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# Tectonic controls on geomorphology and spatial distribution of monogenetic volcanoes in the Central Southern Volcanic Zone of the Andes (Argentina)

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**Highlights**

- Mapping of monogenetic volcanoes in the Southern Volcanic Zones of the Andes
- Presence of nine clusters with cinder cones (*strombolian*) and maars (*phreatomagmatic*)
- Control of oblique tectonics on vent organization, geomorphology and distribution
- Volcano morphology and vent distribution reflect contrasting states of stress
- Relative ages suggest waning magmatic activity

**Abstract**

Monogenetic volcanoes are among the most common volcanic landforms on Earth. The morphology and distribution of small volcanoes can provide important information about eruption dynamics and tectonics. The Southern Volcanic Zone of the Andes (CSVZ) comprises one of the most active magmatic regions on Earth. Characterized by the presence of polygenetic volcanoes and calderas in a complex tectonic setting, this region also hosts hundreds of small, back-arc monogenetic volcanoes. In this contribution, we apply a Geographic Information System (GIS) that combines imagery data and digital elevation models to establish the first comprehensive dataset of monogenetic volcanoes in the CSVZ (38° to 40° S), exploring their eruption dynamics and relationship to tectonic and structural processes. Combining spatial analysis and geomorphological observations, we identify the presence of 356 monogenetic volcanoes distributed into nine clusters, now grouped in the Zapala Volcanic Field (ZVF). The ZVF is marked by the predominance of cinder cones (80%) followed by phreatomagmatic volcanoes (20%), suggesting some influence of external water in the eruption dynamics. Generally, monogenetic vents present a clear association with local and regional lineaments, suggesting a strong structural control on the occurrence of the monogenetic deposits. The higher vent densities are observed in the southern Loncopué Though, an important extensional feature related to tearing of the subducted Nazca plate underneath the South American Plate. Morphometric parameters of cinder cones indicate variable stress orientations in the CSVZ that possibly results from the oblique tectonics in the region. From north to south, the maximum principal stress rotates from NE-SW to E-W and becomes progressively less constrained as it distances from the current magmatic arc. Based on the relative ages, we map the evolution of monogenetic volcanism through time. Our results suggest a waning in the monogenetic activity in ZVF over time. When compared to monogenetic fields in the Central Andes, the ZVF is marked by higher vent densities and number phreatomagmatic landforms, with the absence of lava domes. This ultimately reflects the contrasting crustal structure and climate conditions of these two regions.

**Keywords:** Monogenetic volcanism; Geomorphology; Southern Volcanic Zone; Andes; Spatial Analysis; Geographic Information System.

## 1. Introduction

Small monogenetic volcanoes are among the most common volcanic landforms on Earth (Wood, 1979), and they can occur as isolated vents, grouped in volcanic fields, and as parasitic vents associated with polygenetic systems (Fornaciai et al., 2012; Kereszturi and Németh, 2012a; Uslular et al., 2015). These landforms are generally classified according to edifice morphology, which depends on endogenous (e.g., magma composition and volatile content) and exogenous (e.g., structural context, interaction with surface water, terrain slope, and wind intensity) factors (Kereszturi and Németh 2012a; Kervyn et al., 2012, Di Traglia et al., 2014; Németh and Kereszturi, 2015). Because of these controls, several eruption styles are associated with monogenetic volcanoes, including hawaiian, strombolian, and hydrovolcanic (Kereszturi and Németh, 2012b; Németh and Kereszturi, 2015; Báez et al., 2017).

The morphology of monogenetic volcanoes and their spatial distribution reflect important parameters about the dynamic of the volcanic field and their tectonic controls (e.g., structural control and emplacement dynamics; Bemis and Ferencz, 2017). Several studies have shown that edifice morphology and spatial distribution can be used to identify relevant volcanological and tectonic processes, including eruption dynamics, structural and tectonic settings (Tibaldi, 1995; Kereszturi and Németh 2012a; Haag et al., 2019; Marliyani et al., 2020). In recent years the availability of high-resolution Digital Elevation Models (DEMs) and satellite imagery fostered the remote characterization of monogenetic volcanoes. This approach yielded interesting results, allowing a deeper understanding of volcanology, structural, and tectonic processes related to monogenetic volcanic fields (e.g., Bruno et al., 2006; Kiyosugi et al., 2012; Németh and Kereszturi, 2015; Haag et al., 2019, Morfulis et al., 2020; Uslular et al., 2021).

The central segment of the Southern Volcanic Zone of the Andes (CSVZ) comprises one of the most active magmatic regions on Earth (Stern, 2004). In addition to the presence of polygenetic volcanoes and calderas (e.g., Copahue in Argentina, Callaqui, Antuco and Llaima in Chile), this region also hosts hundreds of small back-arc monogenetic volcanoes (Fig 1). Despite their widespread presence in the area, only a few studies have addressed the occurrence of monogenetic volcanism in the CSVZ (e.g., Muñoz and Stern, 1989; Lara et al., 2006; Cembrano and Lara, 2009) and none of them deals with the geomorphology of these volcanoes.

In this contribution, we use a GIS to report the first complete catalog of monogenetic landforms in CSVZ (henceforth grouped in the Zapala Volcanic Field - ZVF), their morphology, spatial distribution, and structural relationships. Combining satellite imagery and DEMs, we map and classify the monogenetic volcanoes in the region, establishing their eruption dynamics and relationship to tectonic features and processes.

## 2. Geological setting

The CSVZ is located in the southern segment of the Andes and extends between latitudes 37° to 41°5' S, involving regions of Argentina and Chile (Fig. 1). It is part of one of the four volcanic segments associated with the active convergent margin, located on the west coast of South America, where the Cocos, Nazca, and Antarctic plates are subducted by the South American plate (Hickey-Vargas et al., 2002) responsible for the Andean orogeny in the last 200 Ma (e.g., Mpodozis and Ramos, 2008). This zone features hundreds of monogenetic back-arc volcanoes with extensive deposits and variable morphologies, in addition to the presence of numerous large polygenetic systems, such as composite volcanoes and calderas.

The eastern foothills of the Andes between the 31° and 40° S are defined by a significant retroarc basin that comprises a Late Triassic-Early Cenozoic succession called Neuquén Basin (Howell et al., 2005; Fig. 1A). The complex evolution of this basin can be divided in three main phases: (1) the opening of the basin in Late Triassic times, as a result of extensional processes that generated a series of long, narrow depocenters filled with volcanic/volcaniclastic and continental deposits (Vergani et al., 1995; Franzese and Spalleti, 2001; Howell et al., 2005; Carbone et al., 2011), (2) a post-rift phase of thermal subsidence during the Early Jurassic, when an active subduction regime and the magmatic arc are established on the western margin of Gondwana (Franzese et al., 2003; Howell et al., 2005; Mpodozis and Ramos, 2008), and (3) a phase of typical foreland basin between the Late Cretaceous and Early Cenozoic, resulting from the development of a compressive tectonic regime that generated the eastward migration of the orogenic front (Franzese et al., 2003; Howell et al., 2005; Tunik et al., 2010; Gianni et al., 2018).

The magmatic activity retreated toward the west in the Oligocene-early Miocene and a series of extensional basins (e.g., Cura Mallín basin) are generated in the foothills of the Neuquén Andes (Radic et al., 2002; Morabito and Folguera, 2005; Ramos and Folguera, 2005). The second period of deformation of the Neuquén Basin and a new expansion of the magmatism to the foreland is produced during the Middle-Late Miocene (Ramos and Folguera, 2005; Kay et al., 2006). The magmatic front begins to retreat again during the early Pliocene, associated with intense volcanic activity and the opening of the Cola de Zorro Basin in the Main Andes between the 37° and 39°S (Vergara and Muñoz, 1982; Muñoz and Stern, 1988; Folguera et al., 2006; Ramos and Folguera, 2005).

The Pliocene-Quaternary volcanism in the Neuquén region is mainly developed in an N-S belt parallel to the Andean front and the Tromen and Auca Mahuida volcanic fields located further east (Fig. 1B; Folguera et al. 2011). Particularly, a relevant Pliocene-Quaternary activity is focused on the Loncopué Trough (Fig. 1B). This is a narrow, N-S topographic depression of 200 km in length located between the 36°30' and 39°S and limited by the Agrio fold and thrust belt to the east and the volcanic arc to the west (Folguera et al., 2010; Rojas Vera et al., 2010, 2014; Folguera et al., 2011; Pesce et al., 2019). The basal volcano-sedimentary infill of the axial part of the depression starts in the early Pliocene (Cola de Zorro Formation), followed by silicic distal pyroclastic sequences associated with the development of a series of calderas in the west during Pleistocene times, and the posterior emplacement of a basaltic cover in the western sector (Rojas Vera et al., 2014; Pesce, et al., 2019).

Finally, significant Pleistocene-Holocene monogenetic basaltic fields develop in the Loncopué Trough, even extending to the Laguna Blanca/Zapala area (~39°S) (Groeber, 1928; Varekamp et al., 2010; Folguera et al., 2011; Rojas Vera et al., 2014). These flows consist of olivine-rich basalts that have received different names based on their relative age and location (e.g., Hueyeltué, Huechahue, Malleo, Macho Viejo, Los Mellizos, and Laguna Blanca basalts) (Leanza et al., 1997; Zannettini et al.,2010). Varekamp et al. (2010) analyzed the volcanic centers south of the 37°30'S, including those located around the Laguna Blanca/Zapala area (~39°S), and observed transitional chemical features between intraplate and arc magmas. However, the centers located in the northern sector of the Loncopué Trough showing typical arc signatures (Rojas Vera et al., 2014).

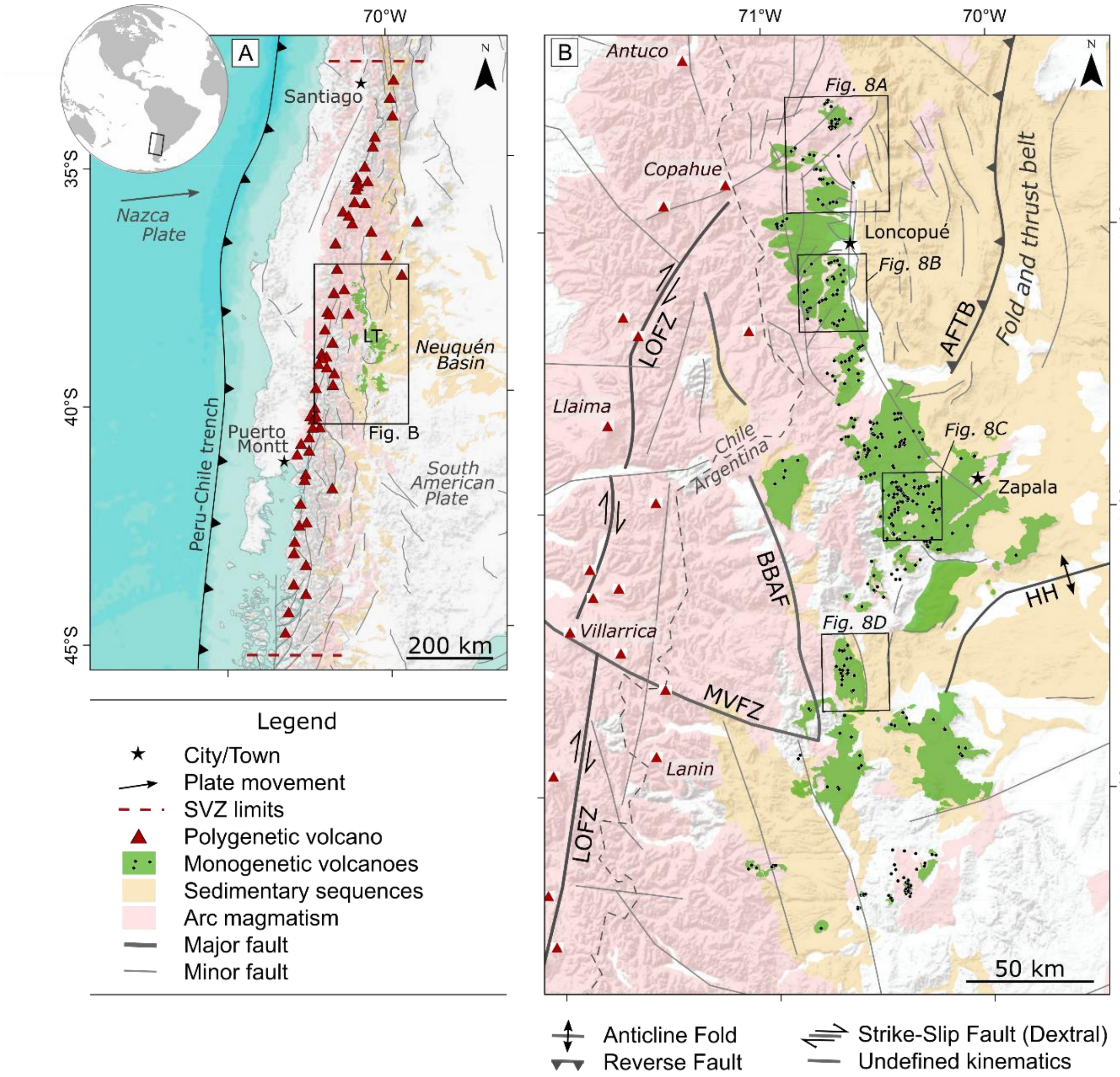



**Fig. 1.** A) Regional context of the studied area in the Andean Belt; B) regional map of the CSVZ with ZVF deposits, polygenetic volcanoes, and the main structural features. LT - Loncopué Trough. Structures are: AFTB - Agrio Fold and Thrust Belt, BBAF - Bío-Bío Fault Zone, HH - Huincul High, LOFZ - Liquiñe-Ofqui Fault Zone, MVFZ - Mocha-Villarica Fault Zone. Geological units after Cordani et al. (2016).

