VOLCANO-TECTONIC SEISMICITY AT VILLARRICA VOLCANO: A DECADE OF EVIDENCE (2014–2023) TO UNDERSTAND ITS INTERNAL DYNAMICS

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Online Resource 1

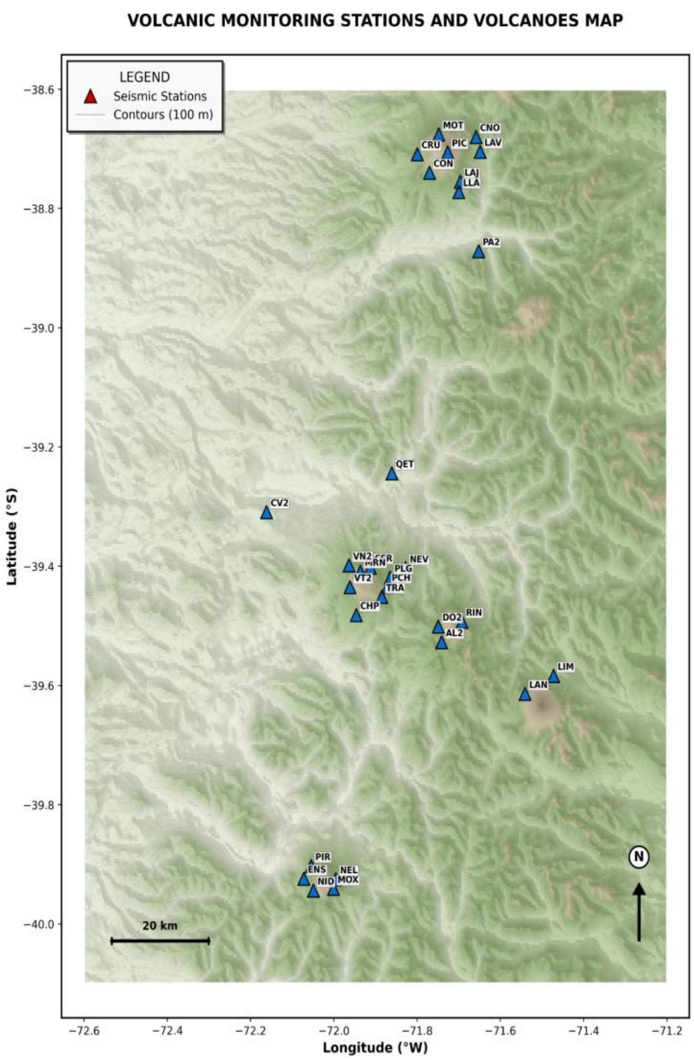

Fig. S1 Map of the seismic monitoring network used to observe the Villarrica, Quetrupillán, Mocho-Choshuenco, Lanín, and Llaima volcanoes, located in the southern segment of the Southern Volcanic Zone of the Andes. Seismic stations are shown as blue triangles.

Table S1 Regional seismic stations deployed at the Lanín, Quetrupillán, Mocho–Choshuenco, and Llaima volcanoes used to complement the local seismic network and improve seismic event relocations at Villarrica Volcano.

Volcano	**Station**	**Sensor**	**Digitizer**	**Installation date**
Lanín	SLIM	Sercel L4C	Reftek 130B	29-12-2020
	SLAN	Reftek 151-30	Reftek 130B	01-01-2016
Quetrupillán	SAL2	Reftek 151-30	Reftek 130B	30-05-2016
	SRIN	Trillium 120P	Reftek 130B	27-03-2019
	SDO2	Sercel L4C	Kinemetrics Basalt	28-03-2019
Mocho-Choshuenco	SMOX	Trillium 120P	Reftek 130B	22-04-2012
	SNEL	Guralp CMG-6TD	—	15-02-2018
	SPIR	Trillium 120P	Reftek 130B	21-12-2019
	SNID	Sercel L4C	Reftek 130B	12-01-2018
	SPIL	Guralp CMG-6TD	—	21-12-2019
	SENS	Sercel L4C	Kinemetrics Basalt	17-03-2020
Llaima	SLAV	Trillium 120P	Kinemetrics Q330	19-05-2010
	SPA2	Guralp CMG-40TD	—	12-02-2018
	SAGU	Trillium 120P	Kinemetrics Q330	19-05-2010
	SCRU	Trillium 120P	Kinemetrics Q330	01-01-2016
	SCON	Reftek 151-30	Reftek 130B	14-10-2016
	SLAJ	Sercel L4C	Reftek 130B	31-03-2012
	SLLA	Reftek 151-30	Reftek 130B	01-01-2017
	SMO3	Trillium 40	Reftek 130B	30-11-2016
	SCNO	Trillium 40	Reftek 130B	13-01-2017

	SPIC	Sercel L4C	Reftek 130B	01-12-2016

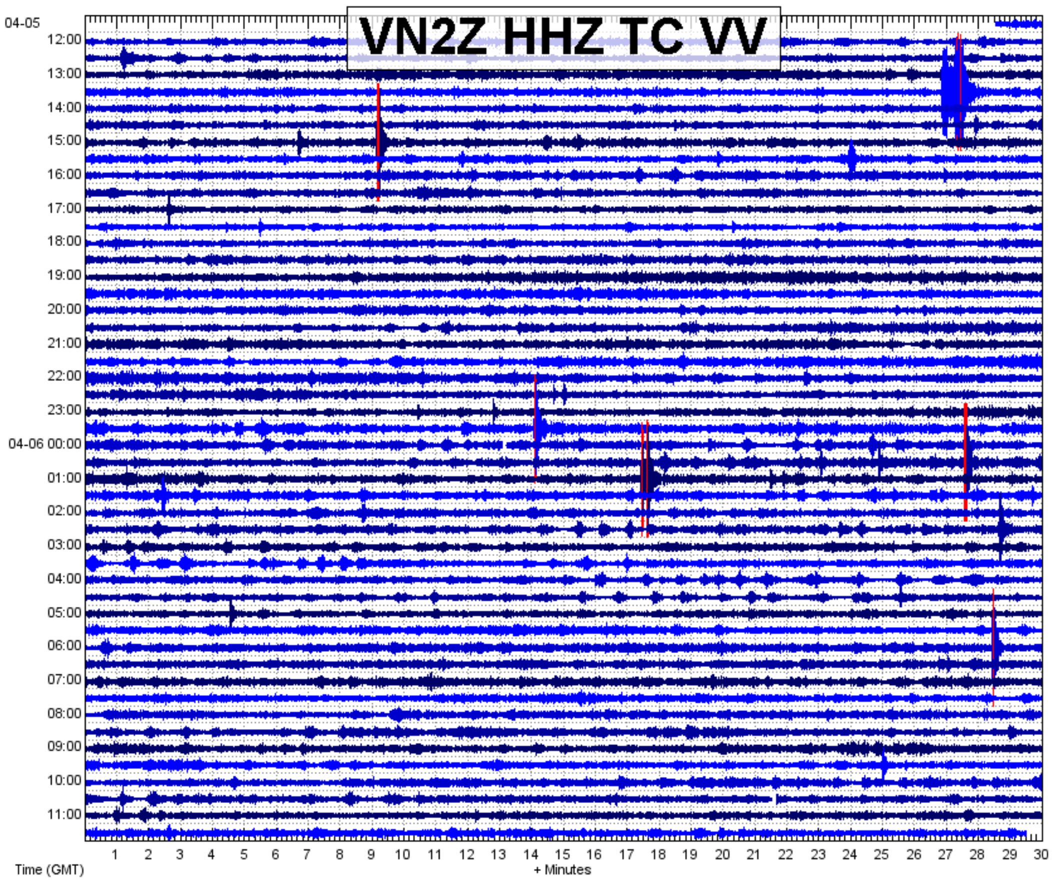

Fig. S2 Example of a helicorder record from seismic station VN2 (HHZ component) during Swarm 5 at Villarrica Volcano on 5 April 2017. The figure shows one full day of continuous seismic recording corresponding to one of the most active days of the swarm, during which 95 VT earthquakes were detected. At the helicorder scale, only the largest amplitude VT events are clearly visible, while smaller earthquakes are not distinguishable in the continuous record. Red markers indicate the most energetic VT events identified in the signal. Time is shown in UTC, and each horizontal line represents a 30-minute interval.

Table S2 One-dimensional (1D) velocity model used for seismic relocation at Villarrica Volcano.

Upper depth (km)	**Lower depth (km)**	**P-wave velocity Vp (km/s)**	**S-wave velocity Vs (km/s)**
0.0	1.0	3.6	2.0

1.0	3.0	4.5	2.5
3.0	6.0	5.4	3.0
6.0	10.0	6.2	3.5

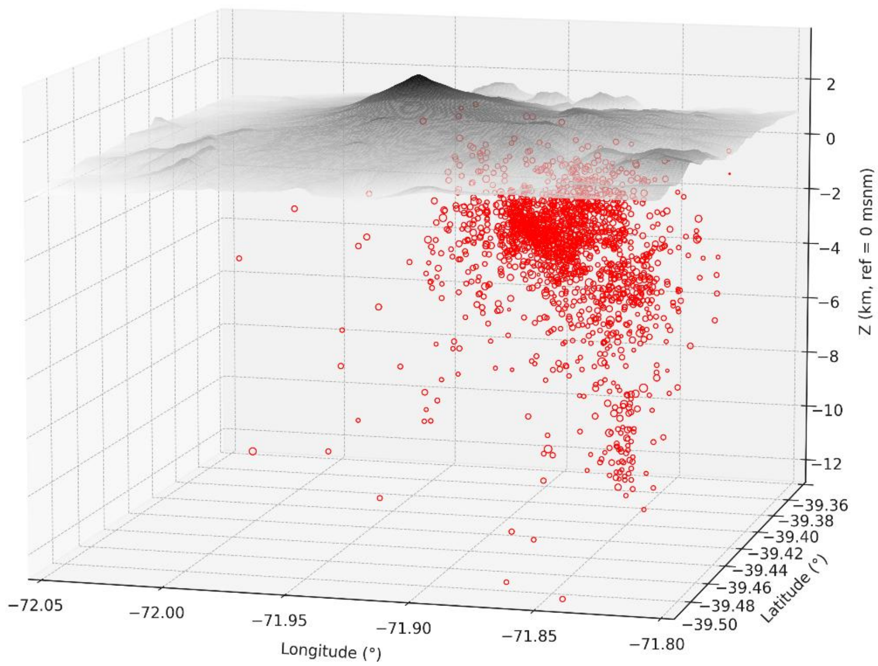

Fig. S3 Three-dimensional distribution of volcano-tectonic (VT) earthquakes beneath Villarrica Volcano during the study period. Hypocenters are shown as red circles and projected relative to the topographic surface of the volcanic edifice (gray shaded relief). The vertical axis represents depth in kilometers relative to sea level (reference = 0 m). The seismicity forms a clustered distribution beneath the central edifice, with most events occurring between ~2 and 6 km depth below the summit area. A subset of deeper events extends to depths of ~10–12 km, suggesting a vertically elongated seismogenic volume that may reflect the deeper portion of the magmatic plumbing system and associated zones of brittle failure within the volcanic crust. The spatial distribution highlights the concentration of VT seismicity beneath the caldera region and along structural domains surrounding the summit area.

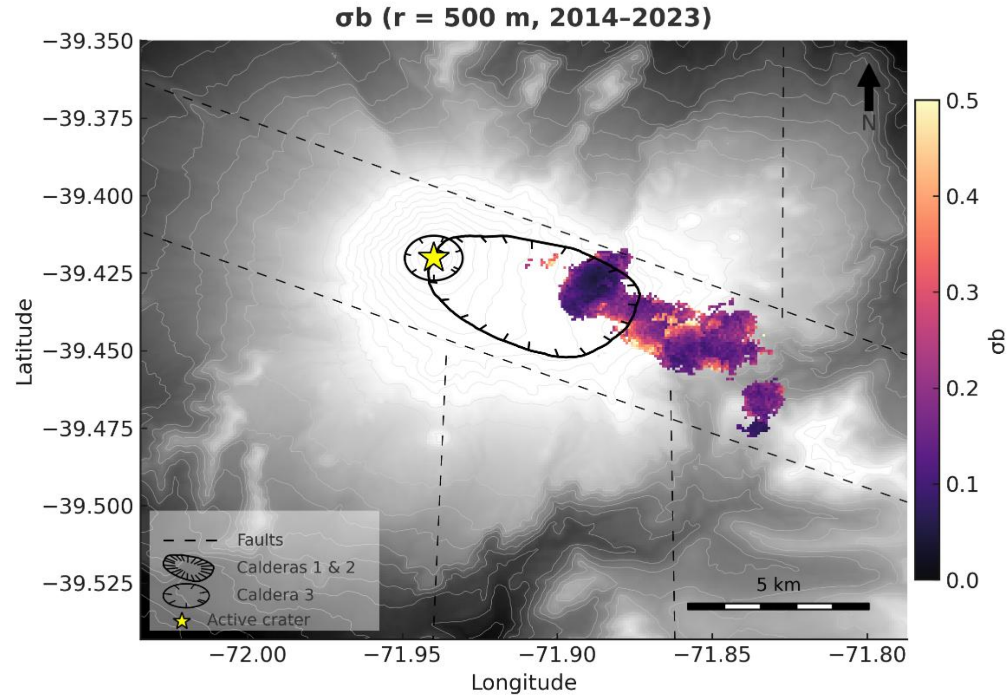

Fig. S4. Spatial distribution of the uncertainty associated with the local b-value estimation (σb) beneath Villarrica Volcano for the period 2014–2023 using a moving-window approach with radius r = 500 m. Colors represent the standard deviation of the estimated b-value within each spatial window, reflecting the statistical stability of the magnitude–frequency distribution. Lower σb values indicate more robust b-value estimates, typically associated with areas containing higher seismicity density. Structural features including mapped faults and caldera boundaries are shown for reference, together with the location of the active crater (yellow star). The spatial pattern highlights that the most statistically stable b-value estimates coincide with the main VT seismic clusters located east of the caldera.

