Biennial report for Permanent Supersite/Natural Laboratory

GeoHazSA: Southern Andes Supersite

Coupled geohazards at Southern Andes: Copahue-Lanín arc volcanoes and adjacent crustal faults

https://geo-gsnl.org/supersites/permanentsupersites/southern-andes-supersite/

2. Scientists/science teams

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3. Research Results 2022-2023

Research Products

Pleaides imagery

Volcano	Request Date	Acquisition date	characteristics	Area (km2)	Total (km2)
Villarrica	22-12-2022	07-02-2023	stereo	100	200
	22-12-2022	11-03-2023	stereo	100	200
	17-05-2023	Not Processed	-	-	-
	14-09-2023	Not Processed	-	-	-
	24-11-2023	04-12-2023	tri-stereo	100	300
Llaima	14-02-2022	12-03-2022	stereo	100	200
	24-11-2023	04-12-2023	tri-stereo	100	300

Table1. Dates of request to CNES for Pleiades imagery, acquisition, and characteristics. Those requested but not processed, were not processed by CNES during the time established in the form request.

These images are an excellent tool for monitoring purposes and hazard assessment. The quota assigned was 1.200 km^2 per year, and this year was used completely; images in mono, stereo and tristereo mode were requested for Villarrica (the most active volcano in Chile, 1st in volcanic risk ranking 2023) and Llaima (3rd in volcanic risk ranking 2023) volcanoes and were used for 1) Volcano monitoring: mapping products, describe geological features changes and build Digital Elevation Models (DEM) for measuring topographic changes and 2) Hazards evaluation and modelling and mapping historical volcanic products with a better resolution than obtained from another sources.

During 2022 Pleaides images allowed to build DMSs (digital surface models) and DEMs (Digital Elevation Models) made by the Remote Sensing team (Sernageomin, Santiago) using Catalyst software Demo version, with no issues, and since the high resolution of images was possible adjust the models despite not having terrain control points. During 2023, a training to learn how to process these products with AMES Stereo Pipeline (ASP) was conducted by experts from Volcano Assistant Program (VDAP), and since then ASP has been used at OVDAS by the geology/geodesy teams to process the stereo or tristereo pairs to obtain DEMs and support monitoring.

During December 2022, aerial photographs were taken, and used to build a DEM using Agisoft Metashape. This model was used to compare with DEMs obtained from Pleaides images.

3.1 Volcano Monitoring

Villarrica volcano

The inputs provided by the SuperSite project for Villarrica volcano have facilitated the characterization and monitoring of the volcano surface activity, which is fundamental for scenario construction during the volcanic crisis occurred between November 2022 and March 2023 (figure 1). During the crisis, characterized by strombolian activity and gaseous and pyroclastic emissions, the material provided by SuperSite allowed us to define the reach of proximal and distal deposits,

which in turn is necessary for the zoning of volcanic hazards and risk management in charge of SENAPRED and authorities.

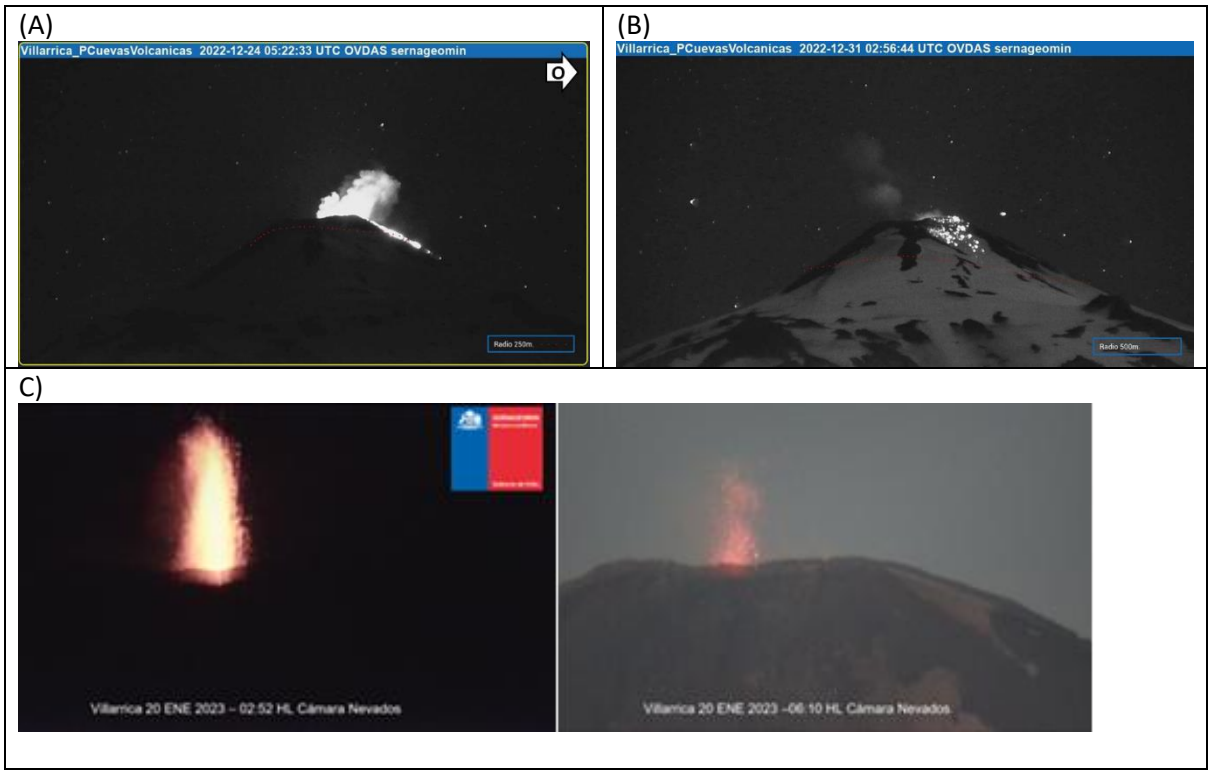

Figure 1: Images from surveillance cameras at Villarrica volcano. (A) Dec-24th-2022: North view of the active crater. Strombolian activity characterized by explosions up to 100 m above the crater level and the emission of ballistic pyroclasts with a maximum range of 330 m to SW. (B) Dec-31st-2022: Northeast view. Emission of incandescent pyroclastic material towards the NW slope are observed. (C) Jan-20th-2023 View from West. High energy strombolian explosions occurred this day, the scope of this activity was characterized with Pleaides imagery of Feb 7th.

