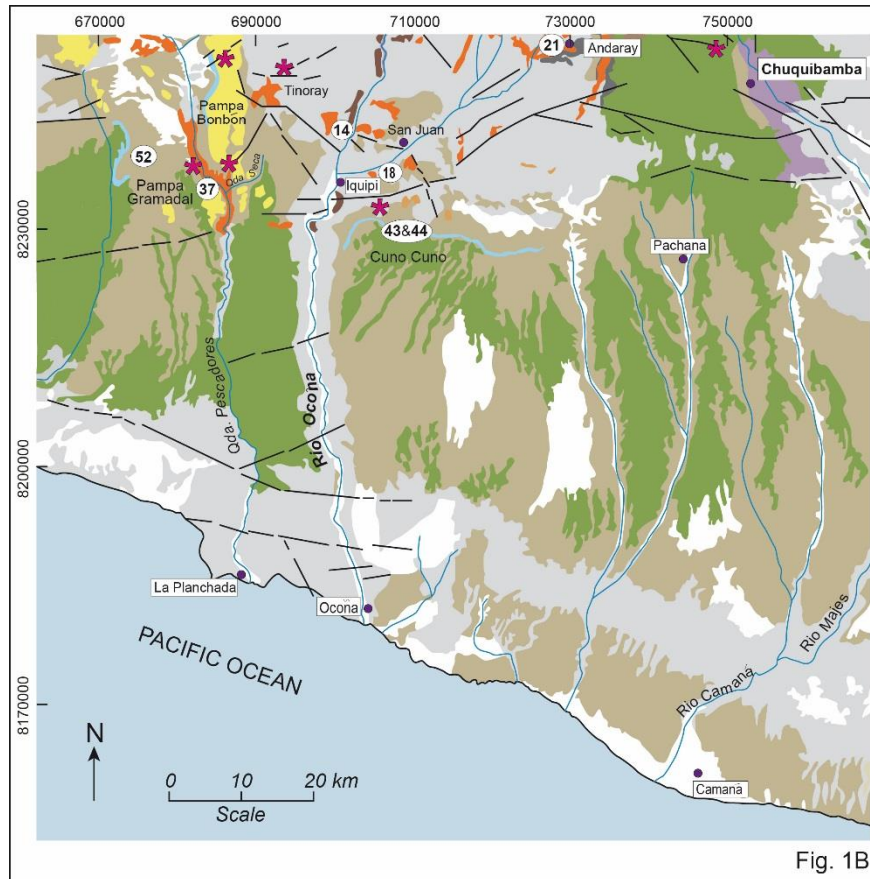


Fig. 1B

Fig. 1C. TAS diagram for OCM ignimbrites

Fig. 1B – South of the OCM region. See caption above.

Two geochronological datasets have been used to constraint the chronology and stratigraphy of the OCM Neogene and Quaternary ignimbrites. There are no discrepancies between ^{40}Ar – ^{39}Ar or U/Pb dates for the same ignimbrite unit, and there are no age discrepancies between chronology and stratigraphy. All 74 dated ignimbrites and lavas are in stratigraphic succession within analytical uncertainty. Dates were obtained from multiple units within the majority of the ignimbrite sheets except for the Capilla, Huarcaya and Majes ignimbrites. Published $^{40}\text{Ar}/^{39}\text{Ar}$ chronology on a number of ignimbrites and lava flows in the OCM region (Schildgen et al. 2007, 2009) are within uncertainty (within 0.1 Myr) of the dataset presented here.

We distinguish and correlate cooling units and, where identifiable, flow units emplaced between c. 24.43 and c. 0.91 Ma on the basis of stratigraphic unconformities, presence of vitrophyres, changes in lithofacies, and $^{40}\text{Ar}/^{39}\text{Ar}$ and U/Pb age determinations. Figure 2 shows how these ignimbrites fit in the 30 Myr OCM stratigraphic scheme compared with the Neogene ignimbrite stratigraphy in adjacent Orcopampa and southernmost Peru.

