

Volcano-tectonic Seismicity at Villarrica Volcano: A Decade of Evidence (2014–2023) to Understand Its Internal Dynamics

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VOLCANO-TECTONIC SEISMICITY AT VILLARRICA

VOLCANO: A DECADE OF EVIDENCE (2014–2023) TO UNDERSTAND ITS INTERNAL DYNAMICS

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Abstract Villarrica Volcano (39.42°S, 71.93°W), one of South America's most active volcanoes, poses a major hazard to nearby communities and ranks first in Chile's volcanic-risk ranking, motivating detailed analysis of its internal dynamics. We analyzed 2,364 volcano-tectonic (VT) earthquakes recorded during 2014–2023, integrating hypocentral distributions, b-values, focal mechanisms, and surface observations. Nine VT swarms lasting 33–194 days were identified. Most showed a recurrent evolution from intracaldera clustering, through the largest-magnitude VT earthquake at 31–64% of swarm duration, to outward redistribution toward the caldera periphery. S6 instead showed inward redistribution, with persistent post-pivot intracaldera activity overlapping extracaldera seismicity, whereas S8 remained entirely extracaldera. Spatial b-values (~0.6–1.8) delineated low-b intracaldera, high-b adjacent, and intermediate-b distal domains, indicating contrasts in stress concentration, fracture state, and potential fluid influence. Predominantly strike-slip focal mechanisms displayed variable P- and T-axis orientations, consistent with local stress-field heterogeneity. The spatial coincidence of the largest VT earthquakes with the low-b intracaldera domain is consistent with shallow magmatic and/or fluid pressurization, brittle failure, and enhanced fracture connectivity, potentially facilitating stress redistribution toward peripheral structures. In four swarms, explosive activity and satellite-detected thermal anomalies increased one to two months after the largest VT earthquake, consistent with delayed hydraulic reorganization and upward transfer or accumulation of fluids, heat, and potentially magma. The absence of comparable responses in the remaining swarms indicates a conditional rather than deterministic relationship. These observations highlight variability in magmatic and fluid-related processes across individual volcanic episodes and provide a multiparametric framework for evaluating future VT swarms at Villarrica.

Keywords Villarrica Volcano · volcano-tectonic earthquakes · spatiotemporal seismic migration · volcanic hazard assessment

1 Introduction

Seismic swarms are a recurrent manifestation of mechanical instability in volcanic and tectonic settings (Mogi 1963). They consist of numerous earthquakes, commonly of low to moderate magnitude, occurring over hours to weeks or months without a single dominant mainshock (Benoit and McNutt 1996; McNutt 2005). Unlike classical mainshock–aftershock sequences, swarms lack a canonical aftershock decay and may display accelerations, fluctuations in seismicity rate, and systematic spatial migration (Mogi 1963; Benoit and McNutt 1996). In volcanic environments, these patterns are commonly interpreted as the response of the brittle crust to transient forcing associated with magma intrusion, pressurization, and/or shallow fluid circulation, which modify stress, effective pressure, and permeability within the volcanic edifice and surrounding crust (McNutt 2005; Roman and Cashman 2006).

A widely used framework links volcano-tectonic (VT) swarms to dike inflation or intrusion, which promotes shear failure on pre-existing faults and fracture networks, particularly around propagating dike tips (Hill 1977). In this context, focal mechanisms may reflect the ambient stress field, but faulting styles can vary from strike-slip to normal depending on local stress conditions, intrusion geometry, and the interaction between magmatic forcing and the tectonic stress field (Hill 1977; Roman and Cashman 2006). Precise relocations of the 1998 swarm east of the Izu Peninsula, Japan, revealed a thin planar structure and rapid vertical migration consistent with buoyancy-driven dike propagation, with earthquakes clustering near the advancing tip (Hayashi and Morita 2003). Building on such observations, Roman and Cashman (2006) synthesized three end-member seismic expressions of magma migration: shear around inflating dikes, propagating seismicity ahead of an advancing tip, and mixed patterns controlled by the interplay between magmatic forcing and regional stress. Accordingly, VT swarms may involve hypocentral migration, focal-mechanism rotations, or both, depending on the mechanical state of the volcanic system (Roman and Cashman 2006).

Volcanic VT swarms may involve thousands to tens of thousands of earthquakes (ML ~ 0–3), typically concentrated in the upper few kilometers of the crust, with durations ranging from days to weeks, although months-long episodes are also documented (Benoit and McNutt 1996; McNutt 2005). Their temporal evolution commonly includes a growth phase, one or more rate maxima, and decay, while their spatial patterns may reveal repeating families, structural alignments, and migration

compatible with either dike propagation or diffusion-driven triggering (Benoit and McNutt 1996; Vidale and Shearer 2006). At Laguna del Maule, in the Southern Andes Volcanic Zone, intense VT activity accompanying rapid uplift has been linked to magmatic pressurization and deformation of the shallow crust (Cardona et al. 2018; Vigide et al. 2025). These observations highlight the value of integrated space–time analyses for distinguishing between structurally controlled seismicity, intrusion-related forcing, and fluid-assisted triggering in volcanic systems.

Magnitude–frequency statistics provide a complementary diagnostic of evolving source conditions (McNutt 2005). In particular, b-value variations during volcanic unrest have been interpreted as reflecting changes in differential stress, accumulated damage, temperature, and pore-pressure conditions near magmatic bodies (Scholz 2015; McNutt 2005). The b-value has been quantitatively calibrated as an inverse proxy for differential stress (Scholz 2015), and its dependence on stress regime is consistent with focal-mechanism observations, with lower values commonly associated with thrust faulting, higher values with normal faulting, and intermediate values with strike-slip regimes (Schorlemmer et al. 2005; Gulia and Wiemer 2010). At Copahue volcano, decadal monitoring using a completeness-robust estimator showed b-value decreases weeks to months before alert escalations, consistent with increasing differential stress and/or evolving effective stress due to pore-pressure changes (Fariás et al. 2023). These results emphasize that b-value analysis is most informative when catalog completeness and magnitude thresholds are rigorously controlled.

Swarms may also be modulated by broader stress transients and volatile-mediated processes that condition the critical state of a volcanic system, alter permeability, and govern the coupled evolution of VT rates, migration, and deformation (Zanon et al. 2024; Seropian et al. 2021). Magmatic and hydrothermal fluids exert first-order control on swarm nucleation and evolution: laboratory experiments show that rapid decompression of fluids in fractured basalt can generate clustered acoustic emissions and low-frequency signals (Benson et al. 2020), while the fault-valve concept describes cycles of fluid overpressure, rupture, transient permeability enhancement, and resealing within fault and fracture networks (Sibson 1996). In compressional to transpressional regimes, such overpressures can activate misoriented faults and promote failure by increasing pore-fluid pressure and reducing effective normal stress (Sibson 1990, 1996; Ellsworth 2013; Goertz-Allmann and Wiemer 2013; Grigoli et al. 2018). Geophysical indicators commonly associated with overpressured, fluid-rich domains include low V_p and V_s , elevated V_p/V_s , and high electrical conductivity, particularly where seismic and electromagnetic anomalies co-locate (Foulger et al. 1995; Cordell et al. 2019; Chiarabba et al. 2020). Exhumed-fault studies further support thermo-hydro-mechanical coupling and transitions from rock-buffered to

fluid-buffered deformation, consistent with episodic, valve-like fluid discharge (Williams et al. 2017; Gomila et al. 2016, 2021; Masoch et al. 2022, 2025).

Here, we focus on Villarrica Volcano (39.42°S, 71.93°W), one of South America's most active volcanoes, as a natural laboratory to investigate how intrusion, fluid circulation, and stress transients interact to generate VT swarms and how these signals track the state of the shallow magmatic system. Using a decade of local seismicity from 2014 to 2023, we aim to: (i) distinguish VT swarms from shallow LP-dominated activity; (ii) quantify swarm duration, size, energy release, and space–time migration; (iii) evaluate dike and fluid-dominated forcing using focal mechanisms and spatially variable b-values; and (iv) interpret these observations within a framework of intrusion mechanics, fault-valve behavior, and elastic–brittle failure, integrating MIROVA thermal anomalies and observations of surface explosive activity. This multi-proxy approach allows us to assess whether recurrent VT swarms at Villarrica represent transient internal reorganization of the volcanic system and to identify parameters that may improve real-time monitoring and early warning at open-conduit volcanoes.

1.1 Volcanic Activity, Structural Setting, and Monitoring Context of Villarrica Volcano

Villarrica (Quitralpillan) is a 2,847 m a.s.l. basaltic-andesite stratovolcano located in Chile's Southern Volcanic Zone (39.42°S, 71.93°W). It is commonly ranked among Chile's highest-risk volcanoes because of its frequent eruptions and proximity to exposed communities and infrastructure (Palma et al. 2008; Moussallam et al. 2016). This ranking is supported by probabilistic reconstructions indicating exceptional recurrence of $VEI \geq 2$ eruptions, with mean and median repose times of ~ 5.4 and ~ 4.5 years, respectively, since the 16th century (Van Daele et al. 2014). Since at least the mid-1980s, magma has often remained at shallow conduit levels, intermittently sustaining a summit lava lake and persistent degassing punctuated by short-lived lava fountaining and Strombolian bursts (Palma et al. 2008; Moussallam et al. 2016). This open-vent state controls eruptive behavior (Romero et al. 2018) and produces coherent multiparametric monitoring signatures in seismicity (Richardson et al. 2014), gas (Aiuppa et al. 2017), and thermal observations (Moussallam et al. 2016).

The present edifice is dominated by lava flows and pyroclastic deposits associated with eruptive styles ranging from violent Strombolian to sub-Plinian activity (Lohmar et al. 2012; Silva Parejas et al. 2010). Although Villarrica's long-term evolution includes multiple constructional stages and caldera-forming episodes, the key feature for this study is the persistence of a shallow, compositionally restricted, and

repeatedly recharged magmatic system (Lohmar et al. 2012; Morgado et al. 2015; Cortés et al. 2024; Pizarro et al. 2019; Boschetty et al. 2022). Two Holocene monogenetic fields, Los Nevados to the east and Chaillupén to the south, indicate that magma ascent has also been influenced by regional fault architecture during the recent evolution of the volcanic complex (Morgado et al. 2015; Cortés et al. 2024). Petrological studies suggest recurrent mixing between a shallow hybrid reservoir and hotter, slightly more primitive, volatile-rich inputs, implying that relatively small variations in recharge or volatile-release rates may trigger rapid transitions from background open-vent activity to paroxysmal behavior (Cortés et al. 2024; Pizarro et al. 2019; Boschetty et al. 2022). Historical lavas, including those that erupted in 1921, 1948, and 1971, show restricted bulk compositions and evidence of cryptic thermal and volatile recharge superposed on resident magma (Pizarro et al. 2019; Boschetty et al. 2022).

In open-vent volcanic systems such as Villarrica, background seismicity is commonly dominated by continuous tremor and high-rate, shallow long-period (LP) events associated with fluid–magma motion within and above the conduit (Palma et al. 2008; Moussallam et al. 2016). At Villarrica, LP rates and RSAM frequently co-vary with outgassing style, lava-lake dynamics, SO₂ flux, gas ratios, and thermal radiance (Richardson et al. 2014; Aiuppa et al. 2017). The 2015 paroxysm was preceded by increased LP seismicity, elevated SO₂ flux and CO₂/SO₂ ratios, and thermal anomalies (Aiuppa et al. 2017), while post-paroxysm episodes in December 2015 and February 2017 included thousands of LP events, MIROVA thermal anomalies, and SO₂ degassing, consistent with a persistently shallow magma column and vigorous convective degassing (Romero et al. 2023).

Within this monitoring context, VT clusters and occasional swarms are interpreted as markers of brittle failure within the volcanic edifice and its periphery (Sielfeld et al. 2019), whereas the continuous LP/tremor background primarily tracks conduit-scale magma circulation, volatile dynamics, and short-term changes in the shallow system (Richardson et al. 2014). Source-physics interpretations suggest that Villarrica's LP wavefield arises from shallow conduit-proximal processes, including gas-slug rise, bubble bursting, and drag forces along rough conduit walls, which generate quasi-repetitive forces and resonance in the upper conduit (Ripepe et al. 2010; Richardson et al. 2014). Therefore, the joint interpretation of LP, gas emissions, thermal anomalies, and VT seismicity provides a key framework for distinguishing conduit-scale activity from deeper brittle deformation processes relevant to swarm development (Richardson et al. 2014; Aiuppa et al. 2017; Romero et al. 2023).

2 Methodology and Database

During the study period, Villarrica Volcano was continuously monitored by a broadband seismic network consisting of 37 permanent stations distributed within an approximate 90 km radius around the volcanic edifice (Online Resource 1, Fig. S1 and Table S1). This network is part of the National Volcanic Surveillance Network (RNVV) and is operated by the Southern Andes Volcano Observatory (OVDAS–SERNAGEOMIN). Installed sensors include Reftek 151-30A, Güralp 6TD, and Nanometrics Trillium 40 and 120 instruments, all with a flat response down to 120 s and a standard sampling rate of 100 Hz. Data are transmitted in real time to the OVDAS monitoring center in Temuco through redundant radio and satellite links, ensuring operational continuity exceeding 95% and hypocentral accuracies on the order of ≤ 1 km for events occurring within or near the caldera.