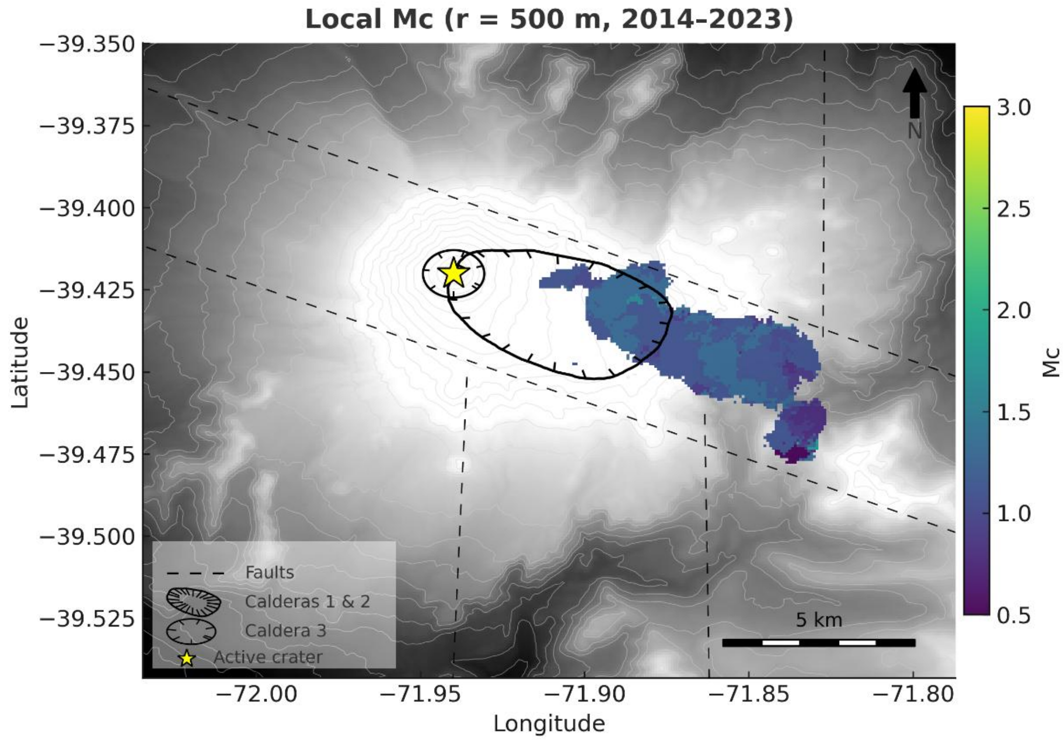

Fig. S5 Spatial distribution of the magnitude of completeness (Mc) beneath Villarrica Volcano for the period 2014–2023 estimated using a moving spatial window (radius r = 500 m). Colors represent the local Mc value calculated for each spatial cell. Structural elements including mapped faults and caldera boundaries are shown for reference together with the location of the active crater (yellow star). The results indicate that Mc remains relatively low and spatially consistent across most of the main seismic cluster east of the caldera, suggesting stable detection capability of the seismic network in the area where most VT earthquakes occur. Slightly higher Mc values are observed toward the periphery of the seismic cluster where event density decreases.

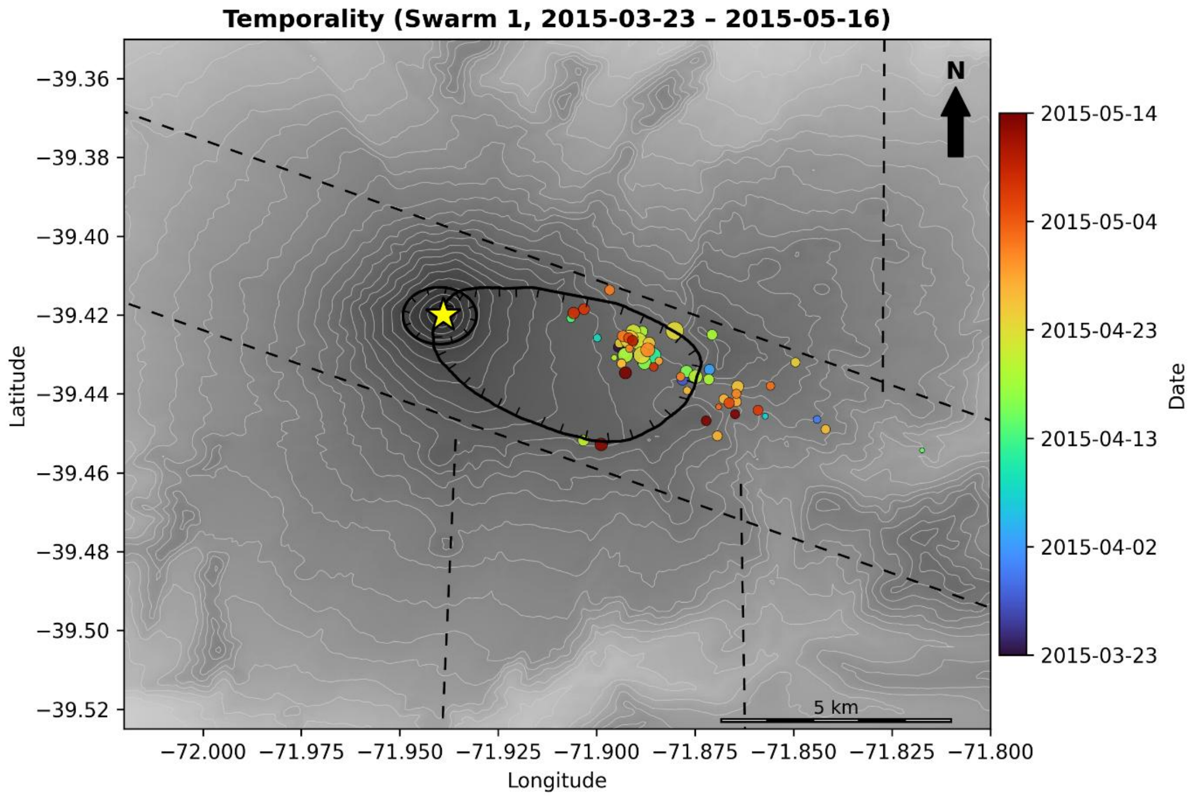

Fig. S6. Spatio-temporal evolution of VT earthquakes during Swarm 1 at Villarrica Volcano between 23 March and 16 May 2015. Each circle represents an earthquake epicenter colored according to its occurrence date, illustrating the temporal progression of seismicity during the swarm. Structural features including mapped faults and caldera boundaries are shown for reference, together with the location of the active crater (yellow star). The distribution highlights a concentration of events east of the summit area within the caldera structure, with a progressive outward migration toward the eastern sector of the volcanic edifice. This pattern is consistent with the general swarm evolution observed at Villarrica, where seismicity nucleates near the summit region and subsequently propagates toward structurally controlled domains surrounding the caldera.

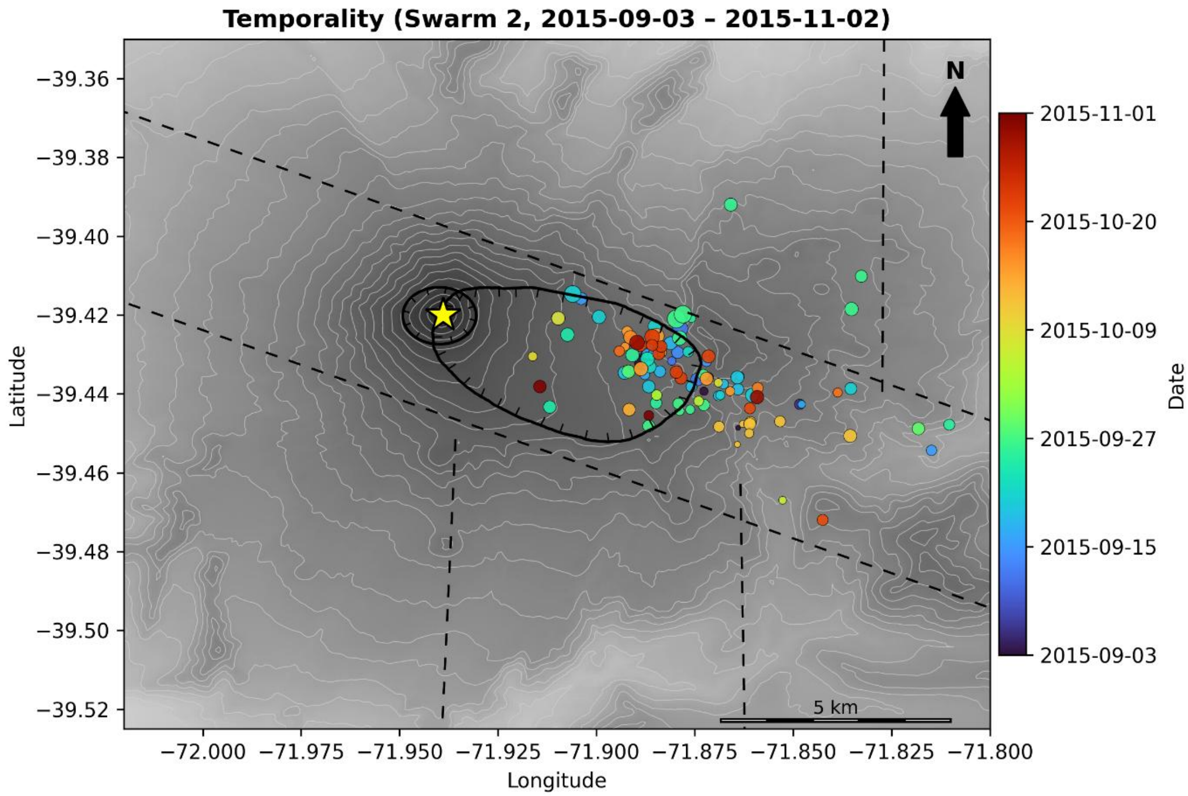

Fig. S7. Spatio-temporal evolution of VT earthquakes during Swarm 2 at Villarrica Volcano between 3 September and 2 November 2015. Each circle represents an earthquake epicenter colored according to its occurrence date, illustrating the temporal progression of seismicity during the swarm. Structural elements including mapped faults and caldera boundaries are shown for reference, together with the location of the active crater (yellow star). The seismicity is mainly concentrated within and east of the caldera structure, showing a progressive migration of events toward the eastern sector of the volcanic edifice. This spatial pattern is consistent with the recurrent behavior observed in several swarms at Villarrica, where seismic activity initiates near the summit region and subsequently propagates outward along structurally controlled domains.

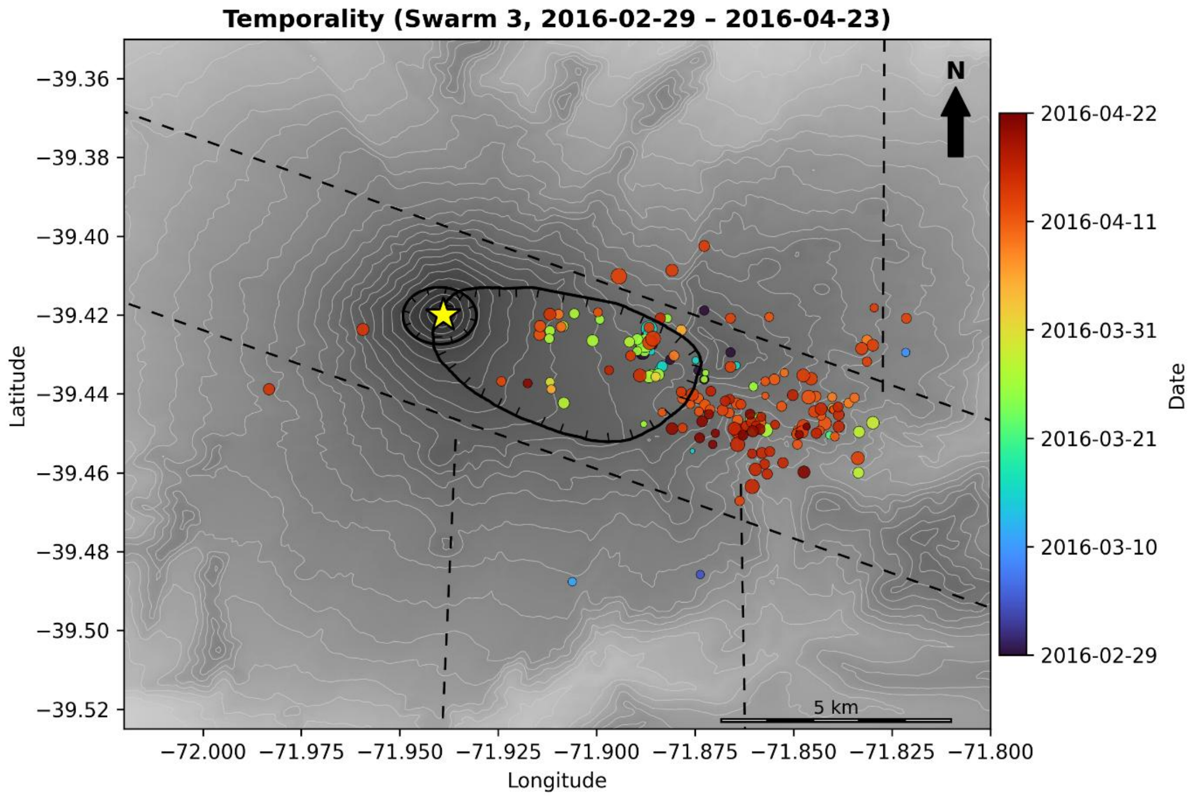

Fig. S8. Spatio-temporal evolution of VT earthquakes during Swarm 3 at Villarrica Volcano between 29 February and 23 April 2016. Each circle represents an earthquake epicenter colored according to its occurrence date, illustrating the temporal progression of seismicity during the swarm. Structural elements including mapped faults and caldera boundaries are shown for reference, together with the location of the active crater (yellow star). The seismicity is concentrated mainly east of the summit area and within the caldera structure, showing a progressive outward migration of events toward the eastern sector of the volcanic edifice. This spatial pattern is consistent with the recurrent behavior observed in several swarms at Villarrica, where seismicity nucleates near the summit region and subsequently propagates along structurally controlled domains surrounding the caldera.