## 3. Methods

### *3.1. Landform identification, mapping a classification*

Monogenetic volcanoes consist of small-volume, nearly circular to elliptical, landforms with either positive (cinder cones, tuff cone, and lava domes) or negative topography (maars - phreatomagmatic structures) (Lesti et al, 2008; Kereszturi and Németh, 2012a; Németh and Kereszturi, 2015; Smith and Németh, 2017; Haag et al., 2019). Based on these criteria, we identified possible monogenetic volcanoes in the study area using Google Earth® (1 to 10 m/px) to establish a primary dataset (Fig. 2A). In this step, we also rely on the available geological maps that contain the distribution of monogenetic deposits (i.e., lava flows) for some regions in the study area (Kay et al., 2006; Melnick and Echtler, 2006; Cembrano and Lara, 2009; Varekamp et al., 2010; Rojas Vera et al., 2014; Pesce et al., 2019, 2020).

This preliminary dataset was then verified using satellite imagery in ArcMap®. In this process, the landforms were classified in the following categories: cinder cone, maar, tuff ring, tuff cone, and lava dome (Fig. 2A), following the categories proposed by Kereszturi and Németh (2012a) and Németh and Kereszturi (2015). Using this approach, we find out that monogenetic volcanoes in the study area are either cinder cones or maars. To characterize these volcanoes and perform the geomorphological measurements, we used a high-resolution (12.5 m/px) DEM derived from the ALOS PALSAR sensor, which provides full coverage of the studied area and can be freely downloaded at the Alaska Satellite Facility website (available at https://vertex.daac.asf.alaska.edu/). To ensure consistency the DEM was set to an equal-area projection (UTM 19S).

From the DEM we used ArcMap® 10.5 to derive several terrain attributes, including slope, contour, and aspect (Fig. 2B), which are useful for mapping the monogenetic volcanoes. Based on these maps and satellite images, we performed a supervised (i.e., manual) geomorphological mapping of the volcanoes and their associated deposits (at a local scale of 1:10,000, Fig. 2C to the left). Based on the mapping and the contour plots, we performed an ellipse fitting and the morphometric measurements using ArcMap Spatial Analyst (Fig. 2C, to the center).

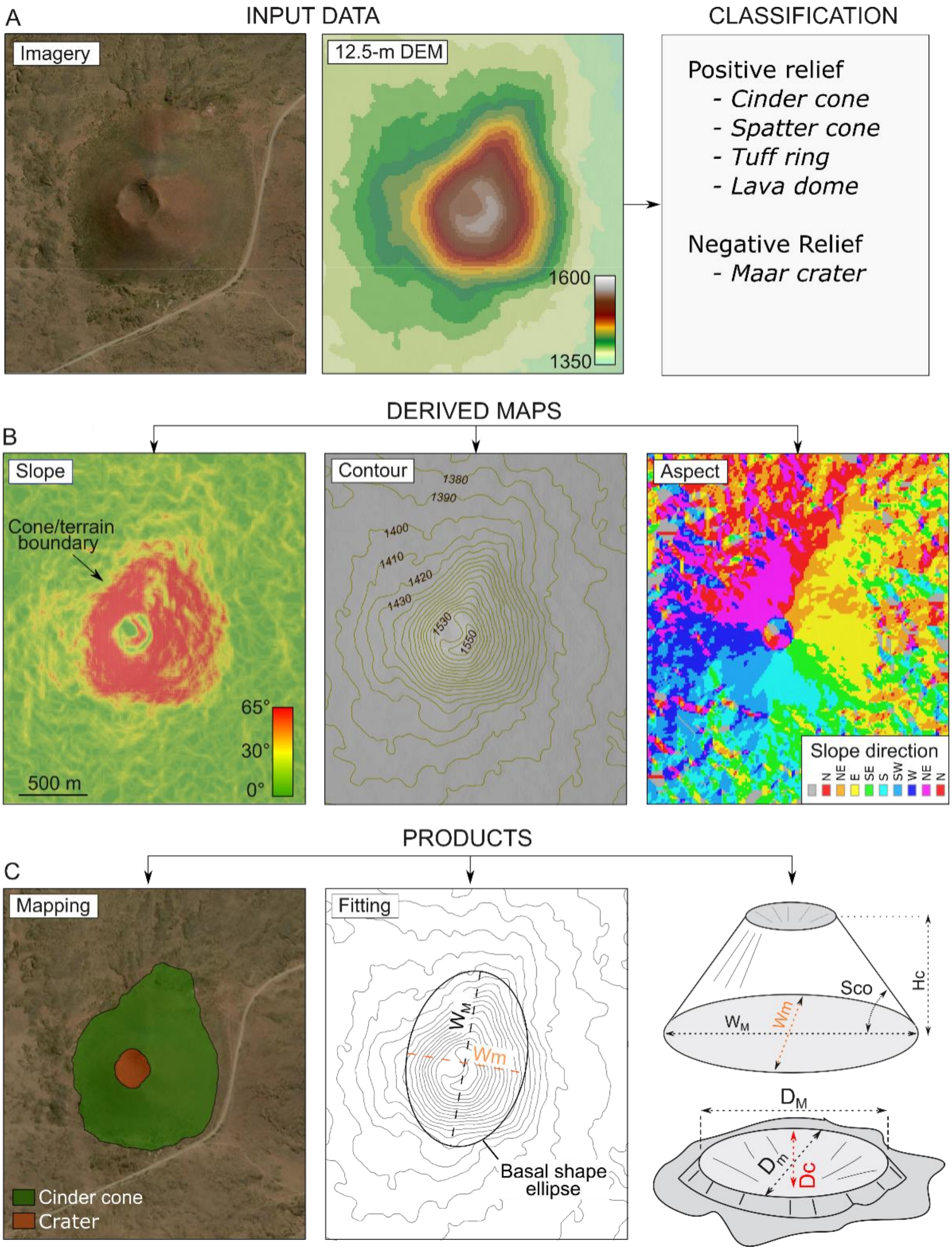



**Fig. 2.** Methodology applied to this study: A) imagery and DEM (elevation scale in meters) comprise input data, which were used to identify and classify the monogenetic landforms; B) DEM-derived maps include slope (scale in degrees), contour (10-m interval curves) and aspects (slope direction); C) supervised (manual) mapping, ellipse fitting and measurements of the monogenetic landforms. Abbreviations are $W_M$ - Cone maximum basal width; Wm - Cone minimum basal width; Hc - cone heigh; Sco - cone flank slope; Dc - maar crater depth; $D_M$ - maximum diameter of maar crater; $D_m$ - minimum diameter of maar crater.

For cinder cones, we measured the maximum basal width ($W_M$), minimum basal width (Wm), height of the cone (Hc), and maximum flank slope (Sco) (Fig. 2C). For maar volcanoes, we measured the depth of the crater (Dc), as well as the maximum ($D_M$) and minimum crater diameter (Dm) (Fig. 2C). We also take the azimuth of the maximum diameter $W_M$ and $D_M$, which is better explained in section *3.3. Morpho-structural analysis*.

### *3.2. Spatial analysis*

The spatial analysis allows the identification of the degree of clustering, the detection of subclusters, and the internal organization of the monogenetic vents. After mapping and classification of the targets, point analyzes were performed using the spatial analysis tools in ArcMap® applying the methodology proposed by Bishop (2007).

The identification of the number of monogenetic clusters in ZVF was based on the methods of Cañón-Tapia (2016), using kernel density functions. According to the search radius, the number of detected clusters follows a power-law distribution in which the inflection point indicates the optimum number of clusters within a monogenetic field (Cañón-Tapia, 2016; Morfulis et al., 2020).

The distribution pattern within each monogenetic cluster was analyzed using the Average Nearest Neighbor (ANN) analysis (Bruno et al., 2004). In this method, the *observed* distance among monogenetic vents (Ro) in a given area ($A_{HULL}$) is compared to the *expected* distance of evenly distributed vents (Re). The R-statistic parameter results from the Ro/Re ratio and indicates whether the points distribution follows a Poisson (R-statistic = 1), clustered (R-statistic → 0.0), or dispersed (R-statistic → 2.0) distribution (Bishop, 2007).

### *3.3. Morpho-structural analysis*

The determination of stress state can be inferred from the spatial distribution of monogenetic vents and their main attributes (Fig. 3; Tibaldi, 1995; Paulsen and Wilson, 2010; Bonali et al., 2011; Le Corvec et al., 2013; Tadini et al., 2014; Haag et al., 2019; Marliyani et al., 2020; Morfulis et al., 2020). In this context, the surface distribution of monogenetic volcanoes and their elongation (Fig. 3A, B; Tibaldi, 1995) can be used to infer the orientation of subsurface structures, such as dike, fractures, and faults, which ultimately reflect the local stress state (Fig. 3C, D).

To determine the relationship between monogenetic vents and the structural setting in the ZVF we followed a similar approach to Tibaldi (1995) and Bonali et al. (2011), using morphometrics to infer the states of stress.

To this end, we measure directional parameters for each monogenetic volcano using ellipses (Fig. 3A) and measuring the basal elongation of cones (azimuth of $W_M$) and crater elongation of maars (azimuth of $D_M$). We also calculate the ellipticity for both cones and maars by dividing the minimum for the maximum diameter of these features ($W_m$/ $W_M$; Tibaldi, 1995). In the case of cinder cones, we did not measure crater elongation and crater-rim depressed points (e.g., Tibaldi, 1995) because these features are either absent or not completely clear in most of the studied cones in the ZVF.

Finally, we also measured alignments of both cinder cones and maars. Vent alignment/dike presence was determined using at least three vents, and by observing the presence of elongated cones ($W_m$/ $W_M$ < 0.8) or dikes (Fig. 3A), following the recommendations of Le Corvec et al. (2013) and Paulsen and Wilson (2010). In this study, we did not use densities plots to infer conduit and dike orientations (e.g., Cebriá et al., 2011; Tadini et al., 2014) because it generally neglects morphometric and field evidence that result in more robust results (Paulsen and Wilson, 2010).

Both vent alignment and the basal elongation of monogenetic volcanoes/maar craters are parallel to the maximum horizontal stress (σHmax) and perpendicular to the minimum horizontal stress (σHmin), as suggested by several studies (Fig. 3C; e.g., Nakamura et al., 1977; Tibaldi, 1995; Lara et al., 2006; Haag et al., 2019; Marliyani et al., 2020). Monogenetic cones may also be slight oblique to the main feeding system, suggesting an *en echelon* distribution (Fig. 3D). In the structural analysis we only consider cones emplaced in flat surfaces (slope < 5°) and without significant modification (i.e., extensively degraded cones and maar craters).