The local seismic network around Villarrica Volcano includes stations located at distances ranging from approximately 1.3 to 22.7 km from the active crater, providing detailed coverage of seismic activity occurring within the volcanic edifice and its immediate surroundings. These stations operate using a combination of broadband and short-period sensors coupled with different digitizing systems, including Reftek 130B, Kinematics Q330, and Kinematics Basalt digitizers. Several stations have been operating since the early stages of the RNVV deployment between 2011 and 2013, while additional instruments were incorporated during subsequent network upgrades. More recent deployments include temporary seismic stations (Universidad de La Frontera network) installed during monitoring campaigns between 2021 and 2024 using Raspberry RS3D systems and SmartSolo IGU-BD3C-5 nodes (Table 1).

To improve the accuracy and stability of seismic event relocations at Villarrica Volcano, additional seismic stations from nearby volcanic centers were incorporated into the analysis. These regional stations, deployed at the Lanín, Quetrupillán, Mocho–Choshuenco, and Llaima volcanoes, were used to complement the local seismic network by enhancing azimuthal coverage, particularly for volcano-tectonic (VT) events and focal mechanism calculations. The incorporation of these stations extends the effective monitoring network to a regional scale, improving the geometry of the seismic array and increasing the number of available phase arrivals used in hypocentral determinations (Table 1; Fig. 1).

Surface activity at Villarrica Volcano was monitored using a complementary network of IP cameras and infrasound sensors. These instruments provide independent observations of explosive activity, degassing, and other surface manifestations, allowing the integration of visual and acoustic data with the seismic record to better characterize surface responses associated with periods of increased volcanic activity.

The camera network allows continuous observation of the summit crater and upper flanks of the volcano, while infrasound sensors detect acoustic signals generated by explosions and gas emissions associated with eruptive activity (Table 1; Fig. 2).

Table 1 Characteristics of the stations used to monitor Villarrica Volcano during the study period

Station	Distance to crater (km)	Elevation (m a.s.l.)	Sensor	Digitizer	Installation date
CV2	16.6	230	GURALP 6TD	GURALP 6TD	08-02-2013
VN2	3.0	1494	REFTEK 151-30A	REFTEK 130B	12-04-2012
KIK	6.4	1636	NANOMETRICS TRILLIUM 120P	REFTEK 130B	16-05-2013
PCH	5.5	1797	NANOMETRICS TRILLIUM 120P	REFTEK 130B	16-12-2015
VT2	2.3	1854	NANOMETRICS TRILLIUM 120P	REFTEK 130B	22-12-2014
TRA	5.7	1883	NANOMETRICS TRILLIUM 120P	REFTEK 130B	20-04-2012
CHP	6.7	1441	NANOMETRICS TRILLIUM 40	REFTEK 130B	16-12-2015
MRA	1.3	2302	NANOMETRICS TRILLIUM 120P	KINEMETRIC S Q330	01-01-2011
CER	3.1	1752	SERCEL L4C	REFTEK 130B	14-01-2014
DO2	18.8	1750	SERCEL L4C	KINEMETRIC S BASALT	28-03-2019
AL2	19.5	1897	REFTEK 151-30A	REFTEK 130B	30-05-2016
RIN	22.7	1865	NANOMETRICS TRILLIUM 120P	REFTEK 130B	27-03-2019
UF1	9.8	1290	Raspberry RS3D	Pi 3 Model B	2020-2022

Station	Distance to crater (km)	Elevation (m a.s.l.)	Sensor	Digitizer	Installation date
			SmartSolo IGU-BD3C-5	32-bit delta-sigma ADC.	2023-2024
UF2	18.1	307	SmartSolo IGU-BD3C-5	32-bit delta-sigma ADC.	2023-2024
UF3	23.2	680	SmartSolo IGU-BD3C-5	32-bit delta-sigma ADC.	2023-2024
IP Camera CLFQ	17.2	377	AXIS P5624-E	—	06-09-2012
IP Camera CCVV	23.5	282	AXIS P5635-E	—	10-10-2019
IP Camera CPCV	5.3	1121	AXIS P5635-E	—	23-09-2019
Infrasound MPVC	3.4	1328	Chaparral 50A	Reftek 130B	04-10-2020
Infrasound MCHL	7.8	1420	Chaparral 50A	Kinematics Basalt	26-11-2018

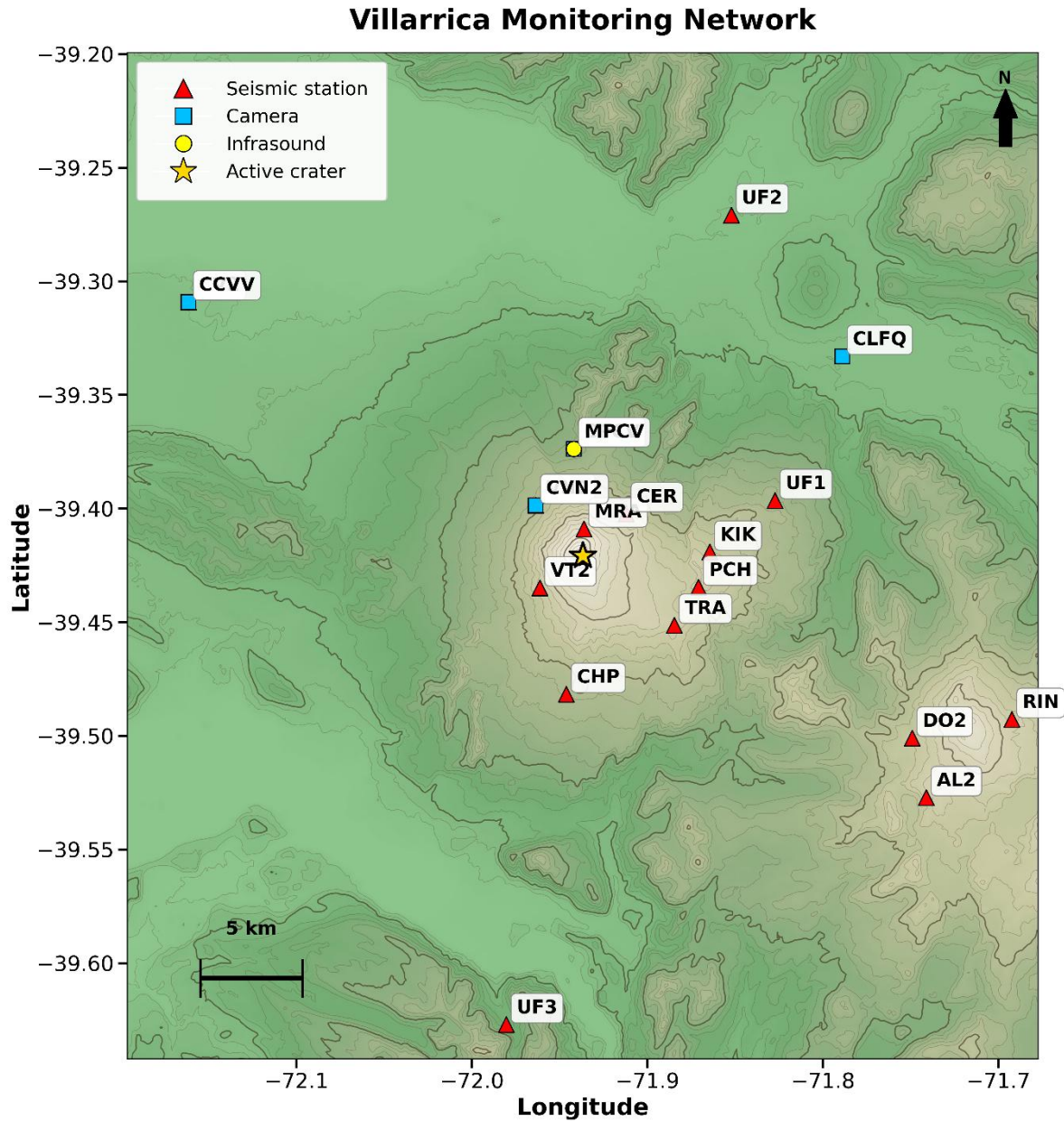


Fig. 1 Map of the local monitoring network deployed around Villarrica Volcano and used in this study. Seismic stations are shown as red triangles, monitoring cameras as blue squares, and infrasound sensors as yellow circles. The orange star indicates the location of the active crater. Station labels correspond to the operational codes of the monitoring network.

The dataset analyzed corresponds to the local seismic catalog of Villarrica Volcano covering the period from January 2014 to September 2023. During this interval, more than 779,000 seismic signals were operationally classified by OVDAS–SERNAGEOMIN as volcano-tectonic earthquakes (VT), long-period events (LP), and explosion-type events (EX). Specifically, the catalog includes 2,364 volcano-tectonic earthquakes, 775,055 long-period events, and 245 explosion-type events. These different event

classes present distinct observational and analytical characteristics. VT earthquakes constitute the only type of event for which reliable hypocentral locations were systematically obtained. In contrast, LP events were not routinely located and were primarily characterized by their seismic amplitude, expressed as reduced displacement (DR). Explosion-type events (EX) were not located either and were assumed to originate from the summit crater of Villarrica Volcano. EX events were identified through the combined analysis of seismic waveforms, visual confirmation from permanent web camera observations, and acoustic signals recorded by infrasound sensors deployed around the volcanic edifice. Infrasound data were used exclusively to identify and validate eruptive explosions, distinguishing them from non-eruptive seismic signals, and were not applied to quantitative energy analysis. For VT events, P- and S-wave arrivals were manually reviewed in order to correct automatic picks and verify arrival-time consistency across the seismic network, ensuring a high-quality and internally consistent seismic catalog. Following quality control and relocation procedures, 1,219 VT earthquakes were successfully located, forming the dataset used for the spatial analysis of seismicity and the calculation of focal mechanisms. LP and EX events were treated separately and were not subjected to hypocentral quality criteria, since their analysis focuses primarily on the temporal evolution of volcanic activity and surface manifestations rather than precise source location. Consequently, these events were analyzed mainly in terms of their temporal occurrence and seismic amplitude characteristics, allowing the evaluation of variations in degassing activity, explosive behavior, and the overall evolution of the volcanic system during the study period.

For statistical and modeling purposes, only well-located events were retained, defined by strict quality criteria: horizontal error ≤ 1.0 km, vertical error ≤ 1.5 km, RMS ≤ 0.20 s, and an azimuthal gap $\leq 180^\circ$. These criteria correspond to events classified as quality A or B, following the standard hypocentral quality classification commonly used in local earthquake location procedures, where events are ranked from A to D according to azimuthal gap, RMS residuals, and location uncertainties (Lee and Lahr 1975; Lee and Valdes 1985). In addition, events selected for focal-mechanism analysis were required to be recorded by a minimum of eight seismic stations, ensuring adequate azimuthal coverage of P-wave polarities, which is a necessary condition to obtain robust and stable focal-mechanism solutions. After applying these filters, the refined catalog constitutes the dataset used for the spatial, energetic, and focal-mechanism analyses developed in this study. Initial VT locations were computed by OVDAS–SERNAGEOMIN using the HYPO71PC algorithm (Lee and Valdes 1985), which estimates hypocentral parameters from P- and S-wave arrival times assuming a one-dimensional velocity model. Event locations were subsequently refined using the Joint Hypocenter Determination (JHD) approach

implemented in VELEST (Kissling et al. 1994). This relocation procedure reduces systematic errors related to network geometry and improves hypocentral consistency in complex volcanic environments.

Radiated seismic energy (E) for VT earthquakes was estimated from local magnitude (ML) using the empirical relationship (Madariaga and Ruiz 2016):

$$\log_{10}(E) = 1.5 ML + 4.8$$

Where E is expressed in joules. These estimates were used to construct two-dimensional maps of cumulative seismic energy and hypocentral density for the entire 2014–2023 study period, allowing the identification of energy concentration zones and the most seismically active volumes within the volcanic system.

The b -value was estimated using the B-Positive method (van der Elst 2021), a robust formulation of the Gutenberg–Richter relationship that does not require the explicit definition of the magnitude of completeness. In this method, the b -value is computed from the average of the positive magnitude increments between consecutive events according to:

$$b = (\log_{10}(e)) / \langle \Delta M^+ \rangle$$

Where $\langle \Delta M^+ \rangle$ represents the mean of the positive magnitude differences between consecutive events. This approach reduces biases associated with catalog incompleteness and is particularly suitable for volcanic seismicity datasets characterized by strong temporal variations in detection capability.

The b -value analysis was applied to the full set of 1,219 well-located VT earthquakes to improve statistical stability. The spatial distribution of b -values was calculated using a regular 100×100 m grid. At each retained grid node, the b -value was estimated from earthquakes located within a 500 m radius, provided that at least 60 events were available. The resulting distribution was interpreted as an integrated indicator of the mechanical state of the seismogenic volume, potentially reflecting spatial contrasts in stress concentration, fracture state, and fluid influence, rather than as a direct measurement of stress or fluid pressure (Scholz 2015; Schorlemmer et al. 2005). Due to the limited number of events within individual swarms, the b -value was not computed temporally or on a swarm-by-swarm basis. Instead, the analysis focused on the spatial characterization of seismicity patterns.

Complementarily, the relative size of LP events was evaluated using Reduced Displacement (DR), following the formulation originally proposed by Aki and

Koyanagi (1981) and later adapted for volcanic environments by Nishimura et al. (2000):

$$DR = (A \times r) / (4\sqrt{2}\pi f)$$

Where A is the peak-to-peak ground-velocity amplitude (m s^{-1}) measured after removal of the instrument response, r is the source–receiver distance (m), and f is the dominant frequency (Hz). Since LP events were not routinely located, the source–receiver distance was approximated using the distance between the recording station and the summit crater of Villarrica Volcano, assuming a shallow source region beneath the crater, consistent with the typical origin of LP events at this volcano.

