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ORIGINAL PAPER

Upper Jurassic event of ignimbrite flare-up linked to extensional tectonics: the beginnings of Andean volcanism in southern Patagonia (~46° S, Chile)

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Abstract

Understanding the origin of Late Jurassic volcanism in southern Patagonia is crucial for unraveling the early Andean orogenic evolution. However, radiometric dating is not connected to stratigraphic analysis along the South Patagonian Andes, which obscures the real duration of the Late Jurassic magmatic activity. In this contribution, we present the results of a volcanic stratigraphy analysis, complemented by structural and petrographic data, on a thick succession of acidic volcanogenic rocks in the Laguna Verde district of southern Chile located along the south shore of General Carrera-Buenos Aires Lake. Through the recognition of igneous stratigraphy, we strategically sampled representative volcanogenic rocks that cover the entire duration of eruptive activity. By doing so, the new U–Pb zircon magmatic ages, combined with a compilation of U–Pb crystallization ages from the South Patagonian Andes, allows us to constrain the volcanic activity in the study area to a period of 8 My (~155–146 Ma, V3 stage) and 11 My considering age inherent errors. The field recognition of normal faults and the syn-kinematic emplacement of sub-volcanic bodies, which are inferred to conform to a ring-fault system, along with the presence of a thick succession of ignimbrites, suggest that the syn-extensional volcanic emplacement occurred in a caldera volcanic environment. This setting was responsible for the short-lived, voluminous eruptions. Furthermore, the high Th/U zircon ratios identified for the ~155–150 Ma period indicate the climax of extensional tectonics. The integration of these data supports the hypothesis that retreating-mode subduction played a major role in producing ignimbrite flare-ups.

Keywords Andean volcanic arc · Jurassic silicic volcanism · Ignimbrite flare-up · Southern Patagonia · U–Pb zircon ages · Extensional tectonics

Introduction

The subduction-related orogens are emplaced along convergent margins (i.e., accretionary orogens sensu Cawood et al. 2009) and constitute the factory of enormous volumes of magma and crustal growth (e.g., Ducea et al. 2015). These orogens can be classified into retreating and advancing modes based on their kinematic framework (cf. Cawood et al. 2009). In the retreating mode, the rollback of the trench causes extension in the upper plate and mantle asthenosphere input, resulting in the formation of juvenile magmatism. On the other hand, the contraction of the upper plate in the advancing mode promotes extensive crustal reworking and production of large volumes of arc magmas (Ducea and Barton 2007; Ducea et al. 2015; Chapman et al. 2021; Oriolo et al. 2023).

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Radiometric dating of plutonic rocks in batholiths and detrital zircons in sedimentary successions indicate fluctuations in the rates of magmatic production (DeCelles et al. 2009; Ducea et al. 2015; Paterson and Ducea 2015). Periods of high and low magmatic production are commonly referred to as flare-ups and lulls, respectively. It is thought that during the short-lived flare-up stages (ca. 15 My), around 80–90% of the total magmatic volume is emplaced (see Ducea and Barton 2007).

There are ongoing discussions regarding the issue of magmatic production, including debates on the nature of the magma source and the tectonic factors that control high-production rates in orogenic systems (Ducea and Barton 2007; DeCelles et al. 2009; Chapman et al. 2021). Some authors (Ducea and Barton 2007; also see Chapman et al. 2021) suggest that flare-up stages in batholiths are more likely to occur during upper plate contraction, which leads to production through the reworking of the continental lithosphere, rather than a source derived from the mantle wedge. However, the correlation between this process and ignimbrite flare-ups is not as clear and the triggers for each phenomenon require specific investigation (de Silva and Gosnold 2007; Gravley et al. 2016). Ignimbrite flare-ups are well-documented in orogenic systems as well as in within-plate regions (e.g., Aguirre-Díaz et al. 2008; Best et al. 2016; Gravley et al. 2016; Fernández Paz et al. 2020; Foley et al. 2023b), such as the Sierra Madre Occidental in Mexico (e.g., Aguirre-Díaz et al. 2008) or Central Patagonia in Argentina (e.g., Fernández Paz et al. 2020). Many examples demonstrate a connection between ignimbrite flare-ups and asthenospheric upwelling (also see DeCelles et al. 2009). However, the mechanism behind asthenospheric upwelling differs in each case, emphasizing the need for a detailed investigation of the local tectonic triggers for each ignimbrite flare-up event.

Our case study focuses on the Jurassic silicic volcanism (~ 193–144 Ma) of the Chon Aike Silicic Large Igneous Province (SLIP) (Kay et al. 1989; Pankhurst et al. 1998; Bryan and Ernst 2008; Navarrete et al. 2020b). These volcanic rocks cover a large area in Patagonia (Fig. 1) and extend to the neighboring Antarctic Peninsula (Pankhurst et al. 2000; Riley et al. 2001; Bastias et al. 2021). The magmatic activity spanned approximately 45–50 My, with the older rocks found in the extra-Andean region around 193 Ma, and the younger ones located along the South Patagonian Andes at around 147 Ma (Figs. 1, 2; e.g., Pankhurst et al. 2000; Pavón Pivetta et al. 2019; Foley et al. 2022). The oldest volcanism occurred in an intraplate setting, while the youngest volcanic products are preserved along the current Cordilleran axis (45–54° S) (Fig. 2). Despite its significance in understanding the initial processes of the Andean orogeny, certain aspects of the Jurassic volcanism remain unclear. In particular, previous authors have conducted geological mapping, stratigraphic analysis, and dating (e.g., Poblete et al. 2014), however, there is still a lack of radiometric data covering the entire stratigraphic column, which obscures the real duration of magmatic activity and its connection to the Mesozoic tectonic regime. Therefore, we strategically sampled the lower and upper volcanic units of the Ibañez Formation as well as a sub-volcanic dome for U–Pb zircon dating (Figs. 2, 3). This selection allows us to cover a wide range of ages within the entire stratigraphic column. By integrating these new ages with published geochronological data, we can determine the duration of the earliest stage of Andean volcanism in the South Patagonian Andes and its correlation with the Mesozoic tectonic regime. From this perspective, we discuss the tectonic significance of these findings concerning the ignimbrite flare-up events.

Geological background

Patagonia, located south of the Colorado River (39° S), is the southernmost region of the South American continent (Fig. 1). Traditionally, it has been divided into northern and southern regions, with the boundary running along the Chubut River (Fig. 1) (e.g., Renda et al. 2019). South Patagonia can be further segmented into across-strike regions. The Andean region is referred to as the South Patagonian Andes (Fig. 2), characterized by the development of a fold-thrust belt during Cretaceous and Miocene times, involving the Jurassic rocks within the deformation (e.g., Ghiglione et al. 2019). The Deseado Massif is situated in the extra-Andean region (Fig. 2) and is known for the widespread Jurassic volcanic rocks that unconformably overlay the igneous-metamorphic Paleozoic–Triassic basement (e.g., Navarrete et al. 2020b).

The Chon Aike SLIP in Patagonia

After a protracted late Paleozoic-early Mesozoic history characterized by terrane accretion and magmatic arc migrations (Navarrete et al. 2019; Suárez et al. 2019; Bastias et al. 2021), a substantial volume of volcanic rocks was erupted during the Jurassic period. The outcrops of Jurassic rocks in Patagonia mainly consist of acidic volcanogenic rocks (Pankhurst et al. 2000; Sruoga et al. 2014; Benedini et al. 2014; Navarrete et al. 2020b; Zaffarana et al. 2020; Gonzalez et al. 2022), which are genetically linked to the Chon Aike SLIP (Kay et al. 1989; Pankhurst et al. 1998; Bryan and Ernst 2008; Navarrete et al. 2020b). The Chon Aike volcanic province is one of the most voluminous SLIPs in the world, with an estimated volume of volcanic rocks of 235,000 km^3 in Patagonia and West Antarctica (e.g., Pankhurst et al. 1998).