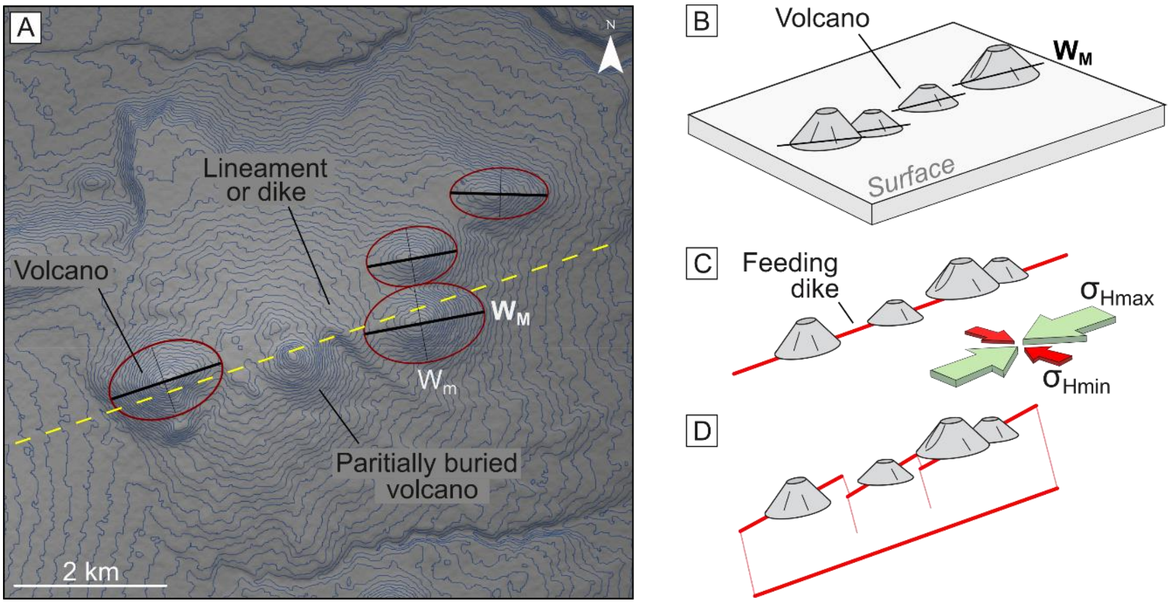



**Fig. 3.** Morpho-structural and lineament analysis. A) Hillshade image with contours used for ellipse fitting and measurement of $W_M$ and Wm for cones or $D_M$ and Dm for maars - cone heigh; B) sketch of the surface expression of monogenetic cones; C) subsurface sketch of inferred plumbing system based on cone basal elongation for normal faulting; D) subsurface sketch of inferred plumbing system for strike-slip and *en echelon* geometries; σHmax - maximum horizontal stress; σHmin - minimum horizontal stress.

### *3.4. Relative age*

In monogenetic fields, the number and distribution of active volcanoes can vary over time (Le Corvec et al., 2013). Differently from other regions in the Andes that have extensive well-dated ignimbrite deposits and abundant radiometric ages, thus allowing a better constraint on the spatial evolution of the magmatism (e.g., the Central Andes, Tibaldi et al., 2017), the volcanoes in the ZVF do not have this database yet.

As an alternative to determine the spatio-temporal evolution of monogenetic volcanism in the ZVF, we assigned relative ages to the cinder cones based on morphometric attributes including crater, cone, and lava flow integrity. These attributes reflect modification stages to the original, conical shape of cinder cones and are mainly based on simulation and geomorphological observations (Hooper and Sheridan, 1998; Fornaciai et al., 2012; Kereszturi and Németh, 2012b; Zarazúa- Carbajal and Cruz- Reyna, 2020).

Following this approach, cinder cones were grouped into four categories (Fig. 4), following an adaptation of the methods of Haag et al. (2019): young - cinder cones with well-defined craters and basal limits, smooth surfaces, and absence of erosional features; moderately young - cones without a well-defined crater and roughly defined basal limits, with deep and well-established gullies and rills; mature - cones without a well-defined crater and roughly defined basal limits, with ravines and rills; old - reduced landforms, without a defined crater basal limit, cut by deep ravines and rills. Using this classification method, we created regional maps of relative age in the studied area, comparing our results with the available absolute ages from the literature (e.g., Ramos and Folguera, 2005).

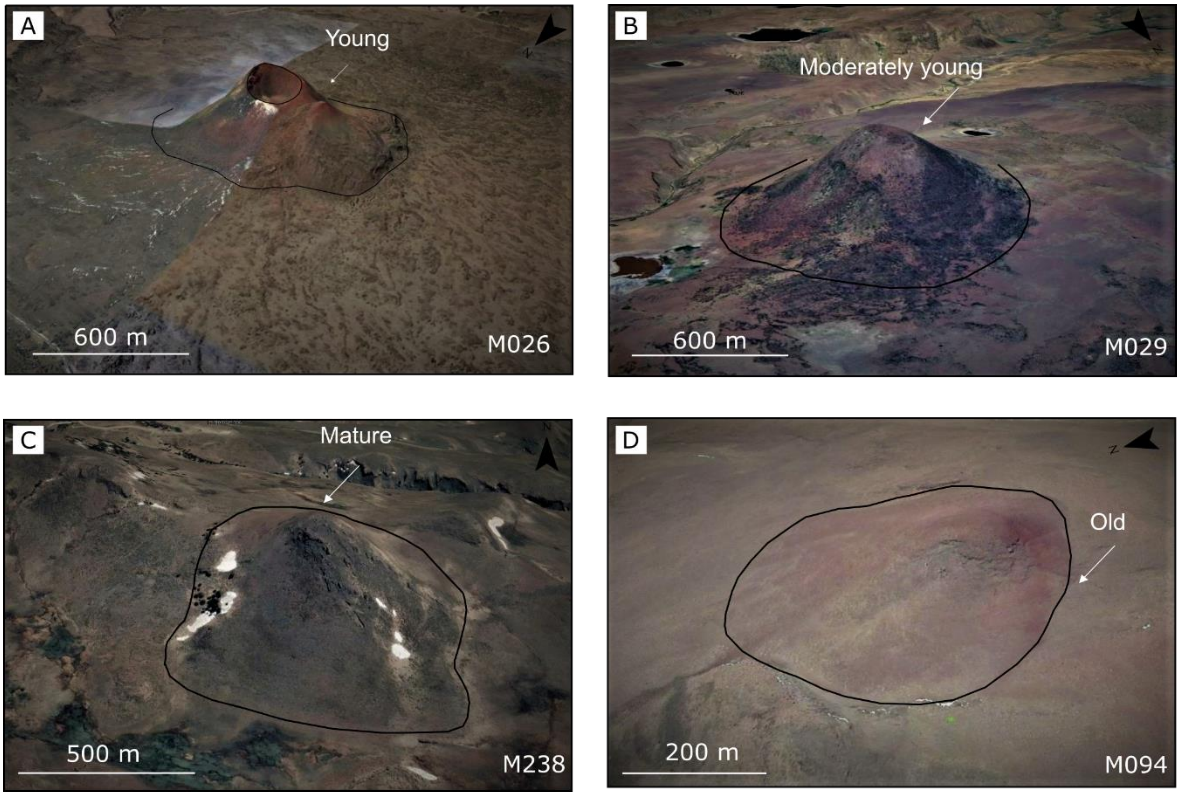



**Fig. 4.** Relative age classes of studied cinder cones. A) young (coordinates are 39° 01’ 22.76” S; 70° 22’ 28.88” O); B) moderately young (38° 58’ 37.84” S; 70° 24’ 31.40” O); C) mature (38° 53’ 30.92” S; 70° 33’ 43.71” O); D) old (37° 59’ 20.14” S; 70° 56’ 31.35” O). Relative scale due to perspective. Vertical exaggeration of 3. Source: GoogleEarth (2021).

## 4. Results

### *4.1. Geomorphology and morphometry*

We identify 336 monogenetic volcanoes in the study area, with a predominance of cinder cones (80%) followed by phreatomagmatic (maars) volcanoes (20%). Monogenetic deposits (volcanoes and their associated lava flows) cover approximately 6.400 km$^2$ in the CSVZ. The main morphological attributes are represented in Fig. 5, while the distribution of monogenetic volcanoes and their main morphometric parameters are reported in Fig. 6A. All elevations are reported in meters above sea level (a.s.l).

#### *4.1.1 Cinder Cones*

Cinder cones are the predominant landforms in the ZVF and exhibit a significant variation in their geomorphologic attributes (Fig. 5A, B, C). They are frequently breached, elongated edifices associated with extensive lava flows (Fig. 5A). In several cases, multiple generations of lava flows are observed, suggesting multiple eruptions in the same region (Fig. 5A). A few cinder cones occur nested inside maar craters that cut older lava flows (Fig. 5B). Several cones form clusters that can be grouped by lineaments and are possible related to dikes and feeding systems (Fig 5C).

Cinder cones occur throughout the entire study area (Fig. 6A, B), at terrain elevations ranging from 900 to 2,200 m a.s.l. (Fig. 6B). They dominate the northern section (above ~ lat. 39°S) and higher terrain elevations (> 1,600 m a.s.l.) (Fig. 6A, B, C). Below ~ lat. 39°S, the presence of maar volcanoes becomes more relevant (Fig. 6A, B, C).

The cinder cones also exhibit a significant variation in their morphometric parameters (Fig 6E). Maximum basal widths ($W_M$) range from 246 to 3,590 m and cone heights (Hc) from 7 to 426 m (Fig. 6E). Most cinder cones are generally elliptical, with $W_M/W_M$ ratios ranging from 1.0 (circular) to 0.4 (highly elliptical) and clustering around 0.80 (Fig. 6E). Flank slope angles (Sco) from 6 to 40º. For a full report on the morphometric attributes please check Supplementary item 1.

#### *4.1.2 Phreatomagmatic volcanoes: maar*

Maar volcanoes are marked by well-preserved, generally circular craters, partially filled by alluvial sediments and saltpans (Fig. 5D, E, F). Crater limits are roughly delimited by small changes in elevations, because ZVF maars often lack external tephra rings and deposits (Fig. 5D, E, F). Maar craters commonly cut lava plateaus (Fig. 5E) and are closely associated with cinder cones (Fig. 5F).

Maar volcanoes are preferentially present south of lat. 39° S (Fig. 6A, B) and at terrain elevations below 1,600 m a.s.l (Fig. 6C). A summary of their main morphometric parameter is presented in Fig. 6F. The depth of the crater (Dc) ranges from 1 to 211 m, and crater maximum axis ($D_M$) ranges from 142 m to 4,900 m (Fig. 6F). Maar craters are often elliptical to nearly circular, with $D_m/D_M$ ratios ranging from 0.99 (circular) to 0.39 (highly elliptical), while most $D_m/D_M$ ratios are below 0.75 (Fig. 6F). For a full report on the morphometric attributes please refer to the Supplementary item 1.