- **Pleaides stereo pair, February 7th, 2023.**

Products built from Pleiades images for Villarrica volcano: Photo-interpretation of the crater rim, structures and vents to the left, and contour lines to determine depth of the lava lake (figure 2) and mapping of pyroclastic products (figure 3).

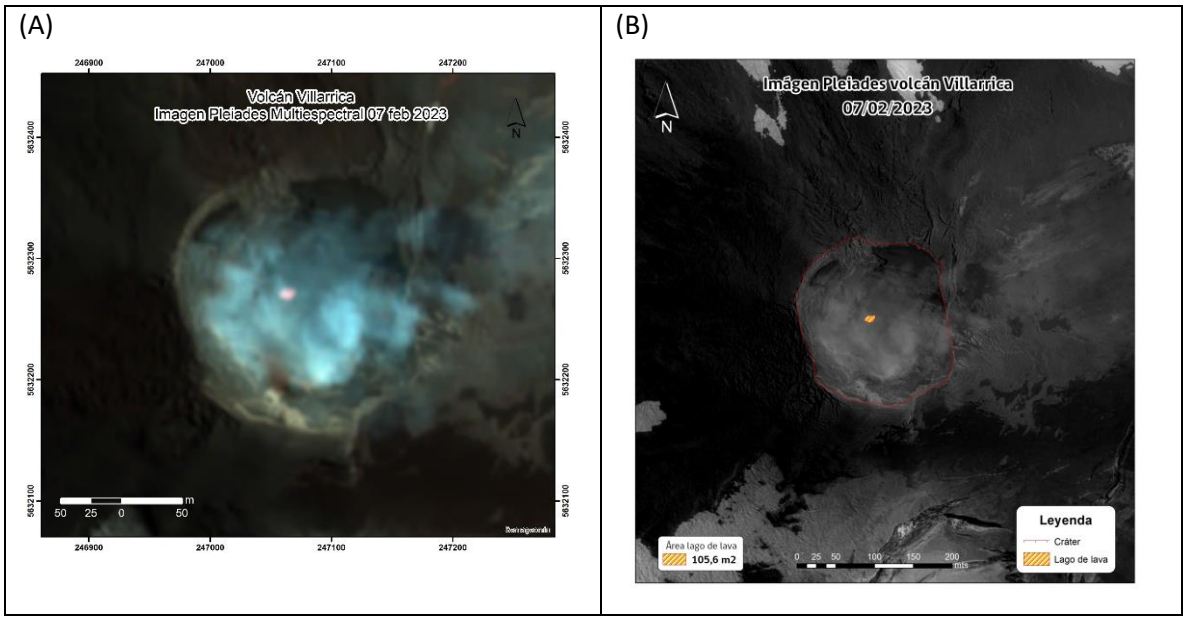

Figure 2: Villarrica volcano image Pleiades of February 7, 2023 (A) Multispectral image and (B) Panchromatic image. Area of lava lake: 105 m^2.

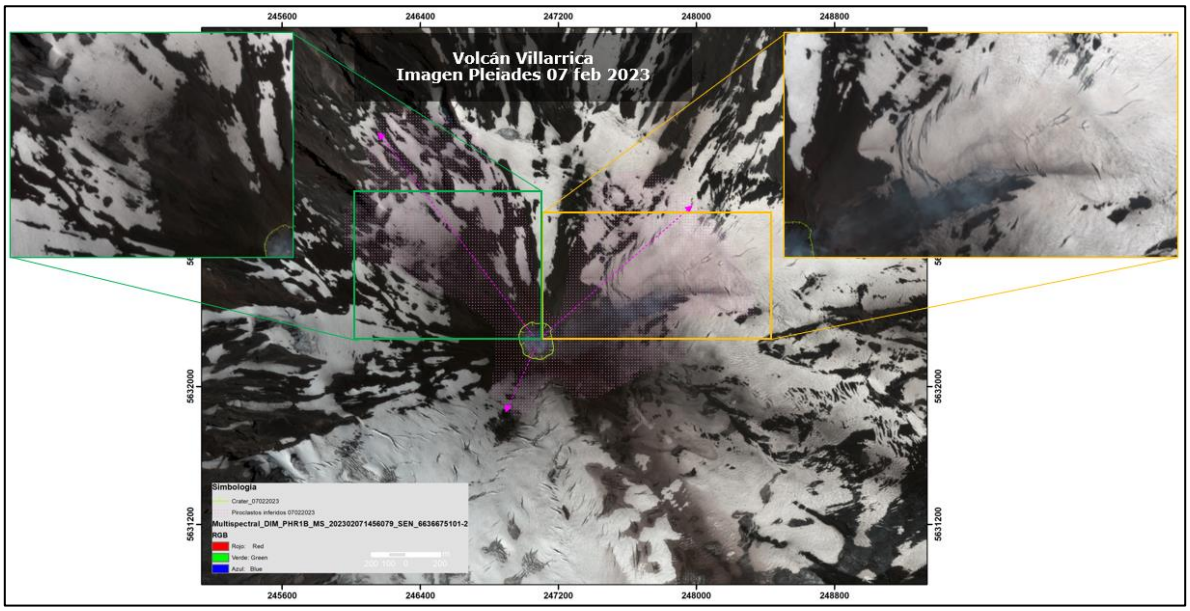

Figure 3: Villarrica volcano image Pleiades February 7th, 2023, extent and distribution of pyroclastic fall deposits. NE of the crater: area of pyroclastic fall deposits (fine ash), matching the column dispersion direction at that time, with a maximum range of 1.2 km. NW: area of pyroclastic deposits inferred from snow texture, with estimated range of 1.1 km (including post-impact displacement). SW: fall deposits (spatters and ballistics), some with post-impact displacement evidenced by snow footprint, with a maximum range <500 m. SE: area affected by pyroclastic fallout occurred before the evaluated period.