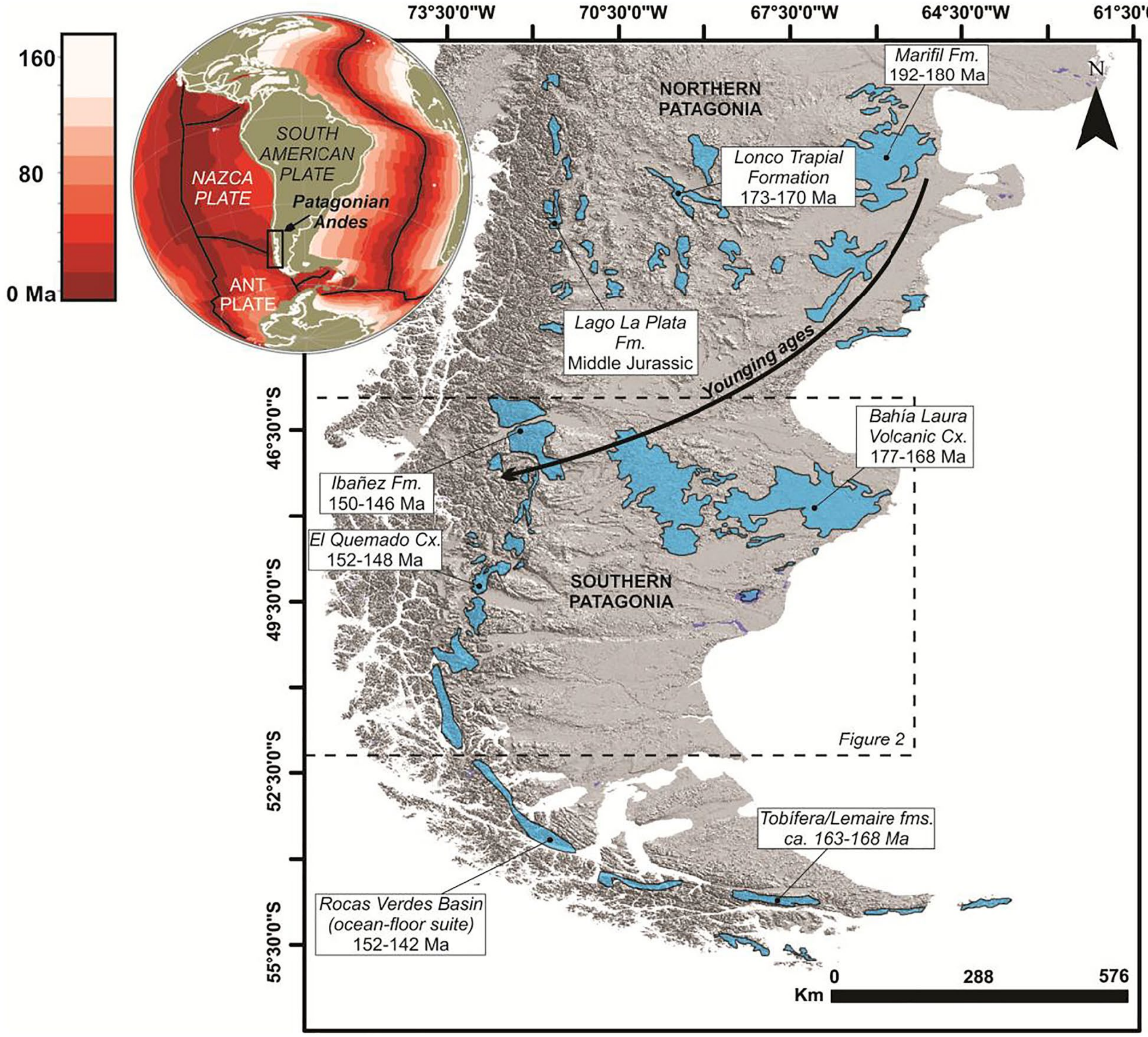
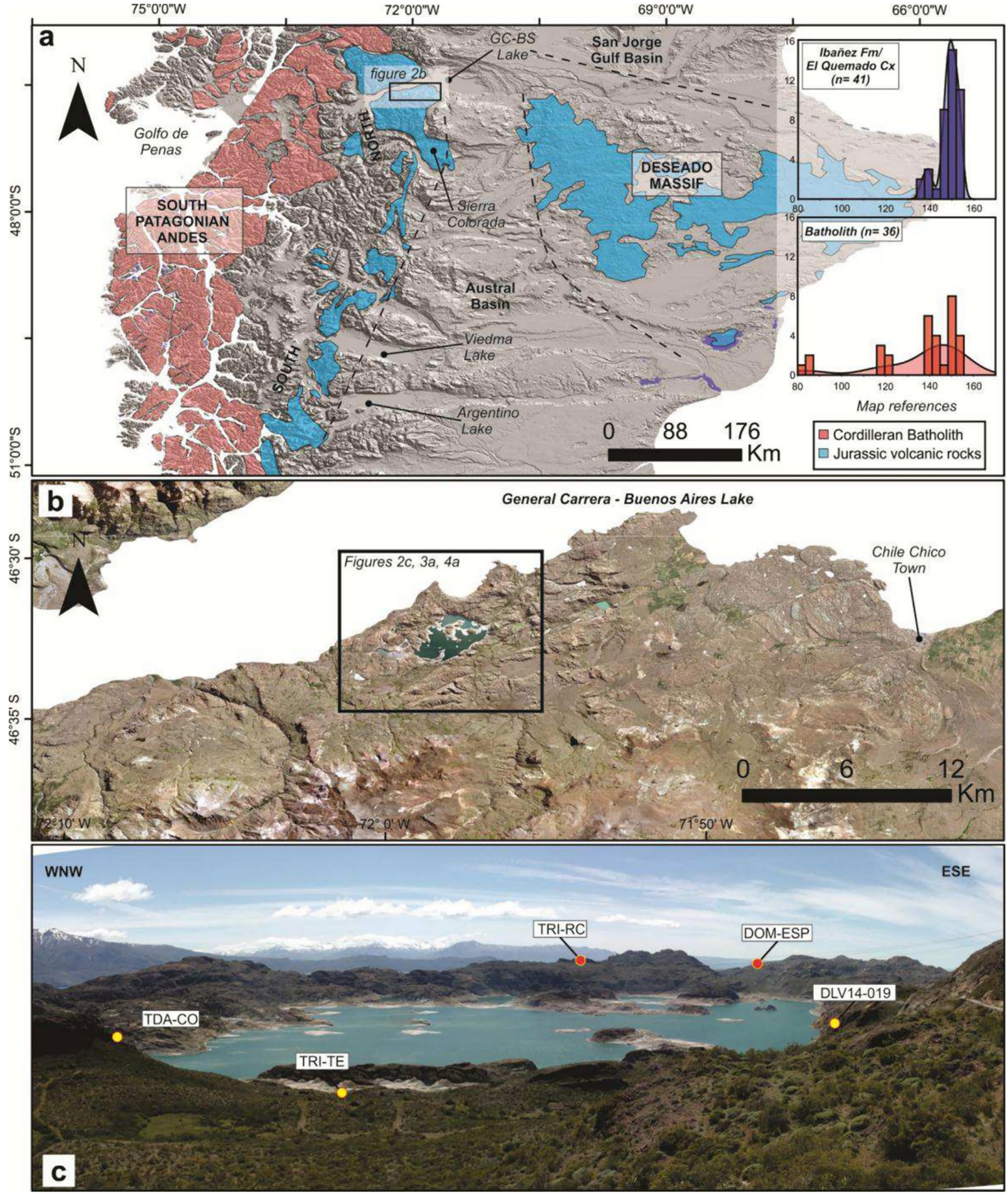


Fig. 1 Regional map of Patagonia showing the exposures of Jurassic volcanic rocks and their representative ages. Modified from Pankhurst et al. (2000). The U–Pb ages in northern Patagonia are from Benedini et al. (2022), Bouhier et al. (2017), González et al. (2022), Pavón-Pivetta et al. (2019), and Zaffarana et al. (2020). The ages in southern Patagonia are mainly based on Calderón et al. (2007, 2013), Foley et al. (2022), Hervé et al. (2010), Malkowsky et al. (2016), Navarrete et al. (2020a), Pankhurst et al. (2000), Palotti et al. (2012), and Poblete et al. (2014). The inset displays the regional tectonic configuration (sea-floor ages are taken from Müller et al. 2016)

The chronology of Jurassic volcanism in Patagonia reveals a general pattern of younger crystallization ages towards the trench (see Pankhurst et al. 2000; also see discussion in Navarrete et al. 2024). Based on this trend, Pankhurst et al. (2000; also see Riley et al. 2001) divided the stages of Jurassic volcanism into V1 (188–178 Ma), V2 (172–167 Ma), and V3 (157–153 Ma). While the V1 and V2 stages represent the older exposures in extra-Andean Patagonia, the V3 stage is exposed along the current Cordilleran axis of southern Patagonia (Fig. 1). This later volcanic stage coincides with the emplacement of the South Patagonian Batholith, a Cordilleran batholith that records subduction processes in southern Patagonia from the Late Jurassic to the Neogene (150 My). Hervé et al. (2007) divided the magmatic activity of the South Patagonian Batholith into five main periods: Jurassic (157–145 Ma), Cretaceous I (144–137 Ma), Cretaceous II (136–127 Ma), Paleogene (67–40 Ma) Neogene (25–15 Ma) (Hervé et al. 2007). Additionally, an older stage of Jurassic volcanism has recently been identified in the eastern North Patagonian Massif, known as V0 (see Pavón Pivetta et al. 2019), with ages around 193–192 Ma (Fig. 1).

Although various petrogenetic models have been proposed to explain the geochemical and isotopic signatures



of the Chon Aike SLIP (e.g., Pankhurst and Rapela 1995; Riley et al. 2001; Navarrete et al. 2019, 2024; Zaffarana et al. 2020; Bastias et al. 2021), current petrogenetic models emphasize on the influence of the subducting slab on magma genesis, within the context of east-dipping subduction

◂**Fig. 2** **a** Outcrops of Jurassic volcanic rocks in southern Patagonia and their respective crustal domains. It should be noted that the opening of the Austral Basin in the Late Jurassic–Early Cretaceous times resulted in the burial of the Jurassic volcanic rocks (e.g., Giacosa et al. 2012; Ghiglione et al. 2019), creating a gap in the surface exposure of volcanic outcrops between the Deseado Massif and the South Patagonian Andes. GC-BS = General Carrera-Buenos Aires Lake. The insets represent the frequency histograms of U–Pb ages (Ma) for the Ibañez/El Quemado Complex (V3) and the batholith. These ages of the V3 stage are derived from Pankhurst et al. (2000), Rolando et al. (2004), Suárez et al. (2009), Poblete et al. (2014), Malkowsky et al. (2016), Foley et al. (2022), Naipauer et al. (2024), and this work. The ages of the batholith are based on Pankhurst et al. (1998), Rolando et al. (2004), and Hervé et al. (2007). **b** Satellite image of the Laguna Verde district. The black inset outlines the study region, specifically the Laguna Verde district (refer to the geological map in Fig. 3). **c** Landscape of the Laguna Verde district on the southern shore of the General Carrera-Buenos Aires Lake and location of the samples. The red and yellow dots depict the location of the samples on the surface and drill core, respectively

beneath the South America plate (Navarrete et al. 2019, 2024; Bastias et al. 2021).

Lithology and stratigraphy of the silicic volcanism in the South Patagonian Andes

The Jurassic V3 event in the South Patagonian Andes (Pankhurst et al. 2000) is represented by two units: the Ibañez Formation (e.g., De La Cruz and Suárez 2006, 2008) and the El Quemado Complex (e.g., Ramos 1982; Sruoga et al. 2014). The Ibañez Formation is found in the northern part of the range, while the El Quemado Complex is exposed in the southern region. Both units are associated with the syn-rift stage of the Aysén/Río Mayo Basin between 43°–46° S and the Austral Basin between 46°–51° S (Suárez et al. 2009; Ghiglione et al. 2010, 2019), and were emplaced in a retroarc position (e.g., Ramos et al. 2019). The thickness of the Ibañez Formation and the El Quemado Complex varies, but in some places, it can reach up to 1000–2000 m (Niemeyer et al. 1984; Bruce 2001; Ramos et al. 2019).

