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Unveiling a major strike-slip fault system associated with the Somún Curá Large Igneous Province in central Patagonia, Argentina

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ABSTRACT

This study presents new evidence of a major, regional strike-slip fault system linked to the emplacement of the Somún Curá Large Igneous Province in central Patagonia, Argentina. Employing a combination of remote sensing techniques and fieldwork, we provide additional insights into the structural complexities underlying this magmatic province, shedding light on its geological evolution. Our findings indicate a compelling correlation between the magmatic products of the Somún Curá Large Igneous Province and the left-lateral strike-slip fault system, resembling similar relationships observed in other magmatic large igneous provinces. Moreover, the strike-slip tectonics delineated in this study likely represent the culmination of the fault system's evolution, possibly originating from a longstanding basement fault and extending beyond the limits of the Somún Curá basaltic plateau.

1. Introduction

The Somún Curá plateau stands out as one of the most prominent geomorphological features in the northern extra-Andean Patagonia (Fig. 1). Its formation is linked to the effusion of a basaltic plateau during the Oligocene and part of the Miocene in the Andean foreland (Somún Curá Large Igneous Province after Kay et al., 2007). Characterised by its uniform composition, it primarily consists of olivine-bearing basalts with varying degrees of vesiculation. Petrologically, its origin is associated with mantle thermal anomalies that interacted with the Andean subduction margin during the Oligocene. Although a fissure-type effusion mechanism has been suggested, there has been no comprehensive structural analysis to fully assess the relation between a regional fault system and the emplacement and eruption of the basaltic. However, some regional lineaments and structures have been suggested to be related to certain effusive centres (Volkheimer, 1973; Salani et al., 2010; Remesal et al., 2012; Cordenons et al., 2020), the most illustrative examples of the relationship between this volcanism and tensile fissures that might have functioned as conduits are represented by small, restricted alignments of monogenetic vents and lava flows (Corbella, 1973, 1974; Yllañez and Lema, 1978; Ardolino, 1981; Giacosa et al., 2007). Moreover, an epeirogenic uplift linked to the weakening of the lithosphere due to a thermal anomaly has been proposed as the mechanism to produce the topographic plateau (Aragón et al., 2011; Gomez Dacal et al., 2017, 2021). According to this proposal, the Somún Curá plateau had worked as a rigid block uplifted along regional lineaments. This idea disregards the internal deformation of the crustal block and a further connection with major faults outside the plateau.

The relation between magmatism and tectonism constitutes a substantial study area within geosciences, which has been extensively explored in numerous research papers. Crucial aspects for this investigation include: 1) the active role of fractures and faults in magmatic processes; 2) the temporal correlation between tectonic events and magmatic activities; 3) whether multi-episodic magmatism is linked with multi-episodic faulting; furthermore, the impact of changes in tectonic regimes on the relationship between faults and magmatism remains a critical matter. Noteworthy instances of these interplay are observed in regions characterised by large effusive volcanism, such as Hawaii (Decker, 1987), Iceland (Hjartardóttir et al., 2012; Parks et al., 2023), Canary Islands (Carracedo, 1994), and even Mars (Wilson et al., 2009; Horvath et al., 2021). In these areas, extensive lava flows arising

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from faults, and other magma-related features such as craters, domes, and subvolcanic structures located aligned along fractures. The prevalent interpretation in these regions is often anchored in a dominant tensile tectonism, where magmatic stress takes a primary role in governing movements along tectonic features (Bourgeois et al., 2005). Nevertheless, complex and intriguing relationships have been proposed, particularly in scenarios where strike-slip faults are implicated in magmatic processes (Bellier and Sébrier, 1994; Acocella et al., 1999; Riller et al., 2001; Cooper et al., 2012; Upton, 2013; Spacapan et al., 2016; Troll et al., 2020). In such cases, long-lived basement faults are proposed as the principal structural elements that channel both tectonic and magmatic stress, thereby serving as the focal point for strain accumulation.

In this contribution, we present the interpretation of regional satellite imagery and local topographic survey focussed on the tectonic features present in the Somún Curá plateau, supported by local field observations, along with our understanding of the local and regional structural context. The aim is to provide insights into specific aspects related to the local and regional tectonics associated with the emplacement of the Somún Curá Large Igneous Province. A noteworthy finding is the identification of a regional strike-slip fault system affecting the basaltic plateau, with more than 100 km in length. The fault system trace geometry suggests this structure responded to a sinistral transtensional tectonics that would have operated synchronously with the emplacement and eruption of the igneous bodies that it contains, and the associated lava flows. Minor structures were inferred and linked to the same transtensional regime, thereby proposing new insights into the regional structural framework within which the Oligocene - Miocene back-arc magmatism developed in Northern Patagonia.

Henceforward, “Somún Curá plateau” will be used to refer to the large, relatively flat region in north-central Patagonia, highlighting its geomorphological significance (following Giacosa et al., 2021a), while “Somún Curá Large Igneous Province” (SCLIP) will be used in the sense described by Kay et al. (2007).

2. The Somún Curá Large Igneous Province summary

The earliest references to the Somún Curá plateau are from Wichmann (1927). This author presented a novel geological map of the entire area and attributed the initial petrographic descriptions of the constituent basaltic rocks of the plateau to Pastore (1915). Later, Ardolino (1981) grouped the basaltic rocks of the Somún Curá plateau within the homonymous formation. This unit is mainly composed of olivine-bearing, vesicular to amygdaloidal, basaltic lava flows and subvolcanic bodies (Stipanicic and Methol, 1972; Ardolino and Franchi, 1993; Kay Mahlburg et al., 2007; Remesal et al., 2018; among others). The Quiñelaf Superunit and Corona Chico Vulcanites are other lithostratigraphic units grouping part of the volcanic rocks and igneous bodies that compose the Somún Curá Large Igneous Province (Franchi et al., 2001; Ardolino et al., 1999; Remesal et al., 2001, 2002; Kay et al., 2007). The Somún Curá Large Igneous Province overlay different rock units spanning an age range from Cambrian to Paleocene (Remesal et al., 2018).