DEM generation and analysis

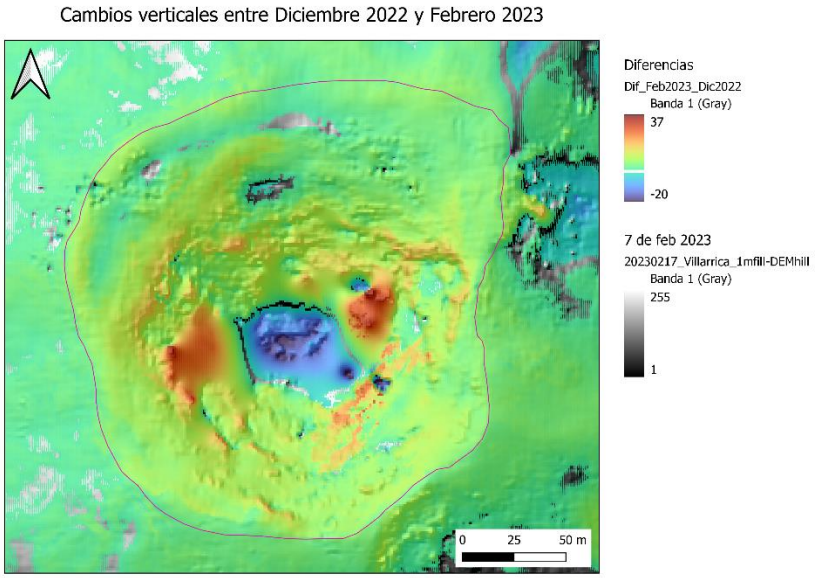

Figure 4. Vertical displacement between December 2022 and February 2023 images (meters).

- **Pleaides stereo pair, March 11th, 2023**

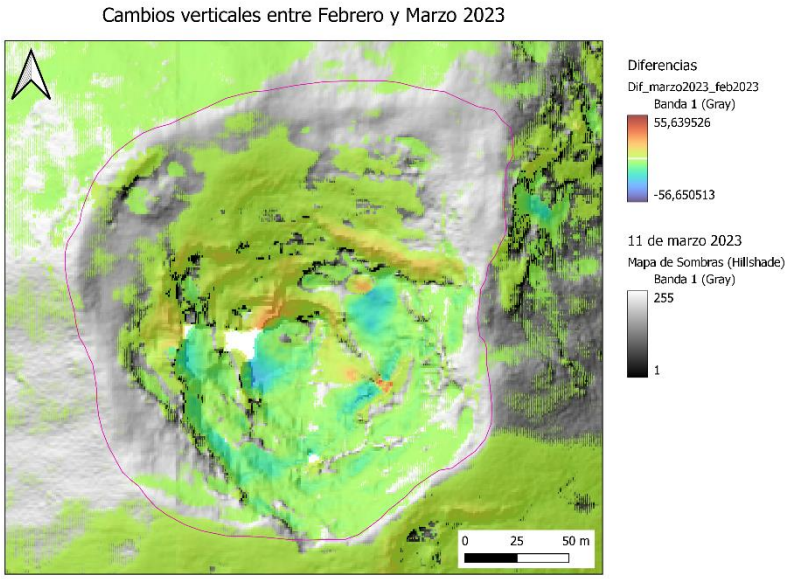

Figure 5. Vertical displacement between February 2023 and March 2023 images (meters).

A comparison of DEMs from February and March 2023, covering the Villarrica volcano crater area, shows a vertical displacement at the center of the crater bottom, coincident with the lava lake location (figure 5). Pyroclastic accumulation levels around the lava lake can also be identified.

A comparison of two DEM dated February 07, 2023 and March 11, 2023, built from Pleaides imagery, showed a 23 m rise of the crater bottom at Villarrica volcano. This result was consistent with material accumulation inside the crater due to several strombolian explosions. The use of these DEM allowed us to quantify this and other morphology and volumetric changes at the crater.

- **Pleaides tri stereo acquisition, December 4th, 2023**

These acquisitions allowed to characterize the crater morphology at a high-detail level. The lava lake was measured to be at 90 m below the west crater rim, and 25 m below the spatter terrace right at the west of the lava lake. The Pleiades pancromatric image captures the moment when pyroclastic material is thrown out of the vent, 45 m above the lava lake.

