Polycyclic scoria cones of the Antofagasta de la Sierra basin, Southern Puna plateau, Argentina

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Abstract: Despite a number of published papers focusing on the geodynamic implications of the recent Southern Puna mafic magmatism, there have been fewer studies of the volcanology and stratigraphy of this outstanding volcanism. This paper presents a detailed map of two well-preserved Quaternary scoria cones showing their complex stratigraphy. Complementary morpho-structural, petrographic and geochemical data were used to reconstruct the evolution of both volcanoes. The occurrence of more than one eruption at each volcano was inferred by the recognition of temporal hiatuses using morpho-stratigraphic criteria. The polycyclic nature of both scoria cones could be related to a combination of a high input magma in response to lithospheric delamination, a favourable regional stress field and the interaction of rising magma with pre-existing faults. The youngest eruptions in both volcanoes were complex, with shifts in the eruptive style from violent strombolian to hawaiian/strombolian phases, and probably lasted for a few years. The explosive activity was accompanied by the emission of lava flows from lateral vents. Phreatomagmatic activity was triggered during the waning stages of the eruptions. The occurrence of more than one eruption in a single scoria cone and the changes in the eruptive style during long-lasting eruptions are important topics for volcanic hazard assessment in the Southern Puna.

Scoria cones are small monogenetic volcanoes produced during eruptions with a broad spectrum of eruptive styles, including strombolian, violent strombolian, hawaiian and phreatomagmatic. Mono-genetic scoria cones are characterized by eruptions lasting from days and months to several years, involving discrete, small-volume magma batches and associated with dispersed plumbing networks (Vesprmann & Schmincke 2000). Scoria cones typically occur as fields of small volcanoes together with other monogenetic volcanic structures, such as maars, tuff rings and lava domes (Connor & Conway 2000; Németh 2010) and are usually controlled by the regional tectonic setting (e.g. Lesti et al. 2008; Pardo et al. 2009). In contrast, poly-genetic volcanoes are characterized by more complex plumbing systems, including the development of relatively large magma chambers in the upper crust. Thus, polygenetic volcanoes show complex patterns of compositional variations, higher magma extrusion rates and long-lived volcanic activity (kyr to myr) consisting of periods of quiescence and erosion (Walker 2000). However, some studies carried out in different geological settings suggest that many scoria cones and maars may actually involve multiple eruptions separated by tens to hundreds of thousands of years with geochemical variations (e.g. Turrin & Renne 1987; Renault et al. 1988; Wells et al. 1990; Bradshaw & Smith 1994; McKnight & Williams 1997; De Benedetti et al. 2008; Sheth et al. 2009; Keresztiuri et al. 2010; Needham et al. 2011; Sheth 2014). In an attempt to clarify this paradoxical situation, Németh & Kereszturi (2015) proposed a new definition for a monogenetic volcano: a volcanic edifice with a small cumulative volume (typically \( \leq 1 \text{ km}^3 \)) that has been built up by one continuous, or many discontinuous, small eruptions occurring over a short timescale (typically \( \leq 10 \) years) and fed from one or multiple magma batches through a relatively
simple, closely spaced feeder dyke (and sill) system with no associated well-developed magma chamber. In addition, Németh & Kereszturi (2015) indicated the existence of departures from the monogenetic volcanoes sensu stricto that create a nearly continuous spectrum to the polygenetic volcanoes sensu stricto. One type of ‘transitional’ volcano is the polycyclic monogenetic volcano (Kereszturi et al. 2010; Németh & Kereszturi 2015). Such volcanoes are formed by multiple and complex eruptive episodes with small volumes of magma and separated by time gaps from thousands to millions of years. Thus the resultant volcanic structures show a complex facies architecture, but morphologically resemble the small-volume volcanoes traditionally defined as monogenetic (Németh & Kereszturi 2015).

The Southern Puna plateau of Argentina differs from the rest of the Andean Central Volcanic Zone (CVZ) as a result of the abundance of late Miocene and younger small mafic (basaltic andesite) back-arc volcanic centres (Viramonte et al. 1984; Kay et al. 1994; Risse et al. 2008; Viramonte et al. 2010). The presence of this mafic volcanism in the Southern Puna plateau is one of the main arguments supporting late Cenozoic lithospheric delamination beneath this region (Kay et al. 1994; Whitman et al. 1996). Despite the publication of several papers focused on both the petrogenesis and geodynamic implications of this outstanding magmatism (Knox et al. 1989; Kay et al. 1994; Risse et al. 2008, 2013; Drew et al. 2009; Ducea et al. 2013; Murray et al. 2015), the stratigraphy of each volcanic centre and its physical volcanology remains poorly studied. The main aim of this paper is to contribute to a better volcanological knowledge of the mafic volcanism in the back-arc region of the Southern Puna plateau by performing a detailed study of the stratigraphy and geological evolution of two Quaternary scoria cones located in the Antofagasta de la Sierra basin: the Alumbra and De La Laguna (also called Antofagasta) volcanoes. The stratigraphic criterion in the field survey and geological mapping was the identification of lithostratigraphic units, including their distribution and stratigraphic relationships. Although no absolute age is available, some hiatuses in the stratigraphic succession were recognized by significant variations in the degree of erosion of each mapped unit. Complementary morphometric, morpho-structural, petrographic and geochemical data were used to reconstruct the evolution of the two volcanoes. The polycyclic nature of both volcanoes and the factors controlling the variations in the eruptive style during a single eruption are discussed and compared with other mafic volcanic centres of the Southern Puna plateau and similar well-known historical eruptions worldwide.

Geological setting

The Miocene–Quaternary volcanic activity in the Altiplano-Puna plateau originated the Andean CVZ (ACVZ) (Fig. 1). A north–south volcanic arc has developed since Neogene times, initially along the Maricunga belts and finally stabilized 50 km to the west in the present day volcanic arc (Western Cordillera) (Kay & Coira 2009; Guzmán et al. 2014). The eastwards broadening of arc magmatism along regional NW–SE vertical strike-slip fault systems can be explained by shallowing of the subducting slab (Viramonte et al. 1984; Viramonte & Petrinovic 1990; Petrinovic et al. 1999; Riller et al. 2001; Trumbull et al. 2006). The orogen-parallel thrust faults also played an important part in focusing the arrest of hydrofractures, the formation of magma chambers and the emplacement of polygenetic volcanoes in the back-arc region (Norini et al. 2013). Major changes in the magmatic and deformational style in the Southern Puna back-arc region began at 7 Ma (Marret et al. 1994; Kay & Coira 2009; Montero López et al. 2010; Guzmán et al. 2014). A shift from a purely contractual to a mixed stress regime with normal, strike-slip and thrust faults, and the eruption of both mafic (basaltic andesite) lavas and the dacitic ignimbrites from Cerro Galán Caldera are considered as superficial evidence supporting the delamination model proposed by Kay et al. (1994) for this portion of the Central Andes. There are currently two different models that are used to explain the lithospheric delamination below the Southern Puna using the geochemical features of mafic lavas. The first model suggests that the mafic magmas were generated from a relatively homogeneous asthenospheric mantle peridotite that upwelled adiabatically and melted in the wake of a large foundering block of lower lithosphere (Kay et al. 1994; Risse et al. 2013). The second model proposes that it is not necessary to catastrophically founder large volumes of lithosphere to generate the Puna mafic magmas, but that the small-scale dripping and melting of heterogeneous dense lower lithospheric blocks (pyroxenites) are the source of these magmas (Drew et al. 2009; Ducea et al. 2013; Murray et al. 2015).