1. Extent, stratigraphy and chronology

The OCM chronostratigraphy and correlations suggest that 12 ignimbrite sheets and PDC deposits (Pyroclastic Density Currents) have erupted every 1.9 Myr on average over the past c. 25 Myr: Nazca 1, Nazca 2, Alpapabamba, Majes, Chuquibamba, Huarcaya, Caravelí, Arma, Lower Sencca, Upper Sencca, Las Lomas and Capilla (Figs 1–2). Additional ignimbrites between c. 30 and 2.7 Ma identified in the adjacent Orcopampa region east of the OCM region (Swanson et al. 2004) support the fact that pyroclastic activity became more sustained while the Cordillera uplift was taking place. No significant (>0.6 Myr) break occurred after 5.1 Ma; instead, quasi-continuous volcanism produced three generations of composite volcanoes with four intercalated ignimbrite sheets and PDC deposits, and Pleistocene monogenetic fields.

1. The Late Oligocene–Early Miocene (30–20 Ma) includes the Nazca group of ignimbrites. We bracket the ‘Tacaza Group’ between 30 and c. 20 Ma instead of 30–24 Ma (Mamani et al. 2010). The upper limit of Oligocene volcanoclastic rocks attributed to this group has been loosely dated between c. 24 or 21.7 and 15.85 Ma. The c. 30 Ma Jallua tuff (Swanson et al. 2004) east of the OCM region near Orcopampa, the oldest known

ignimbrite outside the tuff beds intercalated in the Moquegua Formation, is used here as the base of the Tacaza Group. The uppermost limit coincides with the base of the Alpbabamba ignimbrite dated at c. 20-10 Ma (Fig. 3). Because both Nazca tuffs reflect interspersed

2.2 km a.s.l., was at sea level at 25 Ma as shown by marine sediment of that age at Pampa Gramadal and Cuno Cuno (Cruzado and Rojas 2005). The lithofacies of Nazca and Majes tuff layers in conglomerates suggests emplacement in shallow water bodies. All younger ignimbrites such as Chuquibamba show no evidence for emplacement into water.

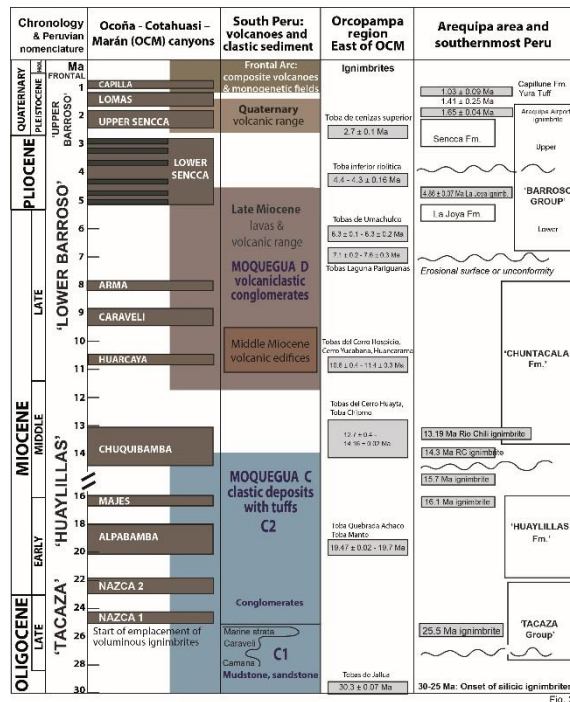


Fig. 2 – Composite stratigraphy of the 12 ignimbrite sheets and PDC deposits of the OCM region, lava flows and their setting in volcanoclastic and continental siliciclastic deposits. Correlations are shown with other formations; in particular, with ignimbrites of Orcopampa east of the OCM region (Swanson et al. 2004), Arequipa (Paquereau-Lebti et al. 2006, 2008) and in southernmost Peru. Stratigraphy of the Moquegua Formation after Sempere et al. (2014).