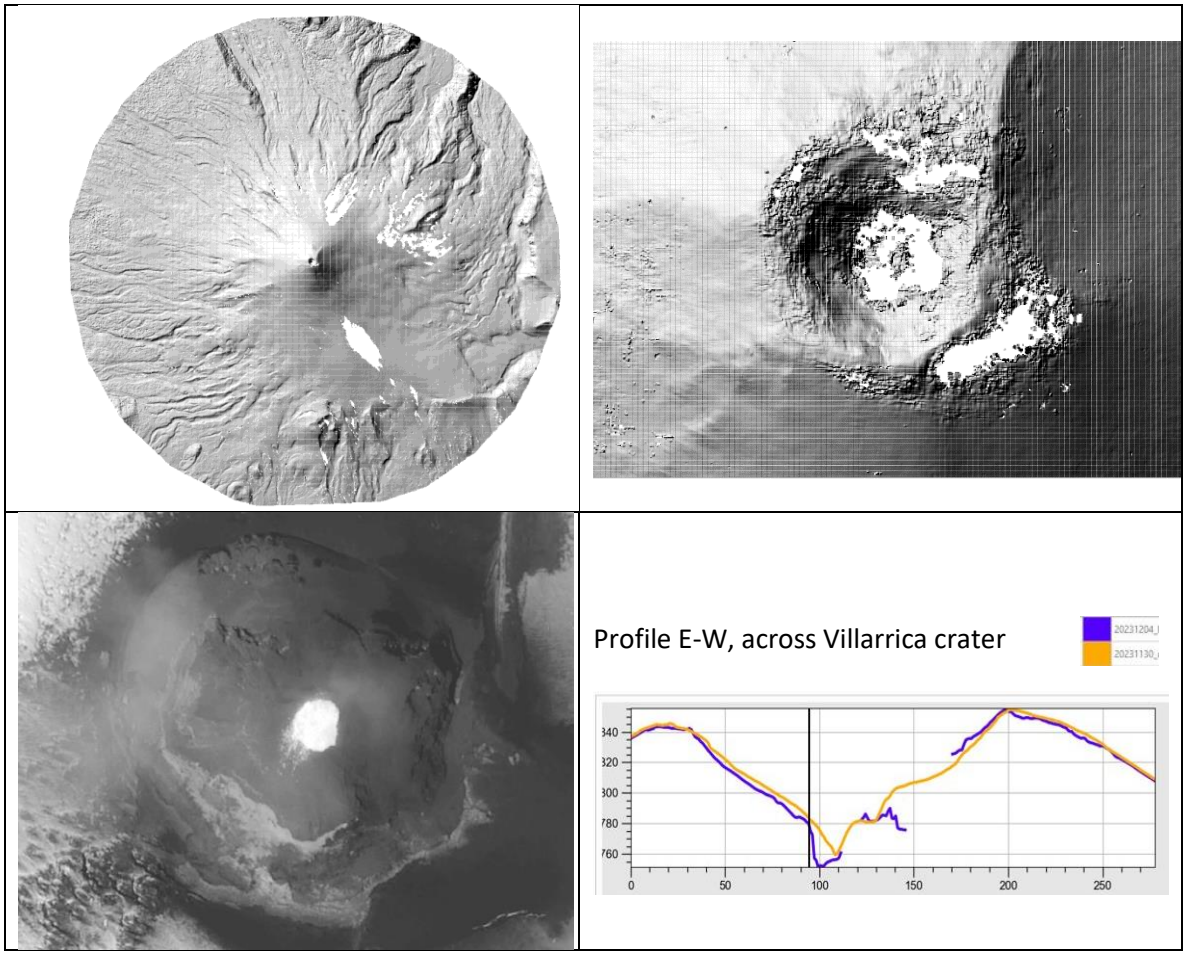

Figure 6. Up, DEM images built from Pleaides tri stereo December 4th, 2023 (zoom to crater area on the right). Down-left: Zoom to the lava lake, where is possible to see explosive activity and spatters distribution. Down-right: E-W profile at the crater, highlighting the crater internal shape.

Llaima volcano

- **Pleiades March 12, 2022**

The Llaima volcano is ranked 3rd in the volcanic risk ranking of active volcanoes in Chile, defined by Sernageomin in 2023. Its western, southwestern and eastern flanks are covered by about 29 km2 of glaciers. Its massive volcanic edifice has a general conical shape with steep areas around the summit; however, it consists of two main peaks and about 40 adventitious emission centers. The northern summit exhibits an open crater 350 m in diameter and more than 300 m deep, while the southern summit presents remains of a small cinder cone nested in an obstructed crater of about 200 m. The volcanic products generated by the Llaima volcano are mainly basalts and basaltic andesites. Additionally, it is located within the Conguillío National Park, one of the most important tourist development poles in southern Chile.
Its historical eruptive record includes 48 documented events between 1640 and 2009, during which the emission of lava flows, the formation of lahars, the projection of pyroclasts and, occasionally, the generation of pyroclastic flows occurred. Its last eruptive cycle began in May 2007 with a weak emission of ash that was followed by various episodes of moderate and vigorous Strombolian activity that occurred during the years 2008 and 2009.

Stereo Pleiades imagery was used to build two DEMs for Llaima volcano (figure 7 and 8). These are the first high-resolution DEMs that our observatory has and will serve as a reference DEM to compare with in the future. It will also serve for modelling near and proximal volcanic products, which is essential for risk management. In addition, DEM complements multi-spectral imagery to increase confidence at photo interpretation. Both DEMs cover the same area, but we hope to cover a bigger one, using new acquisitions.