Regional mapping of the Ibañez Formation, including small areas like Laguna Verde, has been conducted by De La Cruz and Suárez (2006, 2008) and Poblete et al. (2014). From base to top, Poblete et al. (2014) recognized four informal units within the Ibañez Formation, as follows: Unit 1) Andesitic-to-dacitic lavas and volcaniclastic rocks (112 m); Unit 2) rhyodacitic pyroclastic rocks (150 m); Unit 3) volcano-sedimentary units (20–60 m); Unit 4) petrographically similar to Unit 2 (300 m). Additionally, these authors identified acidic, sub-volcanic domes and associated epithermal veins intruding the pile of volcanic rocks (Poblete 2011; Poblete et al. 2014). U–Pb zircon dating carried out by Poblete et al. (2014) yielded ages of approximately ~ 146 Ma for the sub-volcanic domes and ignimbrites, while a cluster of younger ages (~ 80 Ma) was reported for N-S trending domes.

In the Laguna Verde study sector, the Ibáñez Formation is composed of various effusive and explosive units with different compositions (De la Cruz and Suárez 2008; Poblete et al. 2014). However, the lack of lateral continuity and the possibility of multiple eruptive centers make it challenging to establish spatial and temporal relationships between regional and local volcanic products and intra/inter-eruptive processes. To address this issue, we follow the volcanic stratigraphy (e.g., Martí et al. 2018) outlined by González (2012) for the Laguna Verde area, which established stratigraphic relationships in the volcanic succession of the Laguna Verde. González (2012) classified the volcanic stratigraphy of the Ibáñez Formation from the base to the top, into four members: Guadal, Temer, Coigües, and Rodados Colorados, along with the co-genetic intrusive sub-volcanic domes. In this contribution, we simplify the González's (2012) detailed mapping and descriptions to highlight the main geological-structural elements of the Laguna Verde. In this regard, we group the four members of the Ibáñez Formation into two informal units called lower (Guadal and Temer members) and upper (Coigües and Rodados Colorados members), separating them from the sub-volcanic domes. Then, in a broader sense, the Guadal and Temer, Coigües, and Rodados Colorados members are roughly equivalent to units 2, 3, and 4 of Poblete et al. (2014).

Sampling strategy and analytical methods

In the southern Patagonia region, the Jurassic depocenters along the Cordilleran area have been affected by positive tectonic inversion and eroded due to the effects of Cretaceous and Miocene Andean thrusting (e.g., De La Cruz and Suárez 2006; Sruoga et al. 2014; Ramos et al. 2019). However, only a few areas preserved the early Andean volcanic record as erosional windows. One such area is the Laguna Verde district, situated on the south shore of General Carrera-Buenos Aires Lake at 46° S in southern Chile (Figs. 2, 3; e.g., Poblete 2011; Poblete et al. 2014).

Through geological mapping and recognition of volcanic stratigraphy, we strategically sampled each member of the Ibañez Formation to cover the entire lapse of ages. Five samples were selected for zircon studies using the LA-ICP-MS U–Pb method. The location of the samples and units analyzed can be found in Table 1. The zircon crystal separation, mounting into epoxy resin plugs, Cathodoluminescence (CL) imaging, and U–Pb age determinations were performed by the U–Pb Geochronology Laboratory of the Servicio Nacional de Geología y Minería (SERNAGEOMIN, Chile). A Thermo-Fisher ElementXR

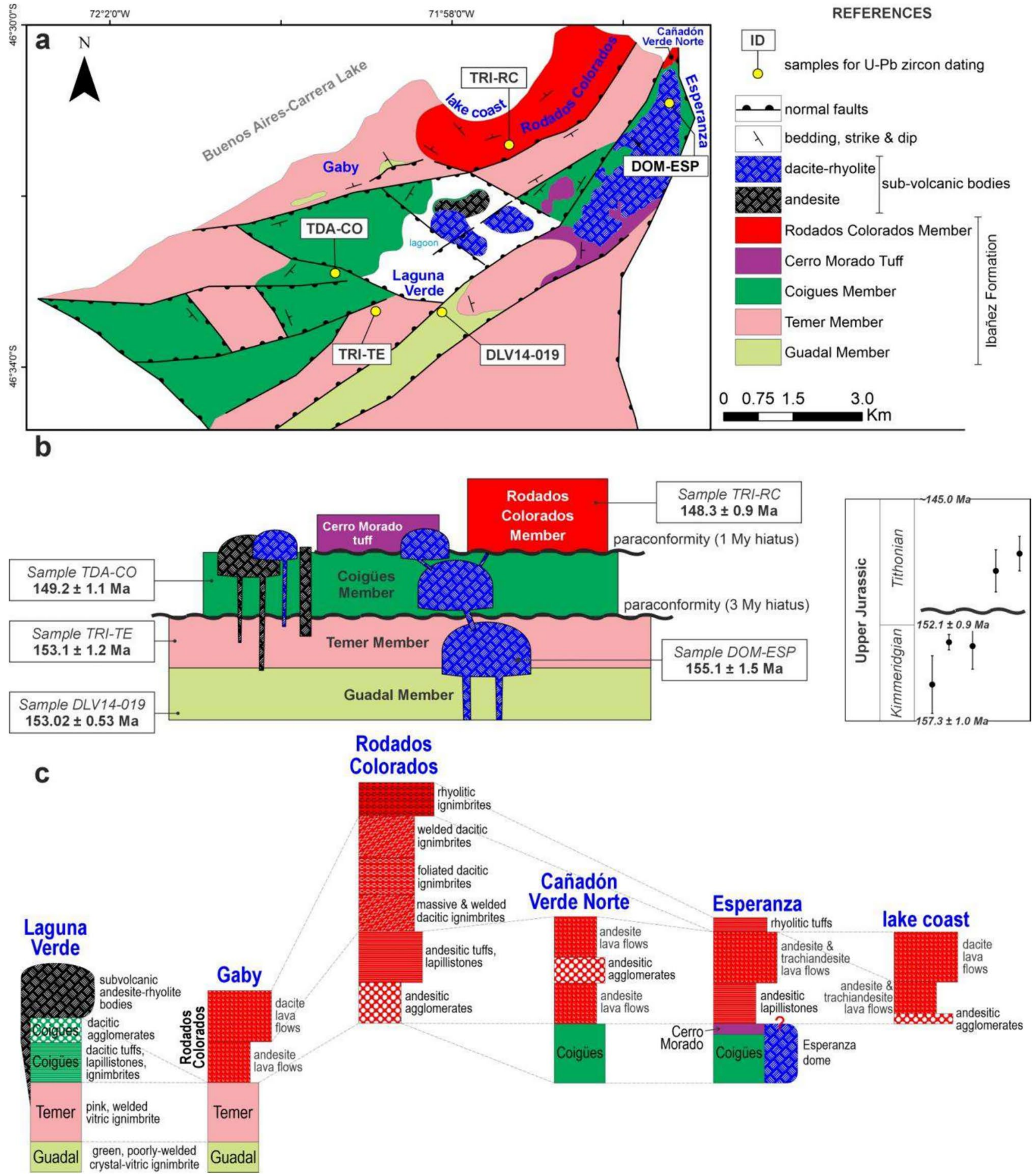


Fig. 3 **a** Detailed geological map of the Laguna Verde district (based on original mapping, De La Cruz and Suárez 2008; Poblete et al. 2014). The crystallization ages are reported in Table 1. **b** Stratigraphic schemes of the area. **c** Representative stratigraphy of each blocks surrounding the Laguna Verde lagoon

laser-ablation multi-collector inductively coupled plasma mass spectrometer equipped with an Analyte 193.G3 Photon laser system was used, following the operating conditions, instrument settings, and laser ablation system described in the laboratory's routine (https://www.sernageomin.cl/geocronologia-u-pb/).

Table 1 Synthesis of the new U–Pb (LA-ICP-MS) zircon magmatic ages presented in this study from the pyroclastic, volcanic, and sub-volcanic rocks of the Ibañez Formation

ID	Coordinates		Unit	Lithology	Age (Ma)
	Lat (S)	Long (W)			
TRI-RC	46.523383	71.95601	Upper Ibañez (Rod. Col. Mb.)	Rhyolitic ignimbrite	148.33 ± 0.87
TDA-CO	46.548342	71.989514	Upper Ibañez (Coigües Mb.)	Dacitic ignimbrite	149.2 ± 1.1
TRI-TE	46.555799	71.981598	Lower Ibañez (Temer Mb.)	Rhyolitic ignimbrite	153.1 ± 1.2
DLV14-019	46.554536	71.969853	Lower Ibañez (Guadal Mb.)	Dacitic ignimbrite	153.02 ± 0.53* 152.9 ± 0.38
DOM-ESP	46.526734	71.933522	Sub-volcanic bodies	Banded rhyolite	155.1 ± 1.5

The location of the samples can be found on the geological map in Fig. 3. The ages refer to the $^{206}Pb/^{238}U$ system, except for (*), which is a Concordia age

The data reduction, age calculation, and representation of analytical results in Tera–Wasserburg diagrams and weighted means (plotting) of overlapping and coherent $^{206}Pb/^{238}U$ ages were performed by using Isoplot/Ex (Ludwig 2003). The details of LA-MC-ICPMS analysis and zircon CL images for each sample can be found in Supplementary Information (SI) 1.

To gain further tectonics insights, we compiled a database of U–Pb ages of individual zircons and their corresponding Th/U values from acidic volcanic rocks in the Central and South Patagonian Andes, taking into account the findings of McKay et al. (2018).

Results

The following section provides a synthesis of the mapping and recognition of volcanic stratigraphy in the Laguna Verde district, including U–Pb zircon analysis.

Structure and volcanic stratigraphy

The outcrops of volcanogenic rocks surrounding the Laguna Verde district are fault-delimited blocks of the Ibañez Formation (Figs. 3, 4). These units are juxtaposed in tectonic contact, although primary volcanic structures are also recognized.

In plan view, two sets of normal faults oriented NE–SW and NW–SE define a conjugate arrangement (Fig. 4). This geometric array of structures is particularly noticeable in the Laguna Verde Lagoon (Fig. 4). The NE-SW-oriented set consists of straight and continuous segments, such as the Cañadón Verde fault. On the other hand, the NW–SE-oriented set consists of short segments that have remarkable control over the emplacement of the sub-volcanic units, such as domes and dykes (Fig. 4). In addition to the tectonic structures, we infer a dissected ring-fault system by aligning the sub-volcanic domes (Fig. 4).