The Somún Curá Large Igneous Province (Kay et al., 2007) comprises

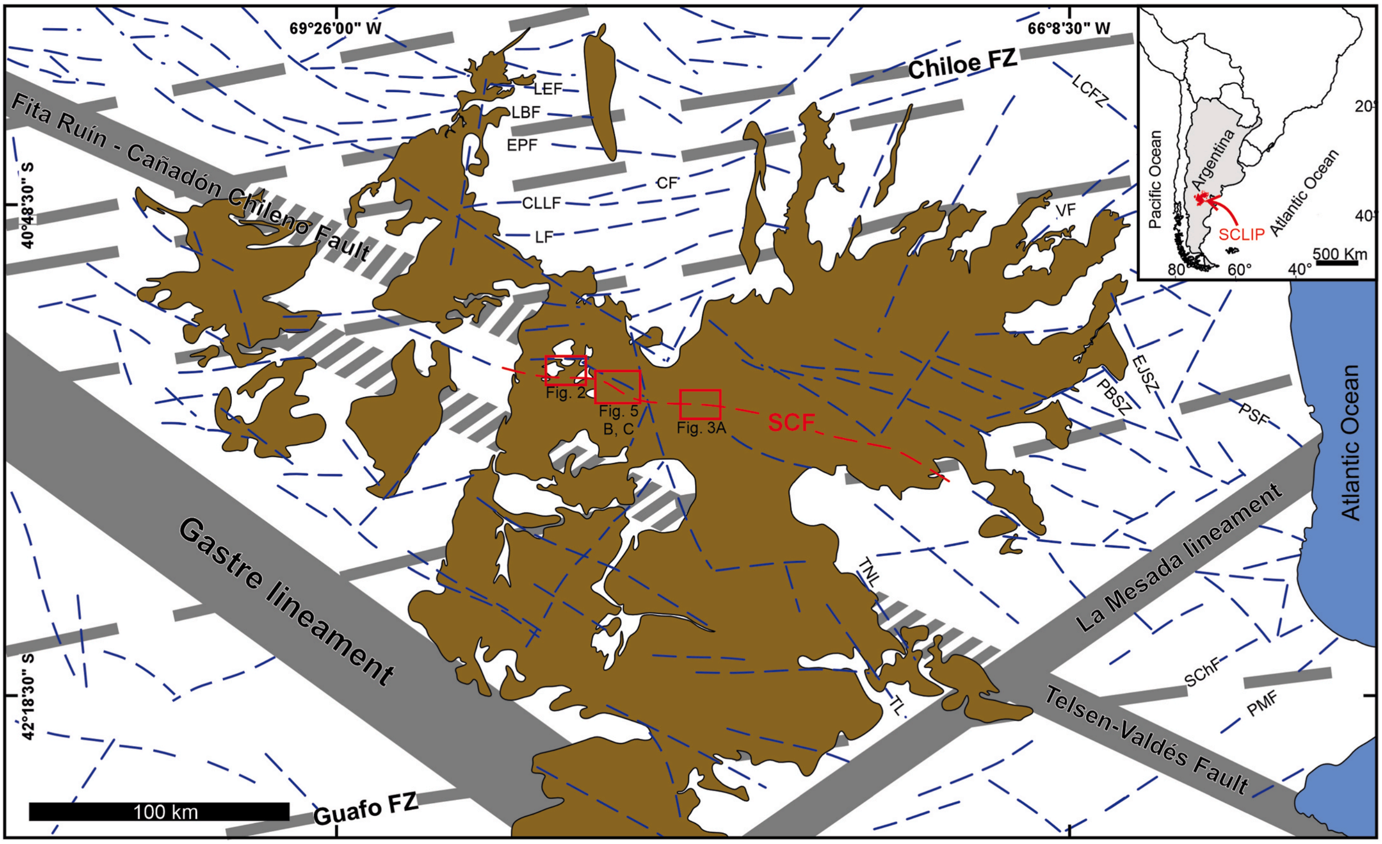


Fig. 1. Regional map showing the distribution of the Somún Curá Large Igneous Province (SCLIP; brown polygons in the map) and the location of the major structural lineaments (light-grey zones). Somún Curá Fault (SCF; see section 4.2 for explanation) is shown as a red dashed line, meanwhile the blue dashed lines represent structural lineaments in Northern Patagonia. Red squares show the location of further figures in this work. Cartography based on Coira et al. (1975), Rosenman (1975), Yllañez and Lema (1978), Page (1987), Cortés (1981), Ciciarelli (1990), Giacosa et al. (2007), Salani et al. (2010), Cordenons et al. (2020), Orts et al. (2021) and our data. Abbreviations: FZ – Fault Zone; LEF- La Esperanza Fault; LBF- Laguna Blanca Fault; EPF- El Piche Fault; CLLF- Cerro La Laja Fault; LF- Lagunitas Fault; CF- Choique Fault; VF- Valcheta Fault; PSF- Punta Sierra Fault; SChF- Sierra Chata Fault; PMF- Puerto Madryn Fault; TL- Telsen Lineament; TNL- Telsen Norte Lineament; LCFZ- Laguna Curico Fault Zone; EJSZ- El Jagüelito Shear Zone; PBSZ- Peñas Blancas Shear Zone.

volcanic rocks resulting from multiple eruptive episodes, many of which are associated with discrete eruptive centres (see Cordenons et al., 2020). Although the plateau's construction involves a combination and superposition of eruptive processes from various volcanic centres, three primary stages can be discerned in its construction (Kay et al., 2007; Cordenons et al., 2020). The onset of magmatic activity tied to the plateau's construction occurred during the early Oligocene (32–29 Ma). From the mid-Oligocene to the early Miocene (29–18 Ma), a peak in volcanic activity is believed to have led to the establishment of major volcanic edifices and the basaltic plateau. These first two stages constitute the plateau construction phase. The volcanic activity waned during the Miocene and concluded in the late Miocene (18–10 Ma) (post-plateau phase). Although there are reports of younger ages within the plateau's scope, their accuracy has been questioned due to analytical uncertainties (Cordenons et al., 2020). These phases do not carry any lithostratigraphic connotation, and their genetic significance has been extensively reviewed by Cordenons et al. (2020).

Different petrogenetic models have been postulated to explain the genesis of the Somún Curá Large Igneous Province, which were summarised by Remesal et al. (2018) and Salani et al. (2021). A prevailing consensus exists regarding the magma's origin, attributed to a mantle thermal anomaly associated with a subduction reconfiguration in the Andean margin during the Oligocene.

Regarding evidence of tectonic structures affecting the basaltic rocks from the plateau, Wichmann (1927) alluded to *encorvamientos* (bendings) and attributed its formation to *movimientos* (regional deformation events). About tectonic structures synchronous with the effusion and affecting the Somún Curá plateau, Yllañez and Lema (1978) have described annular basaltic dykes, using them to interpret a sinistral kinematic for the Telsen lineament. Regional features (i.e. Telsen – Valdés Fault System in Salani et al., 2010, Fig. 1) have been suggested as primary transtensive structure governing the emplacement and eruption of volcanic activity since it display certain geometric resemble with the distribution of volcanic centres (Salani et al., 2010; Remesal et al., 2012). Moreover, a regional geophysical anomaly has been recognized following a WNW-ESE to NW-SE trend across the North Patagonian Massif (Gimenez et al., 2019). Although, no structural analysis of these features has been conducted to shed light on their relationship with the basaltic plateau construction and evolution. Recent studies considered the Somún Curá plateau as a rigid crustal block that experienced epeirogenic uplift during the Cenozoic product of the weakening of the lithosphere due to a thermal anomaly (Aragón et al., 2011; Gomez Dacal et al., 2017; Gomez Dacal et al., 2021). To the north of the study area, Oligocene-Miocene, basaltic volcanic necks emplaced along faults of a Triassic oblique rifting process have been associated with a local extensional reactivation of the structures (Giacosa et al., 2007). In the southern region, encompassing the Cordillera del Buen Pasto, Sierra de la Buitrera, and Sierra Nevada (Chubut province), Giacosa et al. (2021a, b) have described and mapped folded Oligocene to Miocene basaltic lava flows. This deformation has been linked to the Miocene Andean pulse of compression and does not appear to be associated with the effusion of the lava flows.

Pre-Oligocene tectonics have been recorded in the Paleozoic and Mesozoic rocks, and described by several authors (Wichmann, 1927; Croce, 1956; Yllañez, 1979; Haller, 1981; Cortés, 1981; Page, 1987; Ciciarelli, 1990; Giacosa et al., 2007; Rapalini et al., 2013; Giacosa, 2020; Greco et al., 2015, 2021, 2022; González P. et al., 2020; González S. et al., 2021). Faults and shear zones described by the above-mentioned authors, are most related to the Paleozoic and Mesozoic evolution of northern Patagonia and might be related to lineaments observed in satellite images (Coira et al., 1975). Some of these tectonic structures constitute regional lineaments extended over 100 km and were described and analysed in the seminal works of Coira et al. (1975) and Nullo (1979), as the Fita Ruín – Cañadón Chileno Fault (Fig. 1). Additionally, Orts et al. (2021) have proposed a subduction-related control for ENE-WSW lineament development and crustal segmentation (Fig. 1).

2.1. About Cenozoic deformation cycles at the Andean subduction margin

There is a consensus about a contractional regime during the Cretaceous until the Paleocene-Early Eocene. From Eocene and during Oligocene, until Early Miocene, the tectonic regimen might have been extensional (Somoza, 1998; Somoza and Ghidella, 2005). The Oligocene regime change could be a reflection of changes in the geometry and convergence between South American and Farallon/Nazca plates (Salani et al., 2010). During the Miocene, the subduction conditions are reestablished producing a new compressive orogenic cycle. The ages of the Somún Curá Large Igneous Province place its climax during the Oligocene, coinciding with the extensional phase of the Andean orogeny (Remesal et al., 2012).

3. Methodology

Our main goal in this work was to delineate the geometry of tectonic structures, enabling the interpretation of fractures from satellite imagery linking their morphology with kinematics. Subsequently, we compared this morphotectonic and kinematic analysis with published analogue modelling studies to elucidate potential mechanisms underlying their formation.

Coira et al. (1975) and Rosenman (1975) produced seminal works on structural photointerpretation using Landsat imagery (ERTS) in the North Patagonian Massif. In the same way, we conducted photointerpretation over the study area using image galleries from satellite constellations such as Maxar, DigitalGlobe, Copernicus, Landsat, CNES, and Airbus. These constellations provide high spatial resolution images (0.3m) and are integrated into open-source software systems like QGIS, Google Earth, and ArcGIS Earth. Additionally, Landsat 8 and Sentinel 2 satellite images were acquired from the NASA and SENTINEL HUB services. The images were compiled in a Geographic Information System using QGIS free software. An Aster 1-arcsec topographic base was integrated into the GIS.

Using the previous information, we attempted to identify tectonic structures affecting the basaltic units of the plateau, and document their orientation, spatial-geometric relationships, and kinematics. The interpretation and depiction of structural lineaments, based on geological and geomorphological criteria, were manually recorded in the GIS as vector data. The detection of these features was made manually applying geological and geomorphological criteria. Straight and short lines were preferred for representation, aiming to simplify their depiction and avoid overinterpretation.

Models and diagrams were crafted using CorelDraw and based on the previously produced shapefile. The interpretation of the geometry and kinematics of the main structures draws from the studies of Anderson (1951), Riedel (1929) and Davis et al. (1999). Analogue models from Dooley and Mc Clay (1997), van Wyk de Vries and Merle (1998), Norini and Lagmay (2005), Holohan et al. (2008), Wu et al. (2009), Mathieu and van Wyk de Vries (2011) and Dooley and Schreurs (2012) were used to compare geometries and try to establish the kinematic of the observed structures.