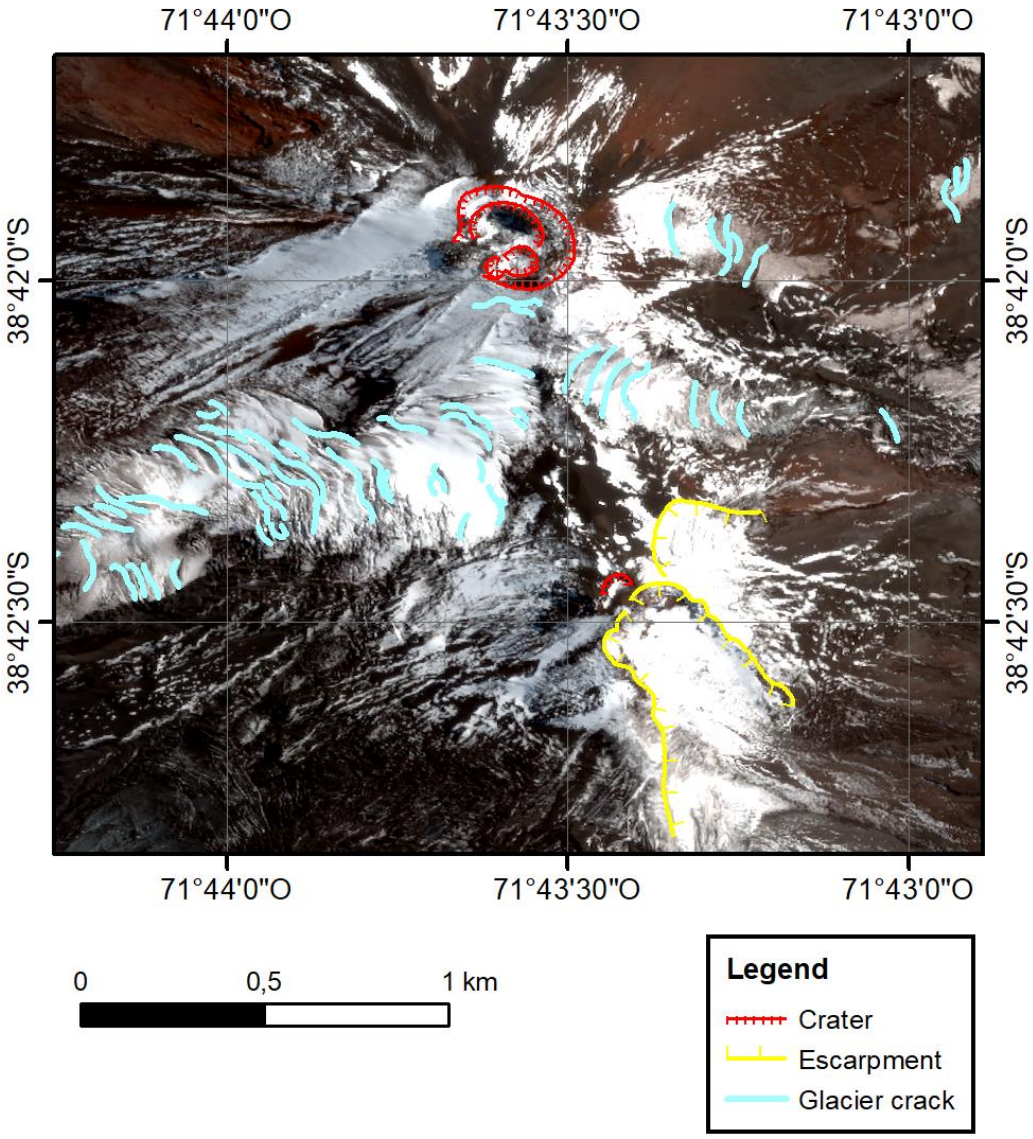

Figure 7. March 12, 2022, Pleiades image. Craters, escarpments, and glacier cracks were identified in this image.

We observe some problems in the resulting DEM (particularly, holes in the crater and flank that could be partially filled by interpolation, figure 8). According to CNES experts, this problem could be addressed by using a tri-stereo acquisition, which was already requested to CNES.

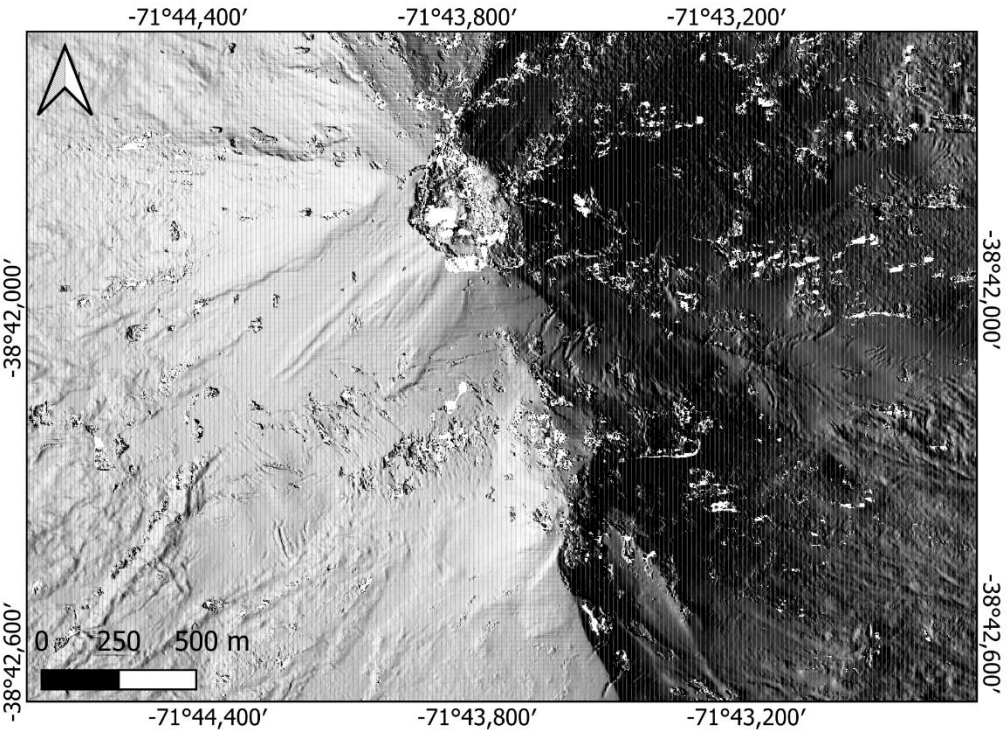

Figure 8. March 12, 2022, DEM Llaima volcano.

- **Pleaides tri stereo acquisition, December 4th, 2023**

A new Llaima DEM was generated from a tri stereo acquisition, as recommended by CNES (Figure 9). The obtained DEM presents problems, in spite of being generated from tri stereo images, unlike the March 12th, 2022 DEM. This problem is attributed to a very recent snow cover occurred hours before the images acquisition, very unexpected for this time of the year.

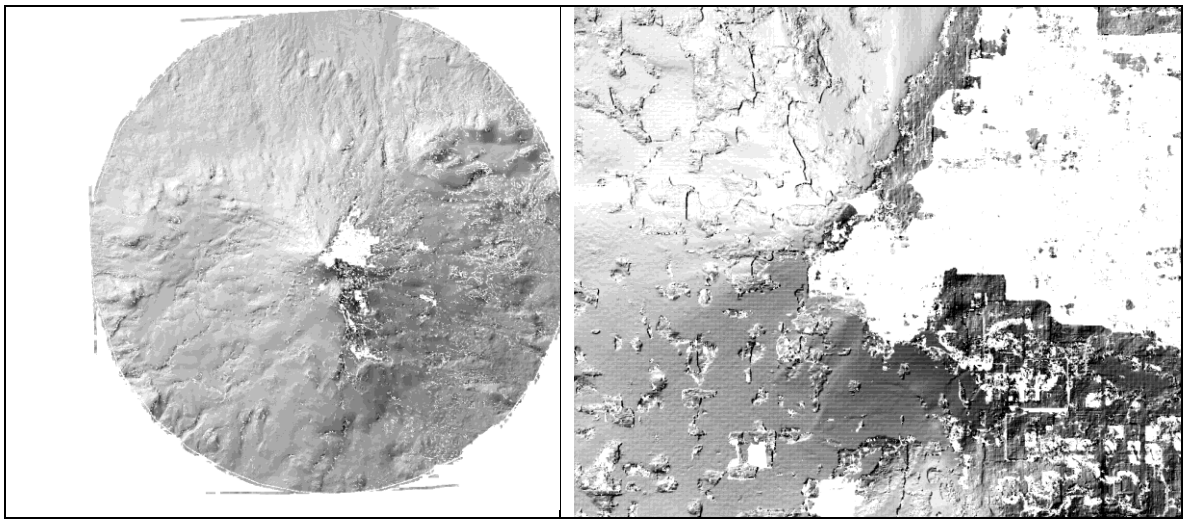

Figure 9. December 04, 2023 DEM Llaima volcano. Total area to the left and zoom to the crater to the right.