Broadly, the entire volcanic succession of the Ibañez Formation consists of alternating beds of pyroclastic rocks, and lava flows with andesitic, dacitic, and rhyolitic compositions, with a predominance of acidic terms (Fig. 3). Besides, the effusive-explosive composite volcanic succession is intruded by consanguineous acidic domes, andesite dikes, and quartz veins. A comparison of the volcanic stratigraphy between the different tectonic blocks is presented in Fig. 3c.

In the study area, the lower unit of the Ibañez Formation (Fig. 3) is composed of the Temer Member, which concordantly overlies the Guadal Member (Fig. 5). These units consist of alternating beds of crystal-vitric ignimbrites of dacite-rhyolite composition, ash-fall tuffs, tuff breccias, and lapillistones. The Guadal Member is characterized by a conspicuous green-colored dacitic ignimbrite (Fig. 5), with a predominance of plagioclase and sanidine crystaloclasts, while the Temer Member is a welded pink-colored rhyolitic ignimbrite (Fig. 5).

The upper unit comprises the Coigües and Rodados Colorados members, which underlies the lower members. The Coigües Member overlays the Temer Member in a paraconformity contact (Fig. 5b). It mainly consists of dacitic tuff and lapillistone beds, with minor intercalations of non-welded dacitic ignimbrites (Fig. 6a, b). Towards the top, it is covered by massive to crudely stratified volcanic breccias (Fig. 3c).

In the Cañadón Verde canyon, the Cerro Morado Tuff overlays the Coigües Member in a paraconformity to low-angle unconformity contact (Fig. 3c). The Cerro Morado Tuff is a local volcanic unit that is bounded by the Coigües Sur fault to the west and the Cañadón Verde fault to the east (Figs. 4b, 6a). It also overlays the Temer Member in a paraconformity contact. The Cerro Morado Tuff consists of massive and stratified tuffs and ignimbrites with varying degrees of welding. The Rodados Colorados Member is juxtaposed in tectonic contact with the underlying members through faults, such as the Coigües Norte fault (Fig. 3a). Additionally,

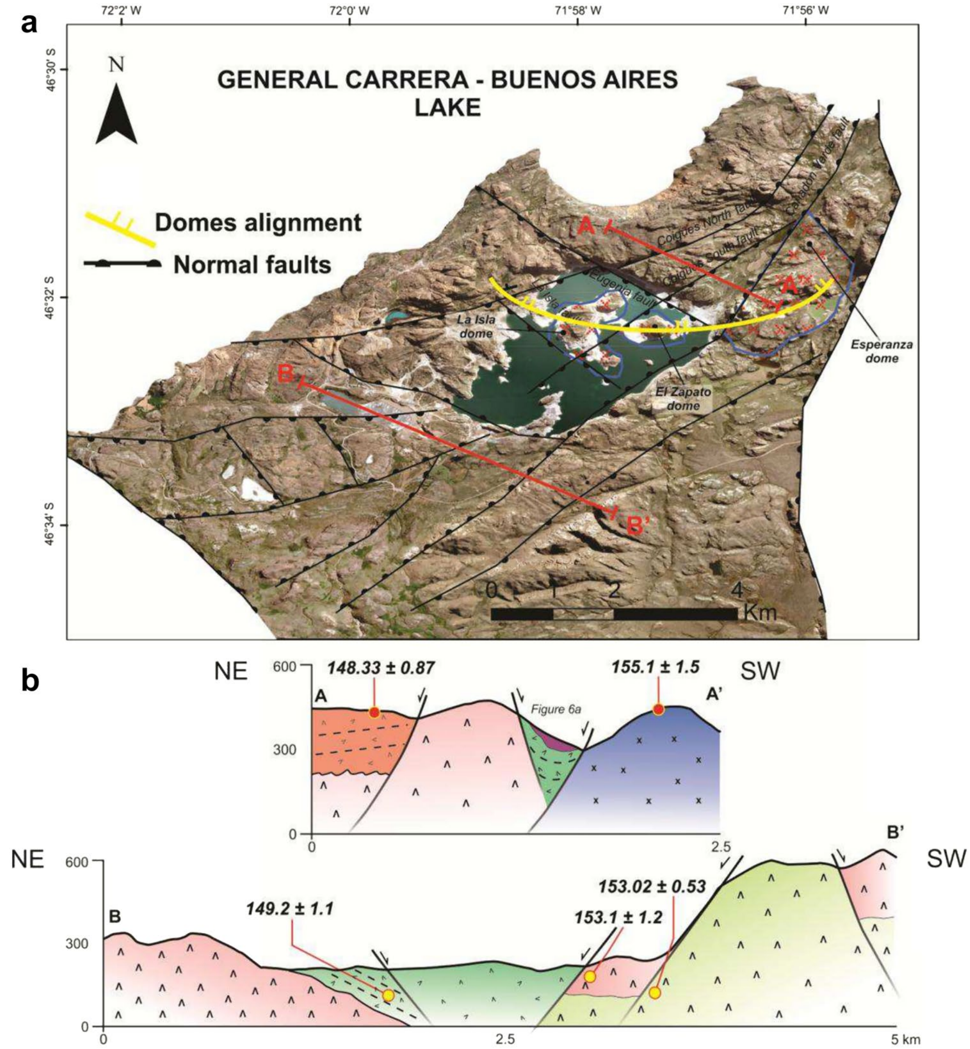


Fig. 4 **a** Map of tectonic and volcanic structures in the Laguna Verde district (Sentinel-1 image was downloaded from https://www.earthdata.nasa.gov). The yellow circle depicts the alignment of domes. **b** Schematic cross-sections (A–A′ and B–B′ red lines), showing the control of normal faulting on the distribution of units. See Fig. 3 for color references

the Rodados Colorados Member overlays on the Temer Member in the Gaby block and the Coigues Member in the Rodados Colorados, Cañadón Verde Norte, and Brillantes blocks, all in paraconformity contact (Fig. 3a, c). The beds of the Rodados Colorados Member are typically vermillion red, and composed of andesite lava flows and agglomerates at the base, crystal-vitric rhyolitic ignimbrites and rhyolitic ash-fall tuffs towards the top. The succession is crowned by fine-grained sandstones and conglomerates containing detrital and pyroclastic inputs (Fig. 3c).

The stratigraphy of this sector is completed by a set of sub-volcanic rocks that intrude the units mentioned above. These rocks consist of flow-banded rhyolitic crypto-domes, sub-volcanic domes (Figs. 6a, d, 7), and andesite necks and dikes (Figs. 3, 7).

U–Pb zircon ages and crystal features

The synthesis of results can be found in Table 1. Figure 8 presents Tera–Wasserburg diagrams and weighted mean plots of the $^{206}Pb/^{238}U$ ages obtained in this contribution.

Sample DOM-ESP

Banded rhyolite dome with a porphyritic texture. It consists of quartz and sanidine phenocrysts immersed in a hydrothermally altered matrix. The zircon crystals are bi-terminated prisms measuring 100–400 µm long, along with fragments. The CL images of the analyzed zircon grains exhibit bright luminescence, well-developed oscillatory growth zoning, and parallel sector zoning. These features, along with the morphology and high Th/U values (0.19–0.44), are consistent with their magmatic

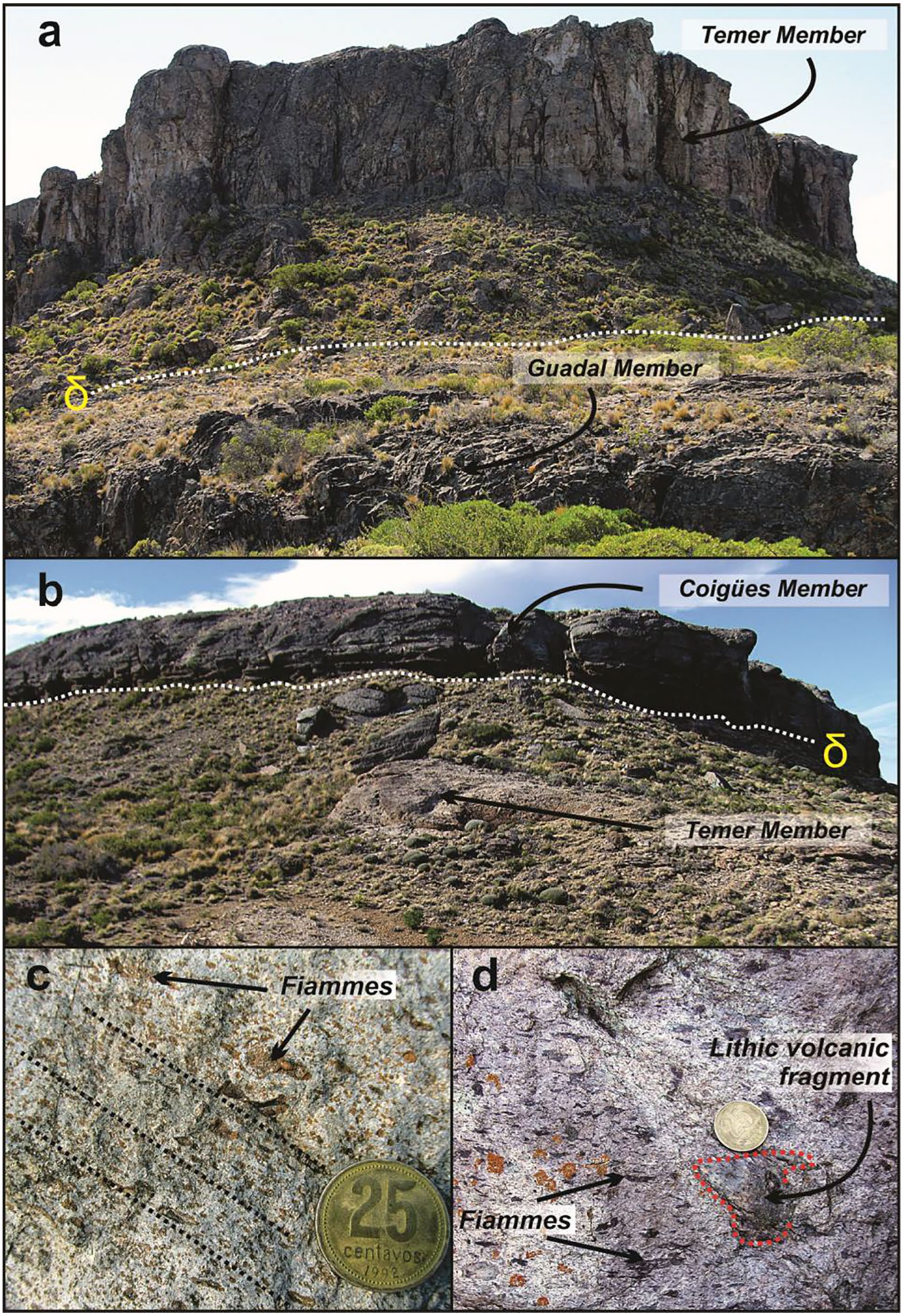


Fig. 5 Stratigraphic relationships and details of the Jurassic volcanic rocks in the field. **a** The Temer Member overlies the Guadal Member in a concordant manner. Note the typical ignimbrite disjunction developed within the Guadal Member. **b** Stratified beds of the Coigües Member can be observed overlying the Temer Member. **c**, **d** depict ignimbrites with eutaxitic texture from the Guadal and Temer members, respectively