explosive activity increasing before (Nazca 1, c. 24–25 Ma) and after (Nazca 2, c. 22–23 Ma) the top of Tacaza Group, we extend its boundary to 20 Ma. 2. The Early–Middle Miocene stage (20–13 Ma) is bracketed by the Alpbabamba composite sheet at the base and the Chuquibamba compound sheet at the top. We bracket the ‘Huaylillas’ Formation between c. 20 and c. 13 Ma (instead of 24–10 Ma; Mamani et al. 2010) on the basis of the two most extensive and voluminous ignimbrites in south Peru (Alpbabamba c. 20.2–18.23 Ma and Chuquibamba c. 14.3–13.2 Ma), and because the Chuquibamba ignimbrite pulse preceded the Late Miocene uplift and deep river incision (Schildgen et al. 2007; Thouret et al. 2007). The Majes tuff (16.25 Ma) and Moquegua C1–C2 volcanoclastic material heralded the increase in eruptive activity recorded in the ‘Huaylillas’ Formation (Decou et al. 2011) at a time when the forearc was not experiencing warping and uplift. The forearc, now

3. The Middle–Late Miocene (11–5 Ma) pyroclastic stage includes the 10.78 Ma Huaracaya ignimbrite, the c. 9 Ma Caraveli ignimbrite and the c. 8 Ma PDC deposits, and the oldest recognizable range of shield volcanoes (7.3–5.3 Ma). This coincides with the most recent pulse of surface uplift of the Western Cordillera (Schildgen et al. 2007, 2010; Thouret et al. 2007). The Caraveli episode was the most recent ignimbrite flare-up. After 7.3 Ma, magma output became steadier albeit smaller and contributed to the intertwined growth of volcanic ranges of composite cones with moderate volumes of ignimbrite sheets.

4. The Pliocene stage is characterized by the emplacement of the composite, multi-layered sheet of the Lower Sencca Group (5.3–2.83 Ma). The latest units of this Group were confined in deep valleys in contrast to the earliest units, which often crown the Alpbabamba or Chuquibamba successions.

5. The Early Quaternary volcanic range grew after 2.27 Ma and their deposits intertwined with the Upper Sencca unit at c. 1.97 Ma on average. Nevado Solimana, one of these edifices, is a probable source of Upper Sencca units and Lomas PDC deposits. The Nevado Coropuna dome cluster has grown on one of the source areas of Chuquibamba and Upper Sencca units.

6. The Pleistocene volcanic range <1.3 Ma was contemporaneous with, and followed the 1.56–1.26 Ma ‘Lomas’ PDC deposits. The latter is slightly younger than the Arequipa Airport ignimbrite (c. 1.65 Ma) and contemporaneous with subsequent PDC deposits near Arequipa. The most recent ignimbrites of sizeable volume (Capilla in the north OCM region, Yura tuffs near Arequipa) erupted between 1.1 and 0.9 Ma.

7. Finally, the Middle to Late Pleistocene monogenetic fields of andesite and basaltic andesite lava flows and cones grew together with the most recent, large composite cones at <0.6 Ma, including the potentially active Sara Sara composite cone and Coropuna dome cluster and eroded by glaciers and landslides.