A brief fieldwork was conducted in the Puesto Chico area (Fig. 2) in order to recognize morphological structures linked to the main structural lineaments interpreted from the satellite imagery. The presence of clear linear structures assimilable to fractures affecting different rock units, and the relative accessibility of the area were the key criteria for selecting this site for fieldwork activities. Preliminary cartography was checked and corrected in the field. We were unable to conduct a comprehensive structural survey as orientation measurements using a magnetic compass were hindered by the high magnetism of the basaltic rocks. During fieldwork, a survey flight was conducted using a DJI Mavic Pro drone along the southeastern border of the Carrilaufquen Depression, where the main structural lineament appears to be present. We

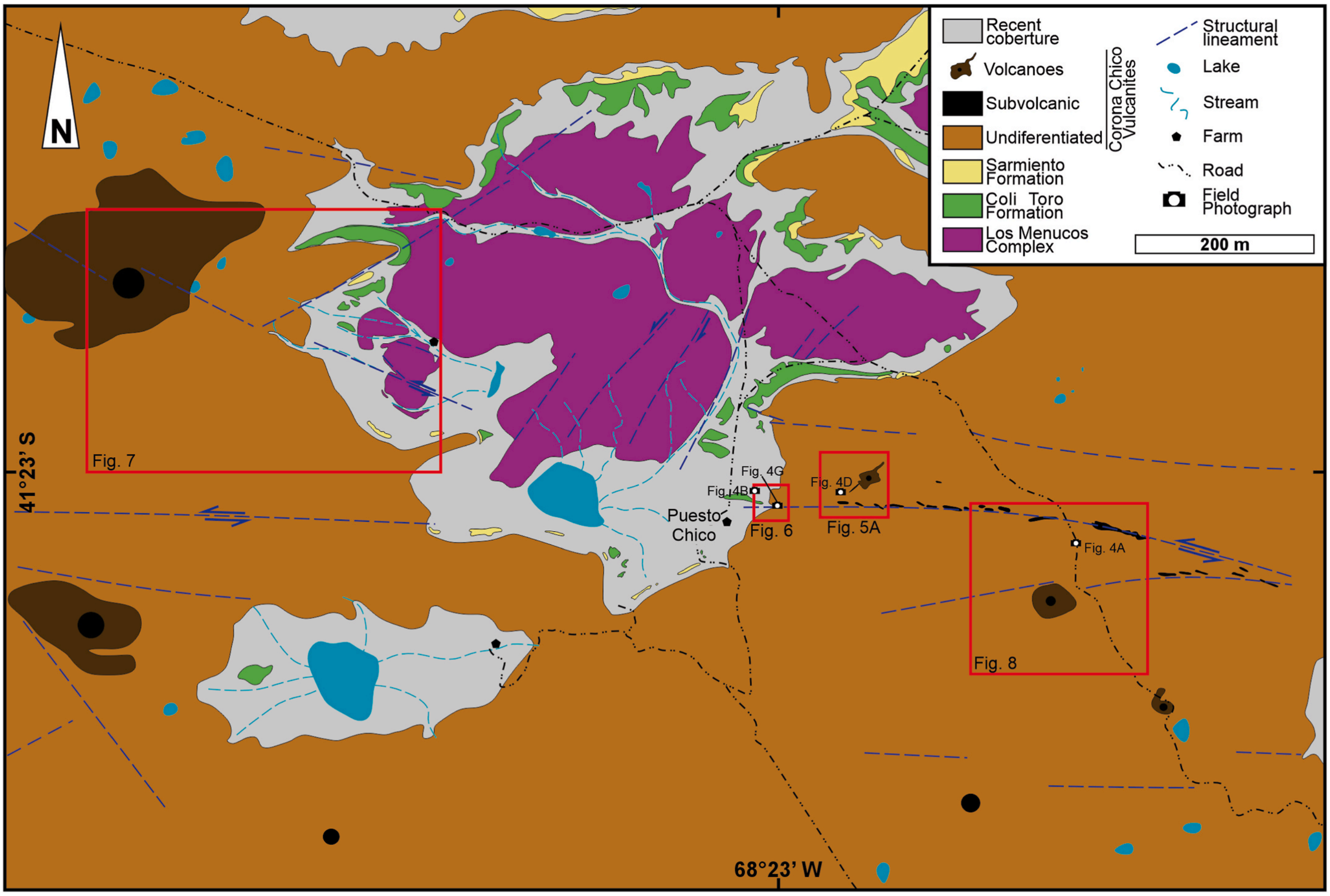


Fig. 2. Local geological map of the Carrilaufquen Depression – Puesto Chico area. The location of detail figures and field photographs (Fig. 4) are indicated by red squares and camera icons, respectively.

used the photographs obtained during this flight to create a photogrammetric 3D model of the outcrop using Agisoft Metashape Professional Edition (Educational License, version 1.5.2) software package. Based on this model, we also generated an orthomosaic and a digital surface model. The methodology followed in this task was described by González et al. (2022). Further details can be found in the supplementary file #1.

4. Results

4.1. Geometry and arrangement of structural features from satellite imagery

Based on the high-resolution satellite image photointerpretation, we identified a regional group of lineaments likely representing a regional fracture system affecting the Somún Curá plateau (Figs. 1 and 2). The system predominantly follows a WNW - ESE orientation with occasional bends developing E-W branches, or NW-SE curves. These fractures are observed eastwards of Carrilaufquen, exclusively affecting the basaltic rocks of the plateau (grouped into the Corona Chico Vulcanites and Somún Curá Formation by Remesal et al., 2001, 2002). They are discernible in satellite imagery, extending over 90 km to the SE (Fig. 1). A specific area has been chosen to illustrate the geometrical relationships of these fractures and present interpretations of their kinematics (Fig. 3A), which bears resemblance to the fracture arrangement derived by Cloos (1928) and Riedel (1929) for strike-slip tectonic analogue models (Fig. 3B). In this sector, a prevailing E-W trend of fractures is observable, albeit with a limited number of scattered features aligning in this direction (Fig. 3A). They correspond to the overall orientation of the fracture system, and we considered this direction as the Y fractures in Riedel's model (Fig. 3B). Notably, an ENE-WSW set of regularly spaced fractures, forming an en-echelon pattern, stands out as the most conspicuous feature oblique to the primary fractures trend (thick white lines in Fig. 3A). A change in rock colour is noticeable between the ENE-WSW fractures, resulting in a darker appearance. In the Chico Farm area (Fig. 2), we observed a similar phenomenon where subvolcanic intrusive bodies were emplaced within fractures affecting the basaltic plateau. Although these bodies have a basaltic composition, their texture differs from that of the surrounding basaltic lava flows. Based on this observation, we attribute the change to variations observed in other areas, likely indicative of subvolcanic bodies emplaced following the weaknesses generated by the tectonic structures. These fractures are 20°–25° from the E-W direction (α) and align consistently with R fractures from Riedel's model (Fig. 3B). An WNW-ESE set of irregularly spaced and discontinuous fractures, arranged at an approximate 20° angle from the E-W direction, could be interpreted as the P fractures from Riedel's model (Fig. 3B). A group of NE-SW basaltic dykes (Fig. 3A) could be interpreted as the extensional fractures of the model (Fig. 3B). Finally, a set of fractures, also irregularly spaced and discontinuous, follows an NNW-SSE direction. These could be comparable to contractional fractures from Riedel's model. According to the described geometry and its following interpretation, the fractures display in Fig. 3A might correspond to a left-lateral strike-slip fracture system developed under criteria proposed by Cloos (1928) and Riedel (1929). Similar fracture arrangements could be spotted all along the regional fracture system affecting the Somún Curá plateau, implying a geometrical consistency