The Southern Puna back-arc mafic volcanism consists of numerous scoria cones, lava domes, lava flows, tuff rings and maars grouped in small volcanic fields, one of them located in the Antofagasta de la Sierra Basin (ASB) (Fig. 1). The ASB is a north–south-trending, thrust fault-bounded, intramontane depression. This tectonic depression is closed to the north by the Neogene volcanic chain Archibarca-Galán (Viramonte et al. 1984; Kay & Coira 2009) and has a floor that dips gently southwards. The sedimentary basin infill is represented by Neogene–Quaternary continental sequences.
and Miocene ignimbrites from the Cerro Galán Caldera (Folkes et al. 2011 and references cited therein). The onset of mafic volcanism within the ASB occurred at c. 7 Ma (Risse et al. 2008) and has probably been active until Holocene times (De Silva & Francis 1991). The youngest scoria cones in the region are located in the middle of the ASB: the Alumbrera and De La Laguna volcanoes. There is only one radiometric age available for these volcanoes, determined in a lava flow associated with the De La Laguna Volcano (0.34 ± 0.06 Ma, groundmass 40Ar/39Ar age; Risse et al. 2008) and there is no report of an historical eruption.

Interplay of morphometry and volcanotectonics

Morphological and morphometric studies of scoria cones provide insights into cone growth, degradation and relative age (Wood 1980a, b; Hase-naka & Carmichael 1985; Martin & Németh 2006; Inbar et al. 2011) and the geometry of the magma-feeding fractures (e.g. Tibaldi 1995; Corazzato & Tibaldi 2006; Lesti et al. 2008). A morphometric analysis was performed in a geographical information system environment by integrating data extracted from high-resolution optical images from Google Earth (cone area, cone major diameter, crater major diameter, maximum crater elongation azimuth, cone and lava flow fields areas), direct field measurements (cone height, crater depth, lava flow thickness), trigonometric equations (cone slope) and simple geometrical equations (cone and lava flow volumes). In addition, the degree of crater ellipticity and degree of cone ellipticity were calculated using the spatial statistics tools of ArcGIS 9.3 software. Morphometric parameters and the estimated volumes of erupted products of the Alumbrera and De...
La Laguna volcanoes are shown in Table 1. The volume of the tephra blanket was not estimated and a DRE correction was not performed. Thus, the volume estimate for each volcano is a minimum bulk volume. A more reliable estimation of the magma volumes issued from both volcanoes requires the use of more accurate methods, such as DSM/DTM/DEM-based volumetric estimates that include pre-eruptive surface constraint and DRE correction (e.g., Kereszturi et al. 2013).

The Alumbrera cone rises 164 m above the floor of the ASB and has an elliptical morphology in plan view (degree of cone ellipticity 1.4), with the maximum elongation oriented N146° and a maximum cone diameter of 1.3 km (Fig. 2a, c). The Alumbrera cone has a volume of 0.12 km³ and an asymmetrical profile, which is possibly associated with the direction of the prevailing winds during the eruption (Fig. 2c). The crater has an elliptical morphology (degree of crater ellipticity 1.2) with a maximum elongation oriented N143° (Fig. 2a) and is 50 m deep. The crater border exhibits an irregular topography with an average altitude of c. 3575 m a.s.l. and the highest elevations in the SE sector (3603 m a.s.l.) (Fig. 2a). In addition to the principal crater, three NW–SE-trending eruptive fissures were mapped (Fig. 2a, e). The orientation of the eruptive fissures plus the directions of the maximum crater and cone elongation axes suggest that the magma-feeding fractures are oriented NW–SE. At the summit of the volcano there is a series of sub-vertical inwards- and outwards-dipping arched faults related to the gravitational instability of the cone. A collapse scarp affecting only the external layers of the cone was identified on the NW flank of the volcano (Fig. 2f). This morphology is not a partial rebuild of a previous horseshoe-shaped collapse (e.g., Németh et al. 2011). The internal surface exposed by the collapse shows a high degree of hydrothermal alteration. The lava flows associated with the Alumbrera scoria cone cover an area of 41.3 km², have a bulk volume of 0.29 km³ and display the spatial distribution of all the lithostratigraphic units described and defined in the field. Temporal hiatuses into the sequence are identified by significant variations in the degree of wind erosion (Figs 5–7) using a relative scale based on direct field observations, the validity of which for relative dating is discussed later in this paper. This qualitative scale includes three levels of erosion (high, moderate and incipient) with respect to ventifact development. In this paper, the term ventifact is used according to the definition proposed by Knight (2008), meaning clasts or bedrock surfaces that have been abraded by the action of wind-blown particles.

The highly eroded units have a homogeneous, light grey, smooth polished surface with well-developed wind-parallel grooves (Figs 5a, b, 6c, f & 7b) regardless of their original surface morphology (e.g., toothpaste and aa lava flows, or scoria and bomb deposits). Some bombs present several opposing facets.

The moderately eroded units have a dark grey colour and preserve much of the original surface morphology. However, on close inspection, surface polishing with a light-reflecting shine is evidenced, particularly in the less vesiculated sector of each unit (Figs 6a, b & 7a). In contrast with the highly
Table 1. Morphometric parameters of the Alumbreña and De La Laguna volcanoes

<table>
<thead>
<tr>
<th>Volcano</th>
<th>Aco (km$^2$)</th>
<th>Sco (°)</th>
<th>Wbco (km)</th>
<th>Hco (m)</th>
<th>Wbcr (km)</th>
<th>Hcr (m)</th>
<th>DCoE</th>
<th>DCoE</th>
<th>MCtEA</th>
<th>MCoEA</th>
<th>V (km$^3$)</th>
<th>A (km$^2$)</th>
<th>V (km$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alumbreña</td>
<td>0.9788117681</td>
<td>32</td>
<td>1.31</td>
<td>164</td>
<td>0.41</td>
<td>49.5</td>
<td>1.2</td>
<td>1.4</td>
<td>143</td>
<td>146</td>
<td>0.1256072228</td>
<td>41.35</td>
<td>0.2894188654</td>
</tr>
<tr>
<td>de La Laguna</td>
<td>0.7966363322</td>
<td>29</td>
<td>1.07</td>
<td>153</td>
<td>0.33</td>
<td>23.5</td>
<td>1.1</td>
<td>1.3</td>
<td>n.d</td>
<td>131</td>
<td>0.0774486561</td>
<td>6.80</td>
<td>0.1087264688</td>
</tr>
</tbody>
</table>

A, area; Aco, cone area; DCoE, degree of cone ellipticity; DCoE, degree of crater ellipticity; Hco, cone height; Hcr, crater depth; MCtEA, maximum crater elongation azimuth; MCoEA, maximum cone elongation azimuth; Sco, cone slope; V, volume; Wbco, cone major diameter; Wbcr, crater major diameter.
eroded units, no wind-parallel groove or facet is present.