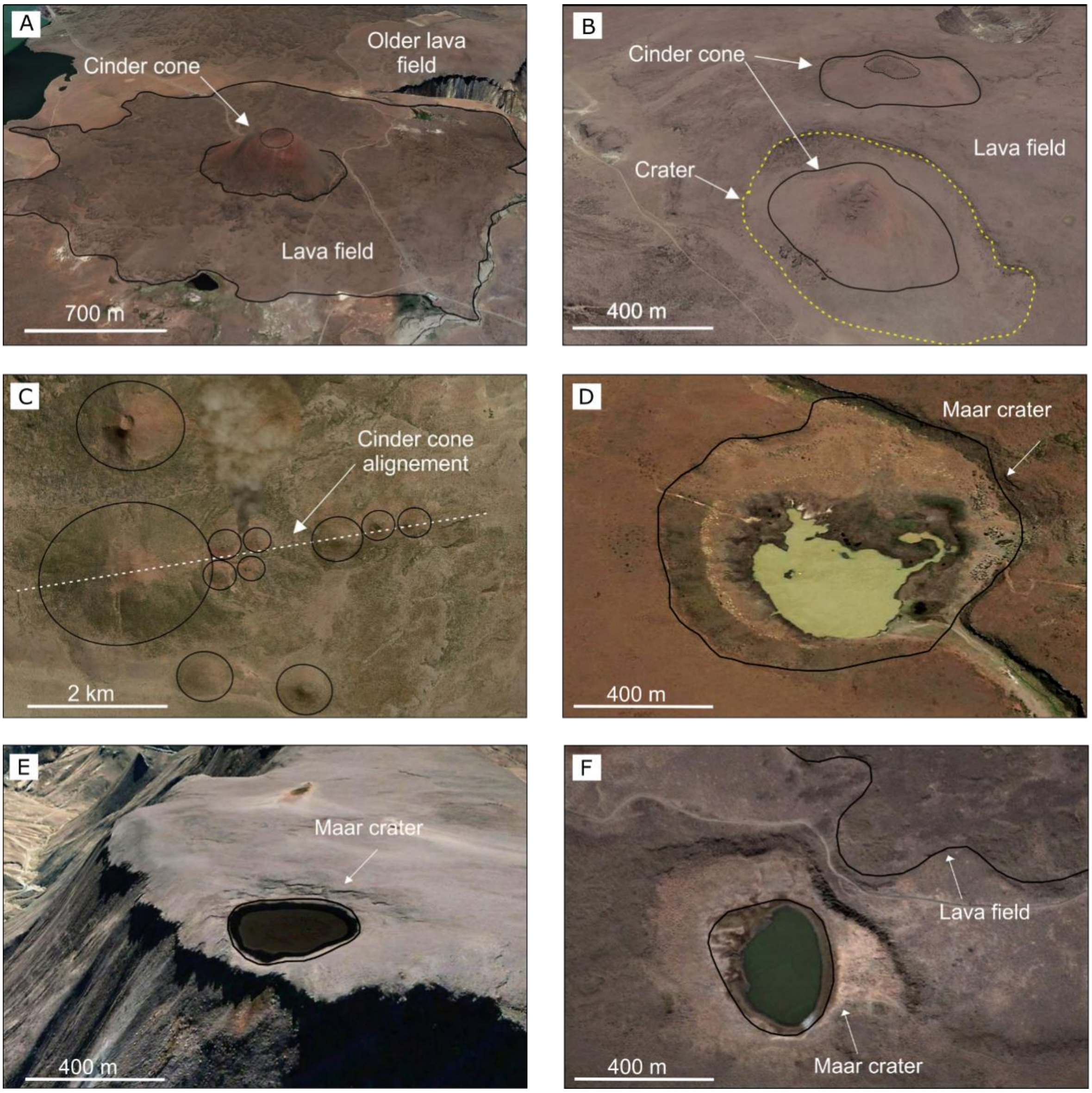



**Fig. 5.** Representative monogenetic landforms in the CSVZ: A) Cinder cone with associated lava flow (39° 05’ 32. 90” S; 70° 23’ 16.80” O); B) cinder cone emplaced inside a maar-crater (39° 09’ 18.90” S; 30° 14’ 25.11” O); C) composite alignment of multiple cinder cones (38° 55’ 59.42” S; 70° 20’ 28.09” O); D) maar crater emplace on top of thin volcanic sequences (39° 46’ 19.97” S; 70° 22’ 54.39” O); E) Maar crater emplace over volcano-sedimentary (39° 16’ 19.83” S; 70° 33’ 42.16” O); F) Maar craters associated with cinder cones (39° 35’ 47.31” S; 70° 37’ 54.10” O). Relative scale due to perspective. Vertical exaggeration of 3. Source: GoogleEarth (2021).

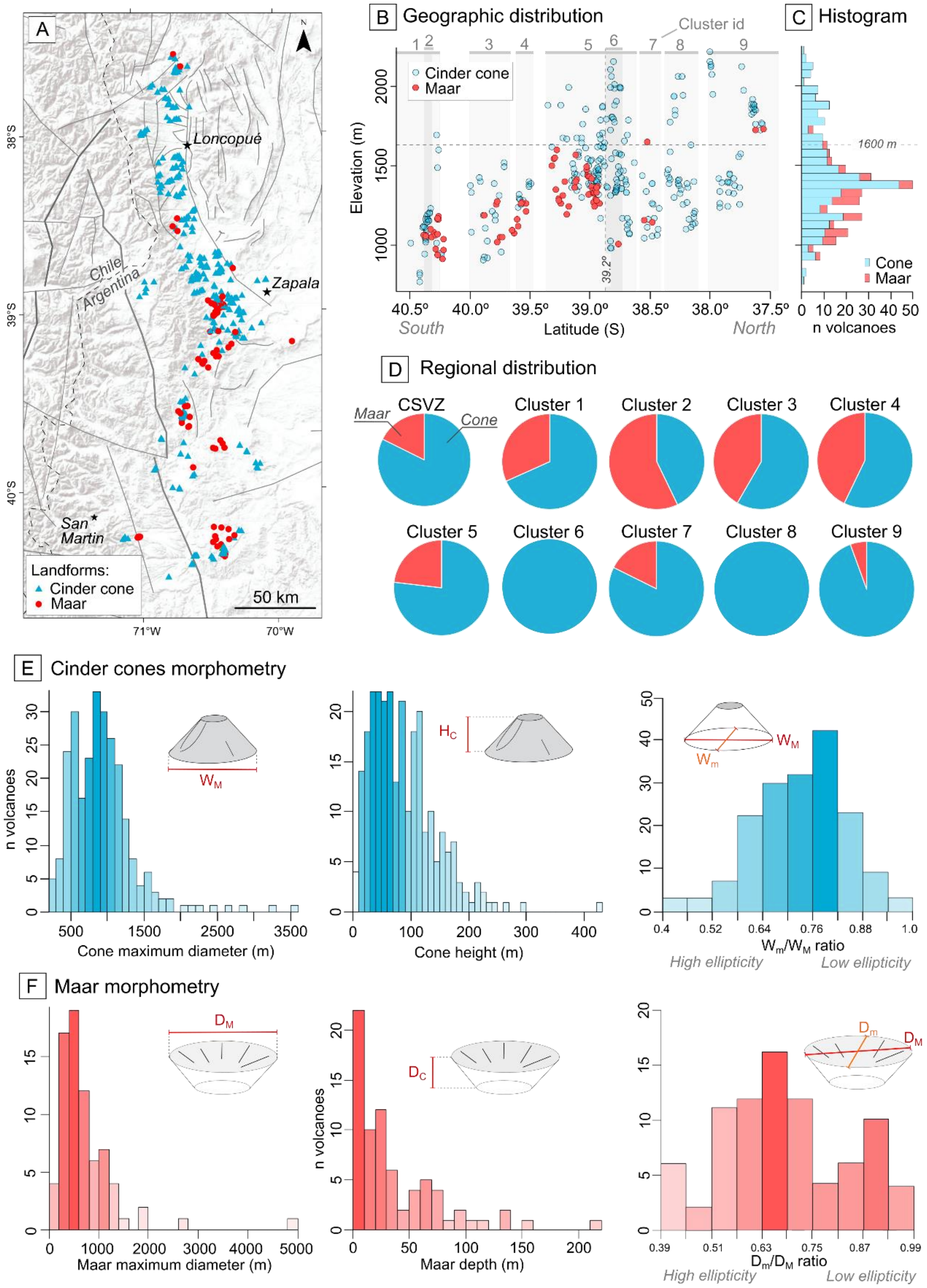



**Fig.6**. Morphometric results. A) CSVZ map with the distribution of monogenetic landforms in the ZVF; B) North to the south geographic distribution of cinder cones and maars; C) histogram with the terrain elevation of cinder cones and maars; D) landform distribution of wet (represented by maars) and dry (represented by cinder cones) monogenetic landforms across the ZVF; E) Morphometric results ($W_M$, Hc, and ellipticity) for cinder cones; F) Morphometric results ($D_C$, $D_M$, and ellipticity) for maar volcanoes.

*4.2. Spatial distribution*

Spatial analysis was performed using Kernel density estimations for cluster identification and Average Nearest Neighbor (ANN) analysis for pattern determination.

*4.2.1. Cluster identification*

The identification of the number of the monogenetic clusters was based on the methods of Cañón-Tapia (2016). Following this method, we observe an inflection point at ~10 km (Fig. 7A; Cañón-Tapia, 2016; Morfulis et al., 2020). This value suggests a total of 9 monogenetic clusters (Fig. 7A, B) in the CSVZ. The vent density of each cluster is presented in Table 1. The maximum density of monogenetic volcanoes (0.144 vents/km$^2$) is located in cluster number 5 (Fig. 7B), about 30 km southwest of Zapala town (Fig. 7C), at the southern segment of the Loncopué Trough.

*4.2.2. Distribution pattern*

ANN analysis indicates a strong clustered pattern for ZVF, with an overall R-statistic of 0.392. A summary of ANN results is presented in Table 1. Individually, each monogenetic group presents variable distribution patterns, from clustered to dispersed (Fig. 8A, B). A clustered pattern is observable in groups 1, 5, and 9 (Fig. 8A), which present R-statistic ranging from 0.719 (less clustered) to 0.648 (most clustered), all well above the -2σ range (Fig. 8A, B). The dispersed pattern is recorded in groups 2, 4, 6, and 7, with R-statistic from 1.22 (less disperse) to 2.30 (most dispersed). Groups 4 and 7 are above 1.65σ, while groups 2 and 6 above 2.85σ (Fig. 8A, B). The Poisson pattern is detected only in groups 3 and 8 (Fig. 8A).

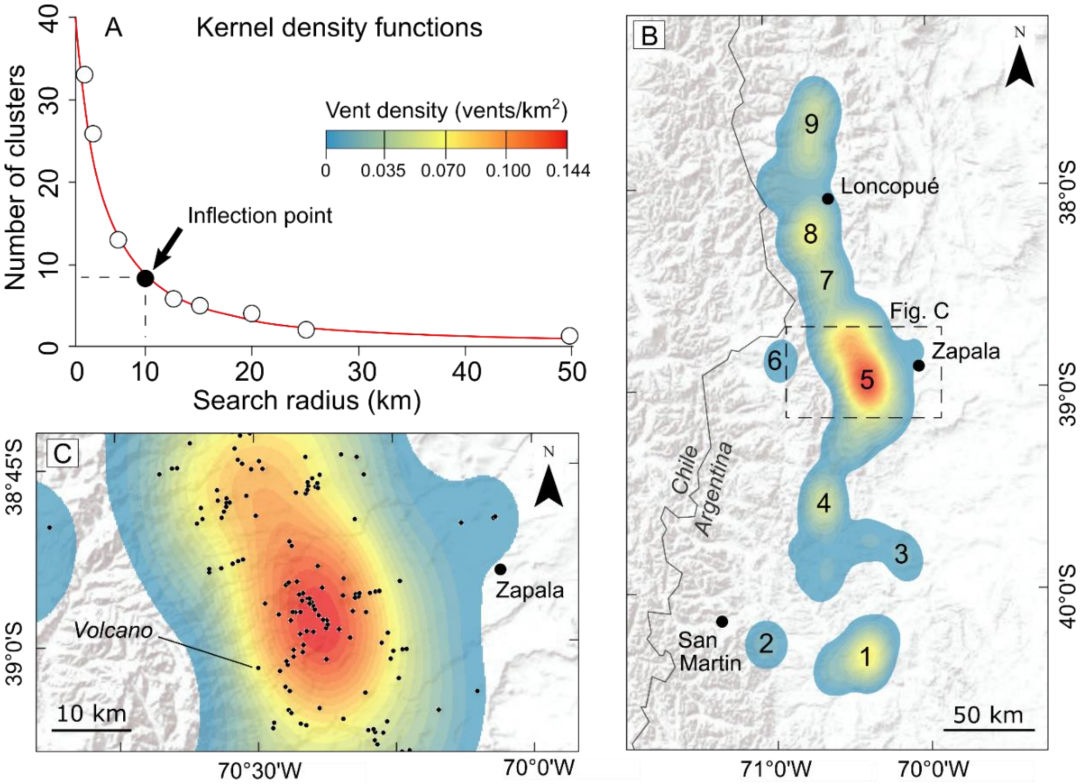



**Fig. 7.** Kernel density analysis. A) Number of kernel clusters as a function of the search radius; B) regional map with identified monogenetic clusters; C) detail map of cluster 5 showing the internal distribution of monogenetic vents in the southern Loncopué Trough.

The spatial pattern and distribution of monogenetic volcanoes is better observed in detailed maps of each monogenetic group. Group 9 displays strongly clustered monogenetic vents (Fig. 8A). These vents form in sub-clusters inside the group perimeter (defined by the convex hull), in E-W trends to the southwest (inferred to be controlled by local structures), and isotropic groups to the north (Fig. 8C). In contrast, group 4 presents an opposite spatial pattern, with vents randomly dispersed inside the group area (Fig. 8D).

**Fig. 8. (below)** Summary of ANN analysis. A) normal distribution with confidence intervals and the R-statistic for each monogenetic cluster; B) plot of R-statistic and number of vents; C) clustered pattern (R-statistic ~ 0.687), cluster number 9, and the respective convex hull area; D) dispersed pattern (R-statistic ~ 1.21), cluster number 4, and the respective convex hull area.