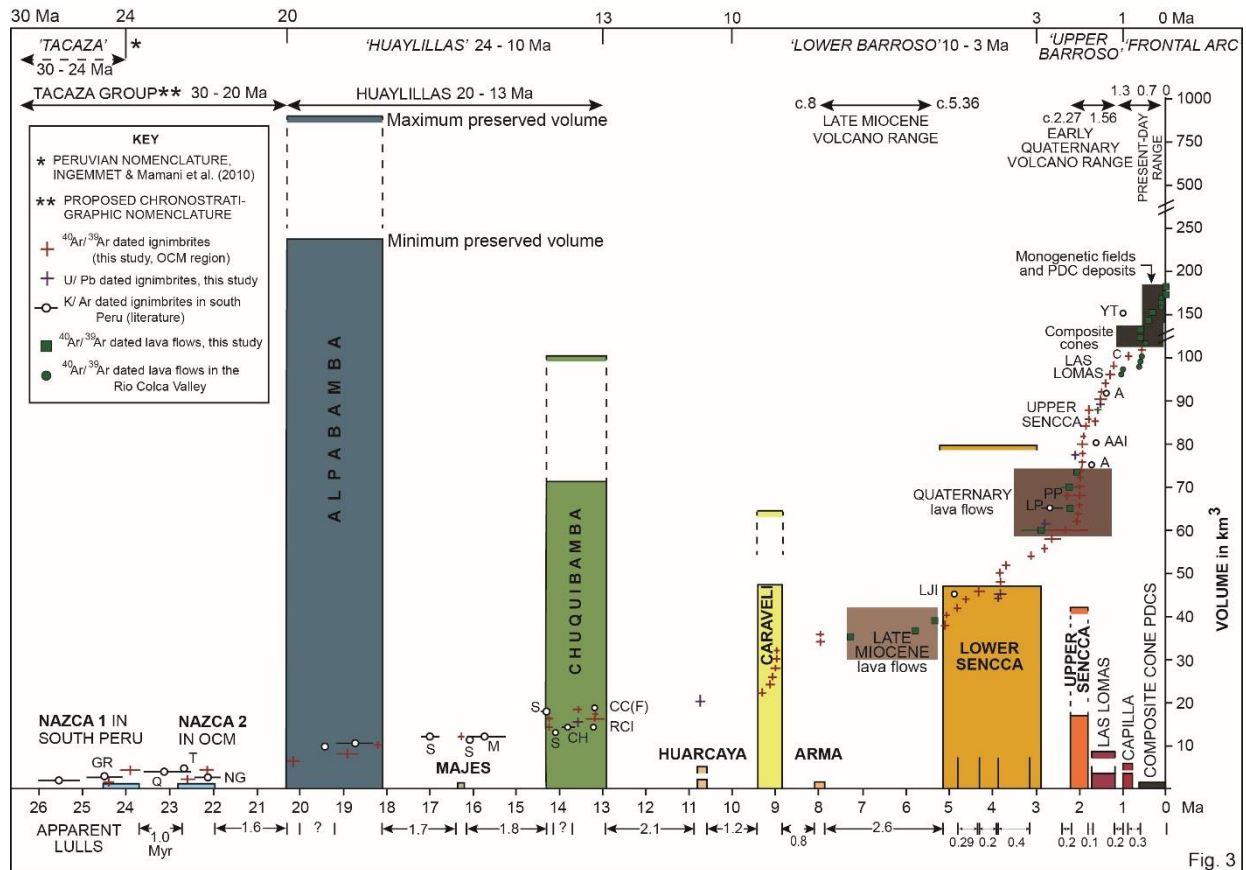


Fig. 3 – Temporal distribution of $^{40}\text{Ar}/^{39}\text{Ar}$ age determinations for the OCM ignimbrites compared with ignimbrites in SW Peru. Histograms show the minimum (continuous lines) and maximum (dashed lines) volume estimates for each ignimbrite sheet. Width of bars expresses the age determination with 2σ error. Three generations of lava flows dated in the OCM region are indicated by brown boxes. The duration of eruptive lulls between the ignimbrite sheets is indicated below the time axis. Distinct eruptive pulses are suggested for the Lower Sencca ignimbrite. *Peruvian nomenclature (INGEMMET & Mamani et al. 2010). ** Proposed chronostratigraphic nomenclature (Thouret et al., 2016, 2017 and references therein).

2. Volcanological implications

Three implications stem from the extent, volume and chronostratigraphy of the OCM ignimbrites (Figs. 1–4): (1) the ignimbrite-forming eruption rate changed after 9 Ma; (2) the growth of volcanic arcs and ignimbrites was intertwined after 9 Ma; and (3) potential sources (calderas) have been identified for the majority of ignimbrite sheets.