Seismic signals were filtered within the 0.7–5 Hz frequency band, and DR values were averaged on a daily basis in order to characterize variations in degassing-related seismic activity. Thermal activity at Villarrica Volcano was additionally evaluated using satellite-derived thermal anomalies from the MIROVA (Middle InfraRed Observation of Volcanic Activity) system (Coppola et al. 2015), which is based on MODIS observations acquired by the Terra and Aqua satellites. MIROVA provides a global near-real-time monitoring of volcanic thermal activity by detecting radiative anomalies in the mid-infrared spectral range (3.9–4.0 μm). The system computes the Volcanic Radiative Power (VRP), expressed in watts (W), which represents the radiant heat flux emitted by hot surfaces associated with lava, incandescent vents, or high-temperature fumaroles. The nominal detection threshold of the algorithm is approximately 1 MW (Coppola et al. 2015), although for this study only thermal alerts exceeding 50 MW were considered, in order to focus on the most significant thermal signals. The temporal resolution of the dataset corresponds to the satellite overpass frequency, typically providing up to four observations per day at the latitude of Villarrica. However, the MIROVA algorithm does not include an automatic cloud-filtering routine; data affected by cloud cover or atmospheric interference were identified and excluded by visual inspection of the thermal maps, following the recommendations of Coppola et al. (2015). Thermal anomalies were defined as pixels exhibiting radiative signals significantly above the background thermal emission of the surrounding terrain in individual satellite overpasses, without requiring temporal persistence. These thermal detections were compared with seismic indicators such as the reduced displacement (DR) of long-period events, in order to evaluate the relationship between subsurface seismic processes and surface thermal manifestations. This comparison allowed evaluation of the coherence between the seismic amplitude of LP events and the surface activity of the volcano. Together, these datasets provide an integrated characterization of the volcanic system's surface response.

Visual observations of surface activity were obtained from the permanent IP camera network operated by OVDAS–SERNAGEOMIN around Villarrica Volcano. The system provides continuous monitoring of the summit crater and upper flanks using high-resolution optical cameras installed at strategic locations. Images are acquired automatically at intervals of 1–5 images per minute, depending on the camera configuration, with typical resolutions of 2–5 megapixels. Several cameras feature optical zoom and infrared night-vision modes (nightshot), enabling observation of incandescent activity during nighttime. Image file sizes typically range between 200 kB and 1 MB, depending on compression and illumination conditions. These visual observations were used to confirm explosive activity, detect degassing pulses, and identify incandescent ejecta or ash emissions. The camera network thus provides an independent dataset that complements seismic and acoustic observations of eruptive activity

Explosive activity was additionally monitored using infrasound sensors deployed around Villarrica Volcano. These instruments detect low-frequency acoustic waves generated by explosive degassing and gas-jet emissions occurring at the summit crater. Infrasound signals were analyzed jointly with seismic waveforms and visual observations obtained from the permanent camera network. The expected acoustic travel time between the crater and each infrasound sensor was estimated assuming a sound propagation velocity of approximately 340 m/s in the lower atmosphere and considering the distance between the summit crater and the corresponding station. For the stations used in this study, located at distances of approximately 4.7–5.3 km from the crater, the expected acoustic propagation delay ranges between ~14 and 16 seconds. This delay is consistent with the temporal offset commonly observed between the seismic signals generated at the source and the arrival of the corresponding infrasonic waves at the sensors. The identification of explosive events followed a multi-step validation protocol consisting of: (1) the detection of impulsive seismic signals interpreted as potential explosions, (2) confirmation through the presence of a coherent infrasonic signal recorded by the acoustic sensors after the expected propagation delay, and (3) visual verification using images from the monitoring camera network when atmospheric conditions permitted. Only events confirmed through this integrated procedure were included in the daily explosion counts used in the analysis. This workflow, combining seismic detection, infrasonic confirmation, and visual validation, allows a reliable discrimination between true eruptive explosions and other seismic signals not associated with surface activity.

Volcano-tectonic (VT) swarms were identified using the temporal evolution of seismic energy release and event occurrence rates derived from the local seismic catalog of Villarrica Volcano. Radiated seismic energy for each earthquake was first

estimated from its local magnitude using the empirical relationship proposed by Madariaga and Ruiz (2016).

To quantify variations in seismic activity through time, the daily seismic energy release was computed as:

$$E_daily(t) = \sum_{i=1}^{Nt} Ei$$

Where Ei corresponds to the radiated seismic energy of the i -th earthquake and Nt represents the total number of VT earthquakes occurring on day t .

The temporal evolution of seismic activity was then evaluated using the cumulative seismic-energy curve together with the daily VT event rate. Periods characterized by sustained increases in the slope of the cumulative-energy curve were interpreted as intervals of enhanced seismic activity. Swarm windows were defined using objective temporal criteria based on the continuity of seismicity. A swarm was considered to begin when a sustained increase in seismic-energy release coincided with the onset of VT activity. Consecutive VT earthquakes separated by 48 h or less were assigned to the same swarm. A swarm was considered to end at the last VT event preceding an interval longer than 48 h. Within each swarm window, the largest-magnitude earthquake was identified and used as a marker of the principal seismic-energy release associated with the sequence. This criterion provided consistent and reproducible temporal boundaries for the identified swarms.

To assess the spatial redistribution of VT seismicity, the earthquakes within each swarm were separated into two groups using the event with the highest ML as the pivot, which was excluded from the comparison. Radial redistribution relative to the center of the Villarrica caldera (39.424667° S, 71.909487° W) was calculated as:

$$\Delta D = median(D_{after}) - median(D_{before})$$

Where D is the horizontal epicentral distance. Positive values indicate redistribution away from the caldera center, whereas negative values indicate redistribution toward the caldera center. Location uncertainty was incorporated using the ERH of each event, with the distance limits defined as:

$$Di- = \max(0, Di - ERHi) \text{ and } Di+ = Di + ERHi$$

Finally, focal mechanisms were computed for the highest-energy VT earthquakes ($ML \geq 3.0$) by inverting first-motion P-wave polarities using FOCMEC (Park et al. 2007) within the SEISAN environment. Only events recorded by a minimum of eight seismic stations, providing well-distributed P-wave polarities across the four quadrants of

the focal sphere, were considered in order to ensure stable and reliable solutions. Mechanism classification (normal, reverse, strike-slip, or oblique), together with the orientation of the pressure (P) and tension (T) axes, allowed evaluation of the interaction between regional tectonic stresses and local perturbations associated with shallow magmatic pressurization, providing a mechanical framework for the interpretation of Villarrica's seismicity.

3 Results

3.1 General Description of the Catalog and Selection of the VT Dataset (2014–2023)

The analyzed local seismic catalog for Villarrica Volcano spans the period from January 2014 to September 2023 and includes events classified by OVDAS–SERNAGEOMIN as volcano-tectonic earthquakes (VT), long-period events (LP), and explosion-type signals (EX). During this interval, the catalog comprises 2,364 VT earthquakes, 775,055 LP events, and 245 explosion signals. After applying strict quality criteria to ensure reliable earthquake locations, including constraints on RMS residuals, azimuthal gap, minimum number of phases and recording stations, as well as limits on horizontal and vertical uncertainties, a refined dataset of 1,219 well-located VT earthquakes was obtained. These events correspond to hypocentral solutions classified as quality A or B, following the standard location-quality classification commonly used in local earthquake location procedures (HYPO71/SEISAN quality scheme). The initial earthquake locations were computed using a 1D velocity model derived from the regional crustal structure of the Southern Andes (Bohm et al., 2002). Subsequently, a joint inversion of P and S arrival times was performed using the VELEST algorithm (Kissling et al., 1994) to simultaneously determine hypocentral parameters, station corrections, and an optimized 1D velocity model representative of the shallow crust beneath Villarrica Volcano. The resulting minimum 1-D model (Online Resource 1, Table S2) has P-wave velocities ranging from 3.6 to 6.2 km/s for depths between 0 and 10 km, referenced to an elevation of 2.5 km a.s.l. After relocation with this optimized model, typical location uncertainties remained below 1 km horizontally and 1.5 km vertically, with RMS values generally lower than 0.15 s.

This refined dataset constitutes the basis for the spatial, energetic, and spatio-temporal analyses presented in this study. In particular, the simultaneous availability of VT and LP time series, together with estimates of radiated seismic energy and local

magnitude (ML) for VT earthquakes and reduced displacement (DR) for LP events, provides a comprehensive description of the seismic processes occurring within the volcanic system. These seismic observations were further complemented by an independent catalog of explosive activity reported by OVDAS–SERNAGEOMIN and by satellite-based thermal anomalies detected by the MIROVA system. The integration of these datasets enables the evaluation of the relationship between internal volcanic processes, such as rock fracturing and fluid pressurization, and their potential surface manifestations over nearly a decade of continuous monitoring (Fig. 3).

3.2 Decadal Temporal Evolution of VT, LP, and Energy Release

Integrated time series show that Villarrica's seismic activity during 2014–2023 exhibits marked variability, alternating background activity with intervals of sustained VT increases and abrupt rises in cumulative radiated energy. In general terms, LP activity fluctuates frequently, consistent with the open-conduit behavior of the volcano, whereas VT seismicity is organized into episodic increases of short to intermediate duration, with a step-like cumulative energy release. Incorporating VT local magnitude (ML) and cumulative radiated energy reveals that energy release is pulsatory: the cumulative energy curve displays well-defined steps associated with intervals of elevated VT rates and the occurrence of higher-magnitude events. These steps constitute a robust signature of internal system reorganization and allow identification and characterization of swarm-type activity periods (Fig. 3).

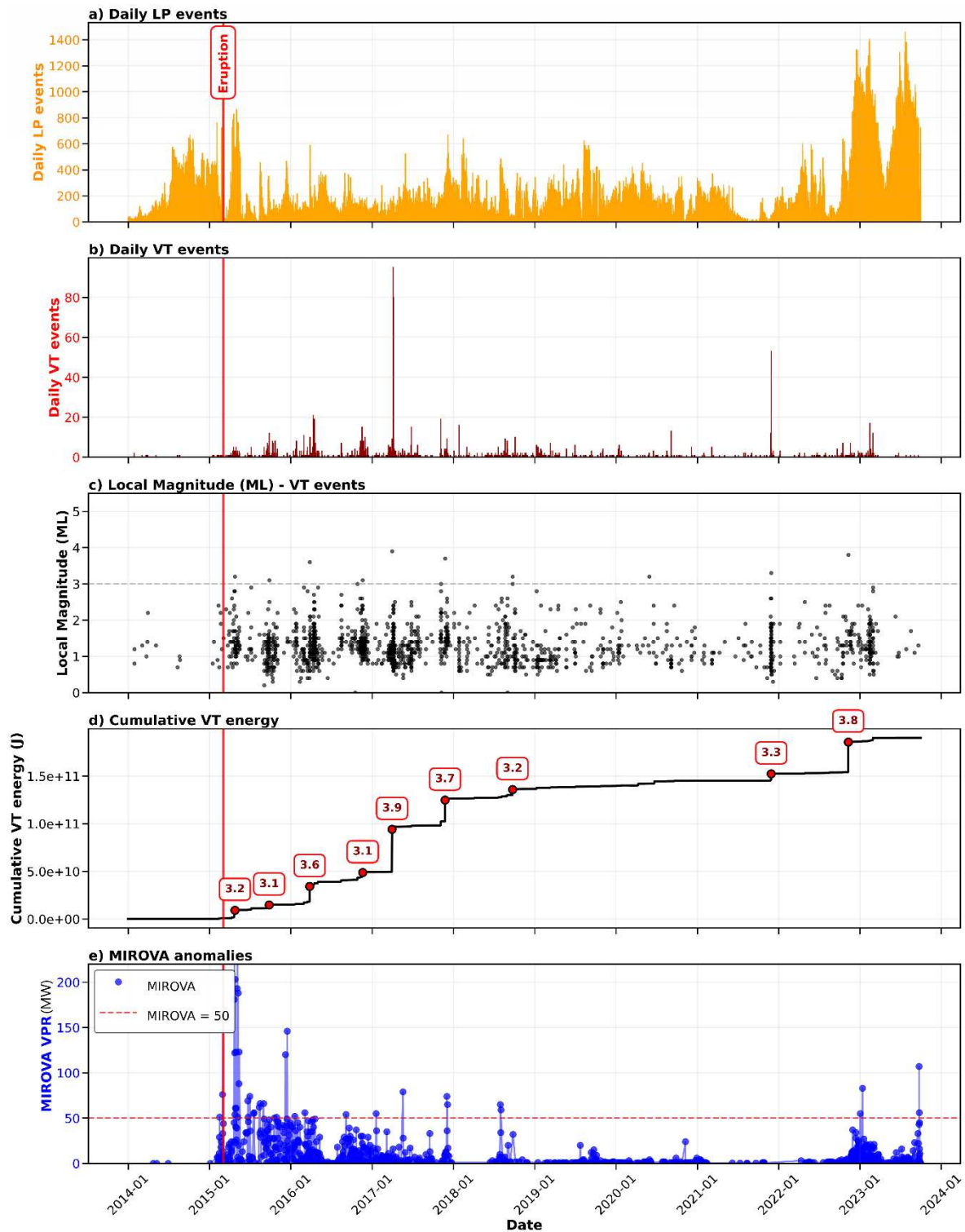


Fig. 2 Multi-parametric temporal evolution of seismic and thermal activity at Villarrica Volcano during the 2014–2023 period. From top to bottom: (a) daily number of long-period (LP) events; (b) daily number of volcano-tectonic (VT) earthquakes; (c) local magnitude (ML) of located VT events; (d) cumulative seismic energy released by VT events, calculated from local magnitude; and (e) thermal anomalies detected by the MIROVA system. The vertical red line marks the 3 March 2015 eruption.