The incipiently to uneroded units have a black colour and preserve all the original surface morphology (Fig. 5c), including delicate features such as small spines on the top of the toothpaste lava flows (Fig. 5d). An incipient surface polishing is present only in sectors highly exposed to wind action and characterized by a non-vesicular lithology (e.g. lava flow edges and bombs along the crater border).

Fig. 2. Photographs showing principal morphological and morphometric features of the (a) Alumbrera and (b) De La Laguna volcanoes. Ellipses, calculated theoretical ellipticity of the cones and craters; solid fine lines, direction of maximum elongation of the cones and craters; solid thick lines, eruptive fissure and inferred eruptive fissure; dotted line, collapse scarp. (c, d) SE–NW profiles of both volcanoes showing their asymmetry. (e) NW flank collapse of the Alumbrera Volcano. (f) Dyke intruding along a SW-trending eruptive fissure.
Alumbrera morpho-stratigraphy

Following these geomorphological criteria, the stratigraphic sequence of the Alumbrera Volcano has been subdivided in older and younger units. The oldest units, which present high to moderate levels of wind erosion, are grouped into the Palaeo Alumbrera Volcano (PAV) units. Differences in the degree of erosion in the PAV units suggest temporary hiatuses between them, but the qualitative criteria used in this paper cannot definitely resolve the length of the temporal gaps in the sequence. The youngest units that are incipient to uneroded are grouped into the Neo-Alumbrera Volcano (NAV) and were probably formed without significant temporal gaps between them.

Fig. 3. Morpho-structural analysis of the study area: (a) manual analysis; (b) semi-automatic analysis; and (c) rose diagrams showing the main directions of the major tectonic features in the study area and their relationship with the inferred magma-feeding system of the Alumbrera and De La Laguna volcanoes.
De La Laguna morpho-stratigraphy

In the same way, the stratigraphic sequence of the De La Laguna Volcano has been divided into the Paleo De La Laguna Volcano (PDLV) grouping the oldest, highly eroded units and the Neo De La Laguna Volcano (NDLV) grouping the youngest, moderately eroded units. As in the PAV, differences in the degree of erosion in the PDLV units could be related to temporal hiatuses that are not possible to define with the methodology applied here.

Fig. 4. Geological map and stratigraphy of the Alumbrera and De La Laguna volcanoes.
Lithostratigraphy and lithofacies architecture

We present here a systematic description of all the lithostratigraphic units mapped during fieldwork. A brief geochemical and petrographic characterization of each unit is also given (Fig. 8a–f). The volcanic products were classified following the criteria used by Murray et al. (2015) for the geochemical classification of the Southern Puna mafic lavas (Fig. 8a, b, Table 2). The percentages of phenocrysts and matrix components are visual estimates aided by abundance charts.

Palaeo Alumbrera Volcano

**AL1 unit.** The stratigraphic sequence of the Alumbrera Volcano starts with a series of highly eroded compound toothpaste lava flows outcropping north-eastwards and southeastwards from the cone. These lava flows are grey in colour and are 2–3 m thick (Fig. 5a, b). The AL1 lava flows are alkaline basaltic trachyandesites with Mg# < 60 and MgO < 7 wt% (evolved, Fig. 8a, b). In thin section they have a porphyritic texture with olivine (c. 15%) and plagioclase (c. 15%) phenocrysts up to 0.5–1 mm in size in a hyalopilitic groundmass of olivine (c. 10%) and plagioclase microlites (c. 30%), opaque oxides (c. 2%) and glass (c. 25%).

**AL2 unit.** The AL1 unit is covered by a series of moderately eroded aa lava flows, which form the AL2 unit. These aa lavas were extruded from the NE eruptive fissure and are restricted to the eastern sector of the study area (Fig. 6). These aa lava flows are reddish brown in colour, 2–6 m thick and preserve typical rough surfaces and morphologies such as channels limited by levees and pressure ridges. The AL2 lavas are subalkaline basaltic trachyandesites with Mg# > 60 and MgO < 8 wt% (primitive, Fig. 8a, b). Microscopically, they have a porphyritic texture with olivine (c. 25%) and clinopyroxene (c. 5%) phenocrysts up to 1–2.5 mm in size in an intergranular groundmass of clinopyroxene (c. 15%), olivine (c. 10%), plagioclase microlites (c. 35%) and opaque oxides (c. 10%). The groundmass commonly shows fluidal structures around the phenocrysts.

Fig. 5. Photographs showing similarities in morphology and texture (toothpaste lava flow) for the Alumbrera Volcano units. (a, b) AL1 unit showing higher degree of ventifact formation compared with (c, d) AL11 unit.
**AL3 unit.** At the margin of the NE eruptive fissures, a poorly sorted, moderately eroded, non-welded fluidal bomb and scoria lapilli deposit crops out (AL3 unit, Fig. 4). The pyroclasts of the AL3 unit have similar petrographic features to the AL2 unit.

**Neo-Alumbrera Volcano**

**AL4 unit.** The NAV stratigraphic sequence starts with the AL4 unit, which constitutes a toothpaste compound lava flow field erupted from the NE eruptive fissure (Fig. 4) and shows incipient wind erosion features. The AL4 lavas are black in colour, have thicknesses ranging from 3 to 20 m and are formed of primary lava lobes and innumerable secondary toothpaste lava tongues. Many of them consist of ‘slab pahoehoe’ derived from mobilization and break-up of toothpaste lava tongues (Peterson & Tilling 1980; Rowland & Walker 1987). The AL4 lava flow field is partially covered by a

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**Fig. 6.** Photographs showing (a, b) moderately eroded lava flows and (c–f) highly eroded lava flows in the De La Laguna Volcano. Note the development of wind-parallel grooves in the highly eroded lava flows (DLL1 and DLL3).
fallout blanket (AL6 unit) and by dilute pyroclastic density current deposits (AL10 unit). The AL4 lava flows have similar petrographic features to the AL1 unit.

AL5 unit. This unit represents the external portion of the scoria cone and is formed by beds, typically 0.1–0.5 m thick, composed of non-welded relatively well-sorted, highly vesicular scoria lapilli to coarse ash and minor fluidal bomb deposits (Fig. 9a). The AL5 unit is interpreted as proximal fallout deposits. The pyroclasts of the AL5 unit are alkaline basaltic trachyandesites with Mg# < 60 and MgO < 7 wt% (evolved, Fig. 8a, b). Under the microscope they have a porphyritic texture with olivine (c. 7%) and plagioclase (c. 3%) phenocrysts up to 0.5–1.5 mm in size in a highly vesiculated (c. 70%) hyalopilitic groundmass of olivine (c. 3%) and plagioclase microlites (c. 6%), opaque oxides (c. 1%) and glass (c. 10%) (Fig. 8d).

AL6 unit. A well-sorted, clast-supported, open framework, massive to planar-stratified scoria lapilli to ash deposit (Fig. 9b) was mapped beyond the cone (as much as 15 km from the vent towards the east). The top of the deposit shows the incipient development of a mega-ripple surface morphology as a result of reworking by wind. The AL6 unit is internally stratified with alternations in grain size throughout the deposit and individual layers ranging from 0.03 to 0.12 m in thickness. The thickness of the whole deposit ranges from 1.6 m (1.5 km from the vent) to 0.4 m (3.5 km from the vent). In the more distal zones the deposit is fully reworked. The AL6 unit is interpreted as a fallout deposit. The pyroclasts of the AL6 unit are subalkaline trachybasalts with Mg# > 60 and MgO > 8 wt% (high Mg, Fig. 8a, b). In thin section, they have a porphyritic texture with olivine phenocrysts (c. 5%) up to 0.5 mm in size in a highly vesiculated (c. 80%) hyalopilitic groundmass of small (<0.03 mm) olivine (c. 1%) and plagioclase microlites (c. 4%), and glass (c. 10%) (Fig. 8f).