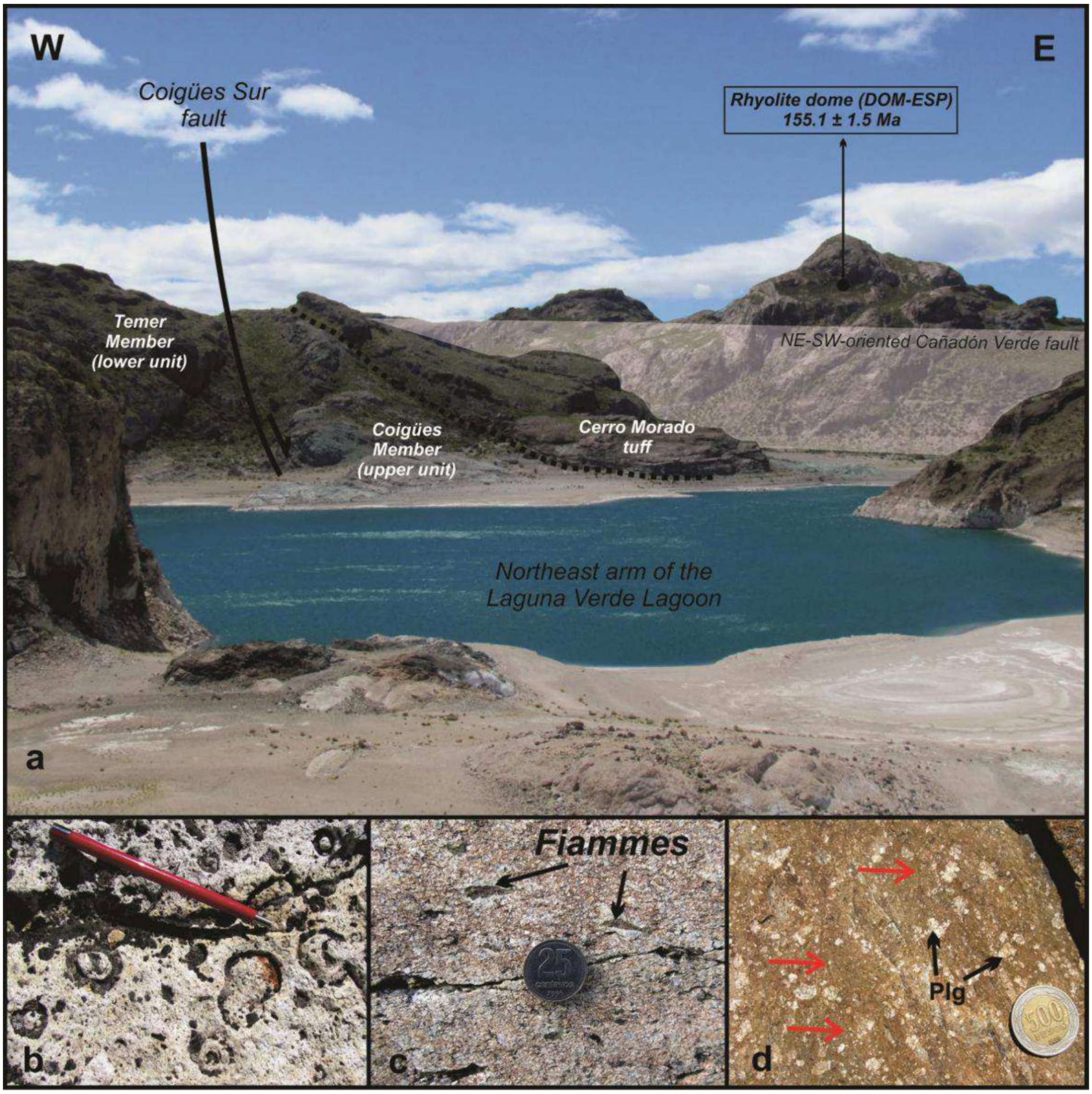


Fig. 6 Stratigraphic and structural relationships around Laguna Verde Lagoon and details of the Upper Jurassic volcanic rocks in the field. **a** The Cerro Morado tuff overlays the Coigües Member, and the set of rocks is in tectonic contact with the Temer Member through the Coigües Sur fault. See geometry in Fig. 4b. **b** The tuff of the Coigües Member exhibits a lithophysae texture. **c** The ignimbrite of the Rodados Colorados Member displays eutaxitic texture. **d** Porphyritic texture is observed in the dacitic dome, characterized by phenocrysts of plagioclase (Plg) immersed in an aphanitic matrix. Red arrows indicate the flow banding

origin (see Hoskin and Schaltegger 2003). Out of the 22 spots analyzed (representing 21 crystals), the 16 most coherent and concordant spots give a weighted mean age of 155.1 ± 1.5 Ma with an MSWD of 1.6, excluding six discordant ages > 10% (Fig. 8a).

Sample DLV14-019

Dacitic ignimbrite from the lower unit (Guadal Member). The zircon crystals exhibit variations, including bi-terminated prisms measuring approximately 400 µm long, short prisms, and zircon fragments measuring 200 µm. Some potentially inherited cores are visible, showing oscillatory growth and parallel sector zoning. The Th/U ratios mainly range between 0.73 and 1.33. Out of the twenty-seven points analyzed, twenty define a Concordia age of 153.02 ± 0.53 Ma, with an MSWD of 0.28. The same cluster of the 20 concordant zircons yielded a weighted $^{206}Pb/^{238}U$ mean age of 152.9 ± 0.38 Ma (MSWD 1.5, Fig. 8b). The remaining seven zircon spots were discarded due to high discordances (> 10%), significant errors, and the youngest age results (refer to Table 1 of the SI).

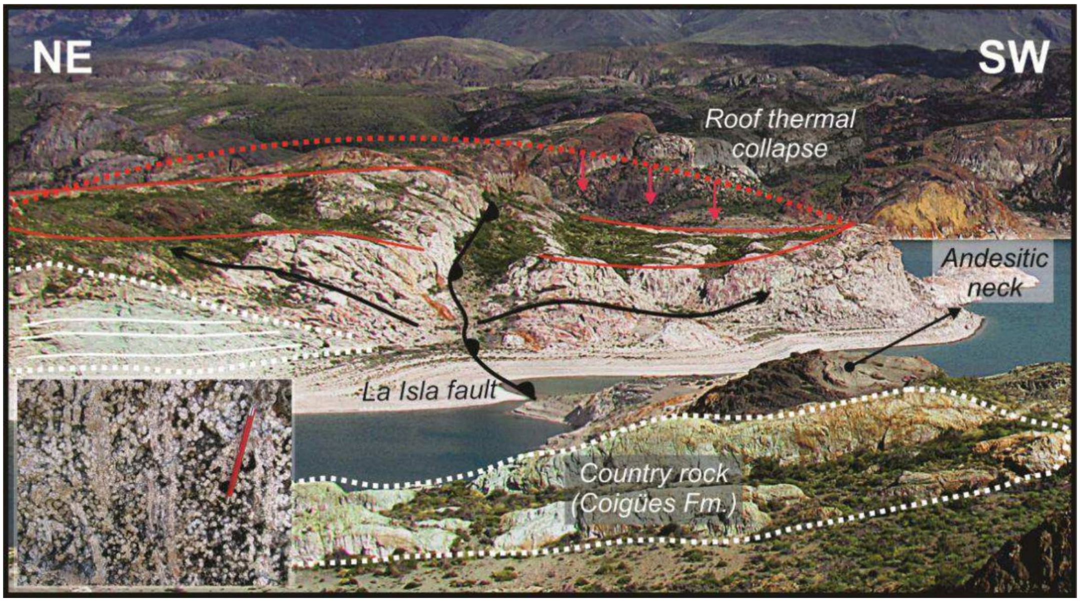


Fig. 7 Photography showing the La Isla dome and related sub-volcanic bodies emplaced through a normal fault. The inset exhibits the spherulitic texture and flow banding of the La Isla dome

Sample TRI-TE

This sample was taken from the lower unit (Temer Member), which is a densely welded rhyolitic ignimbrite, excluding the lithic fraction. The zircon crystals consist of short bi-terminated prisms and fragments measuring up to 200 µm long. They display oscillatory growth zoning and inherited cores. The Th/U ratios mainly range between 0.51 and 1.09. Among the 28 spots (28 crystals) measured, the most coherent and concordant 19 spots give a weighted mean age of 153.1 ± 1.2 Ma with an MSWD of 1.8 (Fig. 8c). Although concordant, one spot was excluded due to its young age and significant error.

Sample TRI-RC

Rich-quartz rhyolitic ignimbrite located at the top of the upper unit (Rodados Colorados Member). Twenty-eight short to long prisms, ranging between 100 and 300 µm in length, were measured. They generally exhibit oscillatory zoning with possible inherited cores. The values of Th/U ratios are low, ranging between 0.12 and 0.36. The degree of age concordance is generally high, and 22 spots (representing 21 crystals) give a weighted mean age of 148.33 ± 0.87 Ma with an MSWD of 1.5 (Fig. 8d). Although concordant, two spots were discarded due to being the oldest ages recorded (refer to Table 1 of the SI).