3.3 Identification of Nine VT Swarms

Based on the combined analysis of daily VT occurrence rates and the cumulative seismic energy evolution, nine principal VT swarms were identified during the 2014–2023 period (Fig. 3, Table 2). These swarms are characterized by sustained increases in the number of daily earthquakes, together with discrete step-like increments in the cumulative seismic energy curve that clearly depart from the background seismicity level. The swarms exhibit total durations ranging from 33 to 194 days, with total event counts varying between 60 and 298 VT earthquakes, and maximum daily rates from 5 to 95 VT/day (Table 2). In most cases, swarm durations are on the order of two to three months, with the notable exceptions of Swarms 7 and 9, which extended for approximately six months (190 and 194 days, respectively), and Swarm 8, which was significantly shorter (33 days). The cumulative energy curves show comparable patterns among the sequences, expressed as well-defined increases in slope associated with concentrated bursts of brittle fracturing within the volcanic edifice. A recurrent feature observed across all swarms is the presence of a dominant earthquake with magnitude generally greater than ML 3 (ranging from ML 3.1 to 3.9). This principal event accounts for a significant fraction of the total seismic energy released during the swarm and corresponds to the most pronounced step observed in the cumulative energy curve (Fig. 3). The largest of these principal events was an ML 3.9 earthquake recorded during Swarm 5 on 31 March 2017, which coincided with the highest maximum daily rate (95 VT/day) and the largest total number of events (298 VT) of the entire sequence. The highest-magnitude earthquakes occurred between 31% and 64% of the elapsed swarm duration, indicating that they developed within ongoing seismic sequences rather than initiating them (Figure 3; Table 2). The temporal architecture of the swarms is therefore highly consistent and can be described by a repeating three-stage pattern: (i) an initial growth phase characterized by progressively increasing VT occurrence rates and accelerating cumulative seismic energy release, (ii) the occurrence of a principal $ML \geq 3$ earthquake marking the main energy release of the sequence, and (iii) a decay phase during which the VT occurrence rate gradually decreases and the cumulative energy curve approaches a stable plateau. This systematic behavior indicates that the swarms correspond to organized fracturing episodes rather than to random or stochastic clustering of seismicity. From 2015 to 2018, the principal $ML \geq 3$ earthquakes occurred at intervals of approximately 4–10 months. This pattern was interrupted by a prolonged gap of approximately 38 months between Swarms 7 and 8, followed by an interval of approximately 11 months between Swarms 8 and 9. These variations indicate episodic, rather than strictly periodic, reactivation of the volcanic system. The mean hypocentral depths of the swarms range from 3.04 to 4.31 km for the first seven sequences, indicating that most fracturing occurred within the

shallow edifice. However, Swarm 8 exhibits a notably greater mean depth (8.61 km), suggesting a possible deepening of the seismogenic zone or a different source of stress perturbation during this later episode. Among the nine sequences identified in this study, Swarm 8 exhibits a distinct temporal and depth-related departure from the general pattern described above. This swarm displays a significantly shorter duration (33 days), a lower number of earthquakes (91 VT) compared with most of the other sequences, and a more abrupt evolution of seismic energy release, together with the greatest mean depth (8.61 km). The reduced temporal development, different energy distribution, and deeper hypocentral location observed during this sequence indicate that Swarm 8 likely reflects a distinct fracturing episode with a different stress evolution compared to the other swarms identified during the study period. Overall, the similarities observed among most swarm sequences indicate recurrent episodes of brittle failure and seismic-energy release at Villarrica, whereas the contrasting behavior of S6 and S8 shows that their spatio-temporal evolution is not universal.

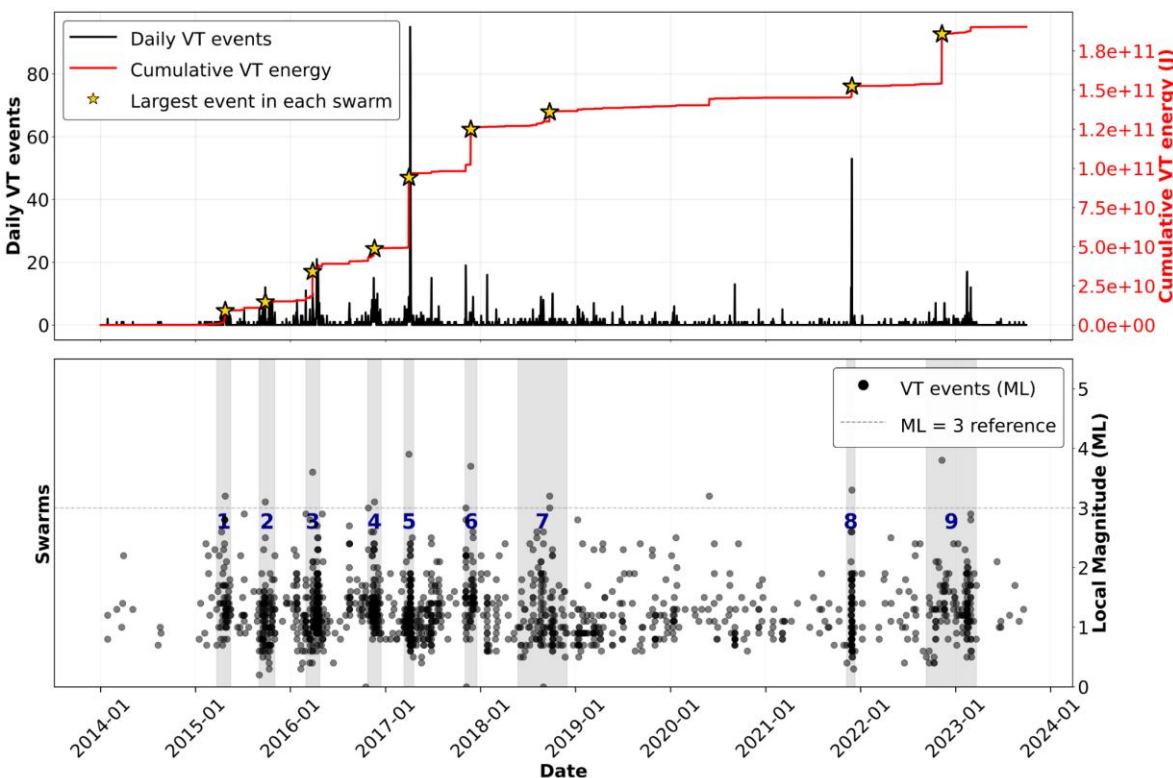


Fig. 3 Temporal evolution of volcano-tectonic (VT) seismicity at Villarrica Volcano during the 2014–2023 period. The upper panel shows the daily number of VT events (bars) and the cumulative radiated seismic energy (red line). Yellow stars indicate events with $ML \geq 3$. The lower panel presents the local magnitudes (ML) of VT events (dots) and the identification of swarms (gray bars).

Table 2 Summary of the nine volcano-tectonic (VT) swarms identified at Villarrica Volcano between 2014 and 2023.

Swarm	Start	End	Duration (days)	VT events	Max VT/day	Max ML	Date Max ML	Mean depth (km)
1	23-03-2015	16-05-2015	55	60	5	3.2	25-04-2015	3.50
2	03-09-2015	02-11-2015	61	99	12	3.1	26-09-2015	3.21
3	29-02-2016	23-04-2016	55	168	21	3.6	26-03-2016	3.52
4	24-10-2016	15-12-2016	53	124	15	3.1	19-11-2016	4.06
5	12-03-2017	19-04-2017	39	298	95	3.9	31-03-2017	3.08
6	02-11-2017	18-12-2017	47	70	19	3.7	24-11-2017	3.04
7	24-05-2018	29-11-2018	190	128	10	3.2	23-09-2018	4.31
8	08-11-2021	10-12-2021	33	91	53	3.3	28-11-2021	8.61
9	10-09-2022	22-03-2023	194	135	17	3.8	09-11-2022	5.00

3.4 Delayed Surface Response: Explosions and MIROVA Thermal Anomalies

Integrating the seismic record with the database of explosions classified by OVDAS, supported where possible by visual observations from the permanent camera network and by thermal anomalies detected by the MIROVA system, allows evaluation of the surface response associated with the identified VT swarms. Results show that not all swarms are accompanied by detectable surface manifestations. However, four of the nine identified swarms (S2, S3, S4, and S5) display a clear temporal association between subsurface seismic activity and subsequent surface phenomena (Figs. 4, 5; Table 3). In these sequences, the occurrence of the principal VT earthquake coincides with the most significant step in the cumulative seismic energy curve and is followed by an increase in explosion-type events together with the appearance of thermal anomalies detected by MIROVA. Figure 4 illustrates the multiparametric identification of an explosive event using visual, seismic, and

acoustic observations. The figure displays the visual observation of the explosion at the summit crater together with the corresponding long-period (LP) seismic signal with $DR = 24.7 \text{ cm}^2$ and the infrasound arrivals (6.2 Pa) associated with the surface pressure wave (*Reporte Especial de Actividad Volcánica REAV*; December 31, 2022; SERNAGEOMIN <https://rnvv.sernageomin.cl/volcan-villarrica/>). The delay between the seismic signal and the acoustic arrival is consistent with the expected propagation time of the acoustic wave from the crater to the infrasound sensors, confirming the explosive origin of the signal and illustrating the relationship between conduit pressurization and surface activity. For Swarms 2–5, increases in explosive activity and thermal anomalies were observed approximately one to two months after the principal VT earthquake. This temporal association is compatible with a delayed connection between subsurface seismic activity and surface manifestations, although it does not by itself demonstrate a causal relationship. In contrast, the remaining swarms (S1, S6, S7, S8, and partially S9) do not show a clear or systematic association with surface manifestations. These sequences are characterized by increases in VT seismicity and cumulative energy release without a corresponding increase in explosions or thermal anomalies. This behavior indicates that fracturing episodes within the volcanic edifice do not necessarily produce immediate or detectable surface activity. It is important to note that the infrasound network became operational only after late 2018; therefore, acoustic observations are available only for the most recent part of the study period. As a result, infrasound data were not used as a primary detection criterion for the earlier swarms and were considered only as complementary evidence for the most recent sequences. Overall, the results indicate that while VT swarms represent recurrent episodes of brittle deformation within the volcanic system, only a subset of these sequences are followed by measurable surface responses, highlighting the complex relationship between subsurface fracturing processes and observable volcanic activity.

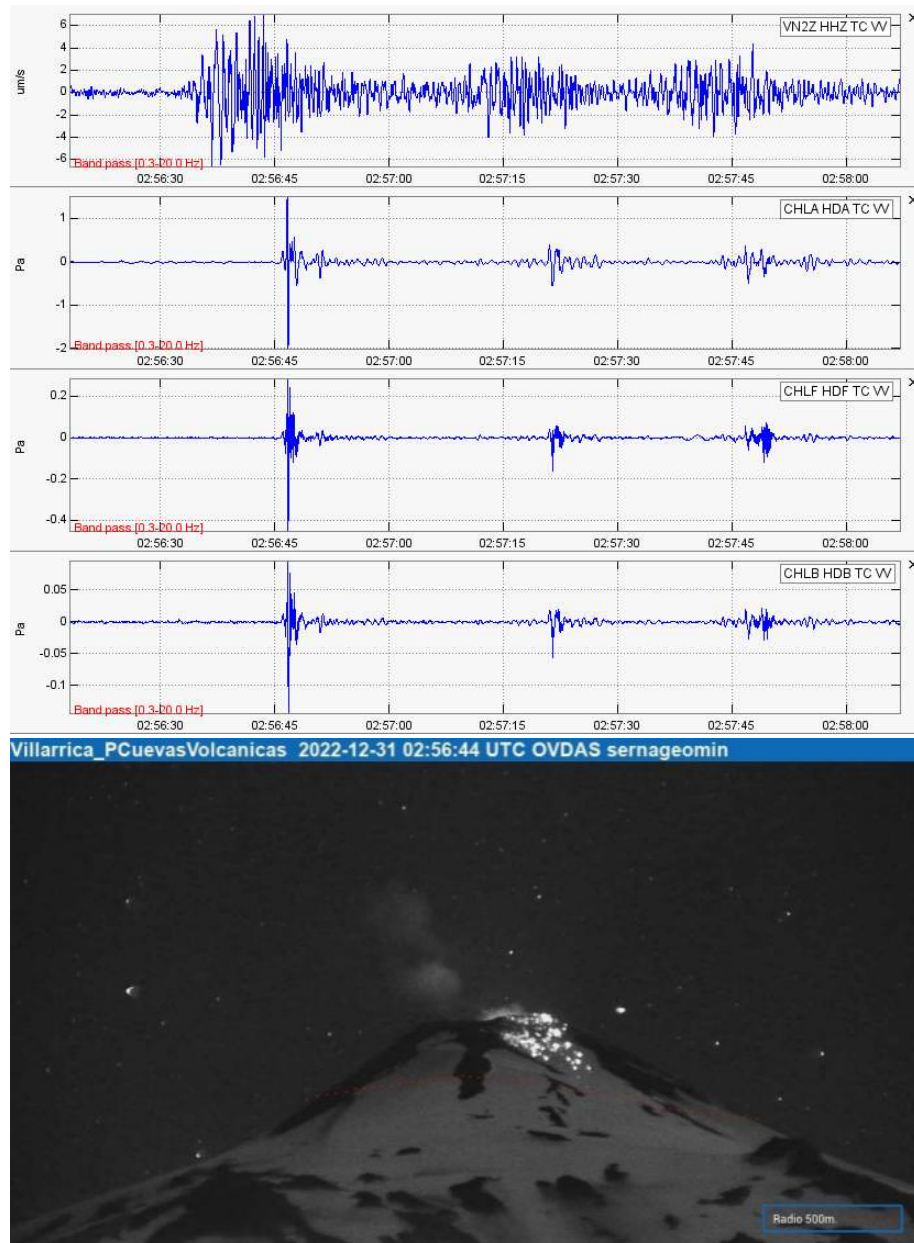


Fig. 4 Example of a coupled seismic–acoustic–visual record associated with an explosive event at Villarrica Volcano on 31 December 2022 at 02:56:44 UTC. **Top panel:** corresponding seismic and acoustic records. The first trace (station VN2; component Z) shows the seismic signal associated with a long-period (LP) event, characterized by emergent onset and dominant low-frequency content. The following traces correspond to infrasound recordings from the acoustic sensors (CHLA, CHLF and CHLB), capturing the pressure wave generated by the surface explosion. The acoustic arrivals occur ~14–16 seconds after the onset of the LP seismic signal, which is consistent with the expected acoustic propagation delay for stations located approximately 4.7–5.3 km from the crater, as described in the methodology section. **Lower panels:** image from the permanent monitoring camera located at *Cuevas Volcánicas*, showing incandescent ejecta produced during a surface explosion at the summit

crater. This example illustrates the coupling between shallow LP seismicity, conduit pressurization, and subsequent surface explosions at Villarrica.