AL7 unit. A deposit with a hummocky morphology and a thickness of 10–15 m was mapped at the NW base of the cone (Fig. 9c). Internally, the deposit preserves a weak subvertical stratification and is formed by scoria lapilli and minor fluidal bombs similar to the AL5 unit. The AL7 unit is poorly exposed as it is overlain by the youngest lava flows (AL11 unit) and it is very likely that it covers most of the original deposit, which is interpreted as a debris avalanche associated with the collapse scarp on the NW flank of the Alumbrera Volcano. The pyroclasts of the AL7 unit have similar macroscopic and petrographic features to the AL5 unit.

AL8 unit. The stratigraphic sequence continues with a partly welded deposit consisting mainly of spatter and minor fluidal bombs. This unit covers part of the inner walls of the crater and shows a crude bedding dipping inwards towards the crater (Fig. 9d). The AL8 unit is interpreted as a proximal fall deposit associated with a lava fountain. The spatters and bombs of the AL8 unit are alkaline basaltic trachyandesites with Mg## < 60 and MgO < 7 wt% (evolved, Fig. 8a, b). Microscopically, they have a porphyritic texture with olivine (c. 20%) and plagioclase (c. 10%) phenocrysts up to 1–2 mm in size in a hyalopilitic groundmass of olivine (c. 10%) and plagioclase microlites (c. 25%), opaque oxides (c. 5%) and glass (c. 30%) (Fig. 8c).

AL9 unit. Around the crater rim, a great quantity of vesicle-poor fluidal bombs up to 3 m in maximum diameter overlie the AL8 unit (Fig. 9e). Some coarse bombs rolled down the cone slopes and were
deposited in the cone flanks and base, including the surface exposed by the partial collapse scarp. The AL9 unit is interpreted as a proximal strombolian deposit emplaced following ballistic trajectories. The bombs of the AL9 unit have similar petrographic features to the AL8 unit.

Fig. 8. (a) Total alkalis vs SiO$_2$ (wt%) diagram showing rock classification fields after Le Bas et al. (1986). (b) Geochemical classification of samples from this study based on wt% MgO and magnesium number, after Murray et al. (2015). NAV, Neo-Alumbrera Volcano; NDLV, Neo De La Laguna Volcano; PAV, Palaeo Alumbrera Volcano; PDLV, Palaeo De La Laguna Volcano. (c–f) Representative microphotographs showing typical rock textures of the (c, d) evolved, (e) primitive and (f) high magnesium geochemical groups. Cpx, clinopyroxene; Ol, olivine; Pl, plagioclase; V, vesicle. Note the similar microlite percentage in (e) the poorly vesiculated spatter deposit from the AL8 unit and in the highly vesiculated scoria from the (d) AL5 and (f) AL6 units.
Table 2. Whole-rock composition of samples from the Alumbrera and De La Laguna volcanoes

<table>
<thead>
<tr>
<th>Sample</th>
<th>Unit</th>
<th>Location</th>
<th>Type*</th>
<th>SiO$_2$</th>
<th>TiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>Fe$_2$O$_3$</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na$_2$O</th>
<th>K$_2$O</th>
<th>P$_2$O$_5$</th>
<th>LOI</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td>ANT-06</td>
<td>DLL5</td>
<td>26.133694' S 67.410333'' W</td>
<td>Primitive</td>
<td>53.83</td>
<td>1.51</td>
<td>15.74</td>
<td>8.69</td>
<td>0.14</td>
<td>7.12</td>
<td>6.85</td>
<td>3.43</td>
<td>2.33</td>
<td>0.37</td>
<td>0.06</td>
<td>99.92</td>
</tr>
<tr>
<td>ANT-07</td>
<td>DLL3</td>
<td>26.129389' S 67.417444'' W</td>
<td>Primitive</td>
<td>53.92</td>
<td>1.39</td>
<td>16.14</td>
<td>8.63</td>
<td>0.13</td>
<td>7.22</td>
<td>7.04</td>
<td>3.31</td>
<td>2.14</td>
<td>0.32</td>
<td>0.08</td>
<td>100.18</td>
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<tr>
<td>ANT-36</td>
<td>DLL1</td>
<td>26.131738' S 67.421698'' W</td>
<td>Evolved</td>
<td>52.19</td>
<td>2.09</td>
<td>16.06</td>
<td>9.20</td>
<td>0.13</td>
<td>6.22</td>
<td>6.74</td>
<td>3.66</td>
<td>2.64</td>
<td>0.50</td>
<td>0.68</td>
<td>99.96</td>
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<td>DLL2</td>
<td>26.139536' S 67.419429'' W</td>
<td>Primitive</td>
<td>53.58</td>
<td>1.40</td>
<td>16.08</td>
<td>8.43</td>
<td>0.13</td>
<td>6.84</td>
<td>6.96</td>
<td>3.41</td>
<td>2.23</td>
<td>0.32</td>
<td>0.69</td>
<td>99.92</td>
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<tr>
<td>ANT-41C</td>
<td>DLL3</td>
<td>26.139345' S 67.418706'' W</td>
<td>Primitive</td>
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<td>1.42</td>
<td>16.23</td>
<td>8.50</td>
<td>0.14</td>
<td>6.94</td>
<td>6.90</td>
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Oxides in wt% by X-ray fluorescence spectrometry. *Classification for the Southern Puna mafic lavas proposed by Murray et al. (2015).
**AL10 unit.** In the summit region of the Alumbrera Volcano, a 4 m thick, non-welded, well-sorted, planar to cross-stratified lapilli and minor ash deposit crops out (Fig. 9f). U-shaped erosional channels within the sequence and bombs (10–30 cm) without basal sag structures are present. The deposit shows a high degree of hydrothermal alteration, which gives a yellowish colour. The AL10 unit reaches 0.5 km beyond the cone and covers the fluidal bombs of the AL9 unit. In the distal facies, the AL10 unit is a reddish, well-sorted, ash–lapilli deposit with planar to low-angle cross-stratification. The AL10 unit is interpreted as a product of dilute pyroclastic density currents. The high degree of hydrothermal
alteration in the AL10 unit hindered its geochemical and petrographic characterization.