2.1. ‘Flare-ups’ before 9 Ma contrast with sustained explosive activity after 5 Ma.

Lulls in eruptive activity, defined as the absence of sizeable ($<1\text{ km}^3$) pyroclastic deposits, reveal that the repose times between very large-volume ($>50\text{ km}^3$) and large-volume ($5\text{--}50\text{ km}^3$, VEI 6) ignimbrites are significantly longer than those between their small

volume ($<5\text{ km}^3$) counterparts. Recorded ignimbrite pulses after 9 Ma, interspersed with the growth of composite volcanoes after 7.3 Ma, suggest a steady eruptive activity. Alapabamba, Chuquibamba and Caraveli ignimbrites were emplaced by very large (VEI 7) or ‘super-eruptions’ separated by long lulls of c. 2–3.8 Myr. The 3.7–3.8 Myr lulls exist between the voluminous Alapabamba and Chuquibamba ignimbrites, the Chuquibamba and Caraveli eruptions, and the onset of Lower Sencca activity. The large-magnitude–low-frequency pattern changed after 9 Ma. The maximum eruption rate decreased from $66.9\text{ km}^3\text{ myr}^{-1}$ prior to 9 Ma to $26.3\text{ km}^3\text{ Myr}^{-1}$ after 9 Ma (Fig. 4). Explosive volcanism shifted to more sustained activity at c. 5.1 Ma producing moderate- to small-volume but frequent ignimbrites separated by lulls that did not exceed 0.6 Myr (Fig. 3). Decrease in quiescence duration between pyroclastic episodes has been observed after 7 Ma in the Orcopampa area east of the OCM region and after 5 Ma in the Arequipa region (Paquereau-Lebti et al. 2006, 2008).

2.2. Growth of three volcanic ranges after 9 Ma intertwined with ignimbrites

The stratigraphy and extent of lava flows depicted in Figures 1 and 2 and age determinations (Fig. 3) demonstrate that eruptive activity has been sustained after 9 Ma. The oldest OCM volcanic range, defined between 8 Ma Arma PDC deposits and 7–5.36 Ma

lava flows, differs from the 10 to 3 Ma interval of the 'Lower Barroso Arc' fixed by Mamani et al. (2010). The oldest OCM range of volcanoes is inferred from a thick succession of lava flows overlapping the Chuquibamba and Caravelí ignimbrites. Eroded piles of thin, low-angle andesitic lava flows (e.g., between Río Marán and Río Cotahuasi, Fig. 1) and glacially eroded and hydrothermally altered edifice cores reflect the growth of shield-like and eroded by glaciers and landslides. Both Arma PDC deposits and 7.3–5.3 Ma lava flows (Río Marán and Río Cotahuasi, Fig. 1) allow us to better constrain the growth of Late Miocene volcanoes in the OCM region. As composite volcanoes are not long-lived (<1 Myr) systems, the deeply eroded, compound edifices claimed to have ages >9–14 Ma NW of the OCM region (Mamani et al. 2010) belong to the Middle Miocene 'Huaylillas' period. Lava-flow chronology suggests that a 3 Myr interval separated the Late Miocene range from the Quaternary volcano range. During this long interval, the Lower Sencca sheet (5.1–2.8 Ma) shortly followed the Miocene range whereas the Upper Sencca and Lomas ignimbrites (2.09–1.26 Ma) coexisted with Quaternary edifices. Instead of the 'Upper Barroso arc', two categories of volcanic range can be distinguished (Fig. 3), as follows:

(i) The OCM Quaternary volcanoes are better preserved than their Miocene counterparts, although they display amphitheatres formed by landslides or flank failures (e.g., Nevado Solimana) and eroded by glaciers. These edifices point to an activity (2.27–1.30 Ma) shorter than the 'Upper Barroso Group' approximated between 3 and 1 Ma (Mamani et al., 2010).