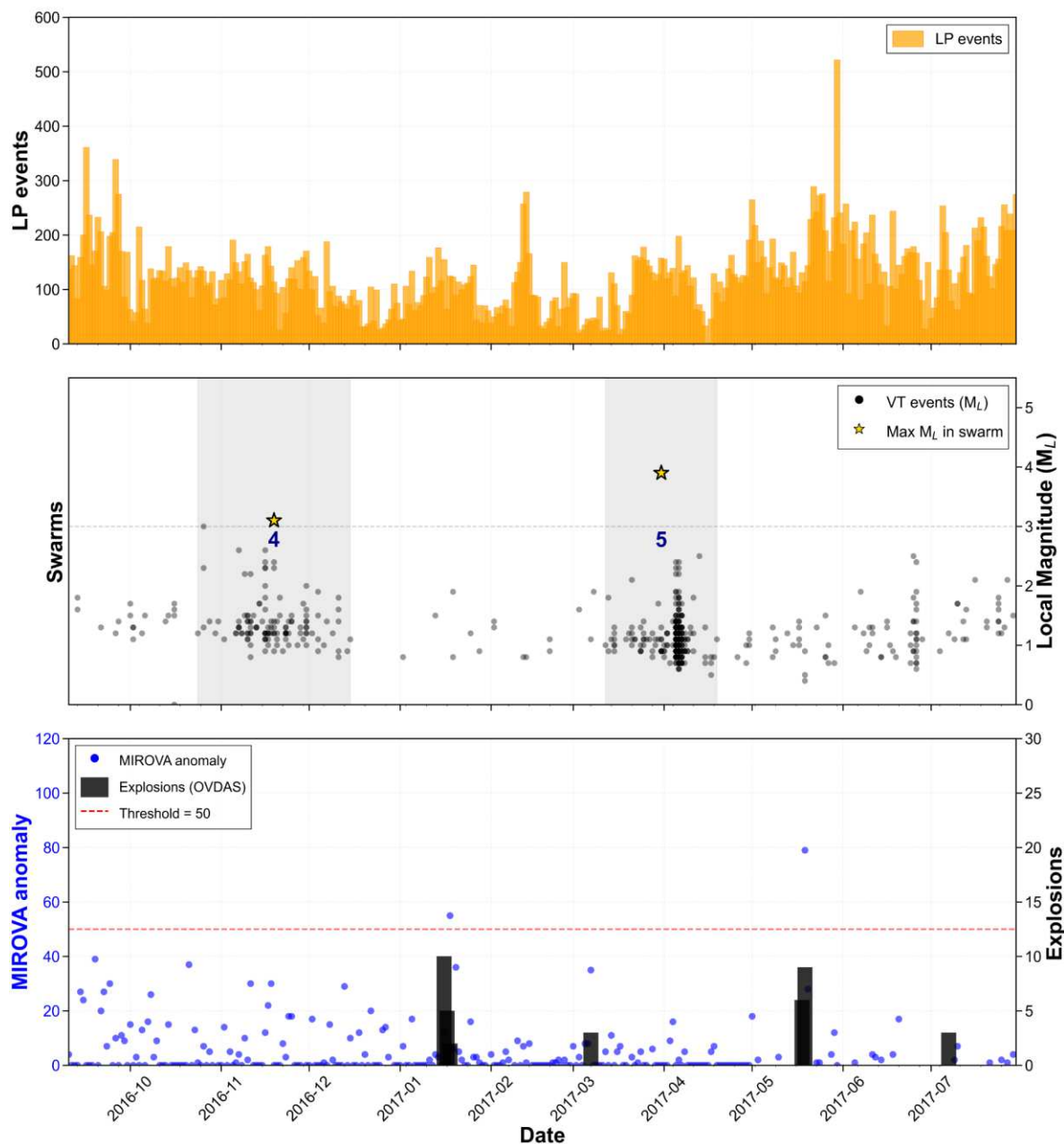


Fig. 5 Temporal correlation between seismic activity and surface response for swarms S4 and S5 between October 2016 and July 2017. The upper panel shows the monthly evolution of the number of long-period (LP) events (orange bars). The middle panel presents the local magnitude (M_L) of volcano-tectonic (VT) events, with the identification of swarms S4 and S5. The lower panel shows thermal anomalies detected by MIROVA (blue dots) and the monthly number of explosions (black bars) reported by OVDAS–SERNAGEOMIN. Thermal anomalies correspond to signals exceeding ~50 MW of Volcanic Radiative Power (VRP). In both swarms, an increase in explosive activity and the

occurrence of thermal anomalies are observed between 1 and 2 months after the main VT earthquake (ML > 3).

Table 3 Relationship between VT swarms, explosive activity and MIROVA thermal anomalies at Villarrica Volcano during 2014–2023.

Swar m	Start date	End date	Principal VT (ML)	Explosive activity (OVDAS / cameras)	MIROVA thermal anomaly	Surface response
S1	23 Mar 2015	16 May 2015	ML 3.2	No clear increase	No	No
S2	03 Sep 2015	02 Nov 2015	ML 3.1	Yes (Dec 2015 sequence)	Yes	Yes
S3	29 Feb 2016	23 Apr 2016	ML 3.6	Moderate increase	Yes	Yes
S4	24 Oct 2016	15 Dec 2016	ML 3.1	Yes (Jan 2017 sequence)	Yes	Yes
S5	12 Mar 2017	19 Apr 2017	ML 3.9	Weak / sporadic	Yes	Yes
S6	02 Nov 2017	18 Dec 2017	ML 3.7	No clear increase	No	No
S7	24 May 2018	29 Nov 2018	ML 3.2	No clear increase	No	No
S8	08 Nov 2021	10 Dec 2021	ML 3.3	No	No	No
S9	10 Sep 2022	22 Mar 2023	ML 3.8	Minor explosions detected	Yes	Weak

3.5 Spatial Distribution of VT Seismicity: Alignments and Principal Domains

The epicentral distribution of the VT events shows a non-random spatial organization, with a dominant and clearly defined NW–SE alignment consistent with the regional structural framework attributed to the Mocha–Villarrica Fault (Fig. 6). Density maps reinforce this observation by revealing high-concentration nuclei and linear corridors (Fig. 7). At the edifice scale, at least two recurrent spatial domains can be distinguished:

1. An internal domain, with high event density within the caldera, frequently concentrated toward the eastern sector of the active crater.
2. An external domain, located beyond the caldera rim and extending preferentially toward the southeast, consistent with the influence of regional structures associated with Mocha–Villarrica Fault and the Liquiñe–Ofqui Fault System.

However, the epicentral distribution shown in Figure 6 reveals that the NW–SE alignment is the most prominent and well-defined structural feature, with a clear linear trend of hypocenters following the orientation of the Mocha–Villarrica Fault System. In contrast, the NS alignment attributed to the Liquiñe–Ofqui Fault System is less clearly expressed, being represented only by a subordinate cluster of events located south of the caldera rim, outside the main volcanic edifice. This suggests that while the regional NS structures may exert some influence on the seismicity of Villarrica, the dominant structural control is exerted by the NW–SE Mocha–Villarrica corridor. The persistence of these domains throughout the decade indicates that Villarrica's VT system is strongly conditioned by the regional structural architecture (ATF–LOFS), upon which internal volcanic processes are superimposed.

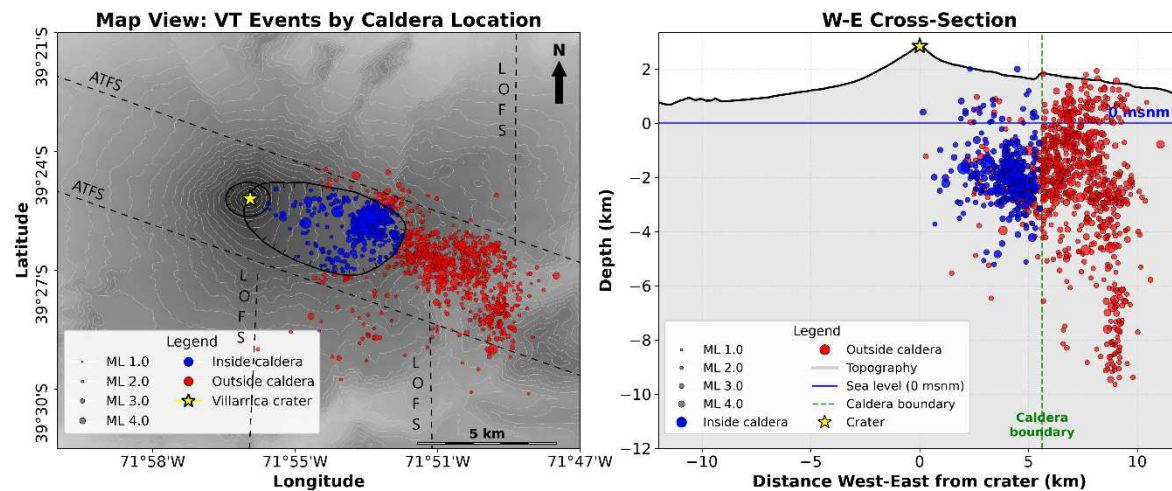
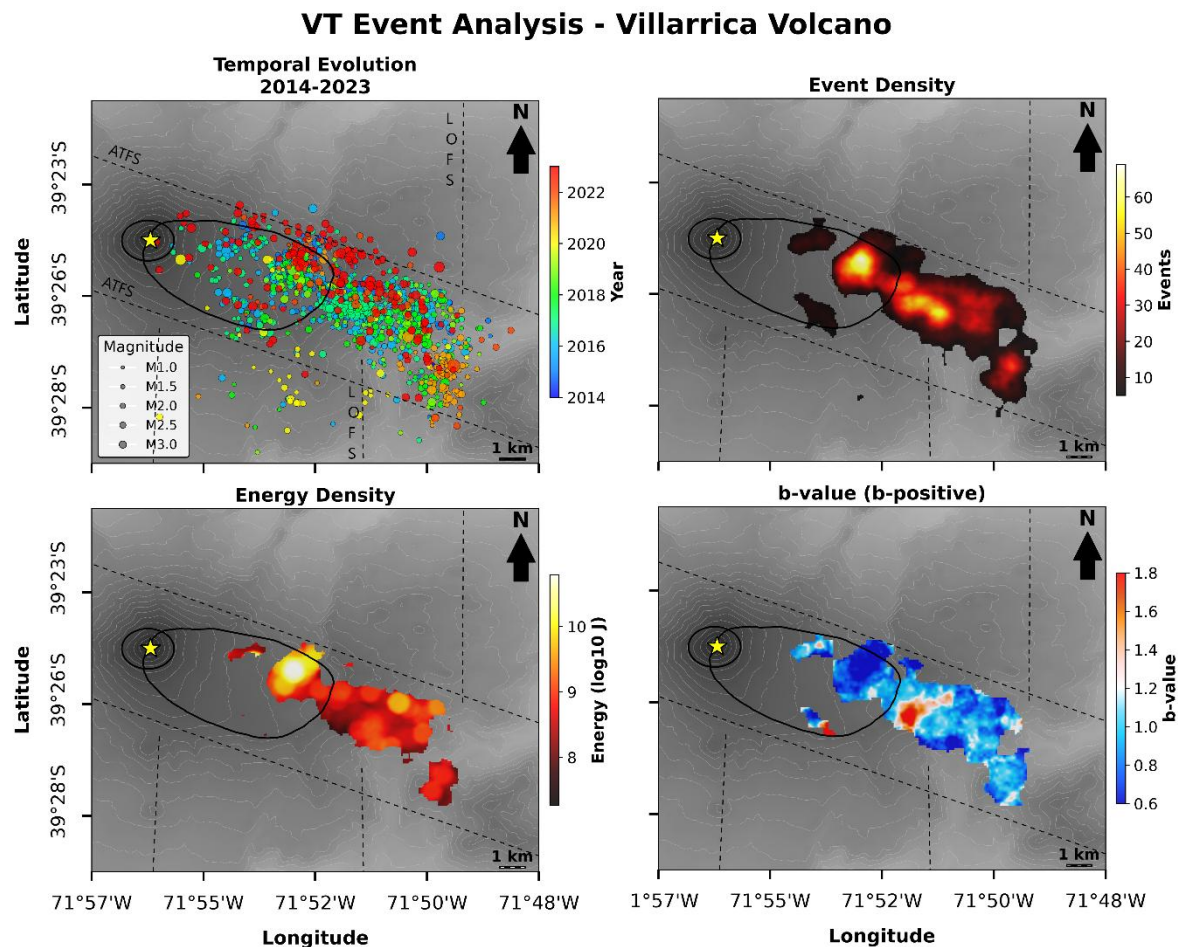


Fig. 6 Spatial distribution of located volcano-tectonic (VT) events at Villarrica Volcano during the 2014–2023 period. Hypocenters are shown as circles scaled by local magnitude (ML). The right-hand panel shows a W–E cross-section with the corresponding depth profile of VT hypocenters. In this cross-section, events are displayed using two different colors to distinguish earthquakes located within the caldera area from those occurring outside it. Dashed lines represent the main regional tectonic structures, including the Liquiñe–Ofqui Fault System (LOFS; NNE–SSW trend) and the Andean Transverse Faults System (ATFS; NW–SE trend). The black outline delimits the caldera area. The yellow star marks the location of the currently active crater of Villarrica Volcano.