**AL11 unit.** The youngest unit of the NAV stratigraphy is a compound toothpaste lava flow field with incipient wind erosion features (Fig. 5c, d). The AL11 unit was issued from many vents along the SW and central eruptive fissures and it constitutes the biggest lava flow field in the study area. The AL11 lava flows are black in colour and have thicknesses ranging from 3 to 40 m. The AL11 lava flow field was divided into two morphological domains. In the western sector the lava flow field fails to spread out as a result of lateral topographic confinement. Consequently, the lava flows exhibit a ‘slab pahoehoe’ morphology and develop very large elongate tumuli (e.g. Glaze et al. 2005; Orr et al. 2015) reaching 800 m in length and 200 m in width (e.g. 26.16248° W 67.41306° S). By contrast, the eastern sector of the lava flow field expanded to the south along the gentle regional slope. As a result, the lava flows have smooth surfaces and preserve the primary toothpaste lava lobe morphology, reaching 600 m in length and 50 m in width (e.g. 26.185114° W 67.385285° S) and innumerable secondary toothpaste lava tongues. Lava tubes and associated pit craters are also present. The AL11 unit has complex stratigraphic relationships that vary from one sector to another, suggesting that its formation occurred during most of the eruption. In the SE sector the fallout blanket (AL6 unit) partially covers the AL11 unit. On the western flank of the cone the AL11 unit overlies the collapse deposits (AL7 unit). The presence of large fluidal bombs emplaced above the surface of some of the AL11 lava flows suggests that part of its emission occurred simultaneously with the Strombolian activity of the central crater (AL9 unit). In the NW sector, the AL11 unit covers the AL10 deposit, indicating that the AL11 compound toothpaste lava flow field was active until the end of the eruption. The AL11 lava flows are alkaline basalts trachyandesites with Mg# < 60 and MgO < 7 wt% (evolved, Fig. 8a, b). In thin section they exhibit a porphyritic texture with olivine (c. 20%) and plagioclase (c. 7%) phenocrysts up to 0.7–1 mm in size in a hyalopilitic groundmass of olivine (c. 10%) and plagioclase microlites (c. 30%), opaque oxides (c. 3%) and glass (c. 30%).

**DLL2 unit.** A highly eroded aa lava flow crops out 1.4 km south of the cone (Fig. 4); its stratigraphic relationship with the DLL1 unit is unknown. Despite its field similarities with the DLL1 unit, the DLL2 lava flow consists of subalkaline basaltic trachyandesites with Mg# > 60 and MgO < 8 wt% (primitive, Fig. 8a, b). Microscopically, they have a porphyritic texture with olivine (c. 15%) and clinopyroxene (c. 10%) phenocrysts up to 3–0.5 mm in size in an intergranular groundmass of clinopyroxene (c. 15%), olivine (c. 10%) and plagioclase microlites (c. 45%) and opaque oxides (c. 5%). The groundmass commonly flows around the phenocrysts.

**DLL3 unit.** The DLL1 and DLL2 units are covered by a series of heavily eroded blocky lava flows outcropping south of the cone. These lava flows are grey in colour with thicknesses ranging from 5 to 15 m (Fig. 6e, f). The frontal lava flow lobes have developed axial cracks 1–3 m wide and 20–150 m long. The DLL3 lava flow are subalkaline basaltic trachyandesites with Mg# > 60 and MgO < 8 wt% (primitive, Fig. 8a, b). Microscopically, they exhibit a porphyritic texture with olivine (c. 25%) and clinopyroxene (c. 5%) phenocrysts up to 1–2 mm in size in an intergranular groundmass of clinopyroxene (c. 5%), olivine (c. 20%) and plagioclase microlites (c. 45%).

**DLL4 unit.** A highly eroded blocky lava flow field was mapped north of the cone (Fig. 4). Despite its field similarities with the DLL3 unit, the DLL4 lava flow field consists of subalkaline trachybasalts with Mg# > 60 and MgO > 8 wt% (high Mg, Fig. 8a, b). In thin section they exhibit a porphyritic texture with olivine phenocrysts (c. 20%) up to 1–1.5 mm in size in a hyalopilitic groundmass of olivine (c. 5%) and plagioclase microlites (c. 15%) and glass (c. 60%) (Fig. 8e).

**DLL5 unit.** A highly eroded deposit formed by fluidal massive bombs and angular scoria crops out at the base of the cone and overlies the DLL2 unit (Fig. 7b). This deposit represents a marginal facies of an older cone covered by the growth of the currently visible cone. The pyroclasts of the AL3 unit have similar petrographic features to the AL2 unit.

**Palaeo De La Laguna Volcano**

**DLL1 unit.** The stratigraphic sequence of the De La Laguna Volcano starts with a series of highly eroded aa lava flows (Fig. 6c, d) outcropping in two small areas located 1.6 km north and 1 km SW from the cone. These lava flows are grey in colour and have thicknesses ranging from 2.5 to 4 m. The DLL1 lava flows are alkaline basalts trachyandesites with Mg# < 60 and MgO < 7 wt% (evolved, Fig. 8a, b). In thin section they exhibit a porphyritic texture with olivine (c. 20%) and plagioclase (c. 7%) phenocrysts up to 0.7–1 mm in size in a hyalopilitic groundmass of olivine (c. 10%) and plagioclase microlites (c. 30%), opaque oxides (c. 3%) and glass (c. 30%).
Neo De La Laguna Volcano

DLL6 unit. The external part of the cone is formed by a non-welded, relatively well-sorted, open framework, highly vesicular scoria lapilli with minor fluidal bombs (Fig. 10a, b). The DLL6 unit is interpreted as a fallout deposit. The DLL6 pyroclasts are subalkaline basaltic trachyandesites with Mg# > 60 and MgO < 8 wt% (primitive, Fig. 8a, b). Microscopically, they exhibit a porphyritic texture with olivine (c. 7%) and clinopyroxene (c. 3%) phenocrysts up to 0.7–2 mm in size in a highly vesiculated (c. 65%) intergranular groundmass of clinopyroxene (c. 4%), olivine (c. 1%) and plagioclase microlites (c. 15%).

DLL7 unit. A well-sorted, open framework, massive to planar-stratified scoria lapilli to ash deposit was mapped 1.5 km beyond the cone towards the NE (Fig. 10c) and is interpreted as a fallout deposit. The youngest lava flow issued from the De La Laguna Volcano (DLL11) and Alumbrera Volcano (AL10b unit) covers the DLL7 fallout deposit. The pyroclasts of the DLL7 unit have similar petrographic features to the AL6 unit (Alumbrera Volcano).

DLL8 unit. The crater is largely filled by a partly welded spatter and minor fluid bomb deposit that shows a crude bedding dipping inwards towards the crater (Fig. 10d). The DLL8 unit is interpreted as a hawaiian lava fountain deposit. The DLL8 spatters are subalkaline basaltic trachyandesites with Mg# > 60 and MgO < 8 wt% (primitive, Fig. 8a, b). Microscopically, they exhibit a porphyritic texture with olivine (c. 20%) and clinopyroxene (c. 10%) phenocrysts up to 0.5–1.5 mm in size in an intergranular groundmass of clinopyroxene (c. 20%), olivine (c. 5%) and plagioclase microlites (c. 45%).

DLL9 unit. Around the crater rim, a great quantity of vesicle-poor fluidal bombs up to 4.5 m in maximum diameter overlie the DLL8 unit (Fig. 7a). DLL9 coarse bombs rolled down the cone slopes and were deposited to form a ring around the base. The DLL9 unit is interpreted as a proximal strombolian deposit emplaced following ballistic

![Fig. 10. (a) Well-sorted, open framework, highly vesicular scoria lapilli and minor fluidal bomb deposit of the DLL6 unit. (b) Detail of the DLL6 deposits showing the well-sorted and open framework internal fabric. (c) Stratified fallout deposit of the DLL7 unit. (d) De La Laguna Volcano crater filled by a partly welded spatter deposit and minor fluid bomb deposit (DLL8 unit).](http://sp.lyellcollection.org/)
trajactories. The bombs of the DLL9 unit have similar petrographic features to the DLL8 unit.