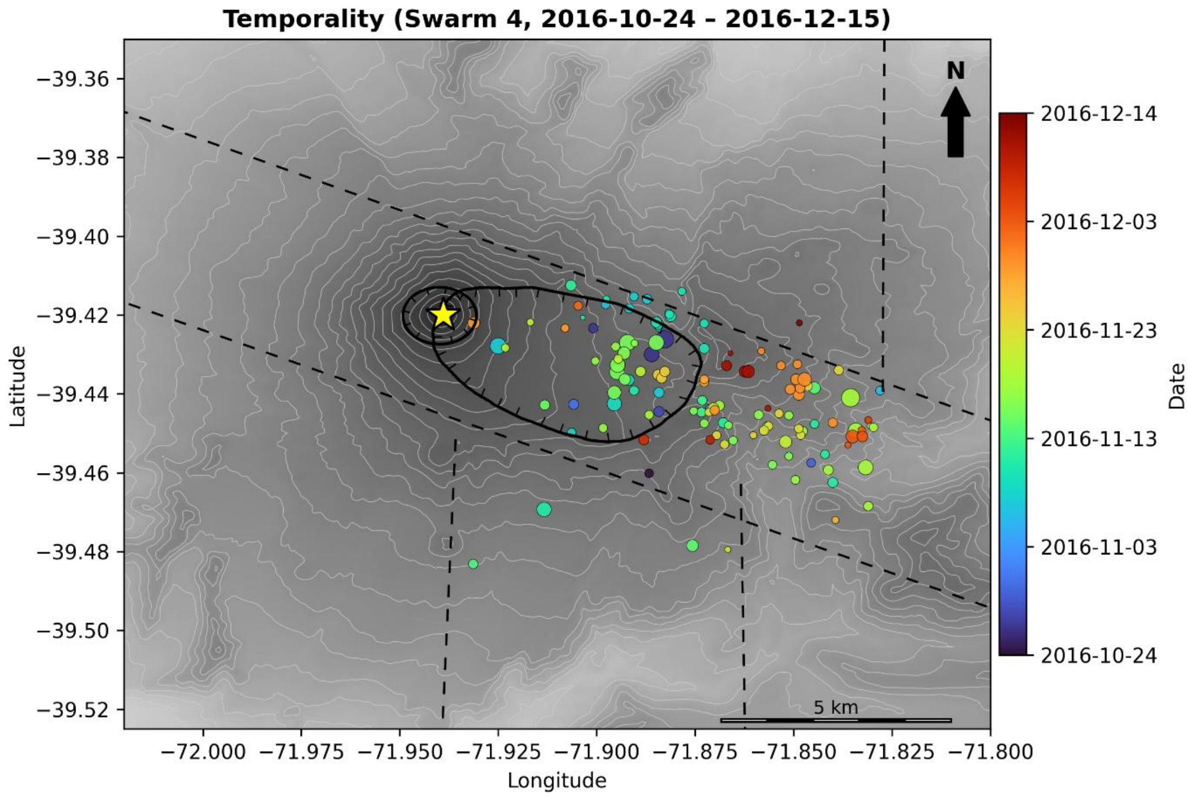

Fig. S9 Spatio-temporal evolution of VT earthquakes during Swarm 4 at Villarrica Volcano between 24 October and 15 December 2016. Each circle represents an earthquake epicenter colored according to its occurrence date, illustrating the temporal progression of seismicity throughout the swarm. Structural elements including mapped faults and caldera boundaries are shown for reference, together with the location of the active crater (yellow star). The seismicity is primarily concentrated within and east of the caldera structure and shows a progressive outward migration toward the eastern sector of the volcanic edifice. This distribution is consistent with the recurrent spatial pattern observed in several swarms at Villarrica, where seismic activity nucleates near the summit area and subsequently propagates outward along structurally controlled domains.

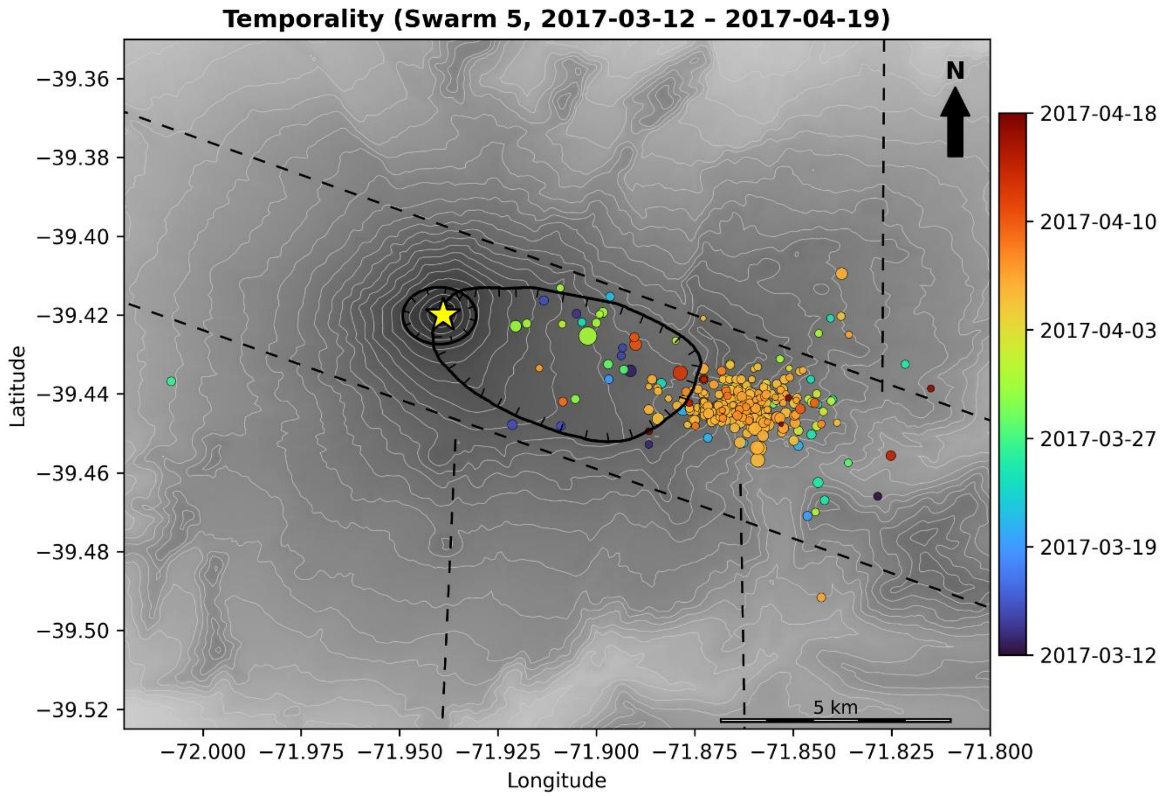

Fig. S10 Spatio-temporal evolution of VT earthquakes during Swarm 5 at Villarrica Volcano between 12 March and 19 April 2017. Each circle represents an earthquake epicenter colored according to its occurrence date, illustrating the temporal progression of seismicity during the swarm. Structural elements including mapped faults and caldera boundaries are shown for reference, together with the location of the active crater (yellow star). The seismicity is concentrated predominantly in the eastern sector of the caldera and adjacent areas, showing a progressive outward migration toward the east–southeast of the volcanic edifice. This distribution is consistent with the recurrent spatial pattern identified in several VT swarms at Villarrica, where seismic activity nucleates near the summit region and subsequently propagates outward along structurally controlled domains.

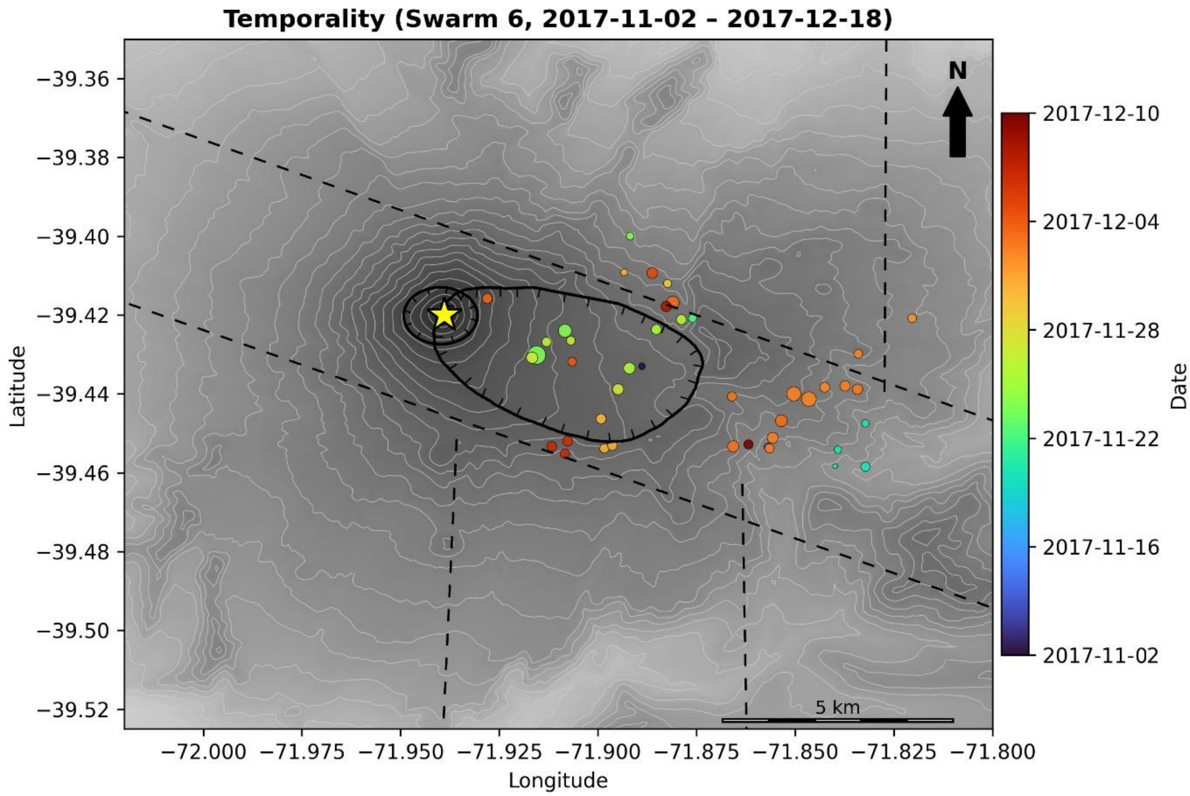

Fig. S11 Spatio-temporal evolution of VT earthquakes during Swarm 6 at Villarrica Volcano between 2 November and 18 December 2017. Each circle represents an earthquake epicenter colored according to its occurrence date. Mapped faults, caldera boundaries, and the active crater (yellow star) are shown for reference. Seismicity occurred both within the caldera and in the eastern extracaldera sector. Later events remained active within the caldera while overlapping temporally with earthquakes outside it, indicating that S6 did not follow a simple internal-to-external progression.

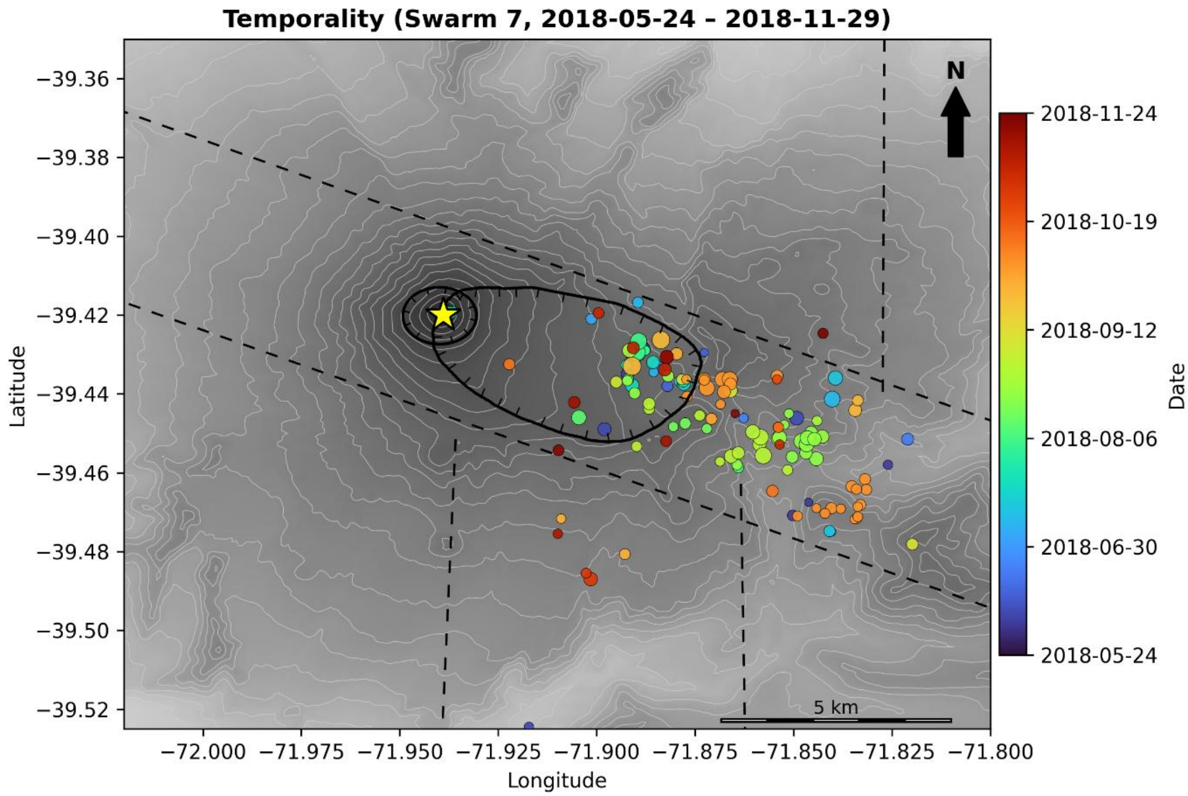

Fig. S12 Spatio-temporal evolution of VT earthquakes during Swarm 7 at Villarrica Volcano between 24 May and 29 November 2018. Each circle represents an earthquake epicenter colored according to its occurrence date, illustrating the temporal progression of seismicity throughout the swarm. Structural elements including mapped faults and caldera boundaries are shown for reference, together with the location of the active crater (yellow star). The seismicity is mainly concentrated within and east of the caldera structure and shows a progressive outward migration toward the eastern sector of the volcanic edifice. This spatial pattern is consistent with the recurrent behavior observed in several VT swarms at Villarrica, where seismic activity nucleates near the summit region and subsequently propagates outward along structurally controlled domains.