(ii) The Pleistocene and present-day volcanic range straddles the west flank of the Western Cordillera. From available $^{40}\text{Ar}/^{39}\text{Ar}$ age determinations and geological maps, the Pleistocene range did not start before 1.3 ± 0.1 Ma and encompasses several coeval composite cones and dome clusters; in chronological order, these are Nevados Coropuna, Firura and Sara Sara. In SW Peru, the Pleistocene range includes (a) volcanic complexes including extinct, eroded stratovolcanoes and dome coulée clusters (Nocarane in Chachani, Hualca Hualca), (b) dormant but youthful eruptive centres (Nevado Chachani, Coropuna, Firura), none having an age >1 Ma, and (c) active composite volcanoes all with ages <0.6 Ma. Nevado Sara Sara, the northernmost Pleistocene composite volcano in the Central Andes, is considered as potentially active, but no Holocene deposits have been dated so far. The most recent lava flows on its east flank have been dated by us between c. 146 and 20 ka.

2.2. Quasi-steady eruptive activity after 2.27 Ma

We argue that the eruptive activity was quasi-steady after 2.27 Ma. Lava flows of that age in Río Ocoña, probably sourced at Nevado Solimana, were immediately followed by 2.09–1.8 Ma Upper Sencca ignimbrites. In South Peru, ubiquitous Upper Sencca ignimbrites encompass a collection of flow units between c. 2.20 Ma (Río Colca) and c. 1.62 Ma (Arequipa Airport ignimbrite: Paquereau-Lebti et al. 2008). The lowermost lava flows of the eroded Quaternary volcanoes overlie the top Lomas deposits (c. 1.36 Ma) indicating almost no lull until the growth of the next generation of Pleistocene volcanoes (≤ 1.3 –0.6 Ma). In the Arequipa region, PDC deposits of c. 1.41 Ma overlie the upper unit of the Arequipa Airport Ignimbrite. The quasi contemporary Capillune Formation has been geochemically correlated with the Yura tuffs c. 1.02 Ma (Paquereau-Lebti et al. 2008). In the north OCM region, Capilla is one of the youngest inflow ignimbrites, dated at 0.91 Ma in the Huarcaya caldera. These Early to Middle Pleistocene ignimbrites clearly post-date the Upper Sencca ignimbrite and pre-date large volcanic complexes (e.g., Chachani) and active composite volcanoes (<0.8–0.6 Ma; base of Misti, Sabancaya and Ubinas). After 0.7 Ma, abundant monogenetic cones (e.g., the AuquiHuato cone with lava flows of 11 km length north of Oyolo town) and lava fields coexisted with composite cones (Fig. 2). Unglaciated mafic lava flows erupted near calderas during the Holocene, such as one 6 km south of the Arcata rim. Monogenetic fields such as the Orcopampa–Andahua–Huambo field 30 km east of the OCM region (Delacour et al. 2007) are associated with deep-seated faults or calderas.

2.3. Revised time constraints on volcanic history

Our chronology of OCM Neogene and Quaternary ignimbrites and lava flows together with correlations across SW Peru help revise the formation nomenclature used in INGEMMET maps and in the synthesis by Mamani et al. (2010) (Fig. 2). This leads to a complex volcanic history that intertwines ignimbrites, composite cone ranges and monogenetic fields.