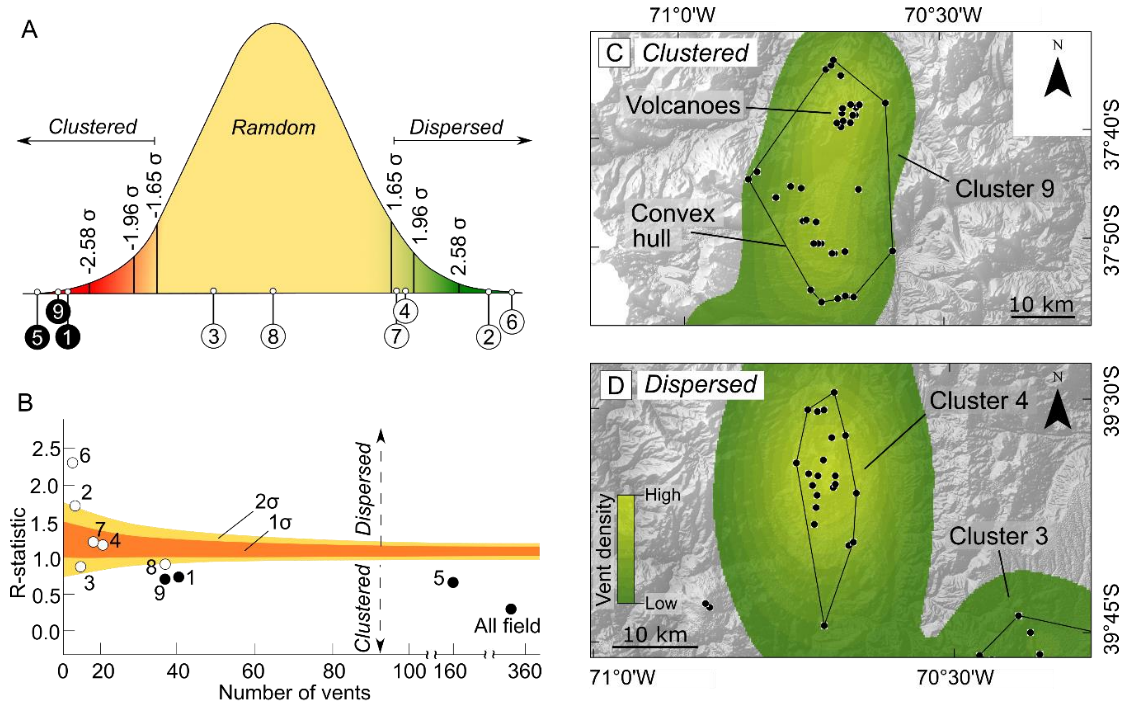



**Table 1.** Spatial analysis results. ANN patterns are clustered (C), Poisson (P), and dispersed (D).

| Parameters | Entire ZVF | Cluster number | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| Vents | 355 | 41 | 7 | 12 | 21 | 160 | 5 | 17 | 37 | 37 |
| Area ($km^2$) | 22.510 | 517 | 10 | 194 | 119 | 3.009 | 33 | 126 | 358 | 649 |
| Average density (vent/$km^2$) | 0.015 | 0.07 | 0.70 | 0.06 | 0.17 | 0.053 | 0.151 | 0.134 | 0.103 | 0.057 |
| Maximum density (vent/$km^2$) | 0.144 | 0.059 | 0.014 | 0.013 | 0.043 | 0.144 | 0.010 | 0.037 | 0.056 | 0.037 |
| Re (m) | 4,932 | 2,347 | 758 | 2,343 | 1,436 | 2,564 | 1,737 | 1,700 | 1,672 | 2,519 |
| Ro (m) | 1,938 | 1,688 | 1,276 | 2,061 | 1,746 | 1,663 | 4,010 | 2,048 | 1,668 | 1,731 |
| R-sta | 0.392 | 0.719 | 1.683 | 0.879 | 1.21 | 0.648 | 2.307 | 1.222 | 0.997 | 0.687 |
| Pattern | C | C | D | P | D | C | D | D | P | C |

*4.3. Structures and lineaments*

Based on the satellite imagery and the available geological maps (e.g., Rojas Vera et al., 2014; Pesce et al., 2019), we map the occurrence of monogenetic centers in the study area and their relationship with structural features. A summary of the main structural settings observed in the ZVF is provided in Fig. 9. Structural data obtained from cone elongation and vent alignment indicate the predominance of E-W, ENE-WSW to WNW-ESE structures in the ZVF, with significant variations among the different clusters (Fig. 9).

Cluster 9 is the closest to the volcanic arc (~ 30 km considering the main trend of active polygenetic volcanoes) and is marked by monogenetic volcanoes mainly associated with E-W structures (Fig. 9A). The northern limit of cluster 9 is characterized by NE-SW alignments, next to the Trolón Caldera (Fig. 9A). Cluster 8 presents a slight change in vent alignment direction when compared to cluster 9, with most features trending ENE-WSW to WSW-ENE (Fig. 9B). Further south, cluster 5 is also marked by ENE-WSW to WSW-ENE trending vents (Fig. 9C). Several NW-SE trending monogenetic volcanoes are also present in the region (Fig. 9C). South of this region, the orientation of vents starts to become more scattered. Cluster 4 shows a variety of orientations, including ENE-WSW, WNW-ESE, NE-SW, and NE-SE trending volcanoes and alignments (Fig. 9D).

A summary of the quantitative structural data extracted from monogenetic volcanoes (cone and maar elongation, vent alignment, and dike orientation) is presented in Fig. 10. From north to south, there is an increase in the scattering of the basal cone orientation, as well as vent alignment (Fig. 10A). Despite this, histograms indicate a predominance of ENE-WSW elongated cones in the ZVF following azimuths ranging from 80 to 95º (Fig. 10B). This orientation is also confirmed by histograms of vent alignment and the orientation of dikes (Fig. 10C). If we consider the basal ellipticity values ($W_m/W_M$ ratios) and exclude the nearly circular features ($W_m/W_M$ ratios > 0.8), it is interesting to note that we still obtain similar results, with higher kurtosis (i.e., more values close to the mean, Fig. 10D). Maar data indicate the presence of highly elliptical craters (low $D_m/ D_M$ ratios) mainly oriented along with ENE-WSW and WNW-ESE directions (Fig. 10E, F).

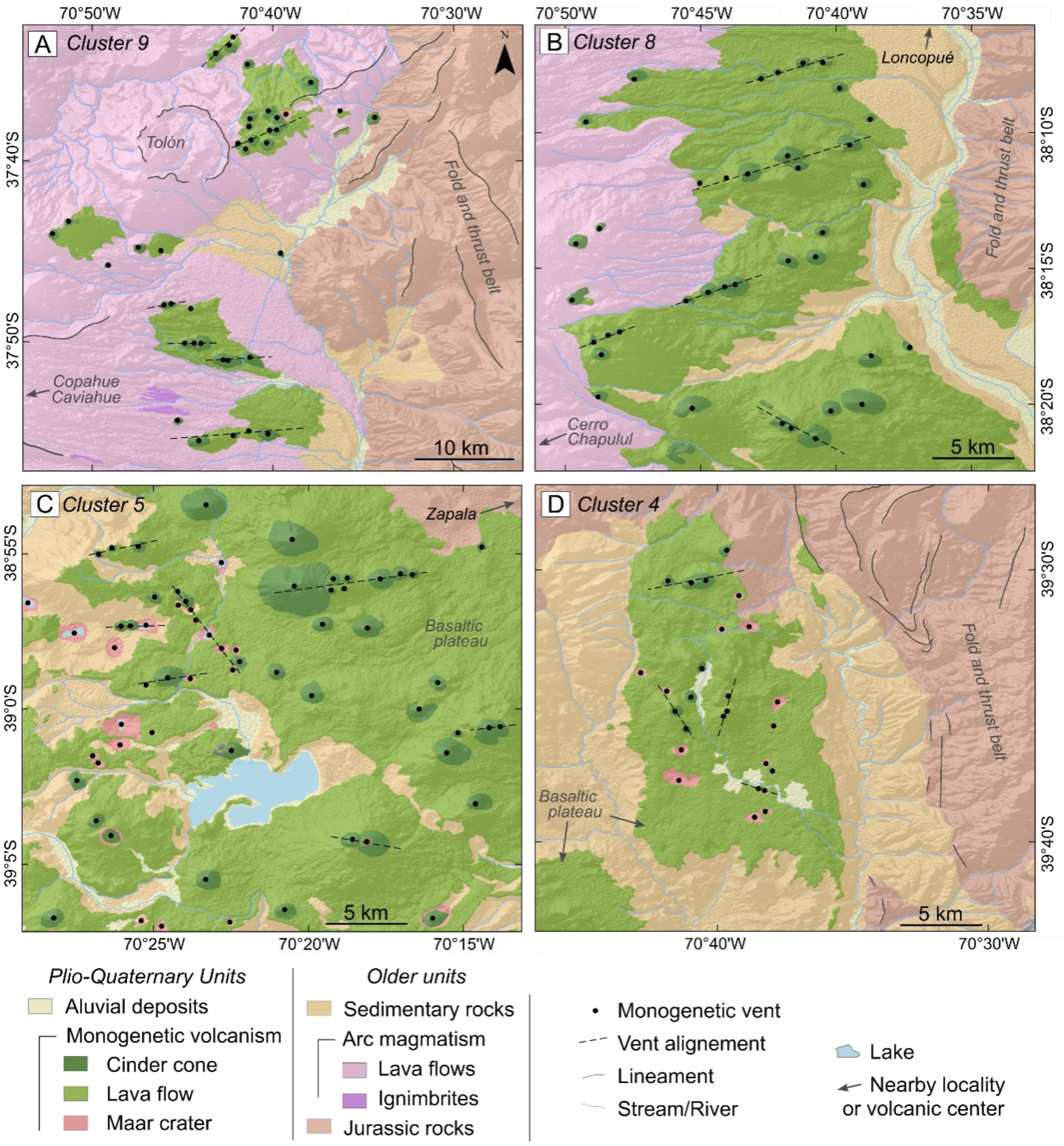
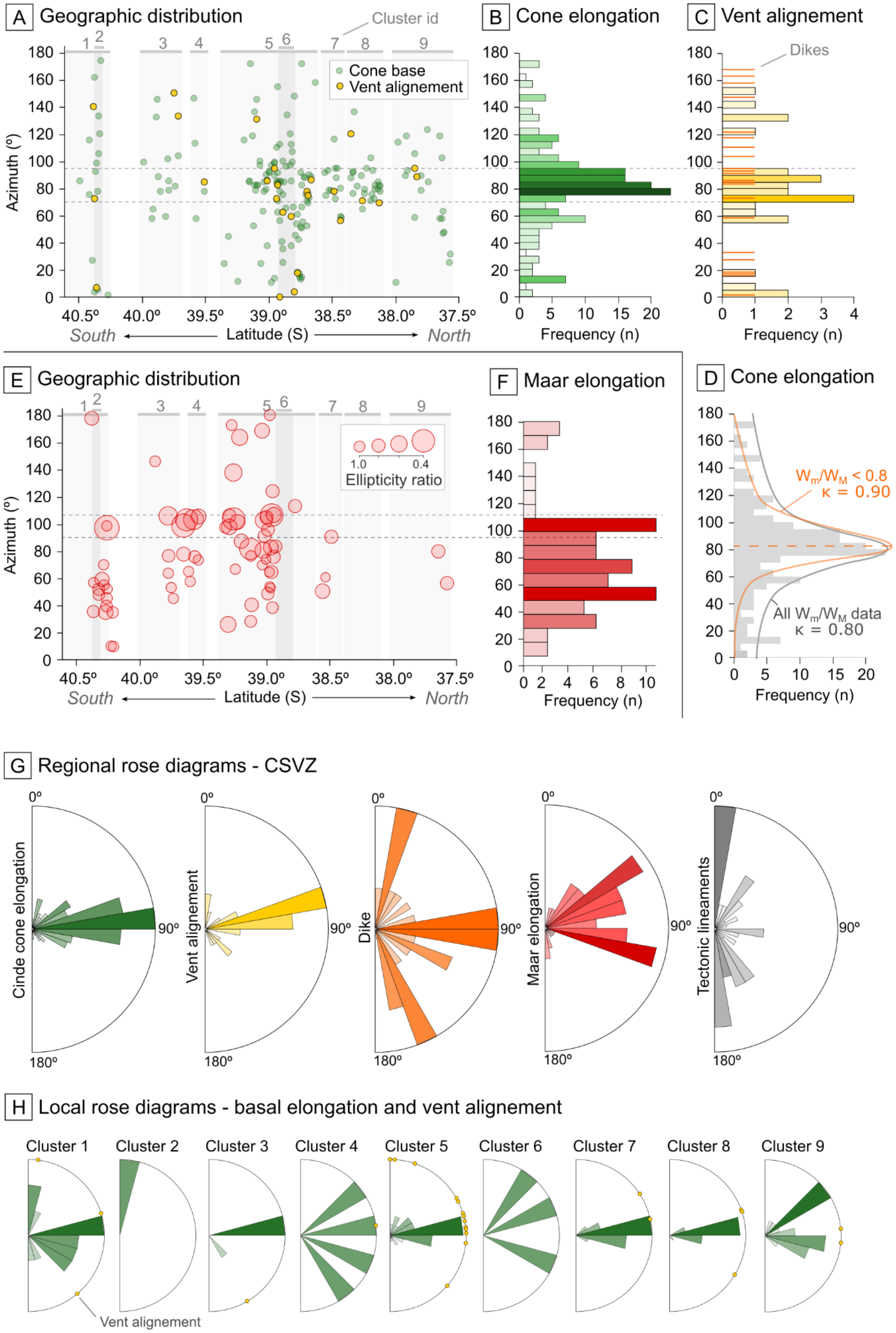



**Fig. 9.** Maps of monogenetic volcanoes in the ZVF and their structures, from north to south. A) cluster 9, with mainly E-W and subordinate NE-SW trending vents; B) cluster 8 with a predominance of NE-SW trending vents; C) southern section of Cluster 5, with E-W and NW-SE trending volcanoes; D) Cluster 4, with WSW-ENE, ENE-WSW, NNE-SSW, and NNW-SSE trending vents. Geological units based on Rojas Vera et al. (2014) and Pesce et al. (2019).