**DLL10 unit.** Two small outcrops of a 0.4 m thick, non-welded, well-sorted planar to cross-stratified lapilli and minor ash deposit were mapped at the western and eastern crater rim, respectively (Fig. 4). The DLL10 unit covers the DLL8 and DLL9 units. The DLL10 unit is interpreted as the product of dilute pyroclastic density currents and its high degree of hydrothermal alteration hindered the geochemical and petrographic characterization.

**DLL11 unit.** To the north and west of the cone, an aa lava flow field with a moderate degree of ventifact development was mapped. The DLL11 lavas show rough surfaces and morphologies such as channels limited by levees and pressure ridges (Fig. 6a, b). The DLL11 unit was issued from an eruptive fissure located on the NW cone flank and overlies the DLL1, DLL3, DLL4 and DLL5 units. The DLL11 unit is covered by the youngest lava flows issued from the Alumbrera Volcano (AL11 unit). The DLL11 lava flows are dark grey in colour and have thicknesses ranging from 3 to 12 m. Compositionally, they are subalkaline basaltic trachyandesites with Mg# > 60 and MgO < 8 wt% (primitive, Fig. 5a, b). In thin section they have a porphyritic texture with olivine (c. 20%) and clinopyroxene (c. 15%) phenocrysts up to 0.4–2.5 mm in size in an intergranular groundmass of clinopyroxene (c. 15%), olivine (c. 10%) and plagioclase (c. 40%) microlites.

**DLL12 unit.** A moderately eroded aa lava flow field was mapped south of the cone (Fig. 4). This lava flow field was issued from a secondary vent located 0.5 km from the cone and overlying the DLL1, DLL2 and DLL3 units. The DLL11 unit is covered by the youngest lava flows issued from the Alumbrera Volcano (AL11 unit). The DLL12 lava flows are subalkaline basaltic trachyandesites with Mg# > 60 and MgO < 6 wt% and have similar petrographic features to the DLL11 unit.

**Discussion**

**Polycyclic nature of the Alumbrera and De La Laguna volcanoes**

The stratigraphic reconstruction of the Alumbrera and De La Laguna volcanoes reveals a previously unreported high complexity in the evolution of some Southern Puna scoria cones. The variations in the degree of ventifact development along the stratigraphic sequences suggest that the Alumbrera and De La Laguna volcanoes could have been formed by more than one eruption. Previous work has questioned the use of the stage of degradation of the scoria cones in the Southern Puna region to obtain information about their relative ages (Risse et al. 2008). Nevertheless, considering that the semi-to hyper-arid climatic conditions of the Southern Puna have persisted for several million years (Alonso et al. 2006), it is reasonable to suggest that morphological parameters, such as gully density and the surface morphology of lava flows, can be used to obtain a relative age for mafic volcanic centres (Hasenaka & Carmichael 1985; Dohrenwend et al. 1986; Corazzato & Tibaldi 2006). The formation of ventifacts and the abrasion rate depend on the position of the rock relative to the direction of maximum wind velocity (Bridges et al. 2004). During fieldwork, systematic variations in the degree of wind erosion for each unit were observed regardless its position respect to the main wind direction. On the other hand, the original rock shape affects ventifact formation, with steeper faces abrading faster than shallower faces and rocks with irregular features, such as pits or grooves, abrading at greater rates than rocks with smooth surfaces (Bridges et al. 2004). In the study area, the presence of units with a similar morphology and texture, but different degrees of ventifact formation (Figs 5, 6 & 7), suggests different ages of emplacement. In addition, the initial conditions of the lava flow surface, such as the presence or absence of a fallout tephra blanket, are important in avoiding an erroneous interpretation of the relative ages of lava fields (Valentine & Harrington 2006; Valentine et al. 2007). However, lava flow fields in the study area with and without a fallout tephra blanket have the same degree of ventifact formation (e.g. the AL4 and AL11 units). In addition, active dunes partially cover some of the lava flows in the study area. However, these aeolian deposits are not related to any particular unit within the stratigraphy of the two volcanoes. Thus the very youthful-looking ventifacts of the Alumbrera Volcano and the absence of ventifacts in the NAV suggest a probable Holocene age for its youngest activity. In contrast, the De La Laguna Volcano presents a greater degree of erosion, which is consistent with the only available radiometric age (0.34 ± 0.06 Ma, Risse et al. 2008). Despite the existence of temporal hiatuses in the evolution of both the Alumbrera and De La Laguna volcanoes, the determination of their durations remains a major challenge and needs high-resolution geochronology. Experimental work in a wind tunnel proved that ventifacts in Antarctica can be formed over a few decades to centuries (Miotke 1982). However, the lack of historical reports and archaeological evidence of volcanic activity in the study area suggests an age of at least a few thousand years for the youngest lava flows without ventifacts. This means that the time required for the full development of...
ventifacts on the surface of a lava field in the Puna environment is probably much greater than that suggested by Miotke (1982). Therefore temporal gaps between different eruptions of decades or centuries cannot be identified in the Southern Puna environment by geomorphological methods. Even though the absolute age of the different units is not known with certainty, the scoria cones studied in this work are considered to be polycyclic (Kereszturi et al. 2010; Németh & Kereszturi 2015) and possibly evolved over thousands of years. In addition, along the stratigraphic sequence of both volcanoes, units with different geochemical and petrographic features are present, including the three lava types proposed by Murray et al. (2015) for the Southern Puna mafic lavas (evolved, primitive and high magnesium; Fig. 8). The emission of successive magma batches with geochemical changes over time in a single scoria cone suggests that both volcanoes are also polymagmatic (sensu Brenna et al. 2010). The geochemical changes could reflect variations in the source and/or crustal storage conditions.

Factors controlling the occurrence of polycyclic scoria cones in the Southern Puna region