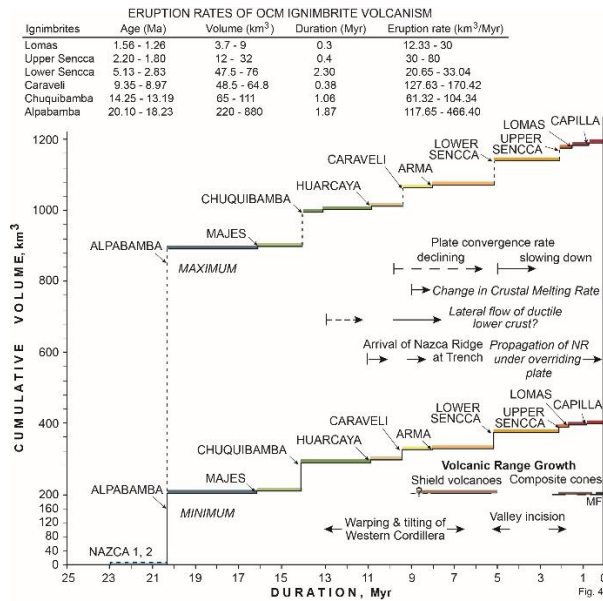


Fig. 4 – Cumulative eruptive volumes of OCM ignimbrite v. time. Maximum and minimum cumulative curves are based on liberal and conservative estimates of thicknesses and original areas of the mapped units (Fig. 1). Bulk volumes are underestimated because of erosion, burial of older units and the unknown extent of large sheets offshore. Timing of three volcanic ranges growth is shown together with processes that may explain the apparent decline in ignimbrite production after 9 Ma. MF: monogenetic field.

The ⁴⁰Ar/³⁹Ar and U/Pb age determinations and correlations (Figs. 2 and 4) are the basis for the statistical analysis of ignimbrite recurrence. Figure 5 proposes a chronostratigraphic nomenclature of six main stages linked with the evolution of the Western Cordillera in the south Peruvian Central Andes (Thouret et al., 2017).

3. Implications for the evolution of the Western Cordillera

The volcanic products can be used as tools for reconstructing the geomorphological evolution of the western flank of the Central Andes over the past 25 Myr. The Neogene to Quaternary volcanic history produced composite cone ranges, ignimbrites and monogenetic fields, and coincided with surface uplift and interfered with valley incision (Fig. 5; Thouret et al., 2007, 2017).

The data suggests: 1. Uplift was gradual over the past 25 Myr, but it accelerated after c. 9 Ma. Valley incision started around 11–9 Ma and accelerated between 5 and 4 Ma. Incision was followed by several pulses of valley cut-and-fill after 2.3 Ma.

2. A post-5 Ma sequence of accelerated canyon incision probably resulted from a combination of drainage piracy from the Cordilleran divide toward the Altiplano, an accentuated flexural tilting of the Western Cordillera toward the SE, and increased

rainfall on the Altiplano after late Miocene uplift of the Eastern Cordillera.

3. Debris avalanches were likely triggered by valley deepening and slope steepening. Large Pleistocene to Holocene landslides decreased rates of incision by periodically obstructing the canyons. As a result, channel aggradation has prevailed in the lower-gradient, U-shaped Pacific-rim canyons, whereas re-incision through landslide deposits has occurred more rapidly across the steeper V-shaped, upper valleys. Existing canyon knickpoints are currently arrested at the boundary between the plutonic bedrock and widespread outcrops of middle Miocene ignimbritic caprock, where groundwater sapping favouring rock collapse may be the dominant process driving headward erosion.

Conclusions

1. A set of 74 ⁴⁰Ar/³⁹Ar and U/Pb age determinations together with lithofacies analysis and mapping allowed us to refine the volcanic stratigraphy and history of the Central Andes in Southern Peru. In the OCM region, 12 ignimbrite sheets and PDC deposits have been emplaced every 1.9 Myr on average over the past c. 25 Myr: Nazca 1 and 2, Alpabamba, Majes, Chuquibamba, Huarcaya, Caraveli, Arma, Lower Sencca, Upper Sencca, Las Lomas and Capilla. Additional ignimbrites between c. 30 and 2.7 Ma identified in the adjacent Orcopampa region east of OCM support the fact that pyroclastic activity became more sustained while the Cordillera uplift was taking place. No significant (>0.6 Myr) break occurred after 5 Ma. Instead, quasi-continuous volcanism produced three generations of composite