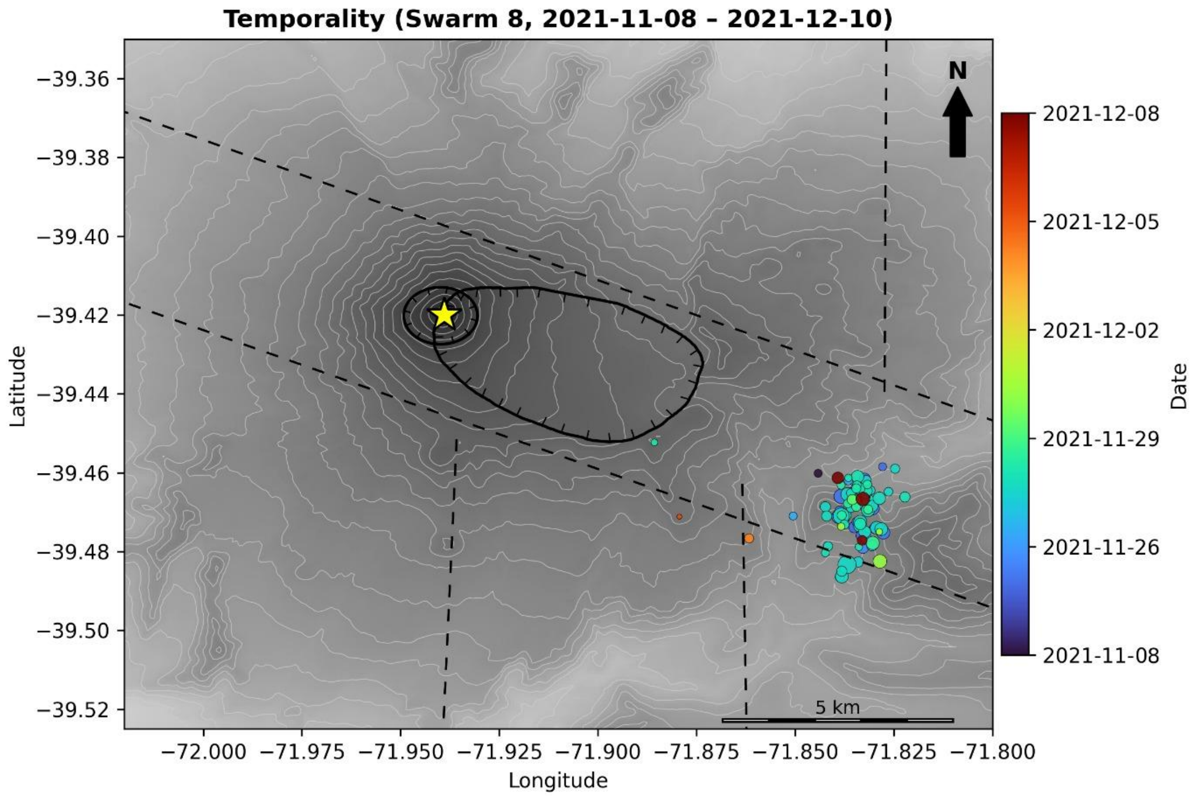

Fig. S13 Spatio-temporal evolution of VT earthquakes during Swarm 8 at Villarrica Volcano between 08 November and 10 December 2021. Each circle represents an earthquake epicenter colored according to its occurrence date, illustrating the temporal progression of seismicity throughout the swarm. Structural elements including mapped faults and caldera boundaries are shown for reference, together with the location of the active crater (yellow star). In contrast to several previous swarms, seismicity during this episode is strongly concentrated in the distal eastern sector of the volcanic edifice, outside the main caldera structure. This cluster suggests activation of structurally controlled pathways toward the eastern flank of the volcano.

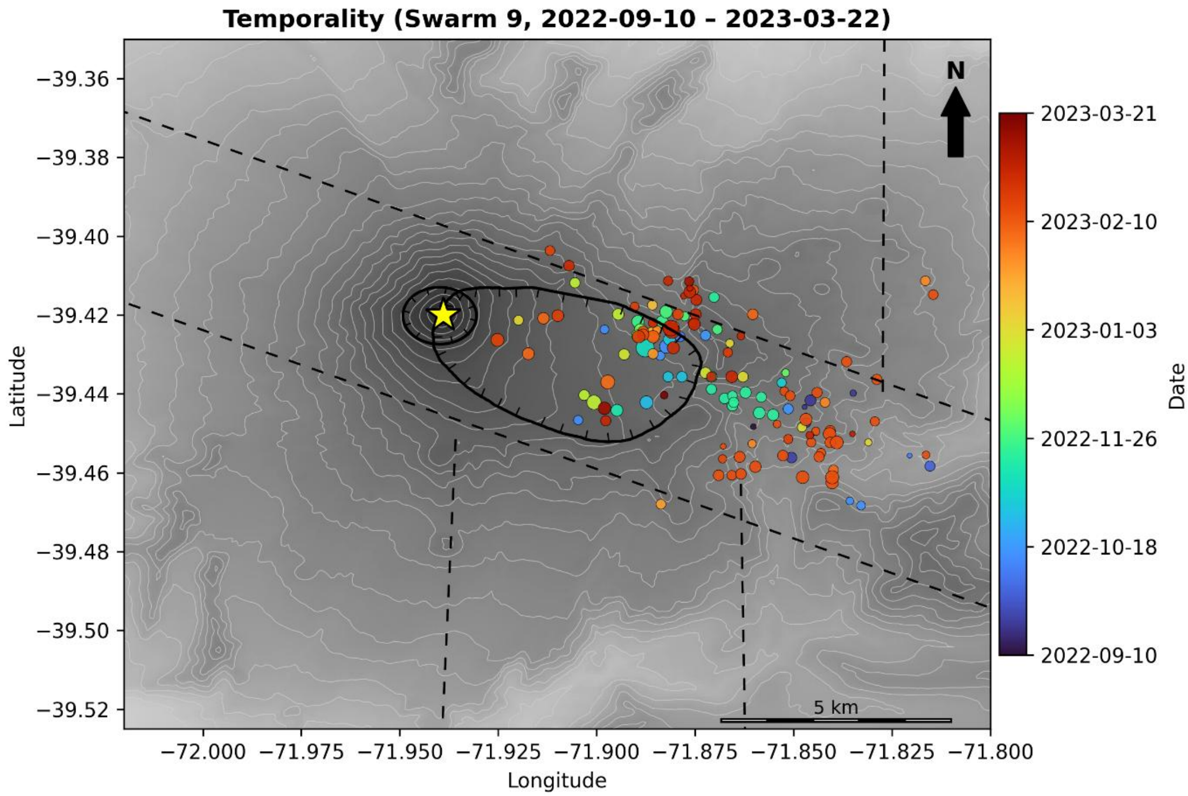

Fig. S14 Spatio-temporal evolution of VT earthquakes during Swarm 9 at Villarrica Volcano between 10 September 2022 and 22 March 2023. Each circle represents an earthquake epicenter colored according to its occurrence date, illustrating the temporal progression of seismicity throughout the swarm. Structural elements including mapped faults and caldera boundaries are shown for reference, together with the location of the active crater (yellow star). Seismicity is distributed both within the caldera structure and toward the eastern sector of the volcanic edifice, showing a progressive migration of events away from the summit region. This spatial pattern is consistent with the recurrent behavior observed in previous swarms, suggesting structurally controlled pathways guiding seismic activity toward the eastern flank of the volcano.

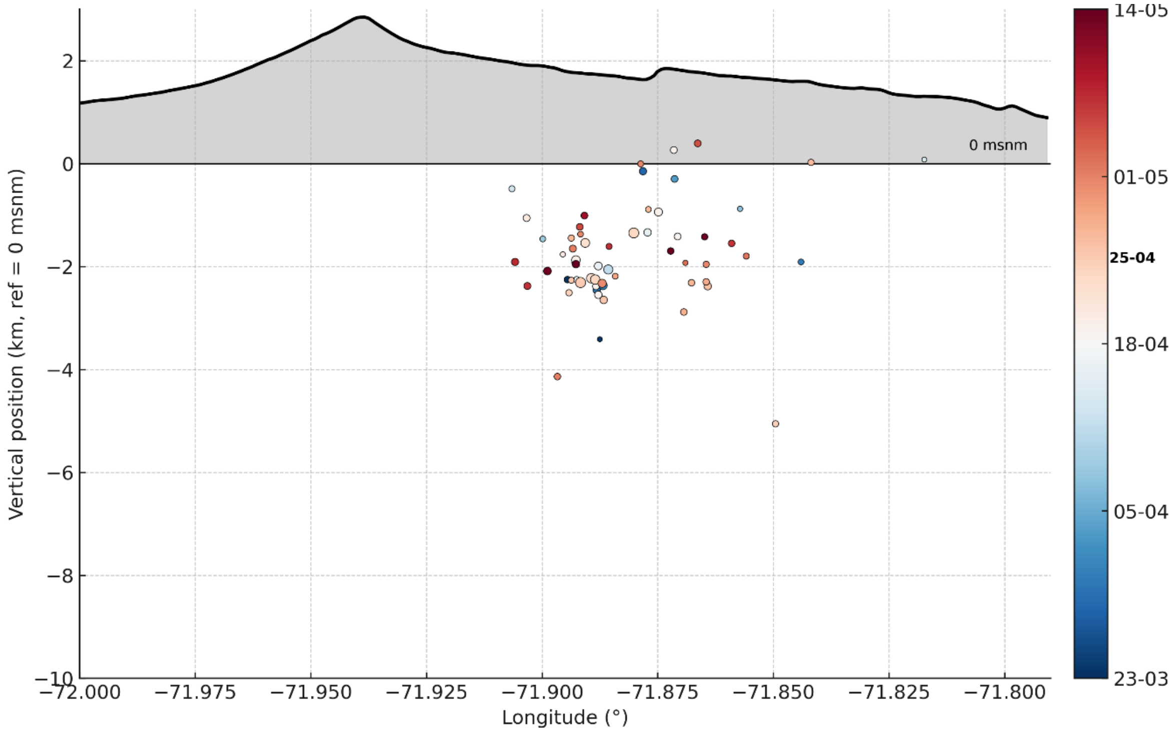

Fig. S15 East–West cross-section of the seismicity associated with Swarm 1 at Villarrica Volcano between 23 March and 16 May 2015. Circles represent hypocenters projected onto an E–W profile, colored according to their occurrence date to illustrate the temporal evolution of the swarm, the date in black indicates the day of the largest earthquake. The upper panel shows the topographic profile of the volcanic edifice along the section line, with elevation referenced to sea level (msnm). The lower panel displays the vertical distribution of seismicity relative to sea level, highlighting the concentration of VT events mainly between approximately 1 and 3 km below sea level beneath the eastern sector of the volcanic edifice. This distribution suggests activation of a structurally controlled seismogenic zone beneath the eastern flank of Villarrica.