3.2 Hazards evaluation and historical lavas

A thesis work was conducted contrasting size and volume of historical products in Llaima and Villarrica volcanoes against published data, in order to re-calculate eruptive parameters as effusion rate. This study was made by Catalina Mellado, from Universidad de O'Higgins to become a Geological Engineer, who used the software Q-LavHA to model lava flows emitted during historical times.

Finally, the Volcano Hazard Team has been working new models of "High resolution volcanic hazards maps" to update the hazard maps of Villarrica and Llaima volcanoes using high resolution DEMs made from Pleaides images. We started using the DEM on Villarrica, with Pleaides images acquired during the previous period, 2020, covering an area of 250 km2 approximately of the north flank of the volcano. This work consists of an objective evaluation of the volcanic hazard in the current geographical context to determine the areas of susceptibility to volcanic processes in different scenarios. It is based on the historical eruptions, the projection of future eruptions and the evaluation and mapping of the different volcanic deposits and products as lahars and lava flows, with a much better resolution than previous hazard maps, and in parallel and complementary, numerical modelling. Most of the used models are implemented over the topography, which must faithfully represent geomorphological features and water networks for achieve reliable results. In this sense, the availability of high-resolution terrain (or surface) models (better than 1 m) constitutes a key input for the evaluation of objective dander and at scale compatible with territorial planning instruments (Figure 10). The "Microzoned Hazard Assessment Map of Pucón, scale 1:25000" was created for Pucón, near to Villarrica volcano, will be published during 2024 and share with community and authorities. This map will be used by authorities and decision makers in emergency situations as a territorial planning tool.

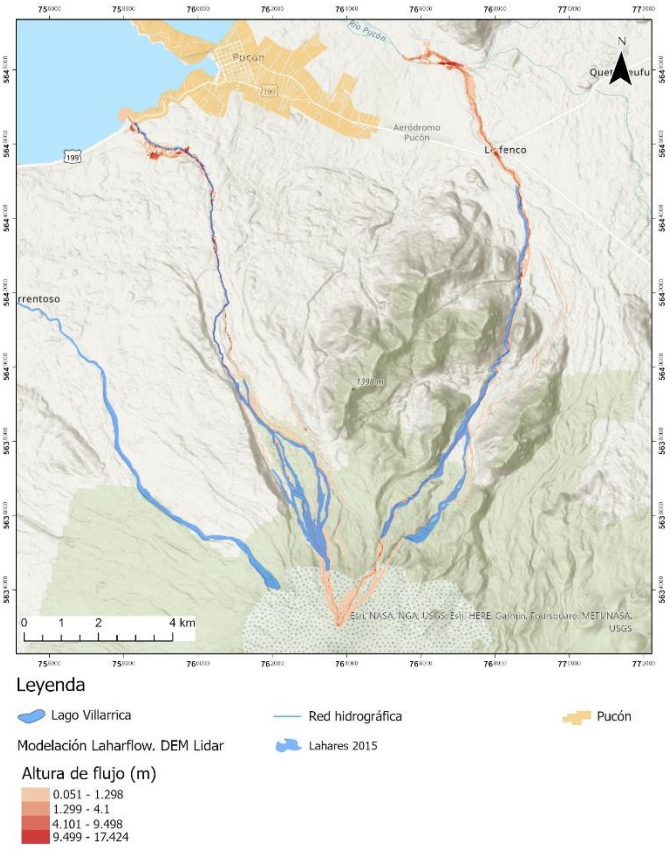

Figure 10. Lahar heights modelled for the north flank of Villarrica volcano, one the products created from high resolution DEM, used for the new detailed hazards maps for Pucón area (in yellow).

Imágenes RADAR: TerraSARX -CosmoSkyMed- SAOCOM

3.3 InSAR studies and related topics

According to the working plan, PhD student (Luis E Lara, advisor) at Universidad de Concepción (Fernanda López) is close to finish her study and results have been published in López et al. 2022, with a second article under review. The first article proposed a method to tackle with the automatized correction of the troposphere effect; the second is a case-study where the correction is used to exemplify the value of having a good estimator in order to avoid contradictory interpretation of the deformation, especially for low-rate processes.

3.4 Monitoring deformation by InSAR and SAR amplitude

TerraSARX images were used to monitor the deformation contrasting interferograms made with Sentinel 1 images above Villarrica (figure 11) and Copahue area, mainly. The frequency of the images is lower than Sentinel, and usually we don't use this technique during the winters since the correlation is too poor. We had checked changes in amplitude around the crater by simple eye inspection, and we think they are a good tool for monitoring bigger changes (not only inside the crater), than we have monitored by Pleaides imagery.