662

663 **Fig. 7** Spatio-temporal analysis of volcano-tectonic (VT) activity at Villarrica Volcano during the 2014–
664 2023 period. The upper left panel shows the spatio-temporal evolution of VT hypocenters, where the
665 color scale represents the time of occurrence of the events (from 2014 to 2023). The upper right panel
666 presents the VT event density map, showing the spatial concentration of seismicity. The lower left
667 panel shows the radiated seismic energy density map. The lower right panel presents the b-value
668 calculated from the magnitude distribution of VT events. Dashed lines represent the main regional
669 tectonic structures. The black outline delimits the caldera area. The yellow star marks the location of
670 the currently active crater of Villarrica Volcano.

671 Spatially, sectors exhibiting the highest VT density also concentrate a significant
672 portion of the cumulative energy release, suggesting that the same structural
673 corridors controlling event locations also govern the episodic and clustered release
674 of seismic energy through time (Fig. 7).

675

3.6 Spatial Distribution of b-value: Mechanical Contrast Between Domains

The b-value was estimated using the B-Positive method from 1,219 well-located volcano-tectonic (VT) earthquakes recorded between 2014 and 2023. This estimator is based on the distribution of positive magnitude differences between successive events and reduces sensitivity to transient changes in the magnitude of completeness (M_c ; van der Elst 2021). The spatial distribution of M_c shows relatively low and spatially consistent values across most of the main seismic cluster located inside the caldera, with localized variations toward its margins (Online Resource 1, Fig. S5). Outside the caldera the b-values increase. The principal high- and low-b zones do not reproduce the spatial pattern of M_c , indicating that these contrasts are not directly attributable to variations in the detectability of small earthquakes. The uncertainty associated with the b-value estimates (σ_b) is lowest within the main seismic clusters and locally increases toward the peripheral sectors. Accordingly, the central patterns exhibit greater statistical stability, whereas small-scale anomalies located along the margins are characterized by greater uncertainty and should be interpreted with caution. The resulting b-value distribution reveals spatially coherent variations across Villarrica's VT seismicity (Fig. 7, lower right panel). These variations correspond spatially to the domains defined by earthquake density and released seismic energy, delineating a heterogeneous organization of the seismogenic volume.

3.7 Focal Mechanisms of Principal Events: Mixed Tectonic–Volcanic Regime

Figure 8 displays the focal mechanisms of the most energetic VT events associated with the nine seismic swarms identified during the 2014–2023 period. The mechanisms are spatially distributed with respect to the main regional tectonic structures of the Villarrica volcanic complex. Most principal events are located within the caldera-related domain, where focal mechanisms show substantial variability in nodal-plane geometry in the orientations of the P and T axes; nevertheless, strike-slip faulting is the dominant style. This dispersion is consistent with a locally heterogeneous stress field during VT swarm activity. Only one principal event (S8) is located outside the caldera-related domain, to the eastern sector of the volcanic edifice.

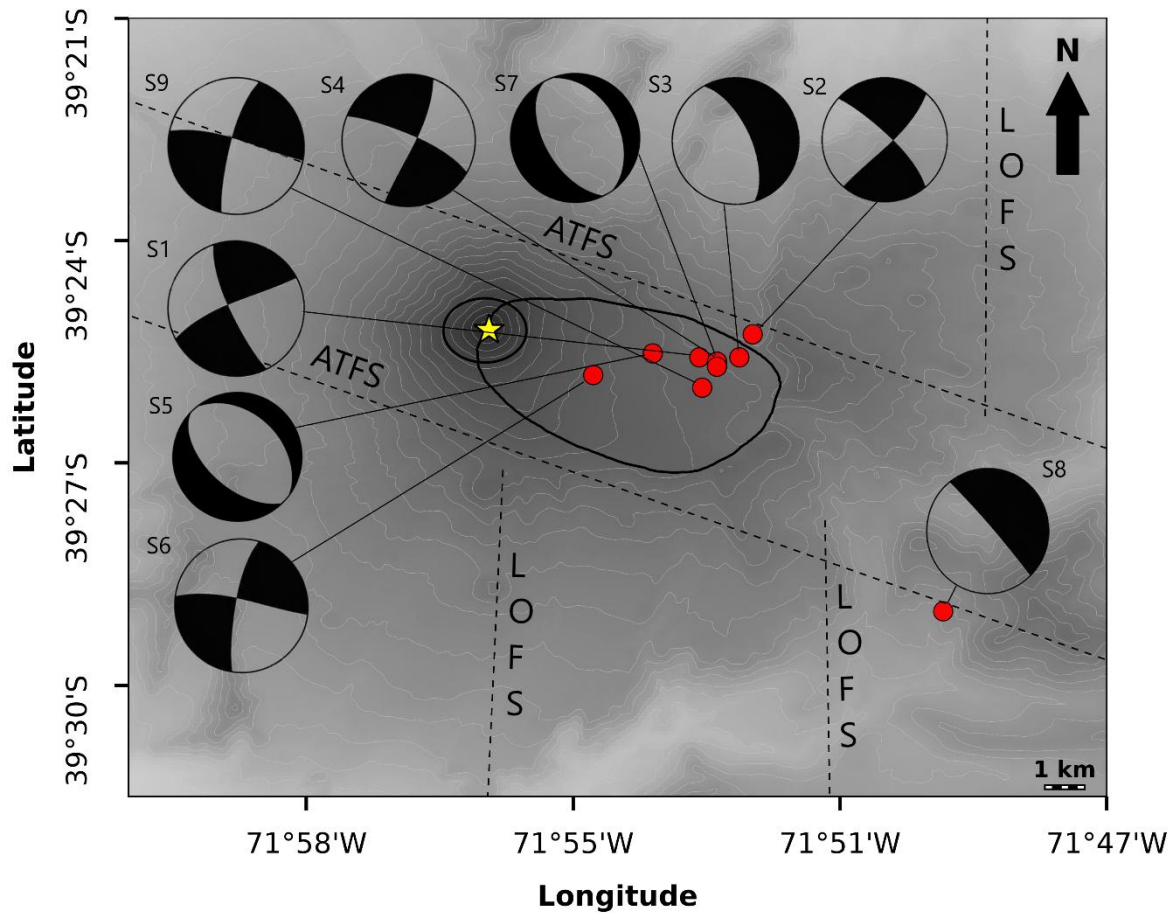


Fig. 8 Spatial distribution and focal mechanisms of the most energetic volcano-tectonic (VT) earthquakes associated with the nine seismic swarms identified at Villarrica Volcano during the 2014–2023 period. Each focal mechanism corresponds to the highest-energy VT event of each swarm (S1–S9) and is displayed as a beachball diagram projected onto the digital elevation model. Hypocenter colors indicate the occurrence date of the principal event of each swarm.

3.8 Spatio-temporal Evolution Within Swarms: Internal → External Migration Pattern

A central outcome of the swarm-by-swarm analysis is the recurrence of a two-phase, although non-universal, spatio-temporal pattern characterized by an internal-to-external redistribution of seismicity. Events occurring before and during the principal VT event tend to cluster within the caldera-related domain, whereas post-main-event seismicity frequently extends beyond the caldera rim toward peripheral domains. To illustrate this behavior, the nine swarms identified in this study are presented here. Most swarms show representative expressions of this internal-to-external redistribution, as illustrated by the hypocentral distributions in Figure 9 and

quantified by the radial-distance analysis in Figure 10. Detailed maps and E–W cross-sections of the individual swarms are provided in Online Resource 1 (Figs. S6–S23). S6 and S8 exhibit distinct departures from this dominant pattern. In S6, intracaldera seismicity persisted after the principal VT event while extracaldera earthquakes were also recorded, whereas S8 developed entirely outside the caldera-related domain (Fig. 9). For each swarm, seismicity was subdivided into two temporal subsets: Phase A, corresponding to events occurring before and during the principal VT event, and Phase B, comprising events occurring after it. The resulting maps show that Phase A is predominantly located inside the caldera, whereas Phase B is commonly characterized by a spatial expansion toward external regions and structurally controlled corridors outside the caldera (Fig. 9; Online Resource 1: Figs. S24–S32).

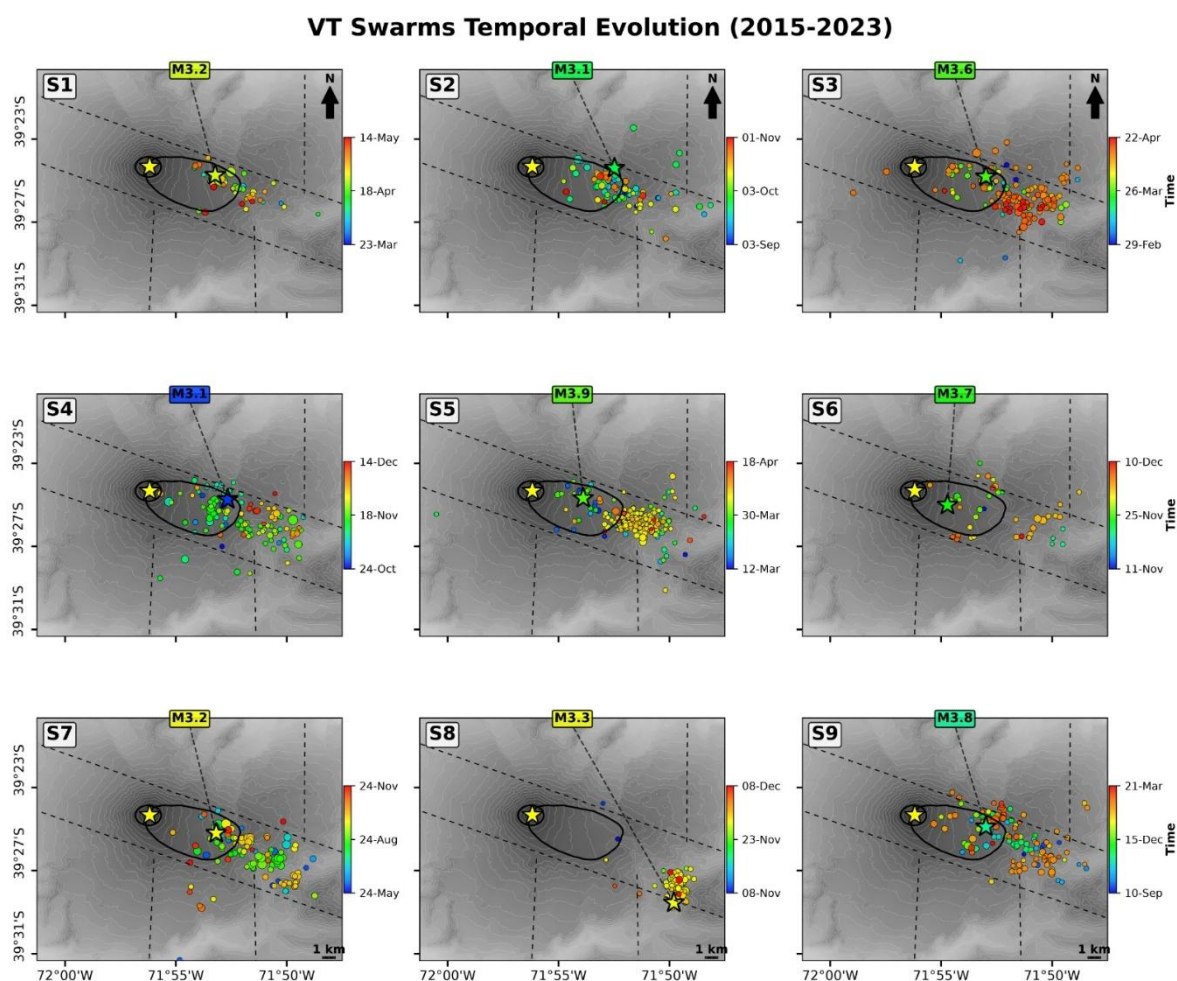


Fig. 9 Spatio-temporal evolution of the nine volcano-tectonic (VT) swarms identified at Villarrica Volcano during the 2014–2023 period. Events within each swarm are depicted using uniform symbology, with color gradation corresponding to the temporal occurrence throughout the analyzed interval. Stars denote the maximum local magnitude (ML) earthquake within each swarm. The caldera

rim is delineated by a dashed line, and the yellow star locates the currently active crater of Villarrica Volcano.