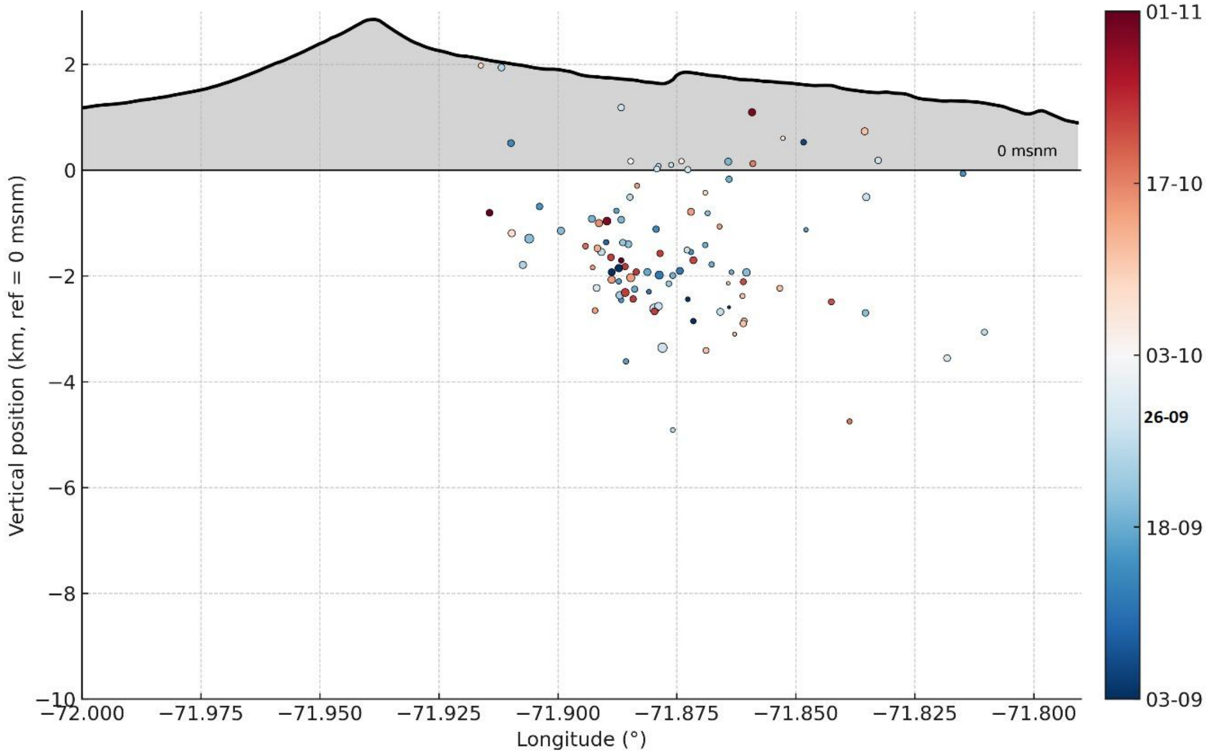

Fig. S16 East–West cross-section of the seismicity associated with Swarm 2 at Villarrica Volcano between 3 September and 2 November 2015. Circles represent hypocenters projected onto an E–W profile, colored according to their occurrence date to illustrate the temporal evolution of the swarm, the date in black indicates the day of the largest earthquake. The upper panel shows the topographic profile of the volcanic edifice along the section line, with elevation referenced to sea level (msnm). The lower panel displays the vertical distribution of seismicity relative to sea level, highlighting the distribution of VT events beneath the eastern sector of the volcanic edifice.

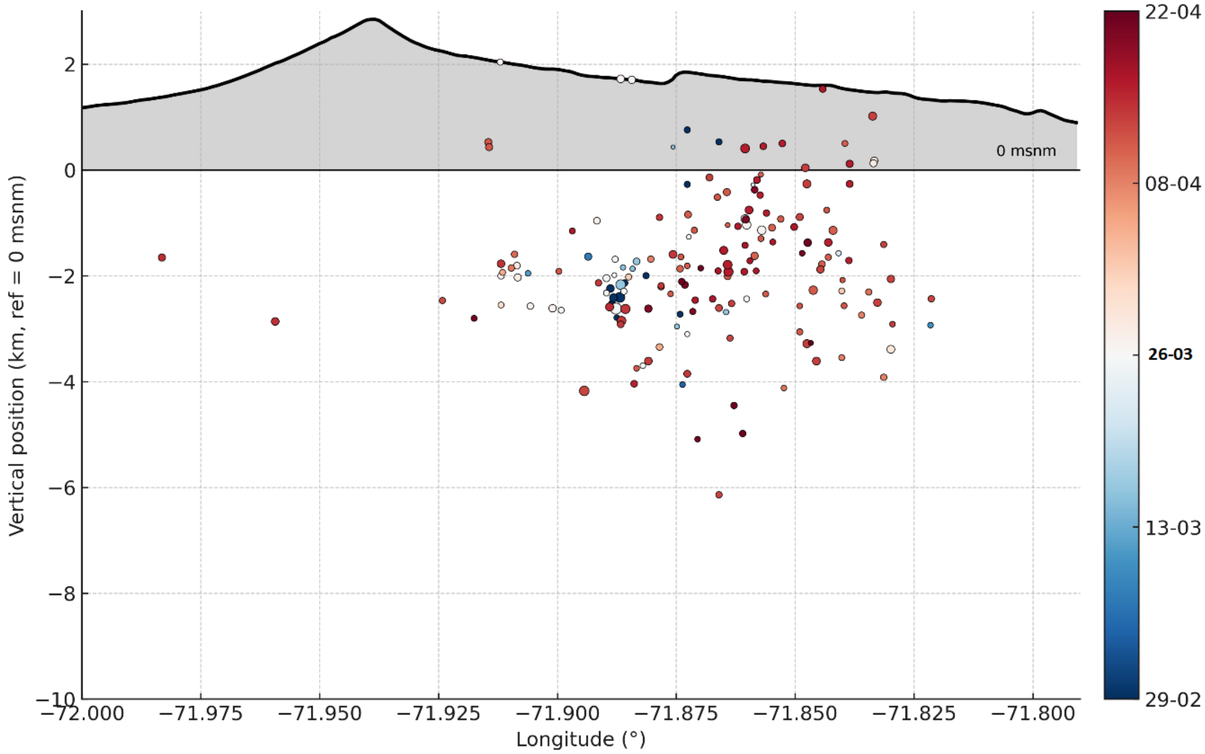

Fig. S17 East–West cross-section of the seismicity associated with Swarm 3 at Villarrica Volcano between 29 February and 23 April 2016. Circles represent hypocenters projected onto an E–W profile, colored according to their occurrence date to illustrate the temporal evolution of the swarm, the date in black indicates the day of the largest earthquake. The upper panel shows the topographic profile of the volcanic edifice along the section line, with elevation referenced to sea level (msnm). The lower panel displays the vertical distribution of seismicity relative to sea level, highlighting the distribution of VT events beneath the eastern sector of the volcanic edifice.

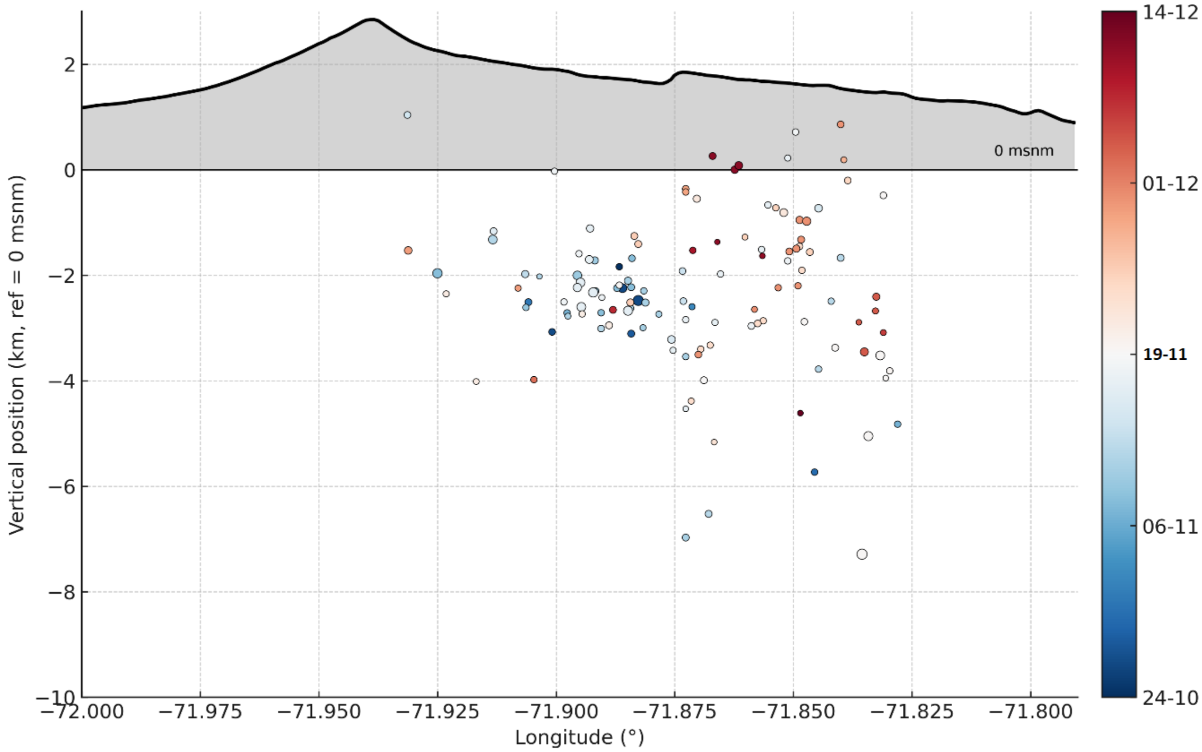

Fig. S18 East–West cross-section of the seismicity associated with Swarm 4 at Villarrica Volcano between 24 October and 15 December 2016. Circles represent hypocenters projected onto an E–W profile, colored according to their occurrence date to illustrate the temporal evolution of the swarm, the date in black indicates the day of the largest earthquake. The upper panel shows the topographic profile of the volcanic edifice along the section line, with elevation referenced to sea level (msnm). The lower panel displays the vertical distribution of seismicity relative to sea level, highlighting the distribution of VT events beneath the eastern sector of the volcanic edifice.

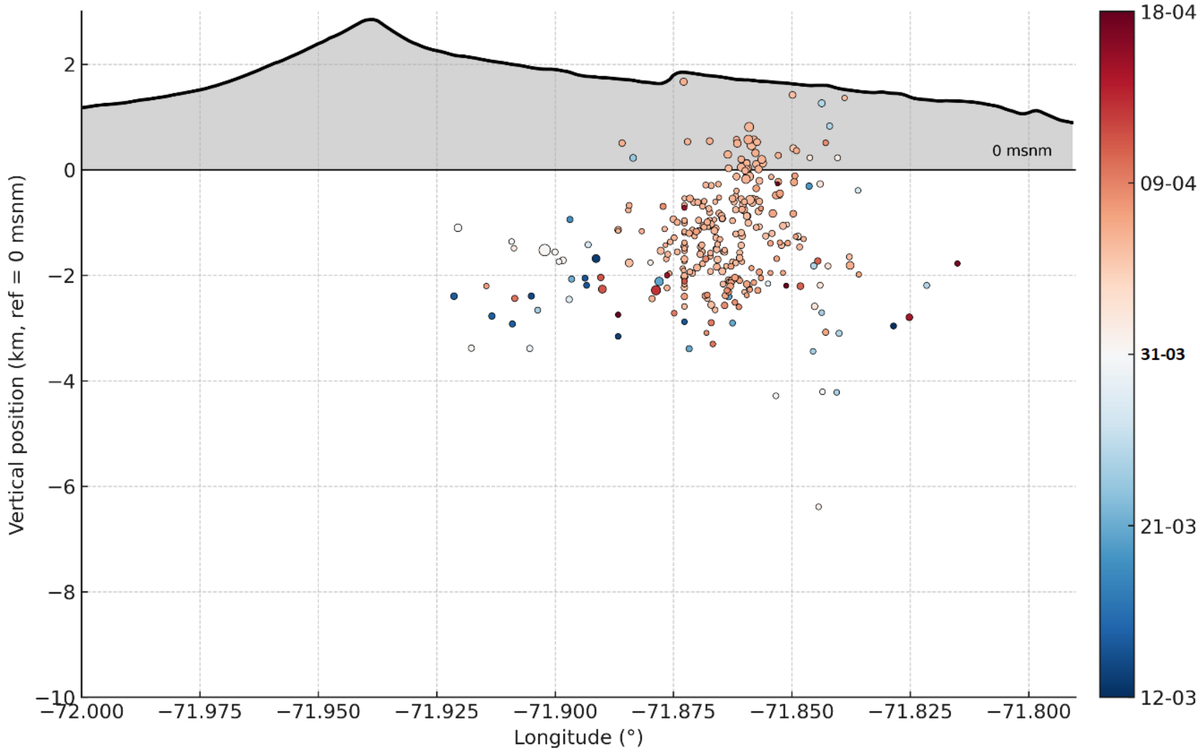

Fig. S19 East–West cross-section of the seismicity associated with Swarm 5 at Villarrica Volcano between 12 March and 19 April 2017. Circles represent hypocenters projected onto an E–W profile, colored according to their occurrence date to illustrate the temporal evolution of the swarm, the date in black indicates the day of the largest earthquake. The upper panel shows the topographic profile of the volcanic edifice along the section line, with elevation referenced to sea level (msnm). The lower panel displays the vertical distribution of seismicity relative to sea level, highlighting the distribution of VT events beneath the eastern sector of the volcanic edifice.