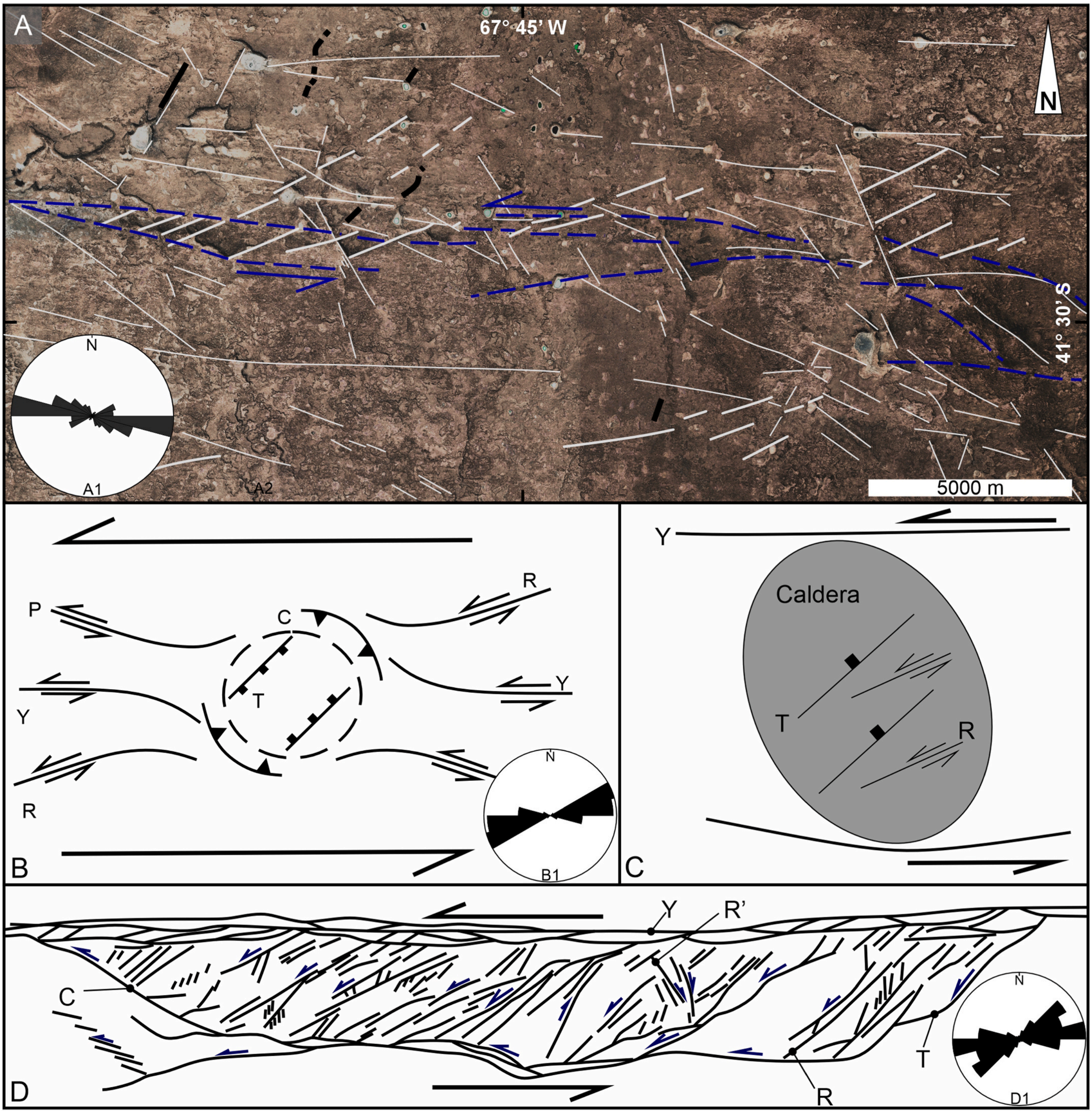


Fig. 3. A structural sketch from a sector on the Somún Curá Fault (see description in the text) to illustrate its fracture arrangement and compare it with theoretical and analogue models. A. structural lineament distribution in the Somún Curá Fault (position of this sector is depicted in Fig. 2). White lines correspond to interpreted minor structural lineaments (thick ones refer to R-type fractures see text for explanation), blue dashed lines show the main lineaments of the system interpreted as Y fractures (see text for details), and black NNE-SSW to NE-SW lines represent basaltic dykes recognized in the satellite image. The A1 rose diagram shows the lines' distribution and frequency; it has been constructed using QGIS Line Direction Histogram 3.1.1 plugin (n = 164). The rose was set with a 15° interval and weighting on length option was enabled; B. Simplified sketch of fracture developed during a Riedel's experiment (redrawn after van Wyk de Vries and Merle, 1998), the B1 rose diagram shows the frequency of fractures in the model (based on Dooley and Schreurs, 2012, Fig. 2, n = 102); C. Simplified model of the relation and structure of the Negra Muerta caldera with major strike-slip faults in Puna Argentina (redrawn after Riller et al., 2001); D. Fracture distribution in a fault zone outcrop at Cape Elizabeth (Maine) showing the sense of displacement (redrawn after Swanson, 2005), the D1 rose diagram shows the frequency of fractures in the example (based on Swanson, 2005, Fig. 5, n = 174). Letters in diagrams symbolise the nomenclature of Riedel's fracture model as follows, Y: Y fracture; R: R fracture; R': R′ fracture; P: P fracture; C: contractional fracture; T: tensile fracture.

for this structural fractures system and alluding it as a regional strike-slip fault system henceforth referred as the Somún Curá Fault.

4.2. Geological evidence from field and remote sensing observations at the Puesto Chico area

We refer here to a synthesis of the observed geology in the field together with local remote sensing observations, at the Puesto Chico farm, western Carrilaufquen (Fig. 2). The lithostratigraphic units are named after Remesal et al. (2001, 2002).

The Carrilaufquen area is a large, topographic depression surrounded by a scarp of tens of metres. At its bottom crop out igneous and pyroclastic rocks from the Los Menucos Complex. They comprise a layer-shaped body-rock intruded by acidic dykes, cut and displaced by NE-SW and WNW-ESE trending faults with sinistral strike separation (Fig. 2). At the base of the scarp and covering the Permo-Triassic rocks reddish sedimentary rocks from the Upper Cretaceous Colitoro Formation discontinuously crop out. Volcaniclastic, white to yellowish rocks are interbedded between the Colitoro Formation and Corona Chico Vulcanites; these rocks were assigned to the Eocene-Oligocene Sarmiento Formation.

The basaltic rocks identified in intrusive bodies and lava flows of the Somún Curá plateau in this area, display notable textural and compositional similarities rendering them nearly identical in hand-specimen samples. They typically appear as dark grey to black, predominantly aphyric, with variable vesicle content (Fig. 4A). These rocks are hypocrystalline and contain euhedral plagioclase, olivine, and pyroxene crystals. Regarding its age, these rocks have been proposed as Miocene (Remesal et al., 2001, 2002). Although there are no available radiometric ages in this area, within a 30 km radius several ages support these temporal constraints (see Cordenons et al., 2020).

The basaltic rocks of the Somún Curá plateau in this area have been assigned to Corona Chico Vulcanites (Remesal et al., 2001, 2002). Its lava flows had produced a flat high ground where later monogenetic volcanoes were constructed, and subvolcanic igneous bodies were emplaced (Figs. 4B and C). In some areas, erosion has gone deep enough to reveal the presence of subvolcanic dykes and necks, offering insight into the subvolcanic layers of the plateau and providing a unique opportunity to observe the relationship between volcanic and subvolcanic products. However, the surface of the plateau has a prominent soil development (20–50 cm) and abundant vegetal cover. This condition produces a reduction of the outcrops, making it difficult to recognize the contacts between rock bodies, which otherwise appear clearly in satellite imagery. We registered at the base of the Somún Curá basalts a laminar, continuous and homogenous basalts sheet (Fig. 4B). This layer exhibits evidence of vertical displacement caused by WNW-striking fractures. Aligned over these fractures several subvolcanic basaltic bodies and cinder cones can be recognized, (Figs. 2 and 4C). These subvolcanic bodies exhibit a rough foliation, aligned with their margins (Figs. 4D–F). Additionally, the plagioclase phenocrysts within them are orientated defining a vertical magmatic lineation parallel to the magmatic foliation.

From satellite imagery, we identified a series of fan-shaped blocky lava flows on the top of the basaltic plateau (Figs. 5A–C). They are characterised by a straight margin aligned with the fault on one side and a lobate margin on the opposite. Some of these lava flows, limited by lava levees, display pressure ridges on their surface, running parallel to the lobated front and curving concavely towards the fault direction (Figs. 5A–C). This configuration indicates a flow direction from the fault towards the frontal lobe, suggesting a fissure-effusion process. The emission centres of these lava flows are consistently located over the structural lineaments (Figs. 5A–C). All the mentioned observations regarding the relationship between the magmatic bodies and the structural lineaments suggest a fissure-related effusive volcanism in the Puesto Chico area.

During fieldwork in the Puesto Chico area, we addressed some aspects related to the morphology and nature of the regional WNW-ESE fracture system (Figs. 2 and 6A). At the southeastern margin of the Carrilaufquen Depression, where the regional WNW-ESE regional fault emerges, we identified a normal, conjugated shear fracture system striking N70°, affecting the basaltic plateau (Figs. 4B, G-I and 6A-D). The conjugated fracture planes dip at a high angle (~70°) both NNW and SSE (Fig. 4G). On these planes, oblique slickenlines pitching 70°–75° were recognized indicating dip-slip dominated displacement with a small strike-slip component (Fig. 4I). This fracture system might be part of the damage zone associated with a larger interpreted ENE-WSW normal fault situated 500 m to the south. A hundred metres eastwards, a basaltic dyke striking N55° crops out, emplaced in the basaltic plateau and tephra deposit from a nearby cinder cone (Figs. 4D–F). During the earlier fracture system description and analysis (section 4.1; Fig. 3A), we considered basaltic dykes as extensional fractures, and considering the similar orientation between the dyke and the normal conjugate shear fractures, we regard them as equivalents since they have geometric and kinematic consistency with the previously described left-lateral strike-slip fracture geometry. Additionally, in the same area, we identified a topographic step in the basaltic layer, interpreted as a fault coinciding with the WNW-ESE regional fault system. South of the fault, the top of the basaltic plateau lies approximately 10 m below the northern edge of the step (Figs. 4B and 6C-D). For a better visualisation of this phenomenon, we generated a photogrammetric model and a detailed digital surface model using images obtained by drone (Figs. 6B–D and Supplementary file #1). These products clearly depict the mentioned step, reinforcing the idea of vertical displacement of the basaltic layer by the regional fracture system. The step could be interpreted as a fault scarp of a dipping south plane. Also, fractures appear as linear features, particularly clear in the digital terrane model (Fig. 6C). These observations support the presence of WNW-ESE faults, along which normal separation occurred after the effusion of the basaltic plateau.