Sample TDA-CO

Dacitic ignimbrite from the upper unit (Coigües Member). Thirty-two crystals (32 spots) were analyzed, with predominantly short prisms and crystal fragments measuring 100–300 µm in length, along with minor equant crystals. Oscillatory growth and parallel sector zonings are noticeable. Some crystals exhibit mainly bright luminescence, while others are darker. Possibly inherited cores and overgrowth rims are also visible. Th/U ratios generally range between 0.31 and 0.59, with one ratio of 0.80 (refer to Table 1 of the SI). The best age is calculated as a weighted $^{206}Pb/^{238}U$ mean age based on 25 spots, resulting in a value of 149.2 ± 1.1 Ma with an MSWD of 1.3 (Fig. 8e).

Discussion

Local volcanic stratigraphy, volcanic edifice, and timing of eruptions

During the Late Jurassic period, the magmatic arc in southern Patagonia was emplaced along the current Cordilleran axis, along with its associated retroarc volcanic products (Pankhurst et al. 1999; Hervé et al. 2007; Poblete et al. 2014; Ramos et al. 2019). Within this context the Ibañez Formation, along with its southern counterpart, the El Quemado Complex, are believed to represent the

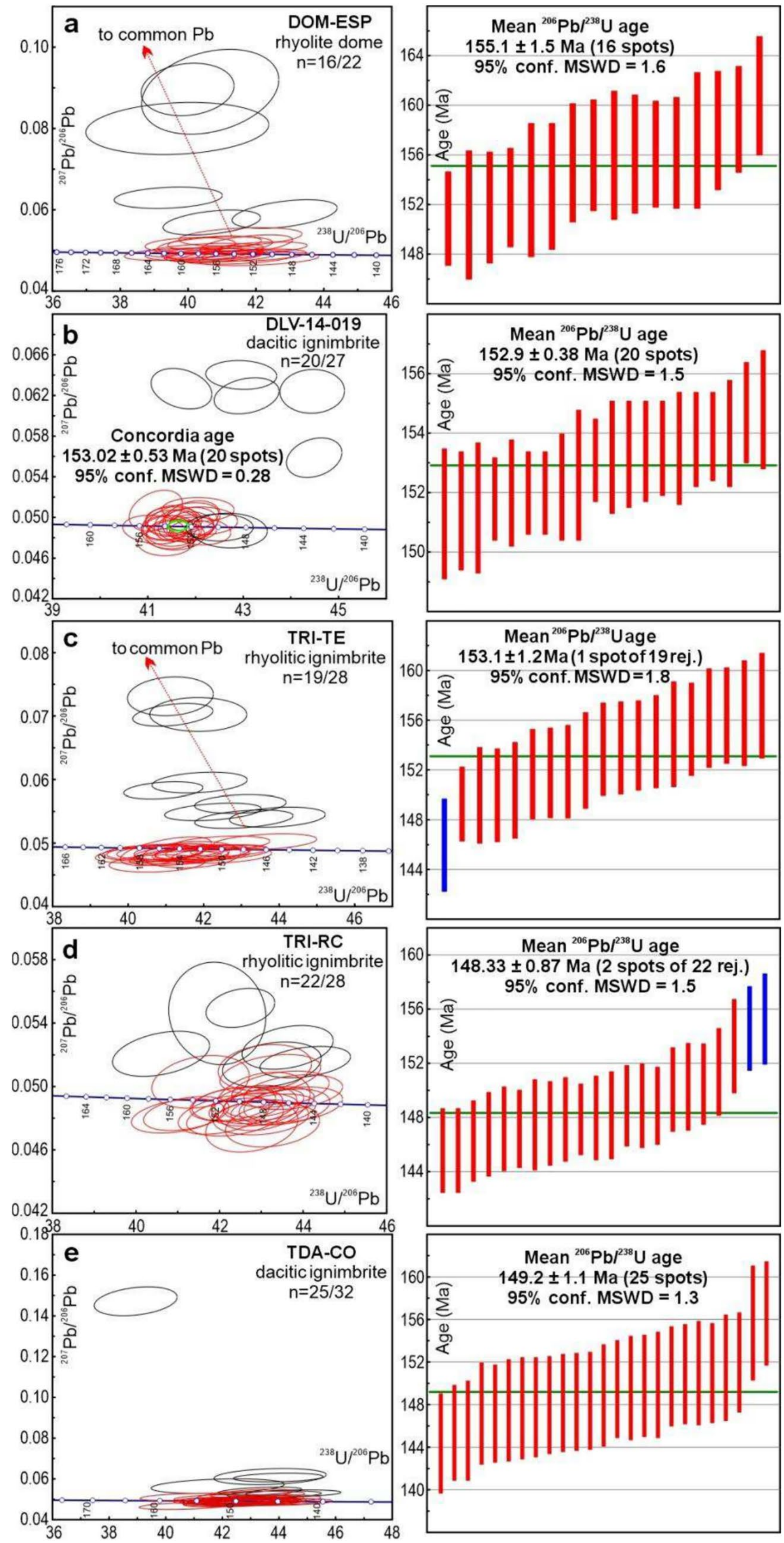


Fig. 8 LA-ICP-MS U–Pb zircon ages obtained in this study. **a–e** refer to the samples DOM-ESP, DLV14-019, TRI-TE, TRI-RC, and TDA-CO, respectively. The left diagram exhibits the ages plotted on an inverse Concordia diagram or Tera-Wasserburg plot (Tera and Wasserburg 1972), while the right column displays the estimated crystallization ages through weighted averages

earliest manifestations of the Andean volcanism in southern Patagonia (Suárez et al. 2009; Ramos et al. 2019). However, the lack of a reliable link between the stratigraphic position of the rock and chronological data has, until now, made it difficult to understand the duration of volcanic activity and its connection with the tectonic regime.

We have identified two significant periods of volcanic activity through the recognition of volcanogenic units and U–Pb dating in the Laguna Verde district, alongside petrography and structural analysis. The first period is represented by the lower unit, which consists of the Guadal and Temer members, as well as related sub-volcanic domes (e.g., Esperanza dome), ranging from 155 to 152 Ma. It is worth noting that this basal unit is exposed along the horst-type structural highs. The second period is characterized by the Coigües and Cerro Colorado members, which can be dated to approximately 149–148 Ma. The Cerro Morado tuff is interbedded between the Coigües and Cerro Colorado members. It is important to mention that exists a hiatus of approximately 3 My between these two main units, represented in the field by a disconformity on top of the Temer Member. In volcanic terrains, these hiatus do not signify any substantial gap or tectonic activity and are confined to local areas (e.g., Martí et al. 2018). Lastly, the El Zapato and La Isla domes intrude the thick succession of ignimbrites. Poblete et al. (2014) obtained ages of approximately ~ 146–145 Ma for a set of N–S-oriented rhyolitic domes, which may indicate the timing of this later magmatism.

The features mentioned above, namely the juxtaposition of sub-volcanic domes and the thick succession of ignimbrites with significant variations in thickness, have been identified by Branney and Acocella (2015) as the key attributes in recognizing silicic exhumed calderas. According to Cole et al. (2005), it is advisable to use descriptive terms rather than interpretative ones when classifying caldera structures due to the complexities involved in these settings. Thus, based on the faulting geometry interpreted in the structural cross-sections (Fig. 4), we classify this caldera structure descriptively as the result of multiple block collapse (cf. Cole et al. 2005). Following models of caldera evolution (e.g., Lipman 2000), the thick acidic ignimbrite successions, breccias, and re-sedimentation of volcanic products, as evidenced by the Upper and Lower units of the Ibañez Formation, suggest events of caldera collapse (Table 2). Additionally, the difference in ages for each unit would suggest different stages of caldera collapse. Therefore, the alignment of sub-volcanic domes that define a curvilinear geometry is often interpreted as part of a ring-fault system (e.g., Tomek et al. 2016), which is a typical feature of resurgent magmatism (Lipman 2000). Consequently, the domes emplaced in the Laguna Verde are representative of this stage in caldera evolution (Table 2). The emplacement of younger domes, such as La Isla and El Zapato domes, within the upper unit and their interpretation as resurgent magmatism implies that they are a few million years younger than the country rock.

The extensive distribution of ignimbrites along the south shore of the General Carrera-Buenos Aires Lake raises the possibility of recognizing other caldera edifices that may constitute a caldera complex (cf. Cole et al. 2005). Numerous authors have recognized similar volcano-tectonic structures as the eruptive mechanism for Jurassic silicic volcanism in southern Patagonia. Sruoga et al. (2014) interpreted a trapdoor-like collapse for the La Peligrosa caldera located in the Sierra Colorada (Fig. 2), 100 km southeast of the Laguna Verde district. Other caldera structures have been identified further east in the Deseado Massif (e.g., Guido 2004; Echavarría et al. 2005; Ruiz et al. 2011; Salani and Chernicoff 2017; Navarrete et al. 2020a). In particular, Navarrete et al. (2020a) described the Deseado Caldera, a graben-type caldera similar to the one described by Aguirre-Díaz et al. (2008) in the Sierra Madre Occidental of North America. Despite the various mechanisms postulated, it appears that tectonics exerted a first-order control in the formation of calderas in the Chon Aike SLIP (cf. Navarrete et al. 2020a).

Table 2 Summary of interpretative eruptive cycles for the volcanic evolution of the Ibañez Formation in the Laguna Verde district

	Eruptive cycle	Units	Lithology	Structural control	Chronology
Ibañez Formation (Upper Jurassic)	Resurgent magmatism	Sub-volcanic complex of Laguna Verde	Rhyolitic domes and andesite dykes	Tectonic <<< Volcanic	Slightly younger than 149.2 Ma
	Multi-episodic caldera collapse	Upper unit	Intermediate-acidic lava flows > acidic ignimbrites	Tectonic < Volcanic	149–148 Ma
		Lower unit	*extensive* ignimbrites > Ash-fall tuffs	Tectonic > Volcanic	155–152 Ma

Chronology of the Late Jurassic volcanism in southern Patagonia

The Jurassic volcanism in southern Patagonia demonstrates a broad pattern of becoming younger towards the Pacific margin (see Pankhurst et al. 2000). The younger volcanic products, which coincide with the onset of the Andean arc (Navarrete et al. 2019; Bastias et al. 2021), are emplaced along the South Patagonian Andes. In the southern region (49°–50° S) of the South Patagonian Andes, Malkowsky et al. (2016) conducted U–Pb dating (LA-ICP-MS) on the entire volcanic rock column of the El Quemado Complex. They evidenced that volcanic activity started around ~ 152 Ma, with later products occurring around ~ 148 Ma. Similar results were recently achieved by Foley et al. (2022) in the same area. In the central region (47°–48° S) of the South Patagonian Andes, a few U–Pb crystallization ages are available, but they indicate values of 154–153 Ma (Pankhurst et al. 2000).