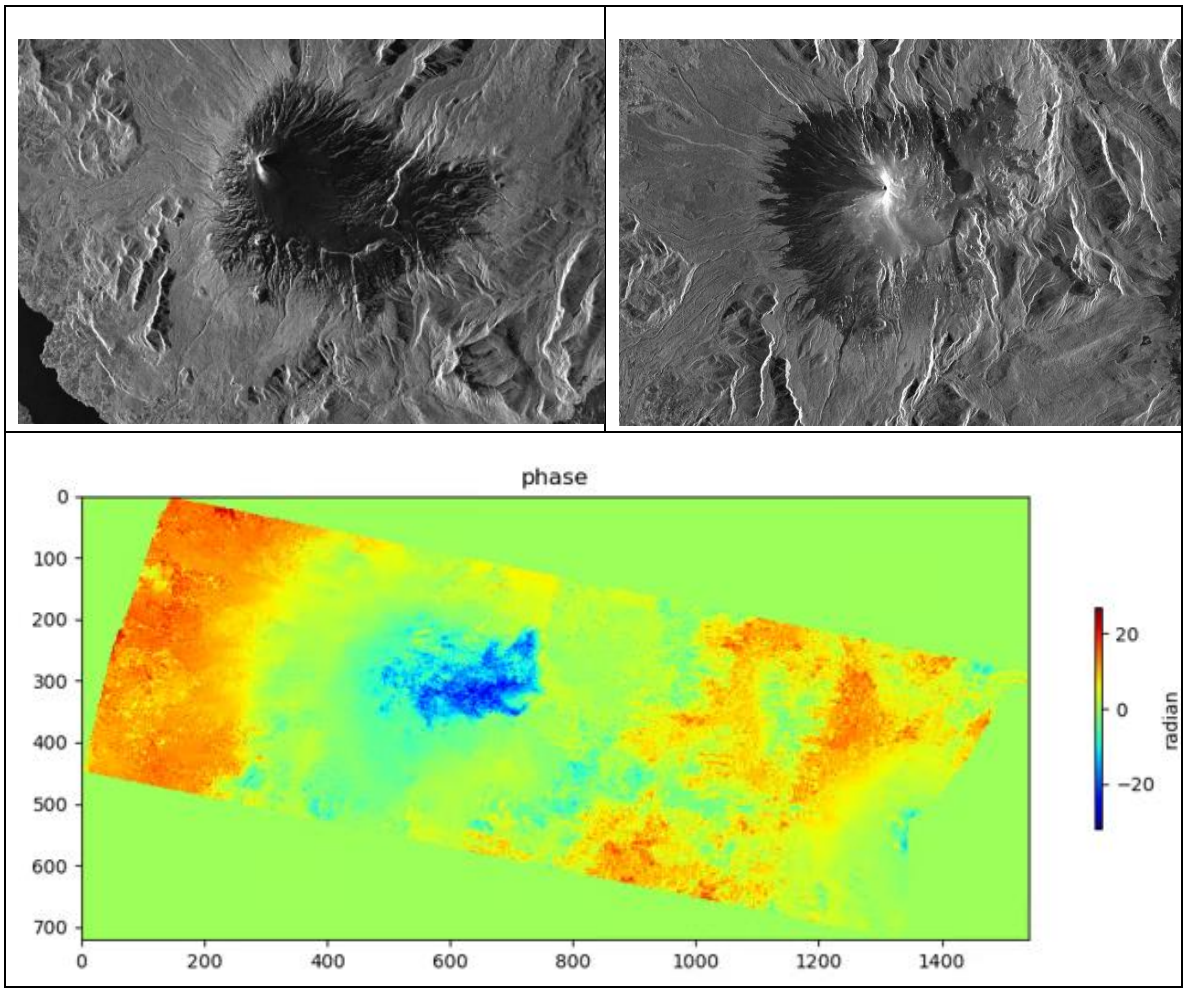

Figure 11: TerrazSARX amplitude images over Villarrica volcano in descending (left) and ascending (right) orbits. The descending image was used to create a 7 months interferogram between March 23th, 2023 and November 17th 2023, showing no deformation during this period, in agreement with GNSS data.

Research product issues

Pleaides

During this period was possible to have a better communication with CNES, since we were aware about the time response and how to ask and fill the request forms. During 2023, was possible to use all the quota assigned. We noticed a positive change in time response during the last request (November-December 2023), but during the previous months and most of 2022, some requests even were not processed, not having answer about them from CNES (table 1).

We have had prioritized acquisition over crater areas for monitoring recent activity. The quota of 1200 km2 is small, considering the need of DEMs covering big areas with good resolution for hazard maps, since the most relevant is the topography of rivers and strings of water until the populated areas which are the main paths for Lahars and lava flows. So far, we only had covered

the north flank of Villarrica volcano (towards Pucón town, the most populated city in the rea), but according to our estimation we would need to cover at least 250 km2 more in the south flank (500 km2 in quota, for a stereo acquisition) to cover rivers and lahars paths to Coñaripe town. Also a DEMS covering a minimum area of 400 km2 for Llaima volcano will be needed to create similar results to Villarrica volcano (1200 km2 in tri-stereo mode, ideal area in figure 12).