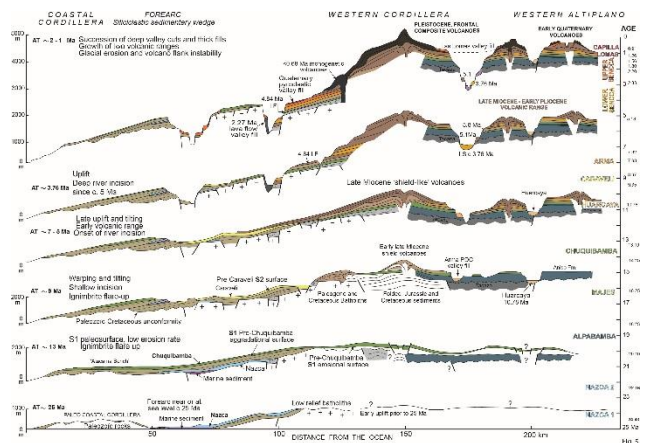


Fig. 5 – Composite, N-S trending cross-sections of the OCM region reconstruct the 25 Myr history of rock uplift, volcano growth and river incision in the western Central Andes, SW Peru. Six time snapshots (c. 25, 13, 9, 7.3, 3.76 and 2-4 Ma) depict a complex history of cross-cutting erosional and other land surfaces, plateau and valley ignimbrites, and valley cut-and-fill involving pyroclastic deposits or lava flows.

volcanoes with four intercalated ignimbrite sheets and PDC deposits, and Pleistocene monogenetic fields.

2. Minimum bulk volumes of c. 400–1200 km³ for ignimbrites emplaced over 25 Myr in the OCM region represent a minimum average volume output of c. 17–50 km³ myr⁻¹. Repeated pulses or ‘flare-ups’ of ignimbrites occurred on average every 2–3.8 Myr between 24.5 and 9.0 Ma. In contrast, quasi-continuous volcanism after 5 Ma produced four smaller ignimbrite sheets and PDC deposits. As a result, the ignimbrite production rate decreased markedly after 9 Ma (from c. 127–171 to c. 12–76 km³ Myr⁻¹). Output became less punctuated after 5 Ma when repose time decreased to 0.85 Myr. The two Early Quaternary and Pleistocene volcano ranges have added more bulk volume (c. 120 km³, i.e. c. 53 km³ myr⁻¹) than the 29.5–46 km³ of ignimbrites after 2.27 Ma. Estimated linear magma output has, however, apparently decreased twofold, 0.15–0.08 km³ myr⁻¹, from the Early Quaternary to the Pleistocene volcano range.

3. We attribute the change in ignimbrite production between 9 and 5 Ma to declining crustal melting. This change coincided with the arrival of the Nazca Ridge at the trench at 5.9 Ma and flat subduction under the overriding South America plate thereafter (Hampel 2002), and with the steady decline of the convergence rate after 10 Ma. Although the interplay of slower plate convergence rate with magma recharge or stagnation in the crust must be considered, the mechanisms that drove changes in crustal melting after 9 Ma remain to be addressed. However, the ignimbrite record together with lava flows can be used as proxies to reconstruct the surface uplift and incision history of the west Central Andes over the past 25 Myr.

4. Following punctuated flare-ups between 25 and 9 Ma during uplift of the Western Cordillera, numerous smaller ignimbrites were emplaced after 9 Ma as the ignimbrite production rate decreased threefold. This decrease may be due to the declining crustal melting rate, decreasing plate convergence rate after 9 Ma, or more magma stagnation in the shallow crust, which promoted the growth of composite cones. Growth of two volcanic arcs has added twice as much volume (c. 53 km³ Ma⁻¹) to the Río Ocoña–Cotahuasi–Marán volcanic field than the ignimbrites after 2.27 Ma.

5. The chronostratigraphic data, which includes marine and volcanic rocks, documents a protracted period ~25 Myr of surface uplift punctuated by at least one pulse of acceleration during the late Miocene to early Pliocene. Valley downcutting began soon after 11 Ma across the western margin of the Central Andes in Peru, but 80% of the total river incision observed today was achieved by c. 4 Ma. The canyons are thus predominantly late Cenozoic

landforms but went through periods of partial fill and re-incision during the Quaternary.

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