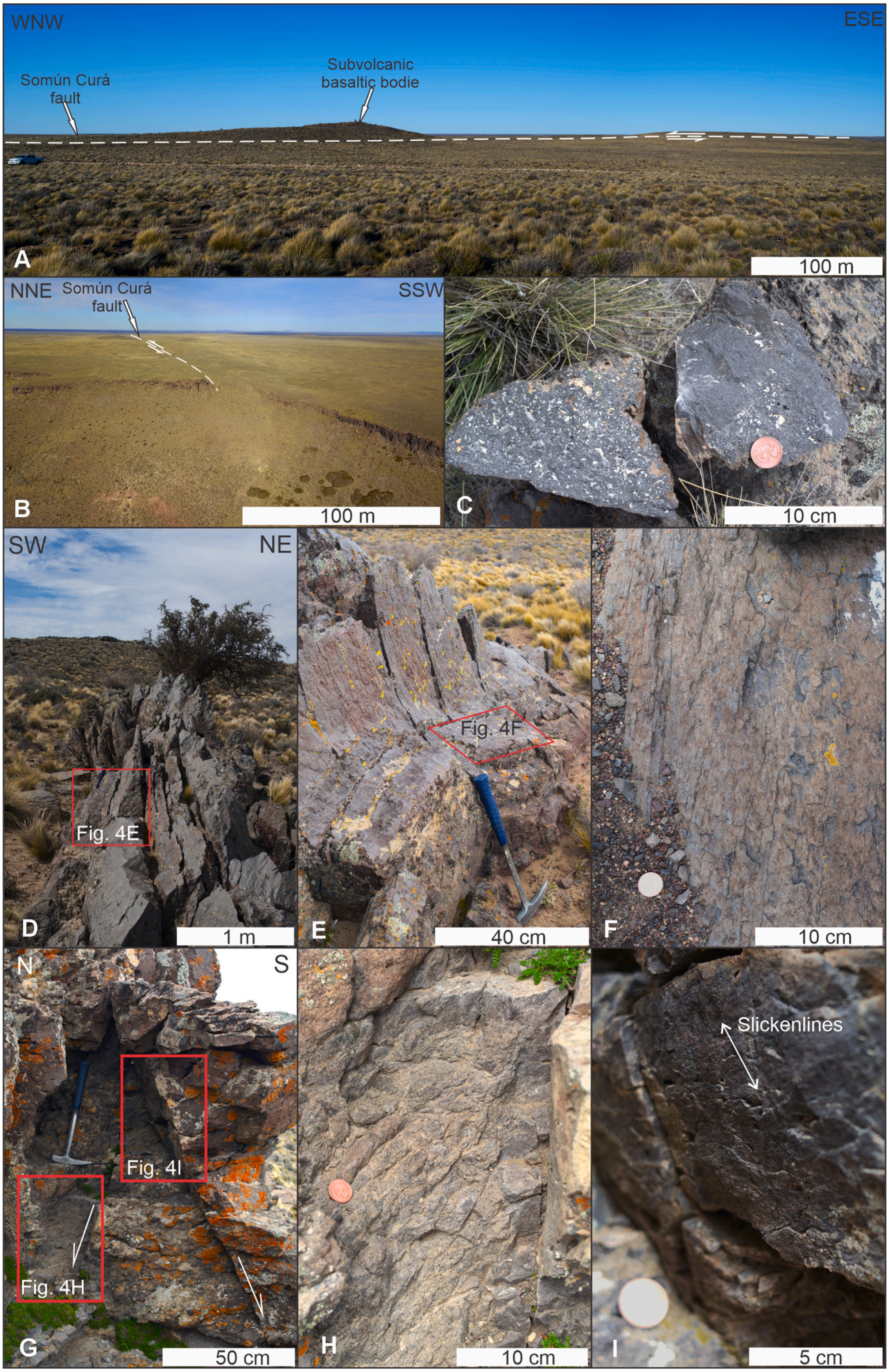
Within the Carrilaufquen Depression, rocks assigned to the Los Menucos Complex display fractures and faults (Fig. 2). WNW and NNW faults exhibit sinistral separation (Fig. 7), while NNE to NE faults show dextral separation. Although fractures associated with these faults are more prevalent in the Permo-Triassic rocks than in the basalts, cinder cones from the Somún Curá Large Igneous Province are located over the fault trace (Fig. 7). The geometric alignment of WNW faults with the regional lineaments system previously described is noteworthy. We have interpreted the WNW faults as linked to the regional fault system. The difference in fracture frequencies, considering the lineaments in the basalt as fractures, may indicate a long-lived fault with multiple reactivations, leading to the accumulation of deformation, as fractures, in the older rock units.

To the west of Carrilaufquen, extending beyond the plateau's influence area, the strike-slip fault system of the Somún Curá Fault appears to continue with the Fita Ruín – Cañadón Chileno Fault to the northwest. This coincides with the WNW path of the Maquinchao River and the southern margin of Cari Laufquen Grande Lake (Fig. 1). The Fita Ruín – Cañadón Chileno Fault has been interpreted as a Paleozoic basement fault with multiple reactivations during the Mesozoic and Cenozoic, with its last activity displaying a sinistral strike-slip movement (Nullo, 1979).

5. Discussion

5.1. Assessment of the Somún Curá Fault by comparison with analogue models

The analogue models presented by Cloos (1928) and Riedel (1929), and subsequent experiments building upon their foundations (for a comprehensive review, see Dooley and Schreurs, 2012), simulate the transmission of deformation from a basement fault to an overlying undeformed overburden. The fault is typically modelled as straight and vertical, susceptible to reactivation, which is a common characteristic of



(caption on next page)

Fig. 4. Field photographs of the Somún Curá Large Igneous Province and Somún Curá Fault (see section 4.2 for explanation) in the surroundings of Puesto Chico (position of each photograph is depicted in Fig. 2). A. hand specimens from the basalts of the Somún Curá Large Igneous Province, although are similar in colour and texture, is conspicuous the difference in vesicle content; B. Air view of the Somún Cura Fault line reaching the border of the Carrilaufquen Depression, the escarpment is due to the basaltic plateau ending; C. General view of the Somún Curá Fault and the subvolcanic bodies emplaced in it. Also, the flat landscape, and the soil and vegetation in the area are noticeable; D. subvolcanic basaltic dyke, in the background is a monogenetic cinder cone. Both igneous bodies are genetically related since they are placed over a structural lineament; E. Close-up on the dyke in (D), showing a fine-grain, foliated margin and a massive core; F. Detail of the foliated, fine-grain margin of the dyke in (D, E); G. High-angle conjugated normal shear fractures cutting the basaltic plateau at the Carrilaufquen Depression margin. They are dip-slip dominated since the striae have a near 80° rake; H. detail of the damage zone associated to the fractures in (H); I. Detail of the oblique slickenlines from the fault plane in (H) with a pitch value of 70–75° (dip-slip dominated fault).

basement faults. The experimental setup consists of two adjoining rigid baseplates with horizontal movement parallel to each other, simulating a vertical basement fault. The overburden rests horizontally on these baseplates. In these experiments, faults in the overburden are secondary, basement-rooted structures and restricted to its immediate vicinity. The resulting fracture pattern (Fig. 3B) has been traditionally analysed in surface view, which is appropriate for our assessment primarily based on satellite imagery analysis. As described previously, the fracture pattern observed in the Somún Curá Fault geometrically resembles Riedel's fracture arrangement (Figs. 3A and B). Therefore, we will now evaluate other aspects of the local geology to make a suitable comparison with Riedel's experiment and also assess other analogue models appropriate for comparison with structures present in the Somún Cura Large Igneous Province.