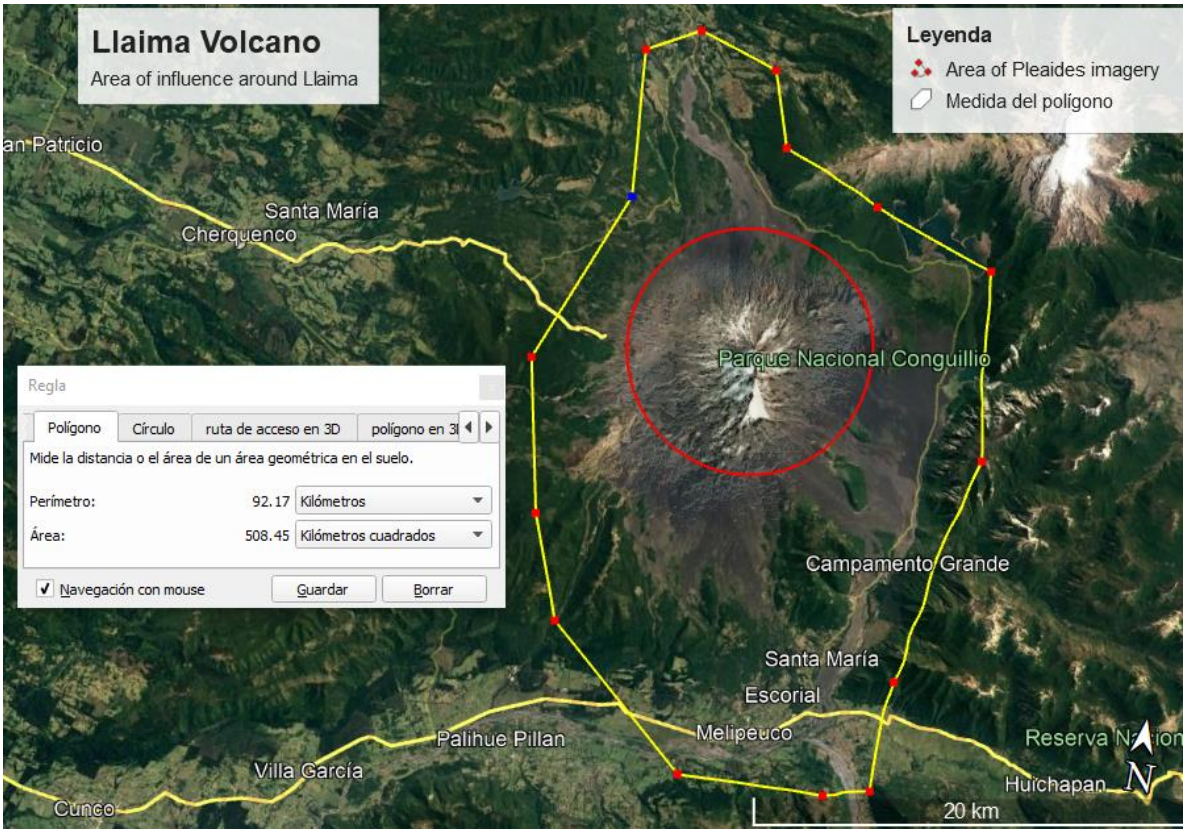

Figure 12: Google Earth image over Llaima volcano, the red circle shows the 100 km2 area covered by Pleaides request and the polygon in yellow shows the area that cover recent lahars and lava flows and main rivers, ideally to modelling volcanic products in this area for management risk purposes according to the Volcano Hazards team.

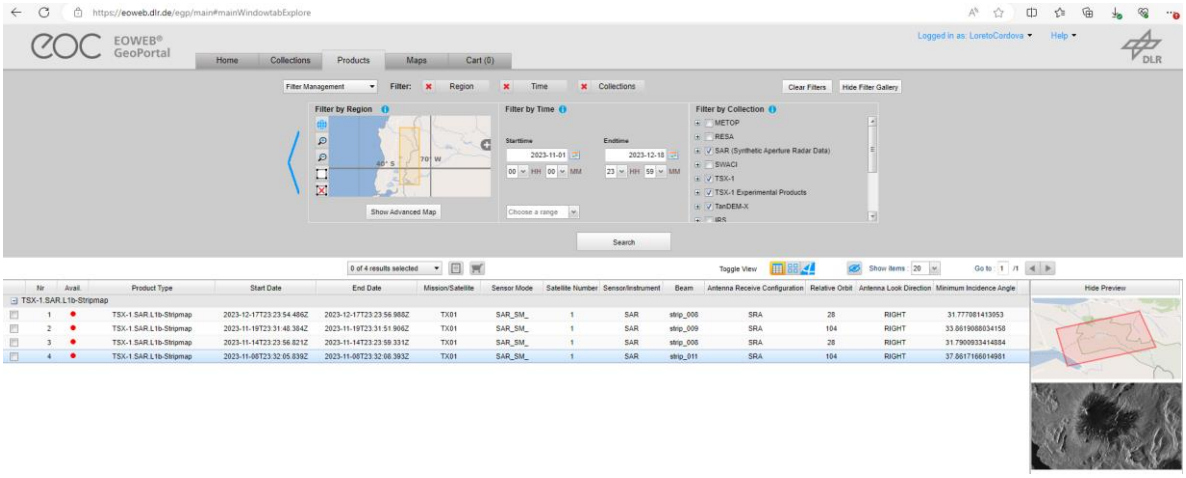

Figure 13: DLR portal of images, showing the availability of images for the entire Supersite area for the last months (before November volcanic areas were still covered by snow). Images are available above Villarrica and Copahue volcanoes.

4. Dissemination and outreach

Fernanda López-Pozo, Rodrigo Abarca del Rio, Luis Lara, 2022; ADTC-InSAR: a tropospheric correction database for Andean volcanoes. Sci Data 9, 526 (2022).https://doi.org/10.1038/s41597-022-01630-w

Catalina Pía Mellado Campos, 2022. Obtención de parámetros eruptivos de las coladas de lava asociadas a las erupciones históricas de los volcanes Villarrica y Llaima (regiones de La Araucanía y Los Ríos, Chile) para la evaluación de peligros volcánicos. Thesis, Geological Engineer degree. This thesis is available on internet, and can help to understand better the distribution and scopes of volcanic products of these volcanoes, improving the geological maps available.

“Microzoned Hazard Assessment Map of Pucón, scale 1:25000” is its final process for publication, and should be available to distribution during 2024 to decision maker during emergencies, community and authorities.

5. Funding

No additional funding was used.

6. Stakeholders interaction and societal benefits

Villarrica volcano has been under yellow alert of activity most of the year, for this reason, meetings each 2 weeks are sustained by the monitoring and volcanic hazard teams. Conclusions are communicated to authorities by virtual or presential meetings, to clarify any concerns or doubts about the level of activity of the volcano. Also the resume of the activity during those 2 weeks is communicated to local population and general public by reports (RAV, Reporte de Actividad Volcánica) published in our webpage (https://rnvv.sernageomin.cl). Deformation and

morphological changes, volcanic products distributions are explained in these reports, and especial reports if activity increases. Pleaides imagery, along with our surveillance cameras, allow to monitor the scope of the volcanic products, proximal and distal deposits, which permits to SENAPRED to stablish zones of potential risk and therefore restrict access to high-risk areas around the crater to people and tourists who climb the volcano.

7. Conclusive remarks and suggestions for improvement

Supersite products are extremely useful and valuable tools for monitoring deformation and morphological changes and improve other geological and mapping products that can help to authorities take better decision in the territory with a direct impact to people during emergencies.
Slowly the teams working with these products have developed strategies to process and evaluate the information that can be obtained from these resources and also got trained to made new products from the radar and optical images by ourselves (DEMs, and interferograms, for example).
As it was explained before, an increase of the quota of Pleaides imagery would help to continue the work related to evaluation of volcanic products and risk management in Llaima and Villarrica volcanoes, among the most dangerous and risky volcanoes in the country.
An improve of the temporal revisit for TerraSAR-X images would be beneficial to include interferograms of these satellites in the monitoring of deformation.
A repository (sftp) to download CosmoSkyMed images is needed, and part of the Information Technology team is working on this but would be very useful to know if another option is available.
We still are not familiar working with SAOCOM images, but we are supported by CONICET scientists, and hope they will help and training us to use these images during the next period of the Supersite.
We think that L-Band would be very useful during volcanic crisis (possibly bigger deformations can be registered) and /or areas with vegetation and snow cover as most of the volcanoes in the region of the Supersite.