Despite the ongoing convergence of the Nazca plate beneath the South American plate, the Southern Puna regional stress field is characterized by sub-horizontal extension with a low deformation rate since late Miocene times (Montero López et al. 2010; Zhou et al. 2013). This horizontal non-lithostatic tension favours ascent through the thick, less dense continental crust and the eruption of small mafic volcanoes (Marrett & Emerman 1992). However, the magma pathway is governed near the surface by the influence of pre-existing fractures rather than the regional stress field (Alaniz-Alvarez et al. 1998; Valentine & Krogh 2006; Lesti et al. 2008; Le Corvec et al. 2013a, b). The mafic volcanism of the Southern Puna region forms clusters with different spatial distributions, total volumes of erupted magma and size of individual volcanoes (Viramonte et al. 2010). Some clusters have a low density of small and simple scoria cones, lava domes, tuff rings and maars, aligned along regional NE–SW-trending faults (e.g. the Arizaro Basin, Viramonte et al. 1984; the Pasto Ventura Basin, Filipovich et al. 2014). In these examples, each individual volcano is related to a discrete small magma batch, which propagates as a dyke with low magma pressure. Thus these dykes are only able to exploit pre-existing faults oriented nearly perpendicular to the minimum principal compressive stress ($\sigma_3 =$ north–south/NE–SW in the case of the Southern Puna region). Such a fault geometry aids the fast ascent of magma through the upper crust, which is reflected by the more primitive composition of the mafic lavas from the Arizaro and Pasto Ventura basins (Murray et al. 2015). In addition, these clusters are related to a low rate of magma input from the source due to either their marginal position with respect to a large delaminated lithospheric block (Kay et al. 1994; Risse et al. 2013) or their position above a small delaminated lithospheric block (Drew et al. 2009; Ducea et al. 2013; Murray et al. 2015). In contrast, the Antofagasta de la Sierra Cluster has relatively large volcanoes with an irregular spatial distribution. Some scoria cones are aligned along regional north–south faults, whereas others, including the Alumbreña and De La Laguna scoria cones, are aligned NW–SE without an apparent relationship with the regional faults. The relatively high volume of each volcanic centre and the total amount of erupted magma in the ASB suggest a high rate of magma input from the source as a result of its position above a relatively large delaminated lithospheric block (Kay et al. 1994; Risse et al. 2013; Murray et al. 2015) (Fig. 11). In this context, the dykes are larger and develop a high magma pressure and thus are able to reactivate pre-existing fractures of any orientation relative to the prevailing stress field (Alaniz-Alvarez et al. 1998; Le Corvec et al. 2013a). An example of this situation is the mafic volcanism located along north–south regional faults (sub-parallel to the minimum principal compressive stress) in the ASB (Fig. 11). The geometry of the north–south thrust fault plains in the Southern Puna region becomes horizontal in a detachment level located at around 11 km depth (Seggiaro et al. 2000). This crustal level with unfavourable geometry should promote the arrest of dyke propagation and sill formation (e.g. Gudmundsson 2011) (Fig. 11). However, if the propagating dyke has enough overpressure and intersects the regional detachment level near the root of a thrust fault, then the dyke may reach the surface (Fig. 11). Moreover, when the magma supply from a deep source is relatively large and sustained over time, it is plausible that the magma will begin to be stored in the detachment level in the upper crust (Gudmundsson 2011) (Fig. 11). Despite the low buoyancy of the mafic magmas in the upper crust, the magma pressure may exceed the lithostatic pressure and any potential differential crustal stress when the accumulation of magma is large enough; the generation of magma-filled tensile cracks is then feasible (Nakamura 1977) (Fig. 11). These tensile cracks will open perpendicular to the minimum principal compressive regional stress ($\sigma_3 =$ north–south/NE–SW in the case of the Southern Puna region). This mechanism in the Southern Puna region is aided by the current sub-horizontal extension and could explain the mismatch between the regional
structures and the inferred magma-feeding system in the Alumbrera and De La Laguna volcanoes. The development of upper crustal mafic magma reservoirs can explain the polycyclic character of both volcanoes. Another possibility is that a buried step-over structure between possible subsurface faulting could be a preferential means of ascent of successive magma batches (Calhoun 2010). Thus the presence of polycyclic scoria cones would only be related to a continuous magma supply in a narrow region during the delamination processes. More detailed structural and petrological studies are needed to fully understand the plumbing system that fed the Alumbrera and De La Laguna volcanoes.

**Eruptive dynamic shifting**

The youngest units in the stratigraphic sequence of the Alumbrera (NAV) and De La Laguna (NDLV) volcanoes were formed without significant temporal hiatuses between them and are interpreted as products of single eruptions that developed in different phases (Fig. 12).

**Neo-Alumbrera eruption.** The AL4 lava flow field covered by the AL6 fallout unit is interpreted as the oldest unit of the Neo-Alumbrera eruption. Thus the eruption probably started by the reactivation of the NE eruptive fissure with an effusive activity. The deposits forming the external part of the cone (AL5 unit) have textural features akin to material deposited by fallout from a sustained column rather than deposition by direct ballistic emplacement (e.g. Valentine et al. 2005). The tephra fallout blanket (AL6 unit) that covers some of the terrain around the volcano probably resulted from the same sustained column phase that formed the AL5 unit. The geochemical and petrographic characterization of the AL5 unit was carried out from a sample located at the base of the deposit. Hence the mismatch in the geochemical and petrographic features between AL5 and AL6 units could be related to geochemical changes during eruption (e.g. Johnson et al. 2008; Brenna et al. 2010; Erlund et al. 2010; Presta & Caffe 2014). A more detailed geochemical stratigraphy of the fallout blanket (AL6 unit) is required to fully assess this topic. The AL11 toothpaste lava flow field is partially covered by the fallout blanket, suggesting that it was initially issued simultaneously with the development of a sustained column phase. The size, internal complexities and stratigraphic relationships of the AL11 lava flow field suggest that it was active during most of the eruption. The formation of scoria cones from sustained columns, with the coeval formation of a tephra blanket beyond the cone, and the duality in the eruption dynamics (with simultaneous explosive activity at the central vent and effusive activity from...
the lateral vents) are common features of typical violent strombolian eruptions (Valentine et al. 2005; Pioli et al. 2008, 2009). The absence of natural cuts or quarries that could reveal the core of the Alumbrera scoria cone limits the inferences about the initial cone formation. Pioli et al. (2009) proposed a model for the historical eruption of the Paricutín Volcano, where the occurrence of violent strombolian eruptions requires that magma from the feeder conduit splits into vertical gas-rich and lateral gas-poor branches somewhere near the base of the previously formed and stabilized scoria cone. In this sense, a phase of mild explosive strombolian activity responsible for constructing the

Fig. 12. Conceptual model for the Neo-Alumbrera eruption explaining the occurrence of the shift in the eruptive dynamics in response to internal factors such as a decline in the mass eruption rate and external factors such as magma–water interactions.
internal portion of the scoria cone is indirectly inferred, which was followed by a high-explosive, violent strombolian phase that formed the external part of the cone (AL5 unit). By comparing similar historical eruptions, the initial strombolian phase probably lasted for several days or a few weeks, during which time possibly coeval lava flows (currently covered) were issued from the same vent to form a horseshoe-shaped cone (e.g. Paricutín, González & Foshag 1946; Navidad cone, Moreno & Gardeweg 1989). The temporal relationship between this inferred mild explosive strombolian activity and the effusive activity in the NE eruptive fissure is unknown. If the AL4 lava flow field development was coeval with the inferred initial central vent activity, it is plausible that the NE eruptive fissure was connected to the main feeder conduit at depth and had a low mass eruption rate ($<10^3$ kg s$^{-1}$), which allowed the passive degassing and dominantly effusive emission of the magma.