Although the spatiotemporal evolution figures suggest a redistribution of seismicity from inside to outside the caldera, this pattern was evaluated quantitatively by comparing epicentral distances from the caldera center before and after the pivot earthquake of each swarm (Fig. 10). The analysis showed positive differences in median epicentral distance for S1–S5, S7, and S9, with the largest shifts observed in S4 and S3. S6 was the only swarm with a negative difference. S8, characterized by extracaldera seismicity, showed a value close to zero, indicating similar median epicentral distances before and after the pivot earthquake.

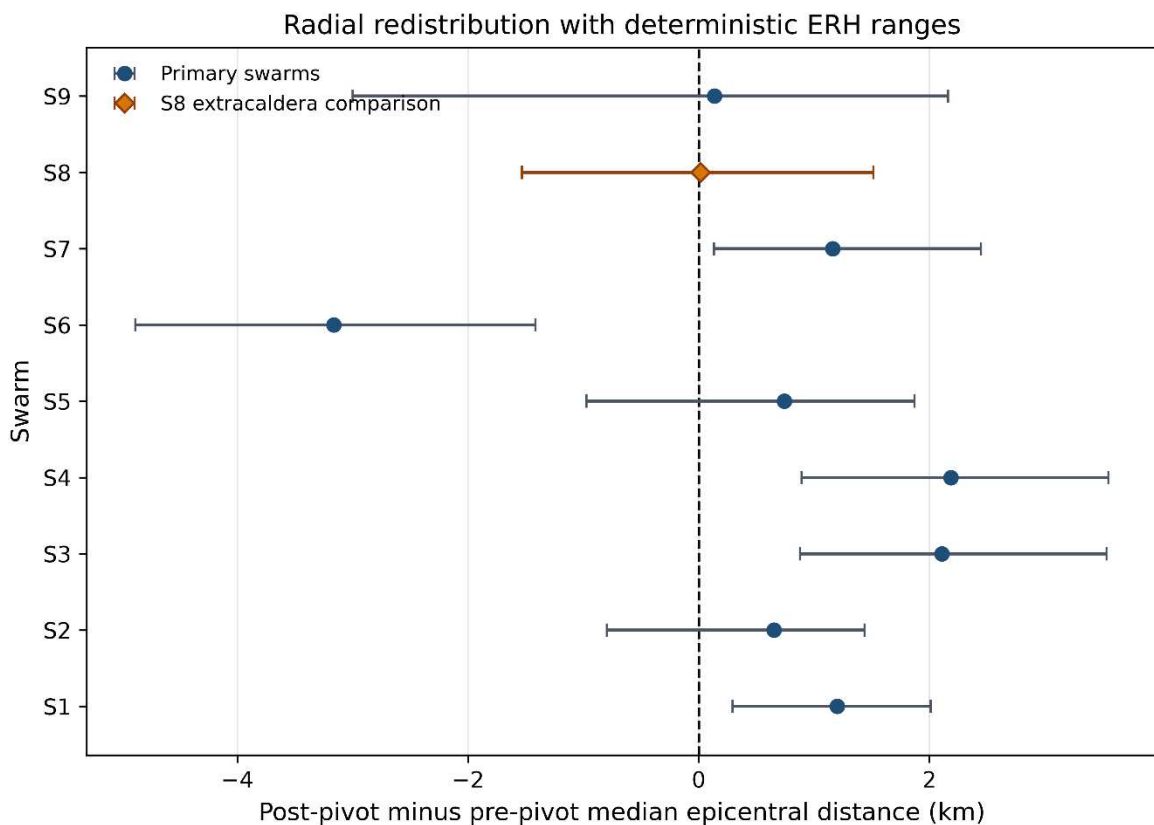


Fig. 10 Swarm-level radial redistribution relative to the Villarrica caldera center, accounting for horizontal location uncertainty. Points represent the difference between the median epicentral distances after and before the largest-magnitude VT earthquake of each swarm. Horizontal bars represent the uncertainty ranges propagated from the individual horizontal location errors (ERH). Positive values indicate outward radial redistribution away from the caldera center, whereas negative values indicate inward redistribution toward the caldera center. S8 is shown separately as an extracaldera comparison.

4 Discussion

4.1 Coupled Volcano–Tectonic Processes and Delayed Surface Response

Although seismic swarms are conventionally defined as earthquake clusters without a dominant mainshock (Mogi 1963; Benoit and McNutt 1996), each sequence identified at Villarrica contained a highest-magnitude VT earthquake ($ML \geq 3$). These earthquakes occurred between 31% and 64% of the elapsed swarm duration and therefore did not initiate the sequences. We interpret them as energetic peaks within already developing episodes of distributed fracturing rather than as mainshocks triggering conventional aftershock sequences (Vidale and Shearer 2006). We therefore retain the term “swarm” throughout this study. This temporal organization is consistent with observations from volcanic catalogs worldwide, in which the largest-magnitude earthquake generally occurs after swarm initiation, supporting the distinction between volcanic swarms and conventional mainshock–aftershock sequences (Godano et al. 2023).

In volcanic systems, such forcing may arise from magma intrusion, fluid pressurization, and their interaction with pre-existing structures (Benoit and McNutt 1996; McNutt 2005; Roman and Cashman 2006; White and McCausland 2016). At Makushin Volcano, for example, an intrusion-driven sequence that included a relatively large-magnitude earthquake was attributed to the activation of relatively large faults within a heterogeneous crust (Lanza et al. 2022). At Villarrica, the recurrent progression from intracaldera nucleation to the highest-energy VT event and subsequent outward spatial redistribution, observed in most swarms (Figs. 9 and 10), supports a coherent coupling between the shallow magmatic system and the surrounding structural framework. The quantitative analysis nevertheless revealed two distinct departures from this dominant pattern: S6 showed inward radial redistribution after the pivot earthquake, whereas S8 remained extracaldera and displayed little change in median epicentral distance. These differences indicate that internal-to-external redistribution is recurrent but not universal. Overall, the dominant pattern is consistent with transient local stress perturbations generated by magmatic and/or fluid pressurization and superimposed on the regional tectonic stress field (Montenegro et al. 2021; Basualto et al. 2024).

In four of the nine swarms, the highest-energy VT earthquake was followed approximately one to two months later by a surface response of variable intensity, expressed as increased explosive activity documented by cameras and/or thermal

anomalies detected by MIROVA (Fig. 5; Table 3). This temporal offset is consistent with delayed coupling between subsurface brittle reorganization and the subsequent transfer of fluids, heat, and potentially magma toward the conduit, as inferred from multi-timescale precursory sequences at other active volcanoes (Stix et al. 2025). However, the absence of comparable surface manifestations following the remaining swarms indicates that this coupling is conditional rather than deterministic, consistent with the occurrence of apparent precursory unrest that does not culminate in eruption (Stix et al. 2025). Thus, intra- to extracaldera migration represents the dominant subsurface evolution, whereas its expression at the surface is likely conditioned by the subsequent hydraulic reorganization of the volcanic system.

4.2 Fault–Fracture Connectivity and Swarm Migration Dynamics

The observed migration of seismicity from the caldera-related domain toward the NW–SE-trending Mocha–Villarrica structural corridor is consistent with the progressive activation of an inherited fault–fracture network. Within the framework of Sibson (1996), pressurized fluids may promote mixed-mode tensile and shear failure, generating interconnected fault–fracture meshes and transiently enhancing structural permeability. At a conceptual level, Hill (1977) provides a complementary geometric mechanism in which magma-filled tensile fractures arranged *en echelon* concentrate stress at their offset tips, promoting rupture along oblique conjugate shear fractures that connect adjacent dike segments. Applied to Villarrica, this mixed tensile–shear configuration could allow a perturbation initiated within the caldera-related domain to propagate through inherited discontinuities toward the Mocha–Villarrica structural corridor. Fracture opening could facilitate magma and/or fluid transfer, whereas shear failure along the connecting structures could generate migrating VT seismicity (Cembrano and Lara 2009; Perez-Flores et al. 2016; Basualto et al. 2024). Exhumed fault systems in Chile, such as the Bolfín Fault, provide geological analogues showing that structurally connected networks can channel hydrothermal fluids through cyclic *fault-valve behavior* (Gomila et al. 2021; Masoch et al. 2025). At Villarrica, however, hypocentral alignments identify potentially activated structural pathways rather than directly demonstrating fluid transport through them.

Swarm S6 illustrates a variation of this dominant pattern (Figs. 9 and 10; Online Resource 1: Fig. S29). After the pivot earthquake, intracaldera seismicity persisted and temporally overlapped with earthquakes located outside the caldera. The persistence of intracaldera activity resulted in a negative difference in median epicentral distance, despite the occurrence of extracaldera earthquakes after the

pivot event. This behavior is compatible with continued shallow magmatic and/or fluid pressurization beneath the caldera occurring simultaneously with stress transfer and the activation of peripheral structures. Thus, S6 does not contradict the coupled volcano–tectonic model; rather, it indicates that intracaldera forcing and the extracaldera seismic response may overlap in time instead of developing as completely separate successive stages.

The Villarrica swarms document a dominant, but non-universal, outward redistribution of VT seismicity after the highest-energy earthquake. Comparable spatial evolutions have been associated with fluid-pressure changes, fracture-network reorganization, and stress transfer along pre-existing discontinuities (Fischer et al. 2014; Danré et al. 2022, 2024). However, the present analysis does not estimate migration velocities and cannot distinguish among fluid diffusion, slip propagation, or their interaction. Accordingly, these processes are considered plausible mechanisms rather than directly resolved drivers. Within the progressive-fracturing framework of Kilburn (2018), the highest-energy VT earthquakes may reflect the interaction and coalescence of fractures or the reactivation of larger pre-existing structures. Rather than constituting demonstrated mechanical thresholds, these earthquakes are interpreted as temporal and energetic pivots that may transiently enhance connectivity between previously isolated structural domains (Sibson 1996, 2020). Thus, the dominant pattern of outward spatial redistribution at Villarrica is consistent with coupled fluid-pressure changes, fracture-network reorganization, and stress redistribution operating within the crustal architecture defined by the interaction between the Mocha–Villarrica Fault Zone and the LOFS. The behavior of S6 further indicates that intracaldera forcing and peripheral activation can overlap in time, emphasizing that the timing and spatial expression of these processes vary among individual swarms.

4.3 b-value Patterns and Fluid–Stress Interactions

The spatial b-value distribution derived from 1,219 well-located VT earthquakes using the B-Positive method reveals coherent variations that are not reproduced by spatial changes in magnitude completeness (van der Elst 2021; Figs. 7, lower right panel). This spatial sampling strategy was adopted to provide sufficient event density for a statistically robust estimation while preserving the spatial variability of the b-value distribution. The lowest uncertainties occur within the main seismic clusters, supporting the statistical stability of the principal spatial patterns, whereas small-scale anomalies toward the margins should be interpreted more cautiously (Online Resource 1, Fig. S4). The b-value describes the relative proportion of small and large earthquakes and commonly varies inversely with differential stress: low values

indicate a comparatively greater proportion of larger earthquakes, whereas high values reflect the predominance of smaller events (Schorlemmer et al. 2005; Scholz 2015). Experiments on andesite have similarly shown decreases in b during fracture interaction and coalescence preceding macroscopic failure (Smith et al. 2009). However, b is not a direct measurement of differential stress or fluid pressure because it may also depend on faulting style, depth, temperature, rheology, and structural heterogeneity (Schorlemmer et al. 2005; Sibson 1996, 2020). Moreover, pore-pressure variations can modify effective normal stress and rupture conditions (Bachmann et al. 2012). Accordingly, the b -value is interpreted here as an integrated indicator of the mechanical state of the seismogenic volume.

At Villarrica, b -values ranging from approximately 0.6 to 1.8 define three spatially coherent domains rather than a simple intra–extracaldera contrast (Fig. 7, lower right panel). First, the eastern intracaldera sector exhibits predominantly low values (~ 0.6 – 1.0) and coincides with one of the main seismic-density clusters (Fig. 7, upper right panel). This pattern indicates a comparatively greater proportion of higher-magnitude earthquakes and is consistent with stress concentration and fracture interaction within a mechanically confined volume. Although it does not demonstrate proximity to macroscopic failure, its intracaldera location suggests that this mechanical state may be influenced by perturbations associated with magma emplacement or pressurization within Villarrica's shallow storage and transfer system, where nearly continuous recharge has been independently proposed (Romero et al. 2023; Boschetty et al. 2022; Cortés et al. 2024).

Second, an immediately adjacent extracaldera band exhibits high b -values (~ 1.2 – 1.8), indicating distributed microfracturing and a lower relative proportion of larger ruptures. This configuration may reflect reduced effective normal stress associated with elevated pore pressure, which can facilitate the reactivation of numerous small fractures (Goertz-Allmann and Wiemer 2013). Comparable spatial contrasts between low- b , stress-concentrated sectors and high- b , more porous or permeable volumes have been reported at Campi Flegrei (Tramelli et al. 2024), whereas temporal increases in b at Copahue have been associated with episodes consistent with fluid injection (Fariás et al. 2023). These comparisons support the mechanical plausibility of a fluid-sensitive domain at Villarrica but do not imply equivalent structural or hydrothermal configurations.