In Riedel's analogue modelling, the cohesion and thickness of the material constituting the overburden are key to predict and evaluate the resulting fracture pattern (Dooley and Schreurs, 2012). For instance, in a thin layer of wet clay (highly cohesive material), clear and regular R fractures will be produced meanwhile R′ fractures will be virtually absent. Because of its composition, we could assume a high cohesivity for the rocks from the Somún Curá plateau. Also, the thickness of the basaltic layer is highly variable and might reach 100 m, although the regular thickness is around a few to tens metres (Ardolino and Franchi et al., 2001; Franchi et al., 2001), Furthermore, in Carrilaufquen area the thickness of the Cretaceous to Miocene rocks laying over the Permo-Triassic rocks, and below the basaltic plateau, is around 55 m. As we previously described, the pre-Jurassic rocks (the basement in terms of Riedel's model) have a profuse deformation with multiple sets of fractures one of which is congruent geometric and kinematically with the Somún Curá Fault and other regional faults (Figs. 1, 2 and 7). Moreover, in the Los Menucos - La Esperanza area (to the north of the study area) local extensional reactivation of Triassic faults has been linked to the emplacement of Oligocene to Miocene volcanic necks (Giacosa et al., 2007). Considering the aforementioned factors, the observed fracture pattern of the Somún Curá Fault is consistent with a left-lateral strike-slip fault system probably developed through the reactivation of a basement fault affecting a relatively thin cohesive layer of basalt. Vertical separation, as recognized in the Chico farm area (Figs. 4B and 6C-D), is consistent with normal, WNW-ENE-striking faults developed in a left-lateral strike-slip Riedel's model fractures, as the one proposed for the Somún Curá Fault.

Building upon the models of Cloos (1928) and Riedel (1929), subsequent analogue model experiments have incorporated specific elements tailored to particular geological scenarios. Noteworthy among these is the work of van Wyk de Vries and Merle (1998), which explores the relationship between strike-slip tectonics and magmatism. In their study, the authors replicated Riedel's experiment while considering the load produced by volcanic activity. In this model, the resulting fracture pattern closely resembles that of the original experiment. However, what makes this model particularly intriguing is its examination of how a volcanic cone would deform and interact with tectonic structures (Fig. 8A). Volcanic cones typically appear circular when viewed from above, but in a strike-slip system, they deform into an elliptical shape (Figs. 8A and B). Furthermore, the construction of the cone produces a volcanic load that influences fracture kinematics by introducing a deep-slip component. This phenomenon is observed in certain monogenic cones within the Somún Curá Large Igneous Province (Figs. 8B and C). The volcanic load exerted on the fractures was evaluated as a triggering factor, where the extensional component induced by the volcanic load may lead to subsequent volcanic effusions, thereby increasing the volcanic load, and so forth. Given the similarity in fracture patterns to Riedel's experiment, the models proposed by van Wyk de Vries and Merle (1998) highlight the crucial role that volcanic loading could have in the evolution of the Somún Curá Fault. Additionally, the regional tectonic strike-slip faults may strongly affect the structural evolution of subvolcanic systems since they could function as discontinuity planes susceptible to being reactivated by magmatic stress (Holohan et al., 2008). The Negra Muerta caldera in the Argentinian Puna, as described by Riller et al. (2001), could be considered an example of the model proposed by Holohan et al. (2008) (Fig. 3C).

Finally, bends in fault trace geometry have been addressed to approach stress distribution and deformation evolution (Swanson, 2005; Mann, 2007). Asymmetric ripout geometries have been recognized at different scales, from outcrop to major crustal strike-slip fault zones, including normal oblique-slip faults as coupled extensional trailing ramps, and contractional ramps as oblique high-angle reverse faults (Swanson, 2005; Mann, 2007). An outcrop scale example from Swanson (2005) is included in Fig. 3D in order to show the similarities between the ripout geometry of realising bends with Riedel's geometry previously described for the Somún Curá Fault. Furthermore, the ENE-WSW fractures observed in the Somún Curá Fault are consistent with the normal oblique-slip faults proposed by Swanson (2005) (Figs. 3A and D).

5.2. *Strike-slip tectonics related to magmatic provinces: study cases*

As previously mentioned, the relationship between tectonics and magmatism has been extensively explored by authors worldwide. For instance, in the British and Irish Palaeogene Igneous Province, major strike-slip faults associated with significant geotectonic events have been proposed as key controlling factors in the magmatic evolution of the province (Geoffroy et al., 1996; Cooper et al., 2012; Troll et al., 2020).

On the Isle of Rum, the regional strike-slip Long Loch fault is widely believed to represent the feeder system of a layered magma reservoir, containing a variety of syntectonic magmatic products. This fault splays, defining a transtensional graben that may alternate between opening and closing episodes, acting as a pulsing magma conduit, and playing a critical role in the evolution of the shallow magmatic system (Troll et al., 2020). Palaeogene tectonic stresses in this area were influenced by a combination of different geotectonic events, including the opening of the North Atlantic, Alpine collision, and the formation of the Icelandic mantle plume, resulting in a complex interaction between tectonics and magmatism (Cooper et al., 2012). The orogenic compression, serving as the primary tectonic control, was periodically overwhelmed by dynamic stresses and uplift associated with pulsed mantle plume-related deformation, leading to associated strike-slip faulting that may have influenced the location of volcanic activity and central igneous complexes (Cooper et al., 2012).

To sum up, the Rum Igneous Centre represents a shallow-crustal magma chamber likely associated with basaltic eruptions of residual magmas, the location, and evolution of which were controlled by the strike-slip Long Loch fault. This igneous centre is described as a highly

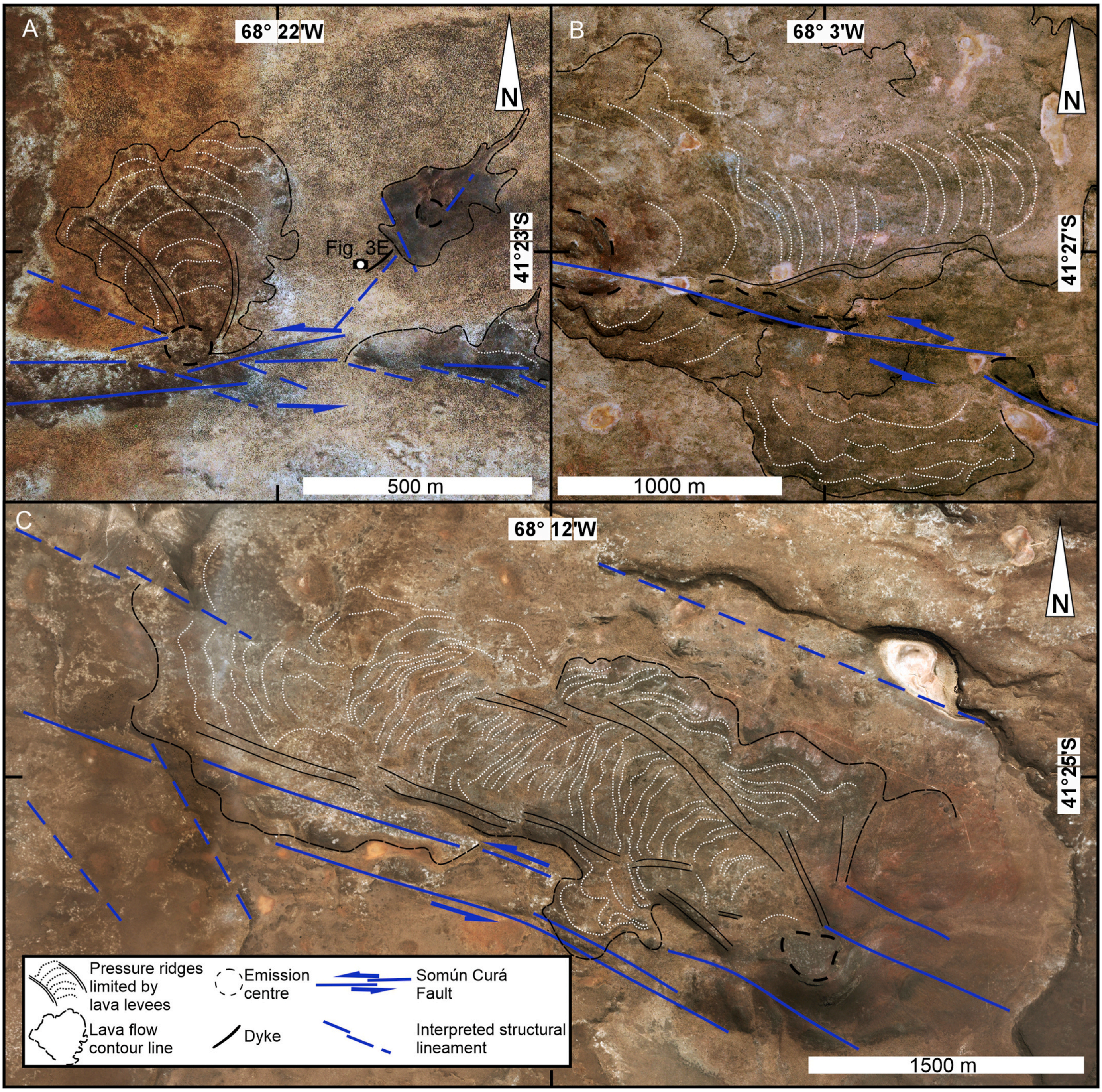


Fig. 5. Satellite imagery showing the presence of emission centres and associated lava flows near the Somún Curá Fault. Each figure outlines the presumed emission centre, lava flow contours, and internal structures such as pressure ridges and lava levees. The position of each sector is depicted in Fig. 2. A. Located near Chico Farm, a lava flow appears to have originated from an emission centre situated along the Somún Curá Fault. Pressure ridges indicate a northward flow direction. Additionally, a likely related NE-SW lineament (T-type fracture; see section 4.2) hosts a basaltic dyke aligned with a cinder cone; B. Situated 26 km east-southeast of Chico Farm, multiple emission centres are observed within the Somún Curá Fault, with associated lava flows displaying pressure ridges indicating an ENE flow direction. Notably, asymmetry is evident in the emission centres, possibly linked to the simultaneous activity of magmatism and tectonism in the area. C. An effusion centre (cinder cone) located 17 km ESE from Chico farm, emplaced over the Somún Curá fault and connected to a large lava flow with pressure ridges and lava levees development. The pressure ridges show a mainly NW flow direction, in this case, parallel to the Somún Curá fault.

dynamic fault-controlled tectono-magmatic system, where the intermittent extraction and the ascent of magma from a deeper crystal mush system were allowed to intrude into the upper crust and eventually erupt (Troll et al., 2020).