Rose diagrams built from these data allow better visualization of the orientation of monogenetic features in the ZVF (Fig. 10G). ENE-WSW to E-S directions prevail among the main orientations for basal cone elongation, vent alignment, and dike orientation (Fig. 10G). In contrast, the orientation of maar craters shows a higher dispersion when compared to cinder cones, with crater elongation ranging from ENE-WSW to WNW-ESE (Fig. 10G). These results contrast with the main lineaments observed in the fold and thrust belt region, which is marked by the predominance of N-S structures (Fig. 10G)

Deviations in basal cone orientation are also observed within each cluster (Fig. 10H). Clusters 1, 4, and 6 tend to show a more scatter pattern, while clusters 3, 5, 7, and 8 are marked by a predominance of E-W trending cones (Fig. 10H). Cluster 9 is the closest to the current volcanic arc (Fig. 9A) and presents a bimodal distribution of cinder cones basal elongation (Fig. 10H).

**Fig. 10** (below). Summary of structural analysis using monogenetic volcanoes: A) south to the north geographic distribution of cinder cones basal elongation and vent alignment; B) histogram of cinder cone elongation direction; C) histogram of vent alignment and dike direction, in orange; D) histogram of cinder cone elongation direction taking into account all cones and only the elliptical cones (Wm/WM < 0.8), κ stands for kurtosis; E) south to the north geographic distribution of maar crater elongation; F) histogram of maar crater elongation direction; G) regional rose diagrams form cinder cone elongation, vent alignment, dikes, maar crater elongation, and the tectonic structures/lineaments; H) local rose diagrams of cinder cone elongation for each monogenetic cluster within the ZVF, vent alignment directions are represented as yellow dots.


A Geographic distribution
Cluster id
Cone base
Vent alignement
Azimuth (º)
Latitude (S)
South
North
B Cone elongation
Frequency (n)
C Vent alignement
Dikes
Frequency (n)
E Geographic distribution
Ellipticity ratio
1.0
0.4
Azimuth (º)
Latitude (S)
South
North
F Maar elongation
Frequency (n)
D Cone elongation
W_m/W_M < 0.8
κ = 0.90
All W_m/W_M data
κ = 0.80
Frequency (n)
G Regional rose diagrams - CSVZ
Cinde cone elongation
Vent alignement
Dike
Maar elongation
Tectonic lineaments
H Local rose diagrams - basal elongation and vent alignement
Cluster 1
Cluster 2
Cluster 3
Cluster 4
Cluster 5
Cluster 6
Cluster 7
Cluster 8
Cluster 9
Vent alignement

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*4.4. Relative age*

Using the relative age classification method, it was possible to map the temporal distribution of cinder cones in the ZVF. Similar to the approach used by Haag et al. (2019), we use relative ages of cinder cones to interpolate regional maps, expressing the results as density maps for each relative age class (Fig. 11A- D).

Our data indicate that the younger monogenetic volcanoes appear to concentrate southwest of Zapala Town (Fig. 11A), with more isolated occurrences a few kilometers northwest of Loncopué Town (Fig. 11A). Moderately young cones present a wide distribution to the eastward, apparently following an NW-SE-trending normal fault and concentrated in the Loncopué Though (Fig. 11B).

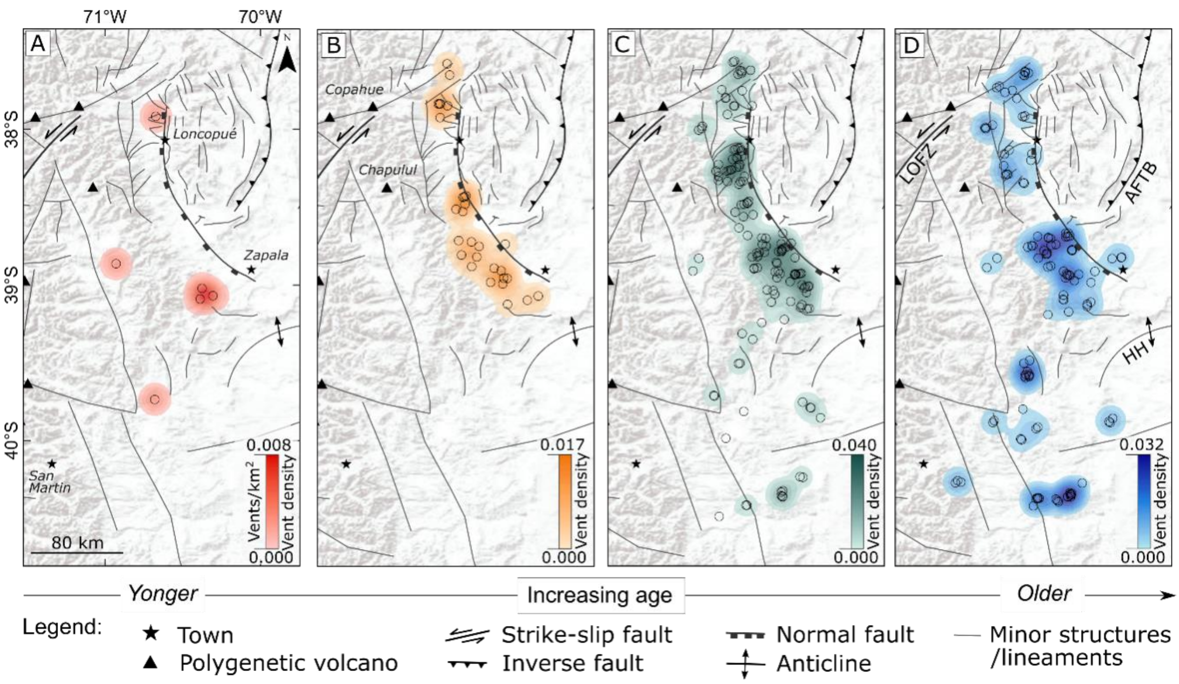


**Fig. 11.** Density maps with the regional distribution of each relative age class: A) young; B) moderately young; C) mature; D) old. Monogenetic volcanoes are expressed by open circles. All densities are in volcanoes/km$^2$.

Mature landforms (moderately degraded landforms) are widespread in the study area and especially concentrate in the northwest and southwest regions of the Zapala and Loncopué Towns (Fig. 11C). These features present a similar distribution to moderately young landforms (Fig. 11B), however mature cones also occur as isolated clusters to the south of Zapala Town (Fig. 11C). Older monogenetic volcanoes are also widespread in the study area, with occurrences to the northwest of Loncopué, and next to the Chapuful volcano (Fig. 11D). Several old cinder cones also occur in the north-northwest of Zapala and in the extreme southwest of the study region, near the city of San Martín along the Neuquén Basin (Fig. 11D).

## 5. Discussion

### *5.1. Geomorphology and morphometry*

The monogenetic volcanism in the ZVF is marked by the predominance of cinder cones that present a clear association with local lineaments, suggesting a structural control on the occurrence of the monogenetic vents. The presence of cinder cones suggests a prevalence of the strombolian style as the main eruption dynamics in the ZVF (Németh and Kereszturi, 2015), similarly to the Puna Plateau in the Central Andes (Filipovich et al., 2019; Haag et al., 2019; Maro and Caffe, 2016; Morfulis et al. 2020). This dynamic is supported by the number of hydrovolcanic landforms in the region (less than 20%), which denotes a limited, however existing, magma-water influence in the eruption history of individual vents of the ZVF

The cinder cones present morphometric signatures (e.g., $W_M$, Hc) similar to extension-related cones when compared to the global dataset of Fornaciai et al. (2012) (Fig. 12A). These cones are marked by lower $Hc/W_M$ ratios when compared to cinder cones associated with compressional environments (Fornaciai et al., 2012).

The use of traditional morphometric parameters (e.g., $Hc/W_M$ ratio) to the determination of relative ages typically results in misleading interpretations (Hasenaka and Carmichael, 1985; Uslular et al., 2021), because after the eruption the morphometric parameters are subject to several modifications related to weathering and tectonics. Furthermore, many syn-eruptive processes can produce a variety of primary landforms, with extensive contrasts in $Hc/W_M$ ratios (Kereszturi and Nemeth, 2012). In contrast, alternative approaches using cone flank slope (Sco) and contour curves have returned valid results (e.g., Inbar et al., 2011; Haag et al., 2019; Zarazúa-Carbajala and Cruz-Reyna, 2020). In ZVF cones, we observe a systematic decrease in Sco following the relative age, in which young landforms tend to present higher Sco values when compared to the older ones (Fig. 12B). Despite this general trend in average values, there is a considerable deviation and scattering in the data (Fig. 12B). This scattering is likely associated with contrasting initial cone morphology, mainly controlled by tectonics, terrain slope, and eruption dynamics (Kervyn et al., 2012; Bemis and Ferencz, 2017; Haag et al. 2019; Uslular et al., 2021).

Phreatomagmatic volcanoes tend to concentrate to the south of 39ºS and typically below 1,600 m a.s.l. (Fig. 6C), suggesting a geographic control on the occurrence of hydrovolcanism in the ZVF. This distribution may be associated with the decrease of water availability with increasing elevation. Using a global dataset of maar volcanoes, Sonder (2018) observed a substantial decrease in the number of maar volcanoes above 2,000 m a.s.l.

The sharp decrease in maar volcanoes observed in Fig. 6A and B may also be associated with geological controls. Phreatomagmatic activity depends on the availability, location and proportion of groundwater (Németh and Kereszturi, 2015; Ureta et al., 2021a). The regional basement to the south of 39ºS is marked by the presence of sedimentary sequences of the Neuquén Basin, which possibly control the distribution of hydrovolcanism in the ZVF (D'Elia et al., 2016).

In contrast to cinder cones, the original morphology and subsequent modifications of maar craters are strongly controlled by substrate rheology. Ross et al. (2011) discuss these factors by comparing the morphology of maar craters emplaced on hard, soft, and mixed substrates in the Pali Aike Volcanic Field (Argentina). Mixed substrates are marked by the presence of soft (typically of sedimentary origin) and hard (typically volcanic or metamorphic) materials. Maar craters in the ZVF present variable depth/diameter ratios, suggesting a predominance of mixed substrates when compared to the dataset of Ross et al. (2011) (Fig. 12C). In the ZVF, maars with similar diameters but deeper craters are typically emplaced on top of sedimentary sequences capped by extensive lava flows, forming volcanic plateaus. In contrast, shallower maar craters are generally associated with soft substrates marked by sedimentary and alluvial sequences.

Additionally, several ZVF maars are proceeded by cinder cones, denoting a shift in the eruption dynamics from strombolian to phreatomagmatic. This dynamic behavior of phreatomagmatic eruptions/systems has been observed in several places around the world, including hyper-arid regions such as the Atacama Desert in Chile (Ureta et al., 2021a, 2021b). Ultimately, phreatomagmatic activity in these regions seems to be controlled by water availability and water table depth (Ureta et al., 2021b).