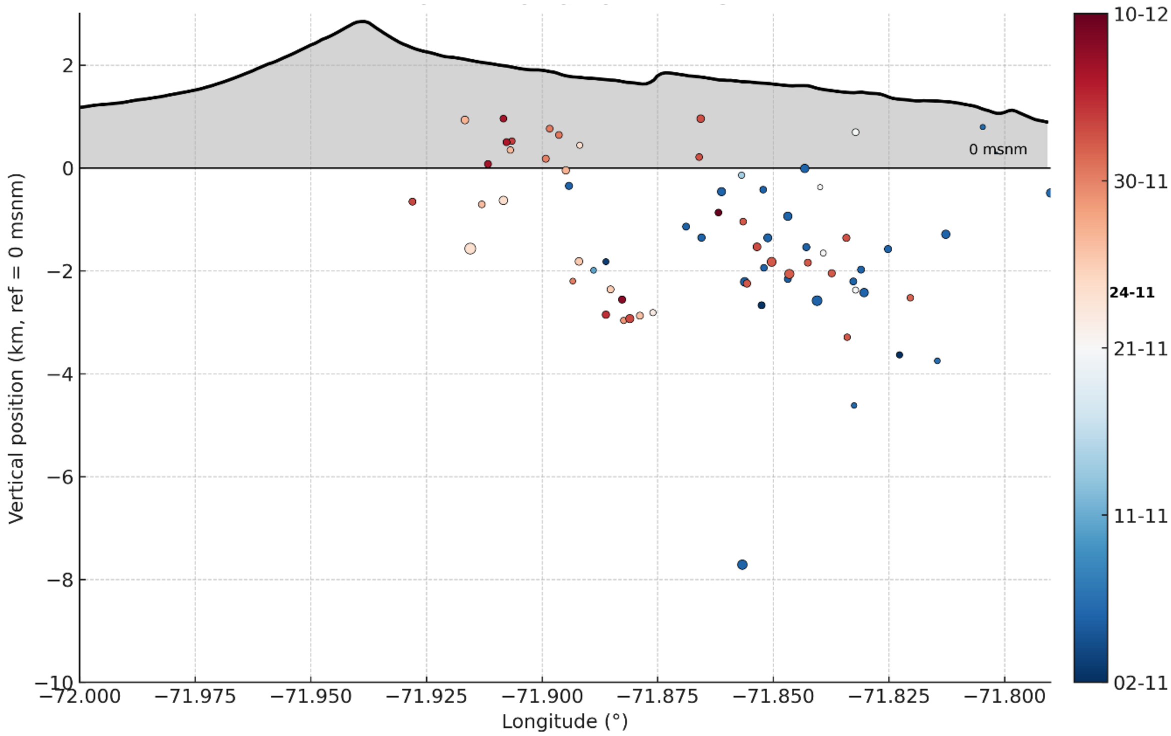

Fig. S20 East–West cross-section of the seismicity associated with Swarm 6 at Villarrica Volcano between 2 November and 18 December 2017. Circles represent hypocenters projected onto an E–W profile, colored according to their occurrence date to illustrate the temporal evolution of the swarm, the date in black indicates the day of the largest earthquake. The upper panel shows the topographic profile of the volcanic edifice along the section line, with elevation referenced to sea level (msnm). The lower panel displays the vertical distribution of seismicity relative to sea level, highlighting the distribution of VT events beneath the eastern sector of the volcanic edifice.

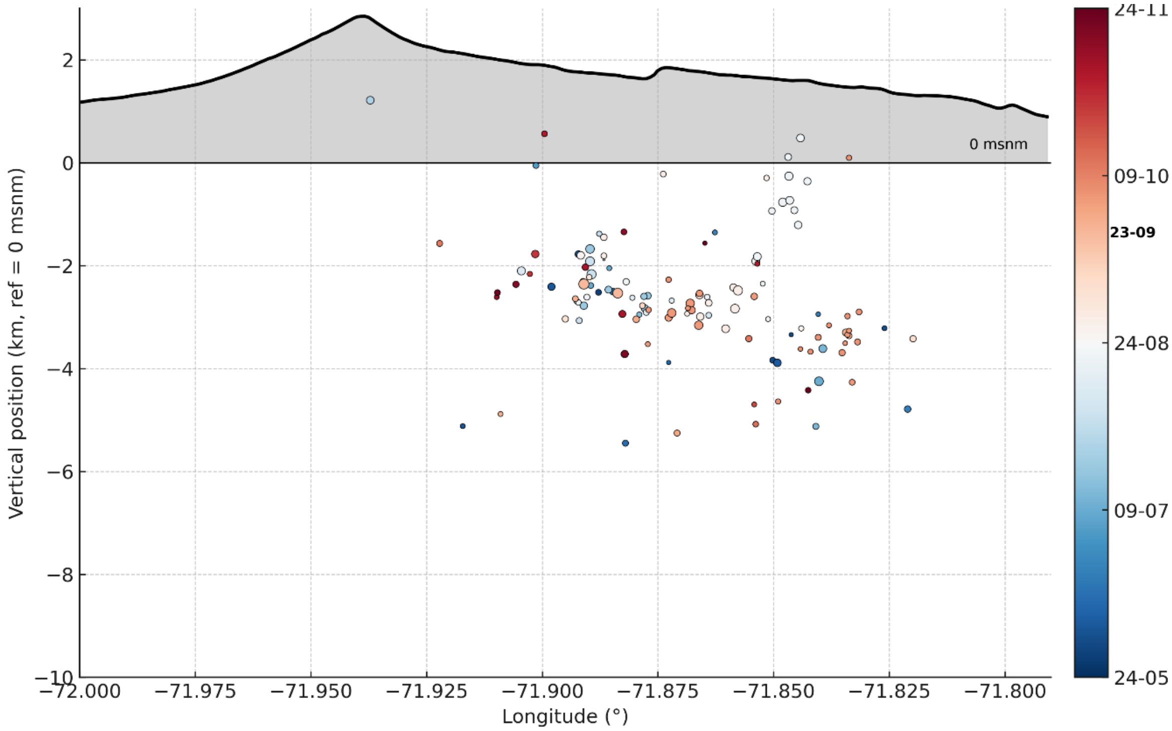

Fig. S21 East–West cross-section of the seismicity associated with Swarm 7 at Villarrica Volcano between 24 May and 29 November 2018. Circles represent hypocenters projected onto an E–W profile, colored according to their occurrence date to illustrate the temporal evolution of the swarm, the date in black indicates the day of the largest earthquake. The upper panel shows the topographic profile of the volcanic edifice along the section line, with elevation referenced to sea level (msnm). The lower panel displays the vertical distribution of seismicity relative to sea level, highlighting the distribution of VT events beneath the eastern sector of the volcanic edifice.

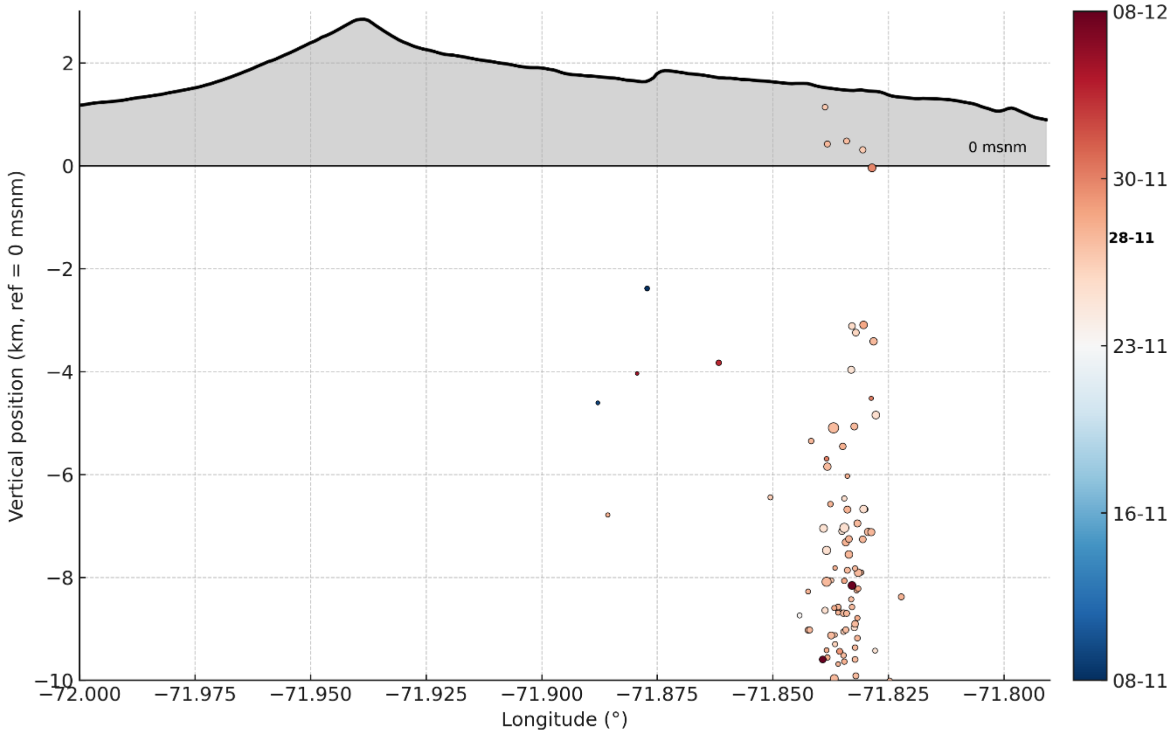

Fig. S22 East–West cross-section of the seismicity associated with Swarm 8 at Villarrica Volcano between 8 November and 10 December 2021. Circles represent hypocenters projected onto an E–W profile, colored according to their occurrence date to illustrate the temporal evolution of the swarm, the date in black indicates the day of the largest earthquake. The upper panel shows the topographic profile of the volcanic edifice along the section line, with elevation referenced to sea level (msnm). The lower panel displays the vertical distribution of seismicity relative to sea level, highlighting the distribution of VT events beneath the eastern sector of the volcanic edifice.

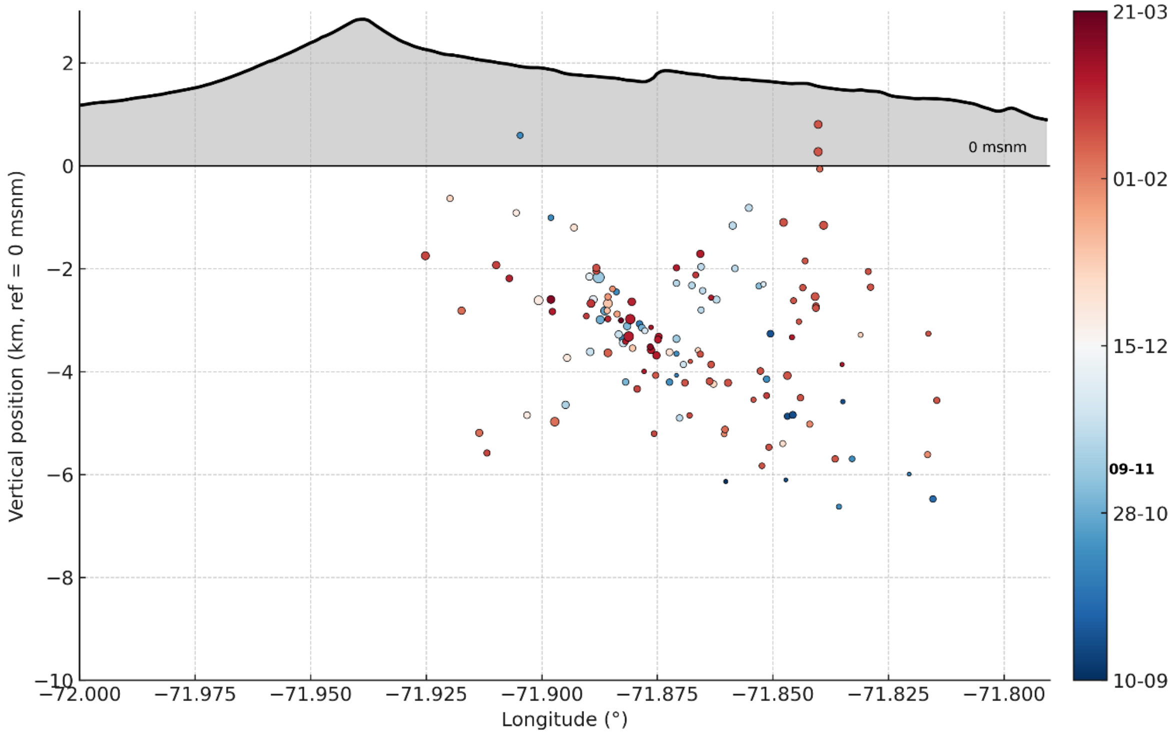

Fig. S23 East–West cross-section of the seismicity associated with Swarm 9 at Villarrica Volcano between 10 September 2022 and 22 March 2023. Circles represent hypocenters projected onto an E–W profile, colored according to their occurrence date to illustrate the temporal evolution of the swarm, the date in black indicates the day of the largest earthquake. The upper panel shows the topographic profile of the volcanic edifice along the section line, with elevation referenced to sea level (msnm). The lower panel displays the vertical distribution of seismicity relative to sea level, highlighting the distribution of VT events beneath the eastern sector of the volcanic edifice.

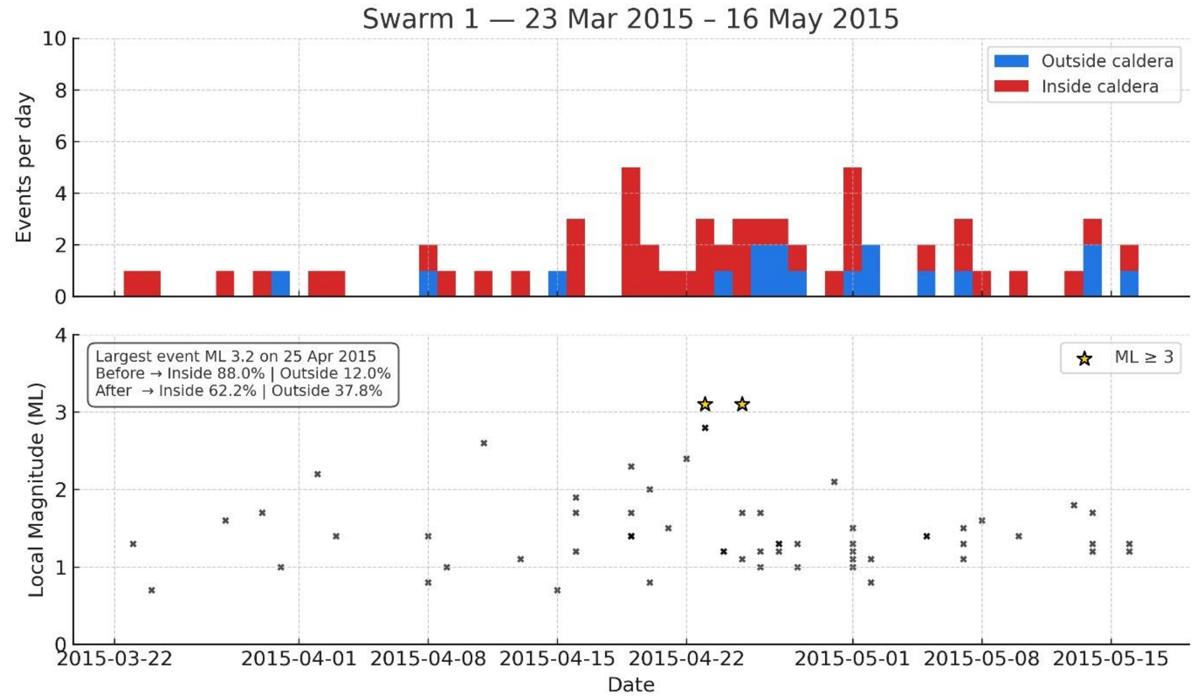

Fig. S24 Temporal evolution of seismic activity during Swarm 1 at Villarrica Volcano between 23 March and 16 May 2015. The upper panel shows the number of VT events per day, distinguishing earthquakes located inside and outside the caldera structure. The lower panel displays the temporal distribution of local magnitudes (ML) for the same period. The largest recorded earthquake of the swarm (ML 3.2, 25 April 2015) is indicated with a star symbol. The inset highlights the proportion of seismicity occurring inside and outside the caldera before and after the largest event, showing a change from 88.0% inside / 12.0% outside before the event to 62.2% inside / 37.8% outside afterward.