The new ages reported in this study for the Ibañez Formation in the northern region of the South Patagonian Andes reveal that the lower section has crystallization ages of approximately 155–152 Ma, while the upper unit yields ages of around 149–148 Ma (Fig. 9). These ages are slightly older than those previously reported by Poblete et al. (2014) for neighboring areas. In northern outcrops of the Central Patagonian Andes, Suárez et al. (2009) obtained younger ages compared to those reported by several authors in the context of the South Patagonian Andes. The ages reported by Suárez et al. (2009) range from 140 to 137 Ma and are interpreted as contemporaneous with the onset of marine sedimentation in the Aysén/Río Mayo Basin. These ages of volcanism are quite similar to the Adularia Ar–Ar ages associated with Ag-Au veins, as reported by Poblete et al. (2014) for the Laguna Verde district.

The ages presented in this study for the Laguna Verde district reveal that large volumes of ignimbrites were erupted from caldera volcanic edifices in a short-lived event of approximately 11 My (including age errors). This significant volcanic activity in such as brief timeframe suggests that the initial stage of Andean volcanism in the Laguna Verde district can be interpreted as an ignimbrite flare-up (see former proposal by Sruoga et al. 2014). On a regional scale, when combined with the compilation of available U–Pb dating along the South Patagonian Andes (46–51° S), it is possible to narrow down the V3 stage to the period between ~ 157–143 Ma (Fig. 9), with the lower boundary being 10 My younger than previously reported (e.g., Pankhurst et al. 2000). However, it seems that neighboring Cordilleran regions document younger silicic magmatism of Berriasian–Valanginian age (Early Cretaceous times), which is interbedded with the basal Mesozoic infill of the Aysén/

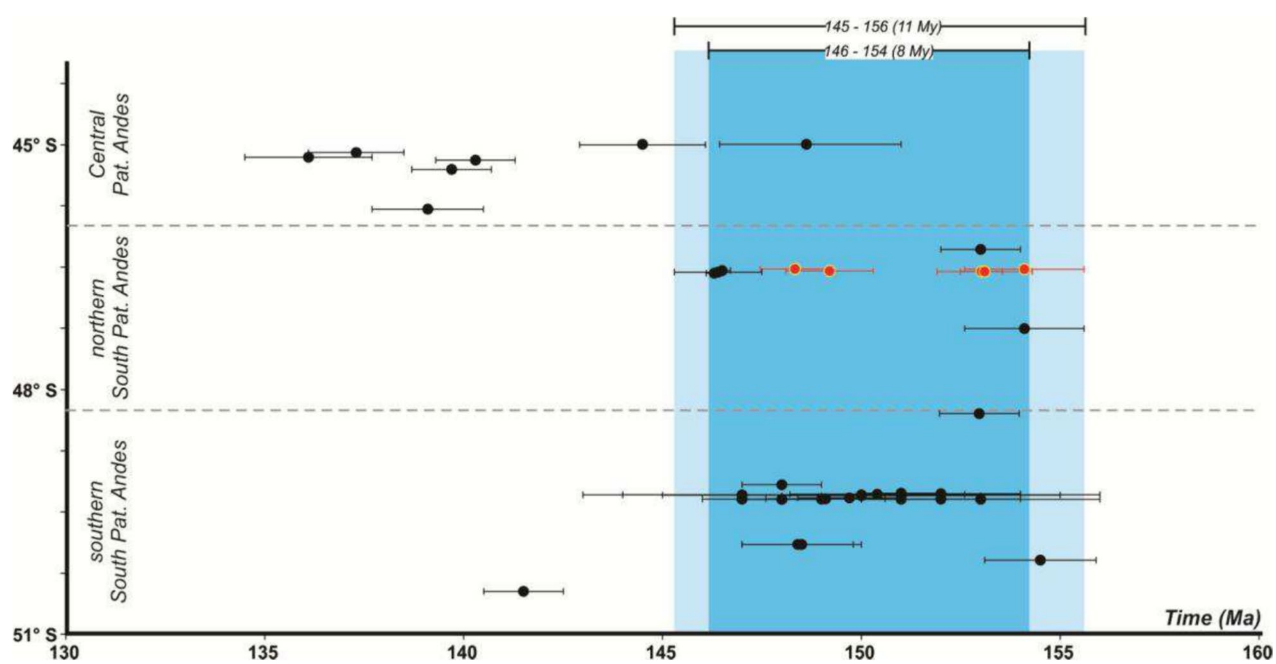


Fig. 9 Diagram of latitude versus U–Pb crystallization age. In our study zone, the U–Pb crystallization ages encompass a lapse of 8 My between 154 and 146 Ma (blue-filled strip) and 11 My between 156 and 145 Ma (including errors) (sky blue-filled strip). The red and black dots correspond to U–Pb ages from this study and compilation ($n = 41$), respectively. The data are taken from Pankhurst et al. (2000), Rolando et al. (2004), Suárez et al. (2009), Poblete et al. (2014), Malkowsky et al. (2016), Zerfass et al. (2017), Foley et al. (2022), and this study

Río Mayo and Austral basins, as reported by Suárez et al. (2009), Bruce (2001), and Zerfass et al. (2017), respectively. This raises the question of whether the Late Jurassic and Early Cretaceous volcanic stages represent continuity or different episodes of volcanic activity.

Tectonic controls on the emplacement of the Late Jurassic ignimbrite flare-up

The tectonic triggers of ignimbrite flare-ups have been the subject of debate in the literature (Best et al. 2016; Gravley et al. 2016; Fernández Paz et al. 2020). Best et al. (2016) conducted a comparison of petrological and tectonic features between the Sierra Madre Occidental (North America) and Puna Plateau (Central Andes) ignimbrite flare-ups. They concluded that ignimbrite flare-up forms during the slab roll-back stage (i.e., retreating mode) which leads to the stretching of a previously thickened continental crust (> 40 km) due to flat-slab subduction.

Field structural data and interpretation of 2-D seismic lines in the South Patagonian Andes indicate that extensional tectonics is the favorable tectonic regime for the emplacement of the Upper Jurassic volcanic units (e.g., Giacosa et al. 2012; Japas et al. 2013; Sruoga et al. 2014; Zerfass et al. 2017; Ramos et al. 2019). Sub-surface seismic images of the Austral Basin have demonstrated that the El Quemado Complex was emplaced in half-graben structures, exhibiting strong lateral variations in thickness, suggesting a syn-extensional nature for these rocks (Fosdick et al. 2011; Giacosa et al. 2012; Zerfass et al. 2017). Similarly, several authors have identified wedge geometries in outcrops (Kraemer and Riccardi 1997; Zerfass et al. 2017; Ramos et al. 2019), further supporting the syn-extensional nature of these volcanic products. Geological mapping in the Laguna Verde district reveals a strong control of normal faulting on the emplacement of the volcanic units (Figs. 3, 4a). Several pieces of evidence support this observation, including: (i) two sets of normal faults delimiting blocks, (ii) significant thickness variations among blocks, and (iii) NE-SW-oriented faults influencing the emplacement of sub-volcanic domes, such as the La Isla fault. However, determining the relative timing of activity among the different sets of normal faults is complex. Additionally, along the south shore of the General Carrera-Buenos Aires Lake, Lagabrielle et al. (2004) analyzed fault-slip data, and found a combination of strike-slip and extensional strain tensors. It suggests that at a local scale, a transtensional regime may have dominated instead of pure extension (see also Suárez et al. 2023).

Regarding the kinematics of the subduction system, Hervé et al. (2007) recognized in the South Patagonian Batholith that granitoids of the Cretaceous-1 stage (144–137 Ma) are emplaced outboard of the Jurassic ones (157–145 Ma). Based on this evidence, Ramos et al. (2019) proposed that the early Andean arc in southern Patagonia (i.e., the South Patagonian Batholith) underwent a retreating stage during the lapse 157–137 Ma, as the locus of arc magmatism migrated outboard up to *ca*. 200 km (see also Gianni et al. 2018).

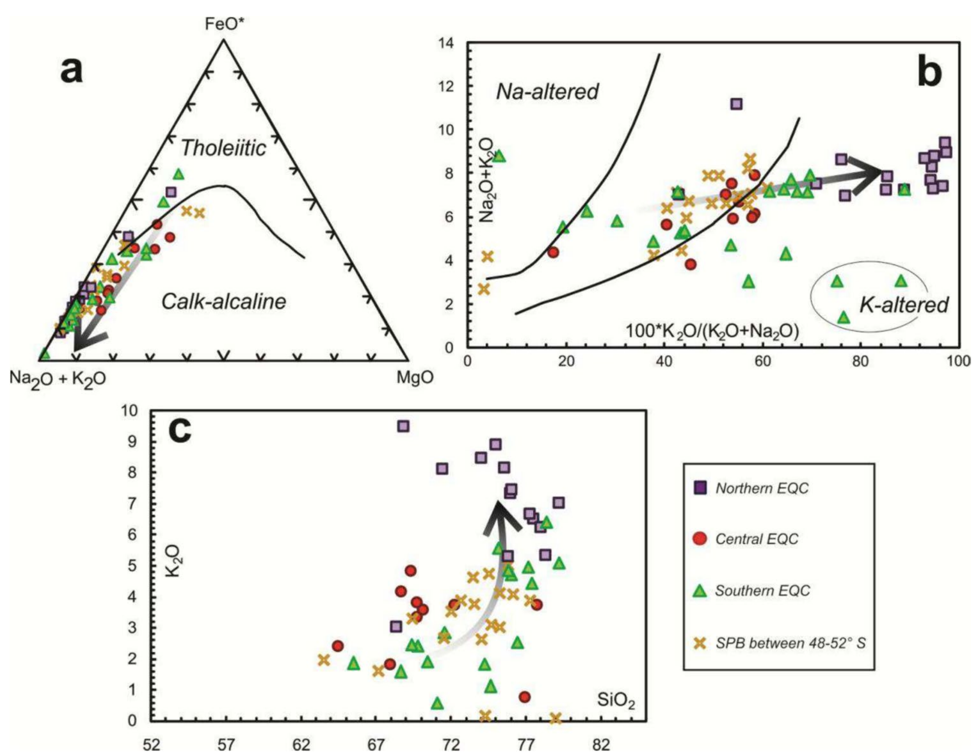


Fig. 10 Compilation of geochemistry data from the South Patagonian Batholith (SPB; Hervé et al. 2007) and the Upper Jurassic rocks of the El Quemado Complex (EQC; Pankhurst et al. 1993; Seitz et al. 2018; Foley et al. 2023a, b). **a** AFM diagram illustrating that the samples follow the calc-alkaline trend. **b** Hughes's (1972) diagram recognizing Na and K alteration, with a few samples plotted in the K-altered field (black circle), and excluded from the SiO_2 versus K_2O plot. **c** Harker-type diagram of SiO_2 versus K_2O showing the K-enrichment of the volcanic rocks compared to the intrusive rocks of the SPB, particularly, in the northern region near the Laguna Verde district