The violent strombolian eruptions have been linked to volatile-rich magmas (c. 4 wt%) and mass eruption rates between $10^3$ and $10^5$ kg s$^{-1}$ (Pioli et al. 2008, 2009). The published olivine-hosted melt inclusion data from the Southern Puna mafic lavas are scarce and suggest that the water contents of some of them are low ($<1$ wt%) compared with arc values (Risse et al. 2013). However, the high vesicularity of the juvenile clasts forming the AL5 and AL6 units suggests that the violent strombolian phase involved volatile-rich magma. The relatively low percentage of microlites in the juvenile clasts forming the AL5 unit (Fig. 8d) also suggests that brittle magma fragmentation due to an increase in viscosity and gas overpressure in response to microlite crystallization during magma ascent was not the dominant process controlling the occurrence of the violent strombolian phase (e.g. Valentine et al. 2005; Houghton & Gonnermann 2008; Vona et al. 2011). The high mass eruption rate for the violent strombolian phase is inferred indirectly by the partial gravitational collapse of the Alumbrera Volcano. Flask instabilities in scoria cones can be caused by the stress applied by magma bulging or fracture propagation (Corazzato & Tibaldi 2006), the weakest zone in the cone (Corazzato & Tibaldi 2006), gradual erosion and lowering of the cone flank due to a lava flow pouring out from the crater or lateral vents at the base of the cone (Tibaldi 1995), the inclination of the pre-eruptive terrain (Corazzato & Tibaldi 2006; Kereszturi et al. 2012) or the prevailing wind direction (Inbar & Risso 2001). Taking into account the gently dipping floor of the ASB and the absence of both a truly horseshoe-shaped morphology in the cone (the scarp only affects the external layers of the cone) and pyroclastic rafts in the lava flows, the partial collapse was possibly related to gravitational instability of the volcano due to its rapid growth (over-steepening) and high internal pressure at the end of the violent strombolian phase. The collapse direction in the Alumbrera Volcano is consistent with a magma-feeding system oriented NW–SE, as expected for a scoria cone grown on a horizontal or sub-horizontal substrate topography ($<9^\circ$) (Corazzato & Tibaldi 2006). In the same way as similar historical eruptions (e.g. Paricutín, Pioli et al. 2008), the violent strombolian phase was strongly pulsatory, resulting in a fine stratification of the tephra blanket (AL6 unit).

The progressive decline in the mass eruption rate ($<10^3$ kg s$^{-1}$) favoured passive magma degassing, producing both lava effusion and low explosive activity. At the central conduit violent strombolian activity changed to a Hawaiian style, with fountaining events forming spatter deposits (AL8 unit). In response to a further decline in the mass eruption rate, a gas-poor magma lake with sporadic strombolian bursts was established. The strombolian activity was caused by the periodic rise of conduit-filling gas bubbles (Taylor bubbles) within the conduit, resulting in metre-scale fluidal bombs with low vesicularity (AL9 unit). The final phase of the Neo-Alumbrera eruption was characterized by the generation of diluted pyroclastic density currents, which travelled at least 0.5 km beyond the cone base (AL10 unit). The occurrence of pyroclastic density currents associated with scoria cones can be related to the collapse of the eruptive column during violent strombolian eruptions (Taddeucci et al. 2004; Valentine et al. 2007; Valentine & Gregg 2008; Kereszturi & Németh 2012) or short-lived phreatomagmatic activity (Valentine et al. 2007; Di Traglia et al. 2009). The stratigraphic record suggests a progressive decrease in the magma supply rate through the development of the Neo-Alumbrera eruption. The high degree of hydrothermal alteration of the AL10 unit and its association with the waning stage of the eruption suggest that this unit was formed by phreatomagmatic activity due to sudden groundwater access to the volcanic conduit in response to a low magma supply rate (e.g. Martin & Németh 2006; Di Traglia et al. 2009). As a result of this highly explosive final phase, the crater of the Alumbrera Volcano acquired its final morphology.

The AL11 lava flow field was issued from many vents located on the western flank of the cone and was formed along the entire eruption. However, most of its growth occurred simultaneously with the low explosive activity in the central crater. Toothpaste lava flows are related to lavas with a similar viscosity to those forming aa flows, but require slower effusion rates (Rowland & Walker 1987). In addition, the occurrence of complex compound lava flow fields with the development of lava
tubes is associated with long-lived eruptions (a few weeks to a few years) with relatively low and steady mass eruption rates (Harris & Rowland 2009). Despite the low mass eruption rate, the large average volume erupted and thermally well-insulated flow allowed the lava to travel up to 7.3 km from the vent. Based on an analogy with historical eruptions that produced similar volumes and types of pyroclastic deposits and lava flows (e.g. the Paricutin and Jorullo volcanoes in the Michoacán–Guanajuato monogenetic volcano field, Mexico, Rowland et al. 2009; the Madinah eruption, Saudi Arabia, Camp et al. 1987), it follows that the eruption could have lasted from a few weeks to a few years.

**Neo-De La Laguna eruption.** The evolution of the youngest eruption in the De La Laguna Volcano was similar to the previously described Neo-Alumbrera eruption. The external part of the cone (DLL6 unit) and the fallout deposit outcropping beyond the cone (DLL7 unit) were formed during a high-explosive, violent strombolian phase developed just after a mildly explosive strombolian phase inferred indirectly. In response to the decline in the mass eruption rate, the eruptive activity becomes less explosive, with a hawaiian eruptive style first and then a strombolian eruptive style, forming the DLL8 and DLL9 units, respectively. In the same way as in the AL10 unit, the high degree of hydrothermal alteration of the DLL10 unit and its association with the waning stage of the eruption suggest that this unit was formed by phreatomagmatic activity. However, the limited distribution of the DLL10 unit indicates that phreatomagmatic pulses during the final stage of the eruption were scarce. The weak phreatomagmatic activity allowed the preservation of the spatter deposits that infill the crater. Simultaneous with the explosive activity in the central conduit, two aa lava flow fields were issued from the base of the cone (DLL11 unit) and from a vent located 0.5 km from the cone (DLL12 unit). The latter was probably generated in the same way as the AL4 unit in the Alumbrera Volcano.

**Conclusions**

This paper presents the first detailed geological map of individual scoria cones (Alumbrera and De La Laguna volcanoes) in the Southern Puna plateau and shows their relatively complex stratigraphy. The occurrence of more than one eruption at both volcanoes was reconstructed by the recognition of temporal hiatuses along their stratigraphy using morpho-stratigraphic criteria. The presence of relatively large polycyclic scoria cones in the ASB is inferred to result from the development of upper crustal magma reservoirs in response to a high input of magma related to the delamination of a large lithospheric block, a favourable regional stress field and the interaction of the rising magma with pre-existing crustal faults. However, more detailed structural and petrological studies are needed to fully understand the occurrence of polycyclic scoria cones in the Southern Puna plateau.

The youngest activity of both volcanoes was characterized by long-lasting eruptions (lasting for a few years by comparison with modern analogues), with shifts in the eruptive dynamics in response to a decrease in the mass eruption rate from high-explosive, violent strombolian to hawaiian/strombolian phases. The explosive activity was accompanied by the emission of lava flows from lateral vents, which occurred mostly during the hawaiian/strombolian phases. During the waning stage of the eruptions, intermittent phreatomagmatic activity developed as a result of the sudden access of groundwater into the volcanic conduit. A gravitational flank collapse of the scoria cone occurred during the Neo-Alumbrera eruption. The development of long-lasting, mafic, high-explosive eruptions and the occurrence of more than one eruption in each individual scoria cone are important topics in the assessment of volcanic hazard in the Southern Puna plateau. The occurrence of violent strombolian eruptions could cause extensive economic and social disruption as far as hundreds of kilometres from the vent as a result of ash dispersion. In addition, the occurrence of a high-explosive phreatomagmatic phase generating pyroclastic density currents during the waning stage of the eruption is a very hazardous feature of this type of volcanism.

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