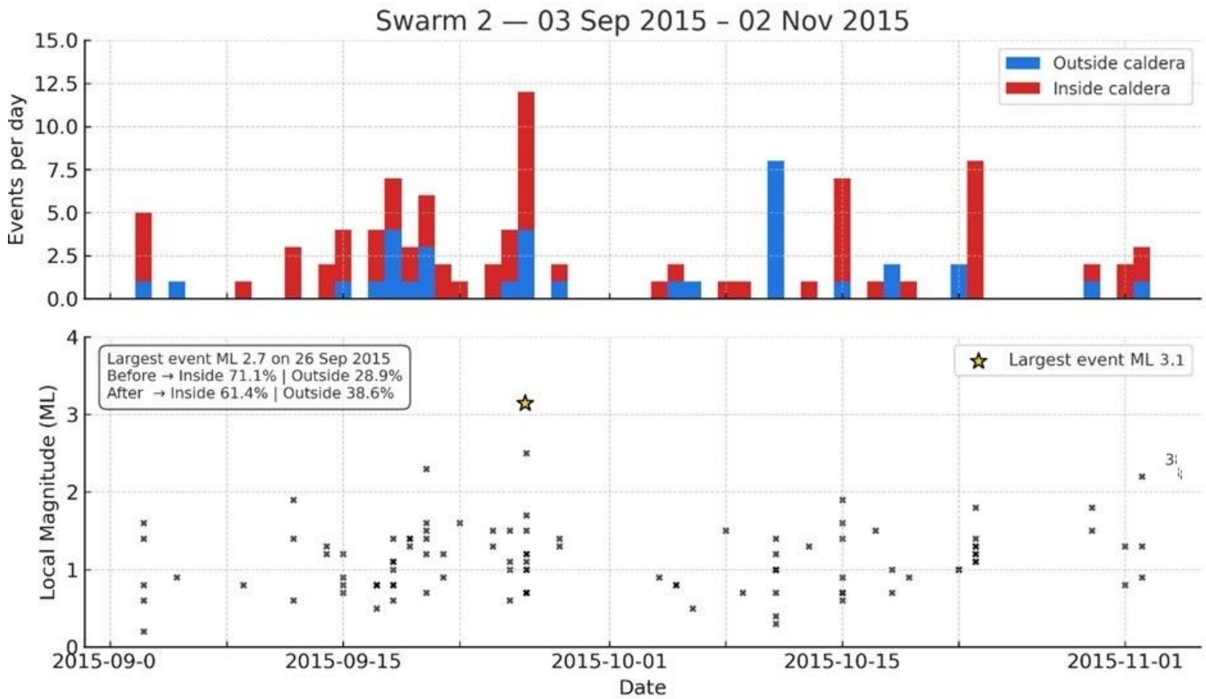

Fig. S25 Temporal evolution of seismic activity during Swarm 2 at Villarrica Volcano between 3 September and 2 November 2015. The upper panel shows the number of VT events per day, distinguishing earthquakes located inside and outside the caldera structure. The lower panel displays the temporal distribution of local magnitudes (ML) for the same period. The largest recorded earthquake of the swarm (ML 3.1, 26 September 2015) is indicated with a star symbol. The inset highlights the proportion of seismicity occurring inside and outside the caldera before and after the largest event, showing a change from 71.1% inside / 28.9% outside before the event to 61.4% inside / 38.6% outside afterward.

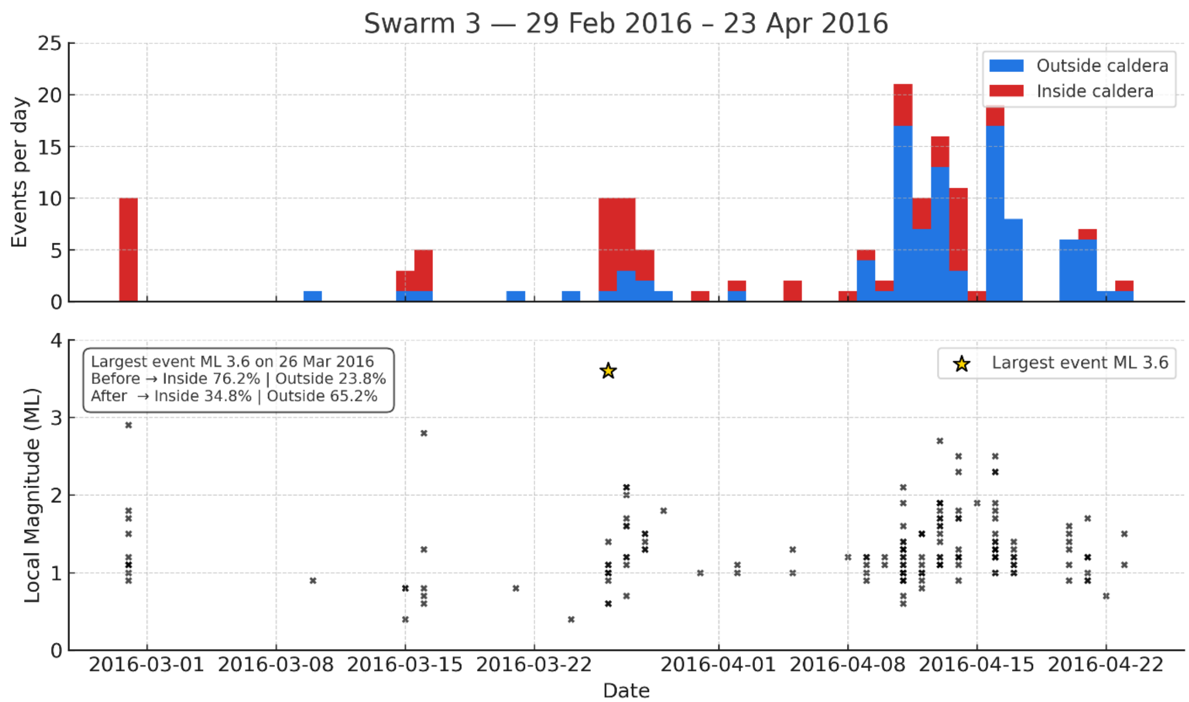

Fig. S26 Temporal evolution of seismic activity during Swarm 3 at Villarrica Volcano between 29 February and 23 April 2016. The upper panel shows the number of VT events per day, distinguishing earthquakes located inside and outside the caldera structure. The lower panel displays the temporal distribution of local magnitudes (ML) for the same period. The largest recorded earthquake of the swarm (ML 3.6, 26 March 2016) is indicated with a star symbol. The inset highlights the proportion of seismicity occurring inside and outside the caldera before and after the largest event, showing a change from 76.2% inside / 23.8% outside before the event to 34.8% inside / 65.2% outside afterward.

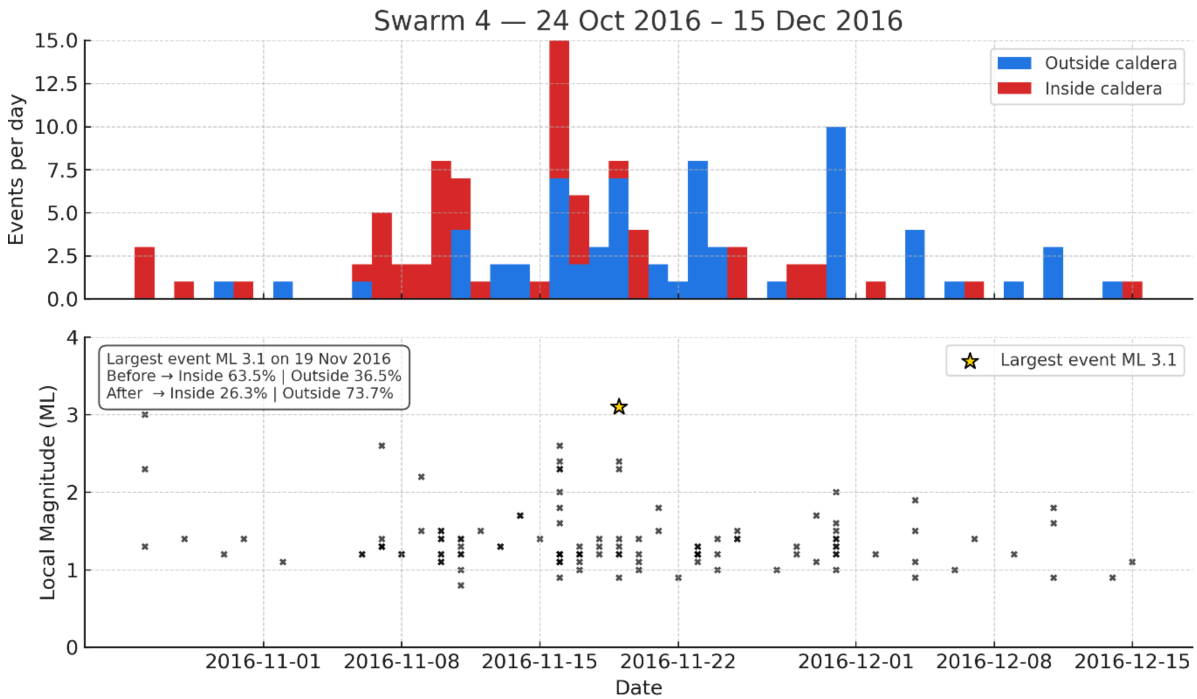

Fig. S27 Temporal evolution of seismic activity during Swarm 4 at Villarrica Volcano between 24 October and 15 December 2016. The upper panel shows the number of VT events per day, distinguishing earthquakes located inside and outside the caldera structure. The lower panel displays the temporal distribution of local magnitudes (ML) for the same period. The largest recorded earthquake of the swarm (ML 3.1, 19 November 2016) is indicated with a star symbol. The inset highlights the proportion of seismicity occurring inside and outside the caldera before and after the largest event, showing a change from 63.5% inside / 36.5% outside before the event to 26.3% inside / 73.7% outside afterward.

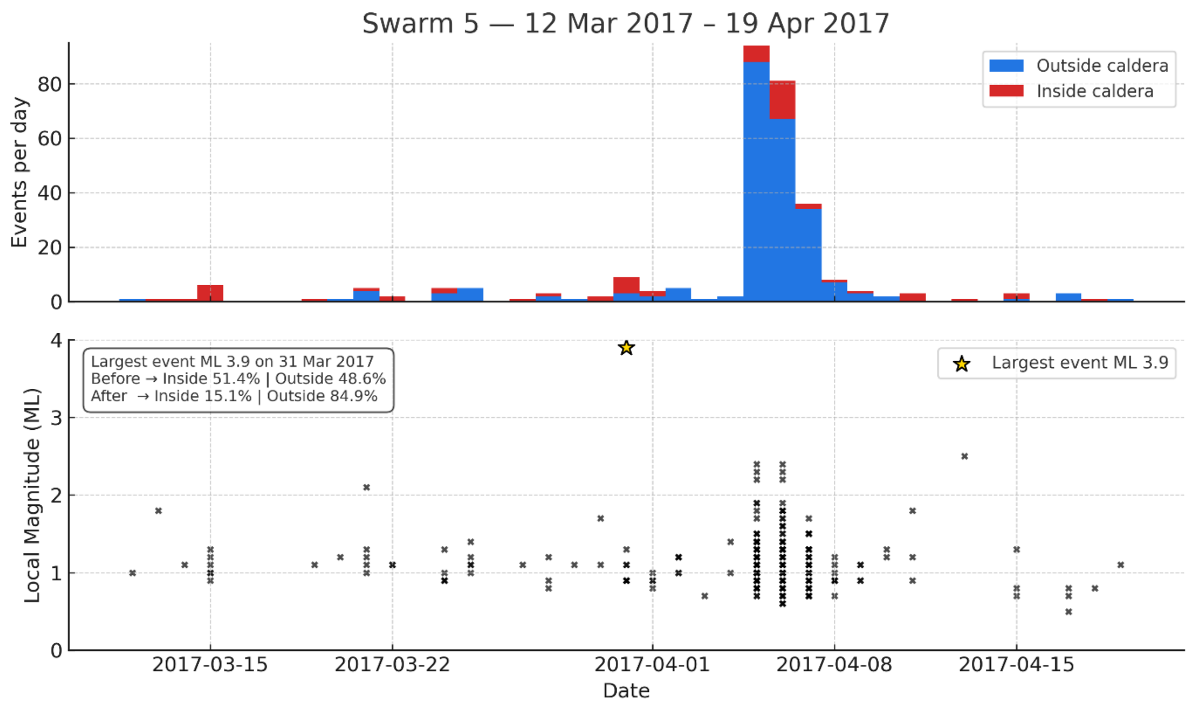

Fig. S28 Temporal evolution of seismic activity during Swarm 5 at Villarrica Volcano between 12 March and 19 April 2017. The upper panel shows the number of VT events per day, distinguishing earthquakes located inside and outside the caldera structure. The lower panel displays the temporal distribution of local magnitudes (ML) for the same period. The largest recorded earthquake of the swarm (ML 3.9, 31 March 2017) is indicated with a star symbol. The inset highlights the proportion of seismicity occurring inside and outside the caldera before and after the largest event, showing a change from 51.4% inside / 48.6% outside before the event to 15.1% inside / 84.9% outside afterward.