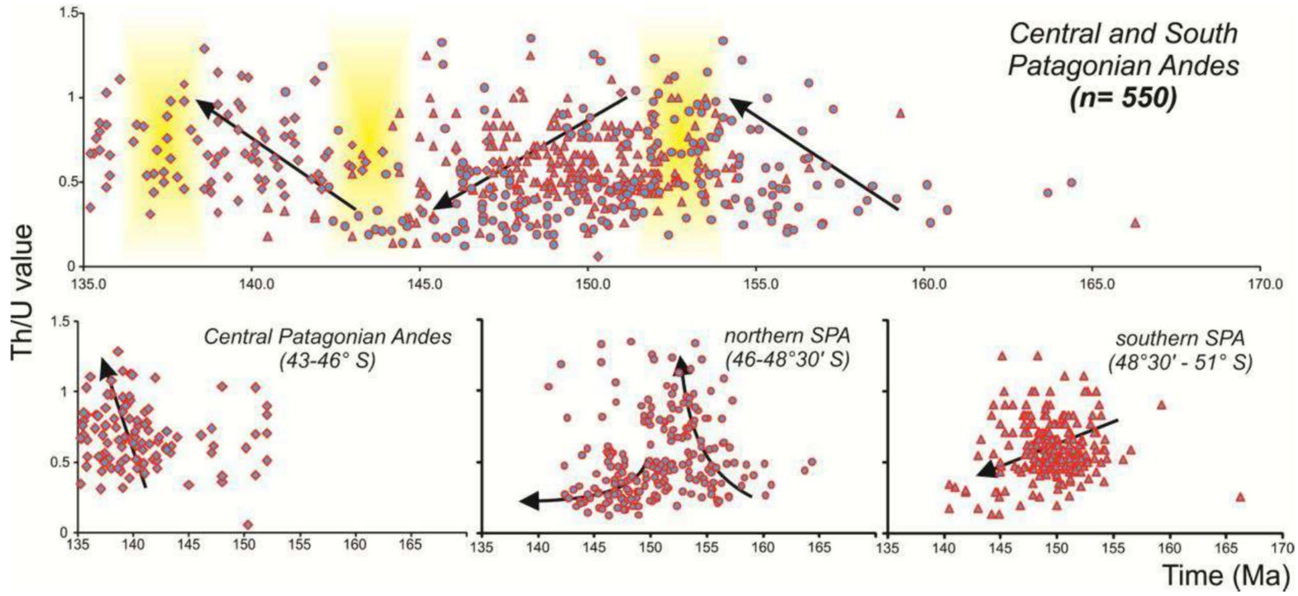


Fig. 11 Diagram of U–Pb age in single zircon plotted against the value of Th/U ratio ($n = 550$) for Upper Jurassic-Lower Cretaceous acidic volcanic rocks emplaced along the Cordilleran axis. The data used in the diagram are from various sources, including Pankhurst et al. (2000), Rolando et al. (2004), Calderón et al. (2007), Suárez et al. (2009), Poblete et al. (2014), Malkowski et al. (2016), Zerfass et al. (2017), and our study. One outlier value of Th/U ratio > 1.5 has been excluded. The red line at 0.52 represents the mean Th/U value for granitic rocks obtained from $n = 1684$ by Xiang et al. (2011). The arrows in the diagram indicate the trend of increasing or decreasing values

The compilation of geochemistry data for both the South Patagonian Batholith and the Upper Jurassic volcanic rocks of the South Patagonian Andes demonstrates that both belong to the trend of calk-alkaline rocks in the AFM diagram. However, we noted that the volcanic rocks have a higher potassium content compared to the batholith. This enrichment cannot be solely explained by alteration (see Fig. 10). A significant participation of the continental crust does results in higher potassium values. Alternatively, in the extra-Andean region of southern Patagonia, the K-enrichment in Jurassic rhyolites is interpreted as an effect of K-metasomatism (e.g., Paez et al. 2010). In either case, there is strong evidence of crustal affinity supported by isotopic data (Pankhurst et al. 1993; Hervé et al. 2007). During this retreating stage, the arc-related granitoids exhibit isotopic values of $\varepsilon Nd_t = -5$ to -4 and $(^{87}Sr/^{86}Sr)_t$ between 0.707 and 0.709, confirming their crustal origin (Hervé et al. 2007). These values of $(^{87}Sr/^{86}Sr)_t$ are similar to those reported by Pankhurst et al. (1993) for the Upper Jurassic volcanic rocks at the Sierra Colorada (Fig. 10). Additionally, Seitz et al. (2018) and Foley et al. (2023a) reported elevated $\delta^{18}O$ values for the El Quemado Complex in both zircon and quartz, which can be explained by crustal contribution during melting through anatexis or assimilation. According to Foley et al. (2023a), approximately ~ 75% melting derived from the metasedimentary basement is necessary to produce this rhyolitic volcanism.

Taking everything into account, it appears that crustal anatexis of a fertile crust in the retroarc setting is the predominant factor in magma production, as recently suggested by Foley et al. (2023b; see also Bruce 2001). Therefore, the subduction kinematics in the retreating mode, which drives the intra-arc to retroarc extension, seems to be the main tectonic factor controlling the emplacement of the ignimbrite flare-up trough of the South Patagonian Andes. This mechanism is similar to the proposal by Best et al. (2016) for the Cenozoic tectonics (Oligocene–Eocene) of North America.

Further tectonic implications based on the Th/U ratio in zircon

Among the geochemical features of zircon, the Th/U ratio is a powerful tool for elucidating melt conditions (Xiang et al. 2011; Kirkland et al. 2015). In magmatic environments, zircon typically has a Th/U > 0.5, with a mean value of ~ 0.65 ($n = 10{,}693$ by Kirkland et al. 2015). In granites (acidic rocks), the Th/U ratio ranges between 0.01 and 3.79, with a mean of around 0.52 (Xiang et al. 2011). However, the Th/U ratio can vary significantly due to intrinsic factors of the melt, such as the chemical composition, the zircon-melt coefficient of partition, and the magma temperature, among others (Xiang et al. 2011; Kirkland et al. 2015; McKay et al. 2018). Additionally, McKay et al. (2018) demonstrated that the Th/U ratio in zircon is sensitive to the tectonic regime, reflecting extensional tectonic regimes with higher Th/U values and compressive tectonic regimes with lower Th/U values. Therefore, the Th/U ratio could provide further insights into the tectonic regime during the emplacement of the flare-up associated with the beginnings of Andean volcanism in southern Patagonia.

The resulting plot of U–Pb age versus Th/U ratio reveals distinct trends for the Jurassic volcanic rocks of the South Patagonian Andes. At first glance, the Th/U values appear to increase around 155–150 Ma and 140–135 Ma, with both ranges interrupted by lower values at approximately 145 Ma (Fig. 11).

Since we only collected data from acidic rocks to maintain a constant whole-rock chemical composition, no variations in the Th/U ratio can be attributed to geochemical variations. In this regard, an alternative explanation can be found in the magma temperature, as mentioned by McKay et al. (2018). While lower Th/U ratios in zircons are associated with cooler melts, higher Th/U ratios in zircons are associated with hotter melts (Kirkland et al. 2015). Specifically, for the South Patagonian Andes, the highest values of the Th/U ratio are observed around 152–150 Ma (Fig. 11). This suggests that the extensional regime reached its peak during this period, which coincides with the upper boundary of the rifting stage in the Rocas Verdes Basin (Calderón et al. 2007, 2013). Then, at 140–135 Ma, the Th/U data reveal a new trend of increasing values (Fig. 11), which coincides with the volcanism synchronous with the marine ingression of the northern sector of the Aysén/Río Mayo basin represented by the Toqui Formation (e.g., Bruce 2001; Suárez et al. 2009). Therefore, the tectonic regime may have influenced the conditions of magma emplacement and, consequently, the chemistry of zircon. It is important to note that this is a preliminary statement, and further studies should be conducted to investigate how the transition from Late Jurassic extension to Early Cretaceous mountain building at 130–120 Ma (e.g., Aramendía et al. 2018; Gianni et al. 2018, 2020; Ronda et al. 2022) affects both whole-rock and zircon chemistry.

Conclusions

The Jurassic period in Patagonia is characterized by the development of the Chon Aike SLIP. During the final stages of this silicic large igneous province, significant volumes of acidic ignimbrites were erupted in the southern region of Patagonia, in a retroarc position. We conducted fieldwork in the Laguna Verde district of southern Chile (46° S), where we strategically sampled ignimbrites and cogenetic units to obtain reliable U–Pb crystallization ages. Our study reveals that during a relatively short period of volcanic activity lasting 8 My (11 My considering inherited errors). This period can be divided into two major stages at 155–152 Ma and 149–148 Ma. The volcanic features we have identified suggest a multiple collapse caldera as the most likely volcanic edifice. Since the extensive distribution of acidic volcanism and the short duration of eruptions, we can classify this event as an ignimbrite flare-up. Moreover, our field observations and petrochronological data supports an extensional tectonic regime, which likely reached its peak around 152–150 Ma. The subduction kinematics, typical of retreating-type orogens, can explain most of the tectonic and petrogenetic features observed in the Late Jurassic volcanism of southern Patagonia.

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Data availability The U–Pb ages presented in this contribution are reported in Supplementary Information 1.

Declarations

Conflict of interest The authors declare that there is no known conflict of interest.

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