Another study case involves a major volcanic field in the Andean foreland where dykes emplaced within strike-slip faults reveal a complex morphology resulting from the interaction between tectonic and magmatic processes (Spacapan et al., 2016). Based on their interpretations, they suggest that magmatism is significantly influenced by pre-existing faults, highlighting the importance of those fault systems over regional tectonic regimes in controlling the emplacement of igneous bodies.

Finally, we would like to emphasise the similarities between the presented study cases, particularly the Rum Igneous Centre as part of a

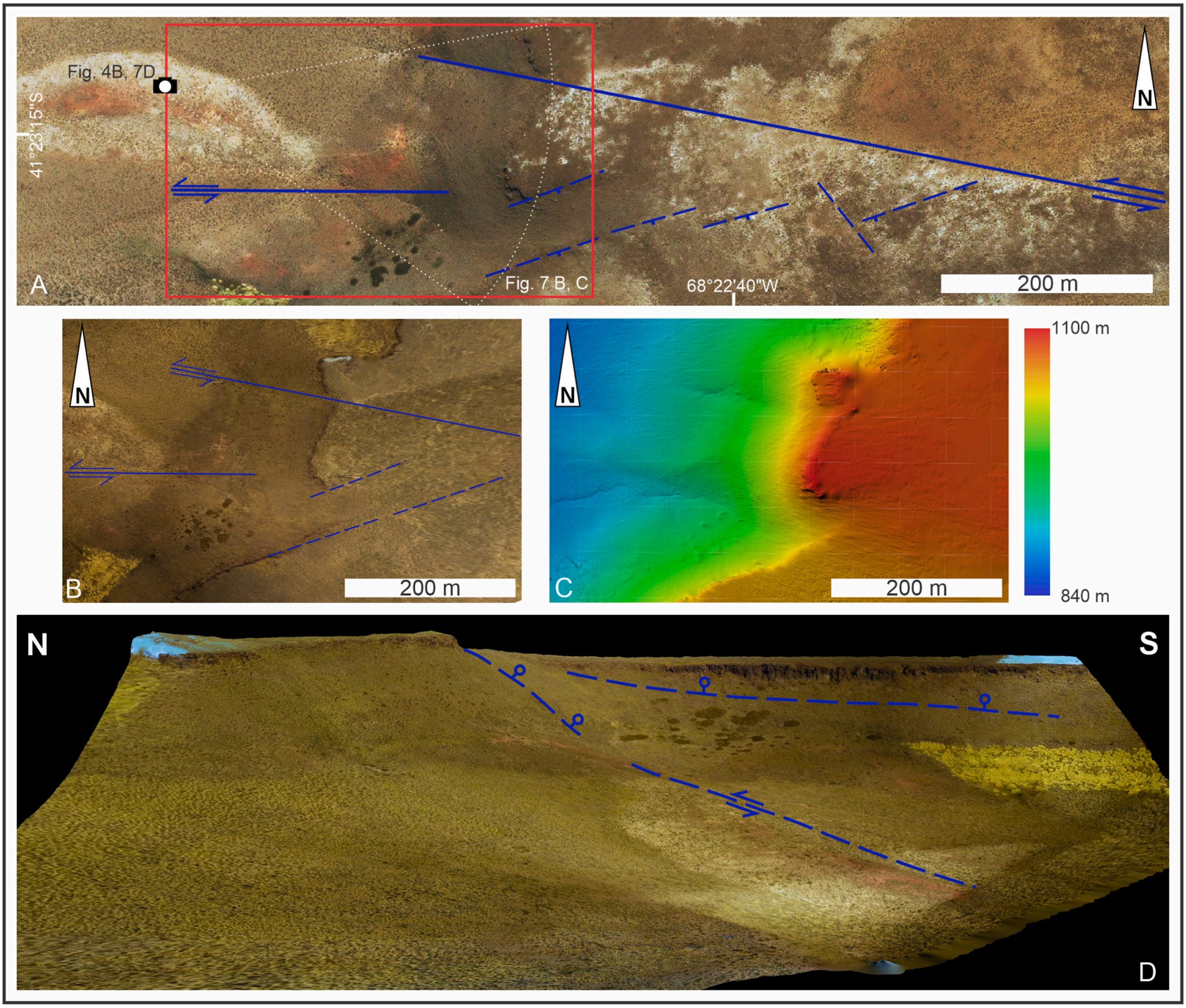


Fig. 6. Photogrammetric products obtained by digital processing of photographs taken by drone. Defective areas in the model are represented by light blue to white shading. Lineaments associated with the Somún Curá Fault are delineated in each image. A. satellite image of the area displaying the position of the drone photographs and the principal faults (continuous line) and shear fractures (dashed line) present in the area; B. Orthomosaic; C. Digital surface model; D. Side view of the generated 3D model, where the fault line is depicted as having a normal component in the topographic slope and a strike-slip component in flat terrain. Additional information regarding model production and the finalised model can be found in the supplementary data. Position of this sector is depicted in Fig. 2.

major magmatic province, and our observations regarding the Somún Curá Fault and its association with the magmatic products of the Somún Curá Large Igneous Province. There is an intimate relationship between the faults and the magmatic products, as they are both emplaced in and deformed by the faults. Although extensional (dilatant) fractures are typically regarded as the primary structures that channel magmatism, strike-slip tectonics seems to play a significant role in the evolution of major magmatic provinces, moreover, the volcanic load might have played a significant (and sometimes overlooked) role in the faults activity. Also, the interplay between magmatic and tectonic stress, likely associated with major long-lived (basement) faults, seems to be a key factor in large igneous provinces for the drainage, movement, storage, and eruption of magma.

6. Concluding remarks and further considerations

First and foremost, it is important to highlight the well-established advantage that satellite imagery, progressively improving in spatial resolution and increasingly accessible at no cost, holds for geological cartography. Through satellite imagery, we were able to identify a prominent first-order tectonic structure, accompanied by associated minor fractures, all of which appear to be genetically linked to the effusion and formation of the Somún Curá Large Igneous Province. The fracture geometry and patterns observed from satellite imagery are consistent with analogue model results and, together with filed observations, allow us to propose a left-lateral strike-slip fracture systems with locally vertical offset.

Previous studies have primarily focused on petrological and geochemical composition, characterization and evolution of the Somún Curá Large Igneous Province. It is generally accepted that the Somún Curá Large Igneous Province developed in a retroarc to intraplate setting, as a product of variations in the Andean subduction geometry coupled with mantle thermal anomalies (see Salani et al., 2021 for a summary of models). Limited attention has been given to the structural

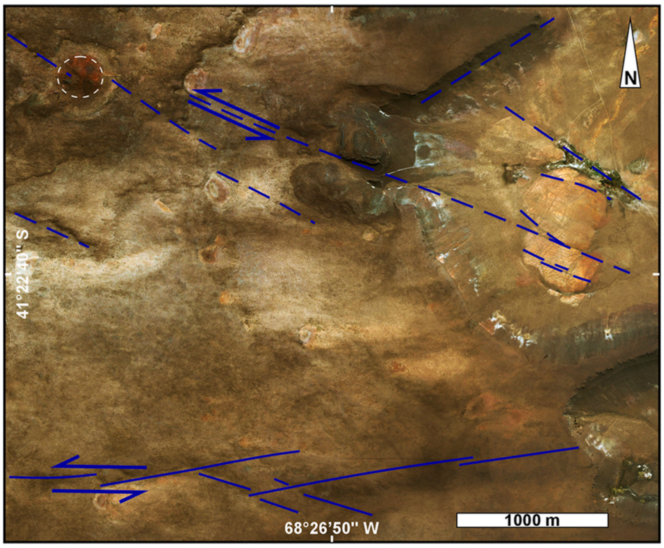


Fig. 7. A satellite image of the southwestern Carrilaufquen Depression showing an E-W to WNW-ESE fault system (blue dashed line) causing a sinistral separation in the Triassic rocks of the Los Menucos Complex. Following the fault trace to the northwest, a cinder cone (monogenetic volcano, white dashed circle) is located over the fault. Profuse fracturing is evident parallel to the interpreted faults, as well as in the NE direction; however, these fractures were not marked to prevent overcrowding the image. To the south, the Somún Curá Fault (blue solid line) is marked. The position of this sector is depicted in Fig. 2.

aspects referred to its evolution, highlighting local volcanogenic structures such as monogenetic cones, calderas and eruptive centres alignment. Some indirect observations have pointed to related the magmatism with tectonic structures as the connection between the Telsen Fault (Ciciarelli, 1990) and the alignment of eruptive volcanic complex of the Somún Curá Large Igneous Province has been proposed (Salani et al., 2010) as well as a major NW-SE gravity anomaly has been mentioned across the North Patagonian Massif (Gimenez et al., 2019). Even the epeirogenic uplift (Aragón et al., 2011; Gomez Dacal et al., 2017, 2021), as suitable as it is for the Somún Curá plateau, lacks an explanation for the internal deformation of the crustal block and to establish a link with the regional basement faults.