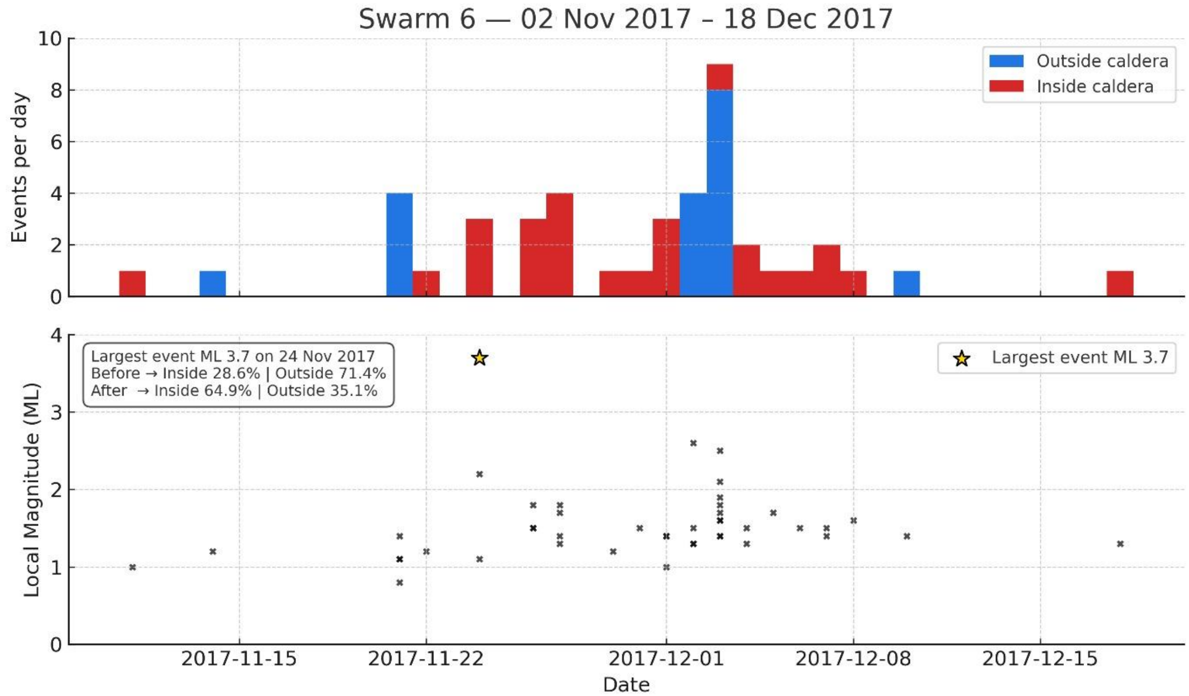

Fig. S29 Temporal evolution of seismic activity during Swarm 6 at Villarrica Volcano between 2 November and 18 December 2017. The upper panel shows the number of VT events per day, distinguishing earthquakes located inside and outside the caldera structure. The lower panel displays the temporal distribution of local magnitudes (ML) for the same period. The largest recorded earthquake of the swarm (ML 3.7, 24 November 2017) is indicated with a star symbol. The inset highlights the proportion of seismicity occurring inside and outside the caldera before and after the largest event, showing a change from 28.6% inside / 71.4% outside before the event to 64.9% inside / 35.1% outside afterward.

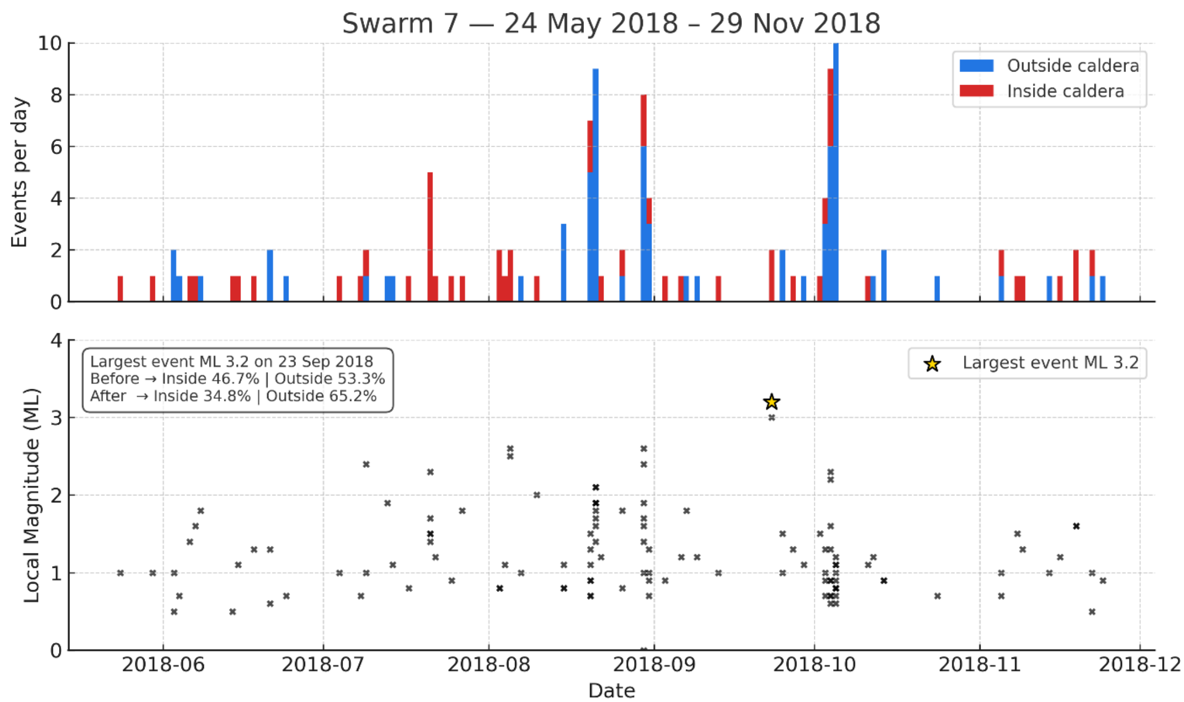

Fig. S30 Temporal evolution of seismic activity during Swarm 7 at Villarrica Volcano between 24 May and 29 November 2018. The upper panel shows the number of VT events per day, distinguishing earthquakes located inside and outside the caldera structure. The lower panel displays the temporal distribution of local magnitudes (ML) for the same period. The largest recorded earthquake of the swarm (ML 3.2, 23 September 2018) is indicated with a star symbol. The inset highlights the proportion of seismicity occurring inside and outside the caldera before and after the largest event, showing a change from 46.7% inside / 53.3% outside before the event to 34.8% inside / 65.2% outside afterward.

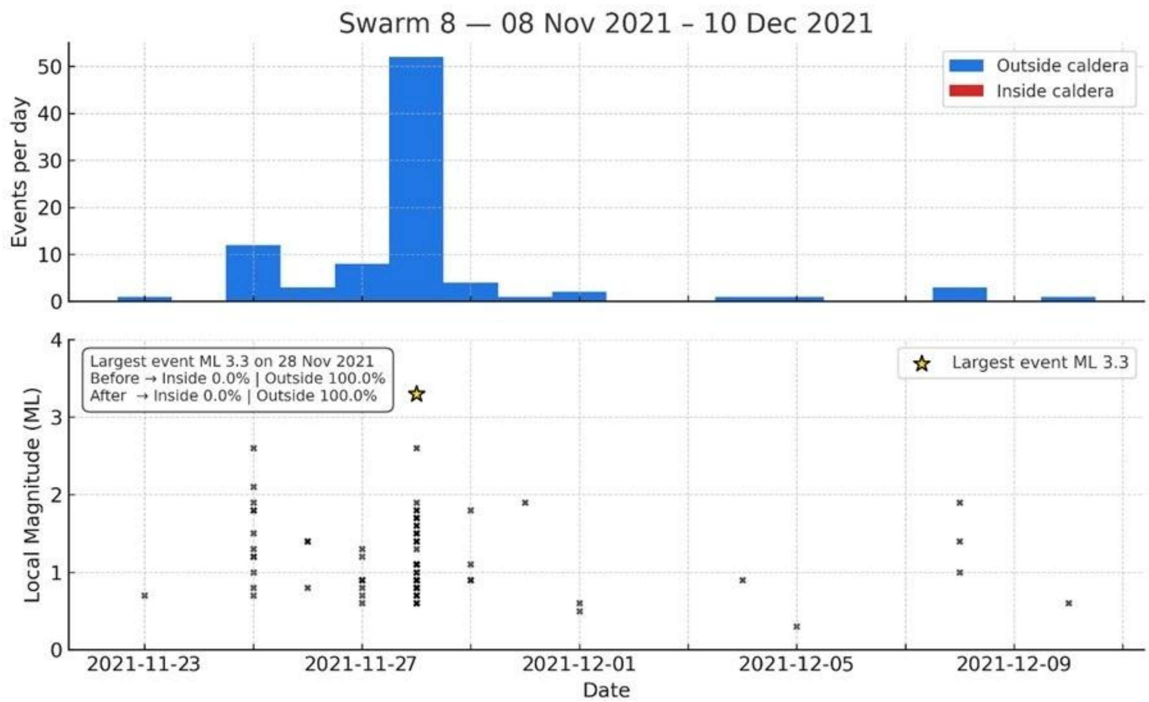

Fig. S31 Temporal evolution of seismic activity during Swarm 8 at Villarrica Volcano between 08 November and 10 December 2021. The upper panel shows the number of VT events per day, distinguishing earthquakes located inside and outside the caldera structure. The lower panel displays the temporal distribution of local magnitudes (ML) for the same period. The largest recorded earthquake of the swarm (ML 3.3, 28 November 2021) is indicated with a star symbol. The inset highlights the proportion of seismicity occurring inside and outside the caldera before and after the largest event, showing that 100% of the events occurred outside the caldera both before and after the largest earthquake.

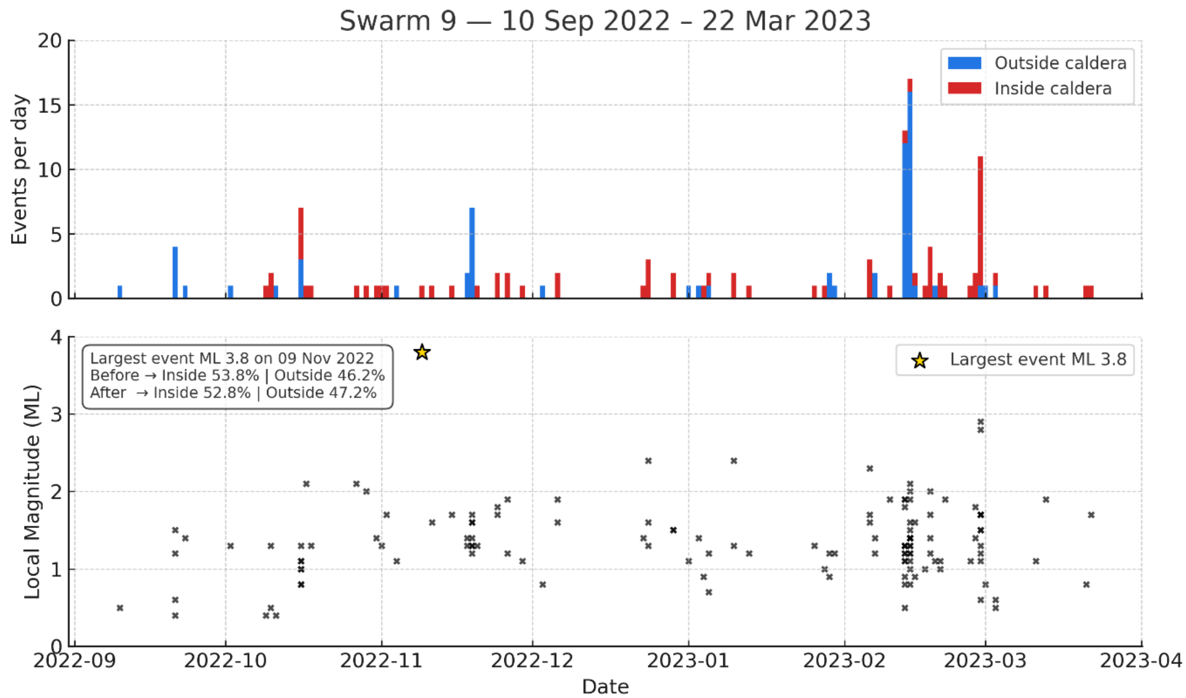

Fig. S32 Temporal evolution of seismic activity during Swarm 9 at Villarrica Volcano between 10 September 2022 and 22 March 2023. The upper panel shows the number of VT events per day, distinguishing earthquakes located inside and outside the caldera structure. The lower panel displays the temporal distribution of local magnitudes (ML) for the same period. The largest recorded earthquake of the swarm (ML 3.8, 9 November 2022) is indicated with a star symbol. The inset highlights the proportion of seismicity occurring inside and outside the caldera before and after the largest event, showing a slight variation from 53.8% inside / 46.2% outside before the event to 52.8% inside / 47.2% outside afterward.