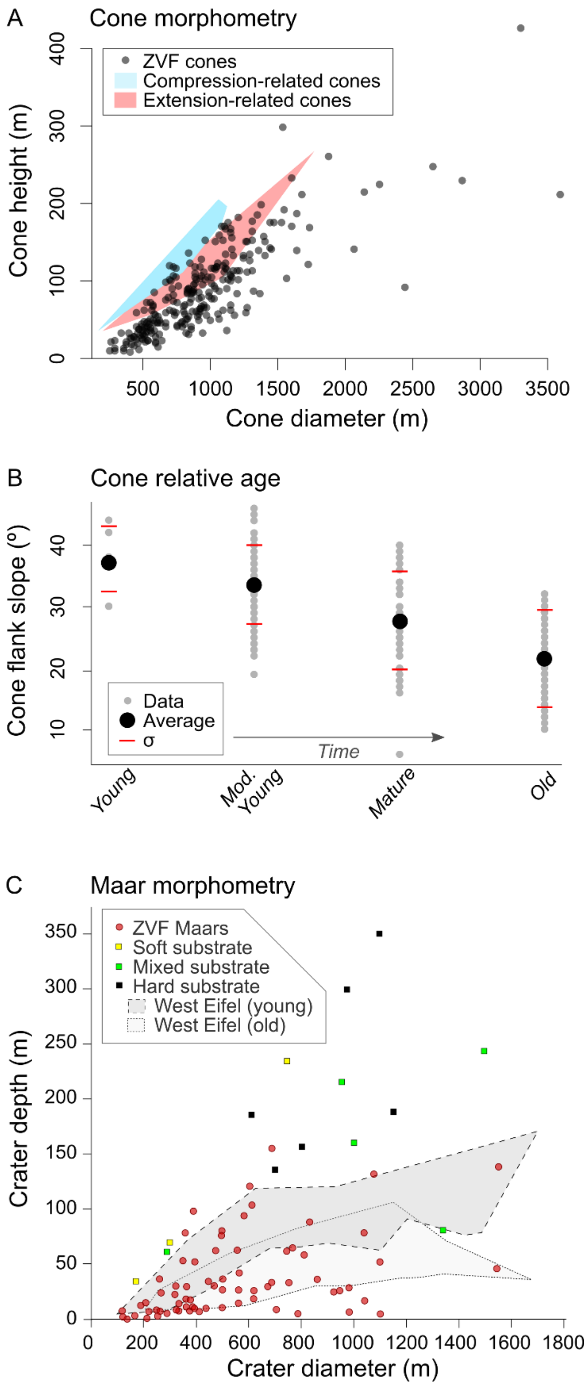


**Fig. 12.** Morphometric comparison of monogenetic landforms presents at ZVF: A) cinder cones morphometry, modified from Fornaciai et al. (2012); σ = standard deviation; B) relative age morphometry; C) maars morphometry and its relationship with substrate styles, modified from Ross et al. (2011).

*5.2 Spatial distribution*

Monogenetic volcanoes in the ZVF present an average vent density of 0.015 vents/km$^2$. When compared to other monogenetic fields, the ZVF average density is higher than values obtained for the Southern Puna Plateau (0.008 vents/km$^2$; Haag et al., 2019), lower than the San Rafael (0.071 vents/km$^2$, in the USA; Kiyosugi et al., 2012), and significantly lower than the Auckland (0.146 vents/km$^2$, in New Zealand; Le Corvec et al., 2013) and the Michoacán (0.260 vents/km$^2$, in México; Pérez-López et al., 2011) volcanic fields. In contrast, the ZVF maximum vent density of 0.144 vents/km$^2$ is comparable to values obtained for the Southern Puna (Haag et al., 2019; Morfulis et al., 2020). Similarly to other monogenetic fields (e.g., Puna Plateau), the higher vent densities in ZVF are observed in the center of the monogenetic field, in cluster 5 (Fig. 7B).

The interplay of tectonics and magmatism controls the distribution of monogenetic volcanoes (e.g., Báez et al., 2017). The understanding of these dynamics and its surface expression has been the focus of several studies (e.g., Tibaldi, 1995; Tadini et al., 2014). Based on the distribution pattern of monogenetic vents in the Southern Puna Plateau, Morfulis et al. (2020) suggest two styles for monogenetic volcanic fields: (I) fields controlled by magmatic activity, with clustered pattern (R-statistic$\rightarrow$ 0.0) and (II) field controlled by tectonics, with Random and Poisson distribution pattern (R-statistic$\rightarrow$ 1.0).

The monogenetic vents in the ZVF present three distribution patterns: clustered (cluster 1, 5, and 9), Poisson distribution (clusters 3 and 8), and dispersed (cluster 2, 4, 6, and 7). This complex pattern is likely related to different magma production rates through the ZVF, where clusters 1, 5, and 9 would represent regions of relatively high and/or long-lasting magma supply (Báez et al., 2017; Morfulis et al., 2020).

*5.3. Tectonic and structural implications*

The Southern Andes is marked by a strong oblique component in the subduction of the Nazca Plate under the South American Plate (Fig. 1A; Stern, 2004). This setting offers a unique opportunity to explore the interplay of volcanic systems and tectonics. The oblique deformation in the Central SVZ is mainly accommodated by the 1200 km-long LOFZ (Cembrano et al., 1996), which controls the distribution of polygenetic volcanoes in the current volcanic arc. To date, the effects of this oblique tectonics on volcanism have been explored by a few studies mainly focused on the orientation and morphology of stratovolcanoes located in the magmatic arc (e.g., Lara et al., 2006; Melnick et al., 2006; Sielfeld et al., 2017).

Cembrano and Lara (2009) identify two sets of volcanic associations in the eastern (Chilean) SVZ based on volcano morphology and distribution: (1) NE-trending volcanoes that reflect the current tensional regime and (2) stratovolcanoes associated with ancient basement reverse and strike-slip faults and monogenetic cones along the LOFZ that diverge in orientation with the current tensional regime. These observations combined with structural data suggest an overall NE-SW trending maximum compressive stress ($\sigma 1$) orientation at the magmatic arc (Fig. 13A; Cembrano and Lara, 2009 and references therein; Melnick et al., 2006; Sielfeld et al., 2017). In contrast, studies about the morphology of monogenetic volcanoes and they relate to stress state in the back-arc SVZ are still scarce.

Based on edifice morphology and vent alignment, our data suggest that monogenetic vents in the CSVZ are preferentially emplaced along NE-SW and E-W trending structures (Fig. 10G). It is important to note that this result is consistent across different values of basal cones ellipticity, and even better constrained when considering only cones with ellipticity $< 0.8$ (Fig 10D). This suggests some common underlying control on the emplacement of the monogenetic cones in the study area. Therefore, this orientation can be used to infer the stress state (e.g., Le Corvec et al., 2013; Marliyani et al., 2020) in the CSVZ back-arc region, implying a maximum horizontal compressive stress ($\sigma Hmax$) with NE-SW to E-W direction, in agreement with Quaternary stress orientation (Cembrano and Lara, 2009) (Fig. 13). The E-W orientation is also in agreement with several structures that control the emplacement of lavas on the Copahue Volcano (Bonali et al., 2016).

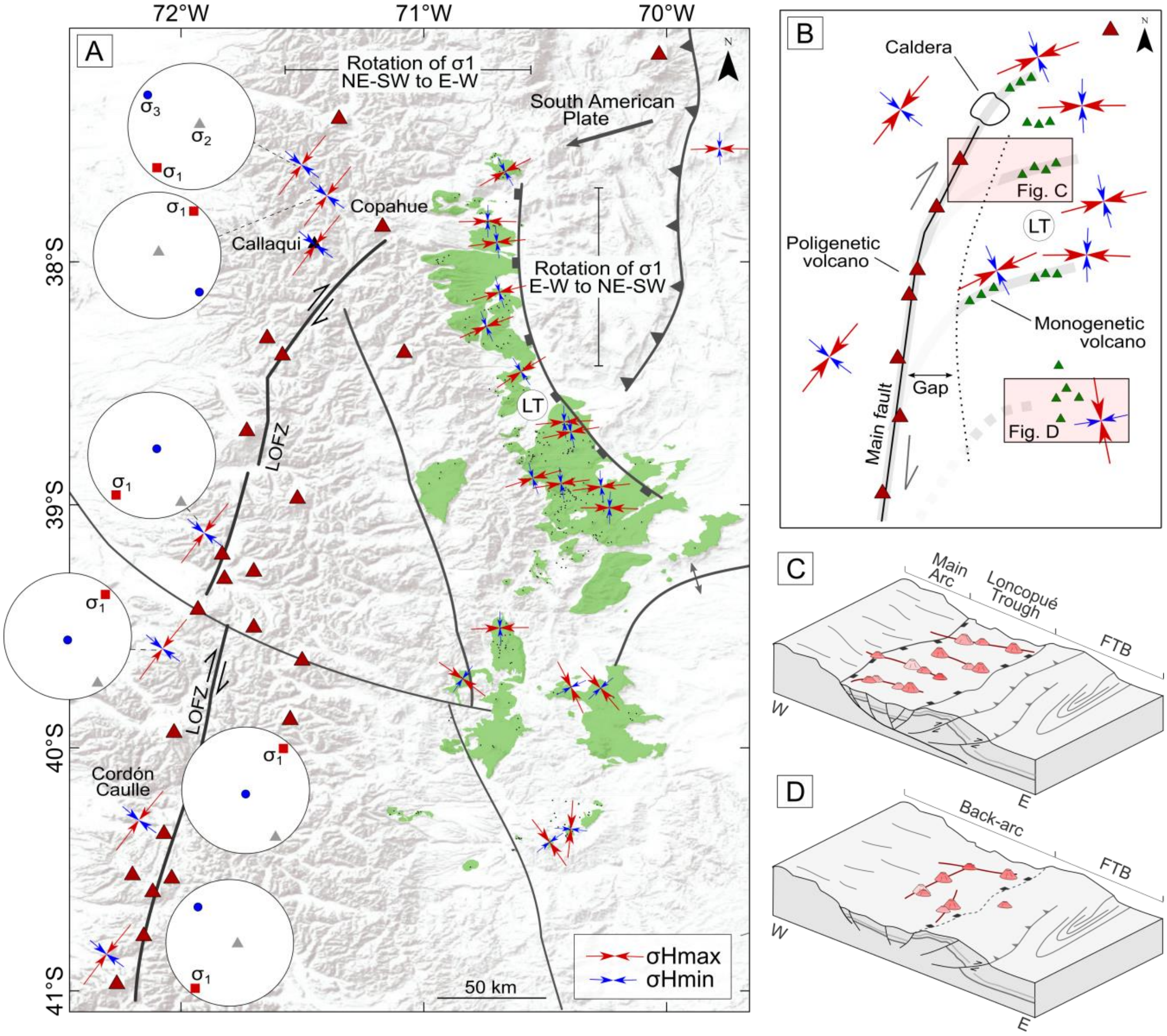


**Fig. 13.** Tectonic model for monogenetic volcanism in the CSVZ: A) regional map with main structural features, polygenetic volcanoes, and monogenetic deposits. B) Conceptual model for the emplacement of monogenetic volcanoes in the CSVZ; C) detail of the Loncopué Trough region next to cluster 5; D) detail of the southern CSVZ. Stereoplots indicate available data from the literature (Lara et al., 2006; Melnick et al., 2006; Cembrano and Lara, 2009, Pardo et al., 2006; Lange et al., 2008; Potent and Reuther, 2001; Rosenau et al., 2004; Lavenu and Cembrano, 1999; Arancibia et al., 1999; Sielfeld et al., 2017). Legends are the same as Fig. 1. LT = Loncopué Trough, FTB = Fold and thrust belt.

Our data reveals that back-arc monogenetic vents seem to concentrate along secondary faults that diverge from the LOFZ (Fig. 13A), possibly because of the strong oblique component acting on the CSVZ. In transtensional environments, secondary structures can diverge from the master fault, forming imbricated fans of extensional fractures (Kim et al., 2003; Fig. 13B). To date, the occurrence of monogenetic volcanism associated with these structures has only been observed in the Wulanhada volcanic field, in Northern China, where a strike-slip dextral fault accommodates deformation and controls the distribution of monogenetic volcanoes (Zhao et al., 2019). In contrast, Wulanhada deposits are considerably smaller (in area) when compared to the CSVZ, with only 41 vents and deposits that cover ~ 180 km$^2$ (Zhao et al., 2019).