Finally, the more distal extracaldera clusters along the NW–SE structural corridor exhibit predominantly intermediate values (~ 0.9 – 1.2). Their location near intersections between NW- and NNE-trending structures suggests an increasing influence of inherited tectonic architecture, where fault interaction may locally concentrate stress and permit rupture across comparatively larger surfaces. Thus, the

spatial b-value pattern delineates an intracaldera domain consistent with greater stress concentration, an adjacent band potentially more sensitive to pore-pressure variations, and distal fault-controlled domains with intermediate mechanical behavior. This zonation does not uniquely identify the underlying forcing mechanism; rather, it demonstrates that the Villarrica seismogenic volume comprises mechanically distinct domains reflecting spatial contrasts in stress concentration, fracture heterogeneity, and potential fluid influence.

4.4 Focal Mechanisms, Local Stress-Field Heterogeneity, and Structural Control

The focal mechanisms of the highest-energy VT earthquakes provide an independent constraint on the interaction between regional tectonic loading and local volcanic perturbations at Villarrica Volcano. The nine solutions are dominated by strike-slip faulting but display marked variability in nodal-plane geometry and P- and T-axis orientations, particularly within the caldera-related domain (Fig. 8). Swarm S8, the only sequence whose principal event occurred outside this domain, exhibits the clearest structural correspondence: one NW–SE striking nodal plane is parallel to the Mocha–Villarrica structural corridor of the Andean Transverse Fault System (ATFS). In contrast, the intracaldera solutions show dispersed orientations. Because the fault and auxiliary planes cannot be distinguished from first-motion solutions alone, and because the ATFS and LOFS have approximately orthogonal regional trends, these ruptures cannot be unequivocally assigned to either fault system. Their variability therefore provides stronger evidence of local stress-field heterogeneity than of the systematic reactivation of a single fault family.

The dispersion of P and T-axis orientations relative to the regional strike-slip stress field is consistent with local stress perturbations superimposed on the regional tectonic regime (Sielfeld et al. 2019; Pérez-Estay et al. 2023). Pérez-Estay et al. (2023) identified at Villarrica a local stress configuration in which the maximum compressive stress is rotated by approximately 50–90° relative to the regional field and interpreted this configuration as potentially associated with transient fluid circulation. Comparable local rotations have been linked to pressurization of a dike network and of a mid-crustal conduit (Roman and Cashman 2006). At Villarrica, however, the available focal mechanisms do not independently demonstrate active magma intrusion, identify the source of pressurization, or resolve temporal stress rotations within individual swarms. Rather, they indicate that the regional tectonic field was locally perturbed, modifying the resolved normal and shear stresses on inherited discontinuities and allowing differently oriented structures to rupture. The

contrast between the structurally compatible S8 mechanism and the dispersed intracaldera solutions therefore supports a coupled regime characterized by stronger tectonic control along the external Mocha–Villarrica corridor and greater local stress heterogeneity beneath the caldera.

4.5 Integrated Conceptual Model of Magmatic Pressurization, Stress Redistribution, and Delayed Surface Response at Villarrica Volcano

Taken together, the results support a coupled volcano–tectonic model in which VT swarms at Villarrica Volcano record recurrent episodes of shallow magmatic and/or fluid pressurization, brittle failure, and stress redistribution (Fig. 11). The dominant subsurface evolution, observed in most swarms, begins within the caldera-related domain and subsequently propagates toward peripheral sectors controlled by inherited tectonic structures. The behavior of S6 indicates that this evolution does not necessarily occur as two discrete stages, because intracaldera activity may persist while peripheral structures are being activated. This interpretation is supported by the joint spatial and temporal relationships among hypocentral clustering, stepwise seismic-energy release, b-value patterns, focal-mechanism variability, and outward migration (Figs. 7, 8, 9, and 10). Independent geophysical support for this interpretation is provided by the spatial and vertical coincidence among the highest-magnitude VT earthquakes, the intracaldera low-b-value domain (~ 0.6 – 1.0), and conductive anomaly C1 (5 – 20 Ωm), identified beneath the eastern sector of the caldera by Pavez et al. (2023) and interpreted as a shallow magma storage zone. This correspondence reinforces the interpretation that magmatic and/or fluid pressurization around C1 may favor stress concentration and the occurrence of the largest VT ruptures. Within this progression, the highest-energy VT earthquake commonly represents a temporal and energetic pivot, rather than the swarm onset or a demonstrated mechanical threshold, after which stress redistribution and enhanced fracture connectivity may facilitate propagation into extracaldera structural domains. Although consistent with pressurization and fluid–stress coupling, these observations do not independently demonstrate active magma intrusion, fluid transfer, or aseismic slip.

The surface expression of this subsurface evolution is conditional. In four of the nine swarms, all nucleated within the caldera-related domain, the highest-energy VT earthquake was followed approximately one to two months later by increased explosive activity documented by cameras and/or thermal anomalies detected by MIROVA (Fig. 5; Table 3). This delay is compatible with the time required for fracture-

980 network and permeability reorganization, together with the upward transfer or
981 shallow accumulation of fluids, heat, and potentially magma. Transient shallow
982 storage may therefore separate the initial seismogenic response from its subsequent
983 surface manifestation (Roman and Cashman 2018), consistent with precursory
984 intervals of weeks to months reported at other active volcanoes (Stix et al. 2025).
985 However, the absence of detectable surface responses following the remaining
986 swarms demonstrates that neither the highest-energy VT earthquake nor outward
987 hypocentral migration constitutes a deterministic eruption precursor. Swarm S8
988 reinforces this distinction because it developed entirely outside the caldera-related
989 domain, exhibited stronger structural compatibility with the ATFS, and showed
990 neither intra- to extracaldera migration nor a detectable surface response (Figs. 9
991 and 10).

992 Accordingly, the conceptual model represents a dominant but non-universal
993 evolutionary pathway rather than a deterministic sequence. Its principal interpretive
994 and operational value lies in the integrated evaluation of seismic-energy release,
995 hypocentral migration, b-value distributions, focal mechanisms, and thermal, visual,
996 and infrasound observations. Figure 11, based on Swarm S5, synthesizes this
997 progression from caldera-centered pressurization and brittle failure to structurally
998 controlled outward migration and, in some cases, a delayed surface response. This
999 multi-parameter framework provides a basis for assessing whether future VT swarms
1000 reproduce the recurrent subsurface evolution identified at Villarrica and whether
1001 their subsequent development indicates an increased likelihood of delayed surface
1002 activity.

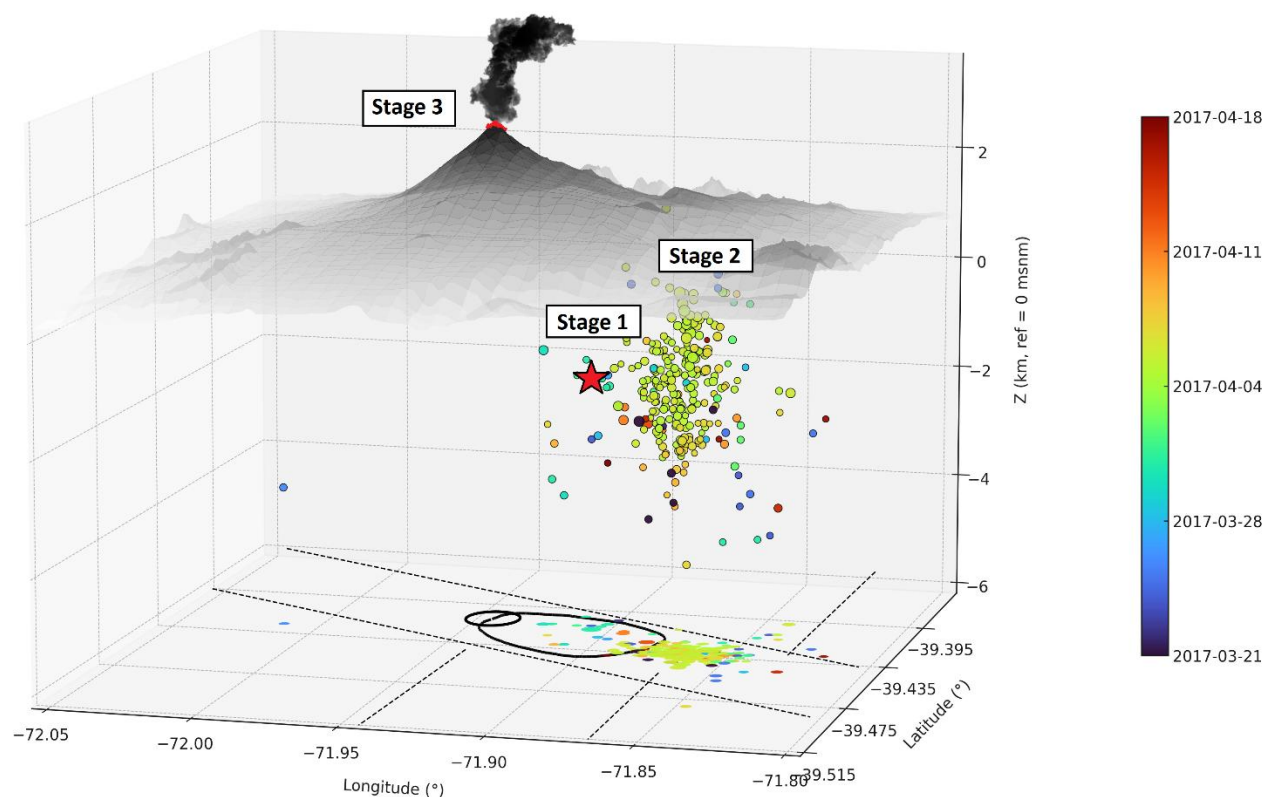


Fig. 11 Three-dimensional conceptual model illustrating the proposed spatio-temporal evolution of VT Swarm S5 at Villarrica Volcano (March–April 2017). Hypocenters are color-coded by occurrence time and illustrate a three-stage conceptual evolution. Stage 1 is characterized by intracaldera clustering of VT seismicity, compatible with brittle failure associated with shallow magmatic and/or fluid pressurization. The largest-magnitude VT earthquake (red star) represents the principal seismic-energy release and acts as the temporal pivot of the sequence. Stage 2 shows an apparent outward spatial redistribution of seismicity toward peripheral, structurally controlled domains, potentially associated with stress redistribution and enhanced fracture connectivity. Stage 3 represents the delayed surface response observed approximately 1–2 months after the pivot earthquake, expressed by increased explosion-type activity (EX) and MIROVA-detected thermal anomalies. Overall, the model summarizes a possible, non-universal relationship among shallow pressurization, brittle failure, stress redistribution, activation of inherited structures, and delayed surface manifestations at Villarrica Volcano.

5 Conclusions

The analysis of nine VT earthquake swarms at Villarrica Volcano reveals a recurrent but non-universal pattern of volcano–tectonic interaction. Most swarms initiated within the caldera-related domain and subsequently showed outward spatial redistribution toward peripheral sectors influenced by inherited structures. S6 differed from this dominant pattern because intracaldera seismicity persisted after the pivot earthquake while extracaldera earthquakes were also recorded, indicating temporal overlap between the internal and external seismic responses. In contrast, S8 remained confined to the external Mocha–Villarrica structural corridor and showed little change in median epicentral distance. The spatial distribution of b-values and the variability of focal mechanisms further indicate that the seismogenic volume comprises mechanically distinct domains, characterized by heterogeneous stress conditions beneath the caldera and stronger tectonic control in peripheral sectors. Within the swarm evolution, the highest-energy VT earthquake commonly represents a temporal and energetic pivot associated with subsequent stress redistribution, although outward propagation is a dominant rather than universal response. Only four of the nine swarms were followed, approximately one to two months later, by increased explosive activity and/or thermal anomalies. Therefore, neither the highest-energy earthquake nor outward hypocentral migration constitutes a deterministic precursor of surface activity. Taken together, the observations are compatible with recurrent episodes of shallow magmatic and/or fluid pressurization interacting with inherited fault–fracture networks. Integrating seismic-energy release, hypocentral migration, b-value distributions, focal mechanisms, and surface observations provides a more robust framework for evaluating the evolution and potential consequences of future VT swarms at Villarrica Volcano.

Declarations

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Data availability: The seismic catalog and volcanic monitoring data used in this study are maintained by the Observatorio Volcanológico de los Andes del Sur (OVDAS) of the Servicio Nacional de Geología y Minería (SERNAGEOMIN). These data can be requested through the Chilean transparency law (<https://www.portaltransparencia.cl/PortalPdT/ingreso-sai-v2?idOrg=undefined>). MIROVA thermal data are publicly available through the MIROVA system (https://www.mirovaweb.it/NRT/volcanoDetails_VIR.php?volcano_id=357120).

Data availability: The seismic catalog and monitoring data used in this study are maintained by the Observatorio Volcanológico de los Andes del Sur (OVDAS) of the Servicio Nacional de Geología y Minería (SERNAGEOMIN). Requests for data access should be directed to the corresponding author and will be considered in accordance with the data sharing policies of the monitoring institutions. MIROVA thermal data are publicly available through the MIROVA system.

Author contributions: JL, DB, LF, JV and AG contributed to the conceptualisation and methodology of the research and performed the formal analysis, visualisation and validation. DB and LF were involved in the funding and supervision of the paper. BH, AB and CC contributed with the supervision, review and editing of the paper. LF, JV, MP, AB and CF contributed to the discussion of the scientific results. All the authors provided input in terms of methodology and the review.

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