Although several works have presented evidence relating strike-slip tectonics with major magmatic provinces, the topic is still a matter of inquiries and discussion. The relation proposed between tectonics and magmatism agrees with the findings from other large igneous provinces (see section 5.1). The observations made as part of this study highlight the presence of a regional-scale strike-slip fault system associated with the emplacement of a part, and probably related to the evolution, of the Somún Curá Large Igneous Province. The fractures composing the Somún Curá Fault are geometrically and cinematically coherent with fracture systems observed in the pre-Jurassic rocks, are considered as the basement underlying the Somún Curá Large Igneous Province (Figs. 1, 2 and 6), both in- and outside of the plateau area. Regarding the nature and geometry of the structure, the Somún Curá Fault seems to take part in a regional lineament showing geographical continuity and kinematic coherence with Fita Ruín - Cañadón Chileno Fault. The Somún Curá Fault can be observed following a parallel trace with respect to the Telsen - Valdés Fault System (Yllañez and Lema, 1978; Ciciarelli, 1990; Salani et al., 2010) (Fig. 1). These large lineaments are usually interpreted as first-order lithospheric discontinuities (Cortés, 1981; Ciciarelli, 1990; Renda et al., 2019). They have by definition a complex structural evolution involving multiple reactivations under different tectonic regimes. A left-lateral strike-slip kinematic has been propose for the Telsen Lineament based on the geometry of annular basaltic dyke complexes associated with the final stages of the Somún Curá Large Igneous Province (Yllañez and Lema, 1978). This kinematic interpretation is consistent with our assessment of the Somún Curá Fault based on field observations and the geometric fracture arrangement (Figs. 3A and 5B, G-I, 6A-C, 7 and 8B-C).

Regarding the age of the deformation implied in the Somún Curá Fault activity, the Miocene deformation has been linked to folds affecting Oligocene to Miocene basaltic lava flows in the Cordillera del Buen Pasto, Sierra de la Buitrera, and Sierra Nevada (Giacosa et al., 2021b). The folds mentioned by Wichmann (1927) as *encorvamientos*, may be considered equivalent to those described by Giacosa et al. (2021b); however, we have not found evidence of these structures. Since these folds are younger than the basaltic layers, whereas the Somún Curá Fault cross-cut to the basaltic plateau and appears to be synchronous with later magmatic events of the Somún Curá Large Igneous Province, we consider two probable scenarios: 1) the fault is related to a pre-Miocene tectonic event, or 2) in the Somún Curá area, Miocene deformation was partitioned and controlled by the fault, and no evident folds were generated. In either case, a link to the evolution of the Somún Curá Large Igneous Province is assumed since they crosscut part of the basaltic plateau, host subvolcanic igneous bodies, control the spill of lava flows, and monogenic cones are aligned over it (Figs. 1, 2 and 3A, 4C, 5A- C, 8B-C). Assuming the observable geometry is a response to the last movement event of the fault, it could be considered as sinistral and occurring during the last volcanic events of the Somún Curá Large Igneous Province, around 18 - 10 Ma. This temporal range allows for the correlation of some activity at the Somún Curá Fault with the Miocene contractional event within the Andean orogeny. However, as was previously mentioned, as the Somún Curá Fault seems to be related to the basement, long-lasting, faults its tectonic evolution might be more complex and could be related to the onset and posterior climax of the Somún Curá Large Igneous Province under different tectonic regimes. We could speculate that the Somún Curá Fault might have acted as a channel for the magmatic products of the Somún Curá Large Igneous Province during the Oligocene extensional phase, and that during the Miocene, it changed its tectonic behaviour to a transtensional regime allowing the emplacement of the final magmatic products.

A comprehensive study of the Somún Curá Fault would be key in reconstructing the structural evolution of the northern Patagonian region during Cenozoic times. Extensive field investigations are imperative to continue the structural cartography and find local details of the structure along its entirety and in order to understand better its relation with the Somún Curá Large Igneous Province. The structure and composition of the northern Patagonia lithosphere is complex, some advances regarding this topic have been published by Gomez Dacal et al., 2017, 2021). However, further investigations are needed to address the nature of magma transit through the lithosphere and how storage processes could affect the rheological properties and behaviour of the crust.

CRediT authorship contribution statement

Santiago N. González: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition. **Gerson A. Greco:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition. **Darío L. Orts:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization.

Declaration of competing interest

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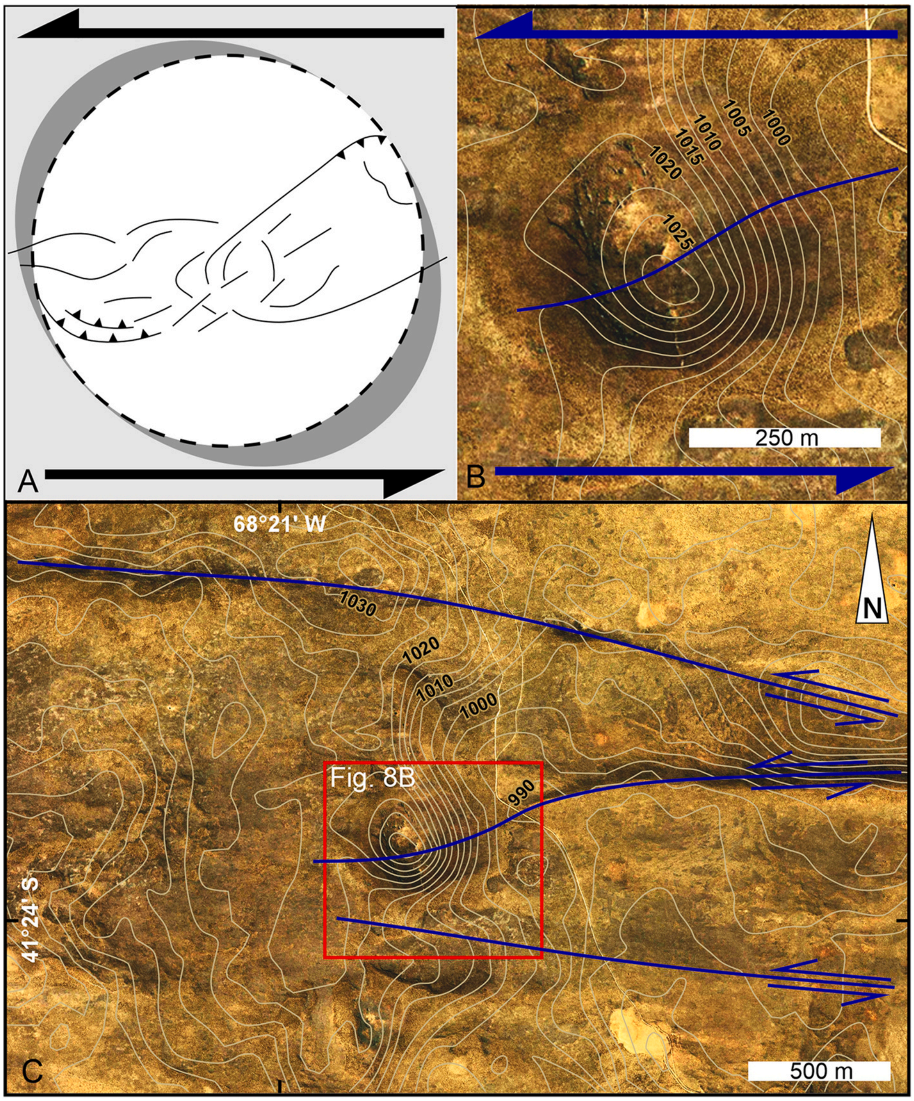

Fig. 8. Deformed cinder cone at the Somún Curá Fault and analogue model for comparison. A. Sketch from an analogue model showing the distortion of an ideal round-base volcanic cone to an elliptical-base cone by the influence of a strike-slip fault system and the associated fractures (adapted from Norini and Lagmay, 2005); B. Close-up view of the monogenetic cone from the satellite image displaying the topographic contour lines to enhance the elliptic form of the base; C. Satellite image illustrating the overall structural setting of the monogenetic cone (position of this sector is depicted in Fig. 2).

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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