Another important feature in the CSVZ is the Loncopué Trough (Rojas Vera et al., 2014; Pesce et al., 2019; 2020). Located between the main volcanic arc and the Agrio Fold and Thrust Belt, this 300 km long extensional structure controls the occurrence of monogenetic volcanism (Rojas Vera et al., 2014; Fig. 13A, C). Inside the Loncopué Trough, the monogenetic magmatism develops as continuous lava plateaus from early Pliocene to present (Rojas Vera et al., 2014). Based on fieldwork and geophysical data, the Loncopué Trough seems to be associated with tearing of the subducted Nazca plate underneath the South American Plate, resulting in abnormal heat flow in the region (Rojas Vera et al., 2014). In this scenario, monogenetic activity seems to be controlled by the extensional regime at the Loncopué Trough, in addition to the oblique tectonics of the LOFZ.

In this setting, the growth and orientation of monogenetic volcanoes can be extensively controlled by transcurrent faults (e.g., Pasquarè and Tibaldi, 2003; Tibaldi and Bonali, 2018; Tibaldi et al., 2017; Zhao et al., 2019). However, Pasquarè and Tibaldi (2003) show that dykes are emplaced parallel to the regional σHmax, regardless to the volcano/fault proximity. This could explain why most monogenetic volcanoes in the ZVF present ENE-WNW trending basalt elongations and alignment, in accordance with the regional shortening induced by the Andean orogeny.

Monogenetic volcanoes in CSVZ also reveal changes in σHmax direction, which seem to be mainly controlled by their distance to the master LOFZ, or possibly by interference secondary structural features in the Loncopué Trough and the fold and thrust belt (Fig. 13A, B, C). The north end of the monogenetic field is marked by NE-SW-trending σHmax, almost parallel to σHmax observed in the main magmatic arc (Fig. 13A). This orientation is compatible with extensional faults and *horsetail splays* frequently observed at the end of strike-slip structures such as the LOFZ (Kim et al., 2003). The northern limit of the Loncopué Trough is marked by a significant change in the σHmax from NE-SW to the E-W (Fig. 13A). This σHmax E-W direction progressively rotates toward NE-SW was we move south in the Loncopué Trough (Fig. 13A). There is another significant change in the σHmax at ca. 38º30’, where σHmax becomes E-W oriented (Fig.

13A). Further south in the CSVZ, σHmax becomes less constrained and presents variable orientations, including NW-SE, NNW-SSE, and N-S (Fig. 13D).

Changes in the stress orientation using volcano morphology have been recently reported in the Java Volcanic Arc (Marliyani et al., 2020). The authors associated the progressive changes in σHmax to relative plate convergence and upper plate structure, while abrupt changes are linked to the presence of preexisting structures, as well as to interference of polygenetic volcanoes (Marliyani et al., 2020). Differently from Java, monogenetic volcanoes in the CSVZ are predominantly located several kilometers away from the main volcanic arc (Fig. 1B). In this context, the only cluster expected to suffer influence from the arc is cluster 9, which presents a bimodal distribution of basal elongation (Figs. 9A, 9F).

*5.4. Timing and recurrence of monogenetic activity*

Absolute ages are scarce for ZVF and mainly concentrated at ~ 39°S.  Most results indicate quaternary ages for the monogenetic activity, although the presence of multiple magmatic pulses is still unclear. Samples from the Loncopué Trough indicate ages between $2.30 \pm 0.3$ and $0.47 \pm 0.2$ Ma (K- Ar whole-rock; Linares & Gonzalez 1990). Ages of $0.130 \pm 0.02$ $0.167 \pm 0.005$ $2.50 \pm 5$ and $809 \pm 12$ ka are also reported for basaltic lavas further along the same structure ($^{40}Ar$-$^{39}Ar$; Rabassa et al., 1987; Rojas Vera et al., 2014). Additional ages ranging from $1.6 \pm 0.2$ and $0.9 \pm 0.3$ Ma (K-Ar whole-rock) are also reported by Muñoz & Stern (1985, 1988) for samples in the Pino Hachado region, in the southermost ZVF.

In this scenario of scarce absolute ages, relative age maps offer an alternative method for mapping the monogenetic activity through time (e.g., Haag et al., 2019). The interpolated relative age maps (Fig. 11) suggest a waning monogenetic activity in the ZVF over time: while the older monogenetic volcanoes are widespread in the ZVF (Fig. 11D), the younger landforms seem to be focused in the central segment of the volcanic field (Fig. 11A), near to the Zapala and Loncopué towns.

Geological mapping and fieldwork in the study area also suggest multiple episodes of monogenetic activity in the region (Rojas Vera et al., 2014; Pesce et al., 2019). Intercalated basaltic flows and glacial deposits are reported along the Loncopué trough (Folguera et al., 2003b), suggesting at least two magmatic pulses in the region. Additional mapping by Báez et al., (2020) in the Caviahue-Copahue Volcanic Complex indicates the occurrence of at least two glaciations in the region (at 57-29 ka and/or 26.5-19.0 ka and at 14.5-11.9 ka). The 809 Ka basaltic flows are incised by a glacial valley in the western Loncopué Trough (Rojas Vera et al., 2014). These glacial valleys also control emplacement of younger, post-glacial activity with estimated ages to be less than 27 ka (Rojas Vera et al., 2014).

Monogenetic eruptions can be triggered by several factors decause of their shallow magma chambers. Bonali et al. (2013) report stress changes induced by earthquakes in the SVZ. In the area, several earthquake-induced eruptions of can occur as far as 500 km from the epicenters (Bonali et al., 2013). This finding highlights the role of earthquakes in inducing monogenetic activity, specially in subduction zones such as the SVZ.

The predominance of E-W and NE-SW feeding systems in the CSVZ is at odds with the regime responsible for the development of the Loncopué Trough, which is mainly associated with N-S normal faults developed under a E-W extension (Rojas Vera et al., 2014). This information suggests a decoupling between the stress state recorded by monogenetic feeding systems and the structural setting at the Loncopué Trough. Curiously, numerous N-S trending normal faults cut the monogenetic deposits to the east of Caviahue and next to the Loncopué Town (Rojas Vera et al., 2014; Pesce et al., 2019), suggesting ongoing deformation of the quaternary monogenetic volcanism.

### *5.5. Comparison with monogenetic fields in the Central Andes*

For a long time, the study of monogenetic volcanoes has been hampered by the coarse resolution of DEMs and imagery data. Therefore, a greater focus has been placed on the study of large, polygenetic volcanoes. However, in recent years, the available high-resolution DEMs allowed the identification of thousands of monogenetic volcanoes in the Andean Cordillera.

Most of these studies have been focused in the Central Volcanic Zone of the Andes (CVZ; 18-28º S; e.g., Maro and Caffe, 2016; Tibaldi et al., 2017; Tibaldi and Bonali, 2018; Filipovich et al., 2019; Haag et al., 2019; Grosse et al., 2020; Morfulis et al., 2020; Ureta et al., 2021c). In contrast, studies involving geomorphologic characterization of monogenetic volcanoes in the Southern Volcanic Zone (SVZ) of the Andes are still scarce. In this section, we compare our results obtained at the ZVF (in the Central SVZ) with the available data for the CVZ (mainly for the southern Puna Plateau). A summary of this comparison is presented in Table 2.

Monogenetic volcanoes in the ZVF present a higher number of phreatomagmatic volcanoes (20%) when compared to other monogenetic fields in the Andes, such as the southern Puna Plateau (Haag et al., 2019). This difference could be attributed to climate variations between these regions: while the ZVF is marked by a wet climate with the presence of lakes and vegetation, the Puna Plateau sits above 3 km and comprises one of the aridest regions on Earth. The presence of sedimentary rocks of the Neuquén Basin as underlying units in the ZVF may also contribute to the occurrence of phreatomagmatism. In contrast, overlying units in the southern Puna Plateau are mainly metamorphic and igneous rocks (Schnurr et al., 2006, Seggiaro et al., 2006).

Another important fact to be considered is the absence of lava domes in the ZVF. Conversely, flat-topped and irregular lava domes are expressive and widespread monogenetic landforms in the southern Puna Plateau (Haag et al., 2019), as well as in the entire CVZ of the Andes (Ureta et al., 2021). We interpret this absence of lava domes in the CSVZ as a result of contrasting melt compositions and evolution in these two areas. Magmas associated with the ZVF are mainly basalts with arc to back-arc signatures (Varekamp et al., 2010; Rojas Veras et al., 2014). In contrast, the monogenetic volcanism in southern Puna Plateau includes more evolved terms, such as basaltic-andesites and andesites.

In this scenario, the presence of lava domes may reflect contrasting petrogenetic conditions in the CVZ and SVZ: while the southern Puna is marked by crustal thickness of ~70 km (Trumbull, et al., 2006), the ZVF crust is considerably thinner, ranging from 30 to 35 km (Munizaga et al., 1988; Nelson et al., 1993; Stern 2004), yielding less evolved magmas and the absence of lava domes.

**Table 2.** Comparison of monogenetic volcanism in the SVZ and the CVZ of the Andes.

| Parameters | Region of the Andes | |
|---|---|---|
| | South (Central SVZ at ZVF) | Central (Southern Puna Plateau) |
| Edifice morphology | 80 % Cinder Cones<br>20% Pheatomagmatic<br>0% Domes | 76% Cinder Cones<br>15% Domos<br>7% Pheatomagmatic<br>(Haag et al., 2019) |
| Cone diameter - Wco (m) | 246 to 3590 | 200 to 3800<br>(Haag et al., 2019) |
| Cone height- Hco (m) | 7 to 426 | 2 to 308<br>(Haag et al., 2019) |
| Average vent density (vents /km²) | 0.015 | 0.0083<br>(Haag et al., 2019) |
| Maximum vent density (vents /km²) | 0.144 | 0.149 to 0.237<br>(Haag et al., 2019, Morfulis et al., 2020) |
| Exogenous controls - climate | Dry and wet | Predominately dry<br>(Filipovich et al., 2019; Haag et al., 2019) |
| Subduction style and regional σ1 | Oblique, NE-SW<br>(Lara et al., 2006 and references therein) | Almost orthogonal, NW-SE (Marrett and Emerman, 1992) |
| Vent alignment | E-W to ENE-WSW (primary) and N-S (reactivated?) | NNE-SSW (reactivated); NW-SE (normal; strike-slip)<br>(Haag et al., 2019) |
| Monogenetic magmatism | Waning | Waxing (Haag et al., 2019) |
| Crustal thickness | 30- 35 Km (Munizaga et al., 1988; Nelson et al., 1993; Stern, 2004) | ~ 70 Km (Trumbull et al., 2006) |
| Geochimical origin | Arc to back-arc<br>(Varekamp et al., 2010; Rojas Vera et al., 2014) | Lithospheric delamination<br>(Kay and Kay, 1993) and foundering (Schoenbohm and Carrapa, 2015) |
| Age | 2.3 Ma - Recent (Linares & Gonzalez 1990; Rabassa et al., 1987; Muñoz & Stern 1985, 1988) | 9.0 Ma - Recent<br>(Risse et al., 2008; Drew et al., 2009; Schoenbohm and Carrapa, 2015) |

## 6. Conclusions

In this work, we combine imagery and digital elevation models to map the occurrence of monogenetic volcanoes in the back-arc region of the Central Southern Volcanic Zone (CSVZ) of the Andes. The main conclusions are:

1. The CSVZ presents a predominance of cinder cones (80%) followed by a significant number of phreatomagmatic volcanoes (20%). This data implies the strombolian as the main eruption style but also reveals an important role of water and hydromagmatism in the eruption dynamics of monogenetic vents. The occurrence of phreatomagmatism is either associated with climate (elevations below 1.600 m a.s.l.) or geological controls (basement porosity and water availability).

2. Monogenetic volcanoes are grouped into nine clusters. The higher vent densities are observed in the center of the CSVZ to the south of the Loncopué Though. Each cluster is marked by contrasting vent distribution and organization that reflect the interplay of tectonics and magmatism (e.g., Báez et al., 2017; Morfulis et al., 2020).

3. Monogenetic vents show a clear association with local and regional lineaments, suggesting a strong structural control on the occurrence of monogenetic deposits. The main controls on the distribution of monogenetic vents are the oblique tectonics of the Liquiñe-Ofqui Fault Zone and the extensional Loncopué Though.

4. Based on edifice morphology and distribution, monogenetic volcanoes are preferentially emplaced along NE- SW and E-W trending structures that reflect the stress state in the CSVZ (e.g., Le Corvec et al., 2013; Marliyani et al., 2020).

5. With scarce absolute ages for the region, relative age offers an alternative approach to map monogenetic activity over time. This data suggests a decrease in the aerial extend of monogenetic activity in the CSVZ.

6. When compared to monogenetic deposits in the Central Andes, the Southern Andes are defined by higher vent densities, a higher number of phreatomagmatic landforms, and the absence of lava domes. This likely reflects climate and crustal structure differences of these two regions.

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