Seismic Investigation of the Ojos del Salado Volcano, Chile: The Highest Altitude Volcano in the World!

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Poster Number: EGU24-17156
Hall X1, poster board X1.55

Aim of Investigation

Ojos del Salado Volcano, the highest active volcano in the world, lies on the southern end of the **Central Andean Volcanic Zone**, to the south the **subduction angle of the down-going Nazca plate shallows** coinciding with a **gap in volcanism**. The area has **geothermal activity** and **remnant glaciers and permafrost**, however, how these interact with the local volcanism is still poorly understood, likewise, the shape and extent of the magma chamber, or chambers, beneath Ojos del Salado is poorly constrained.

The investigation has two main goals:

1. The study of **crustal** events in the vicinity of Ojos del Salado: to better understand the structure of the magma chamber, and near surface events that could be related to hydrothermal fluid motion in the crust
2. The characterization of **deeper**, subduction related seismicity: combining seismic and InSAR data to gain insight into the larger scale stress field and deformation

Network Deployment

- A **2022 pilot study** deployed seven geophones with the aim of detecting fluid movement between Ojos del Salado and Laguna Verde
- Within two weeks **almost 50 events** were recorded, but the events were **mainly close to Ojos del Salado itself!**
- Based on this, the **2024 network** is **denser on the flanks of Ojos del Salado**
- Stations were grouped into **five mini-arrays** so that array techniques can be used to better locate regional events, with remaining stations filling in the network

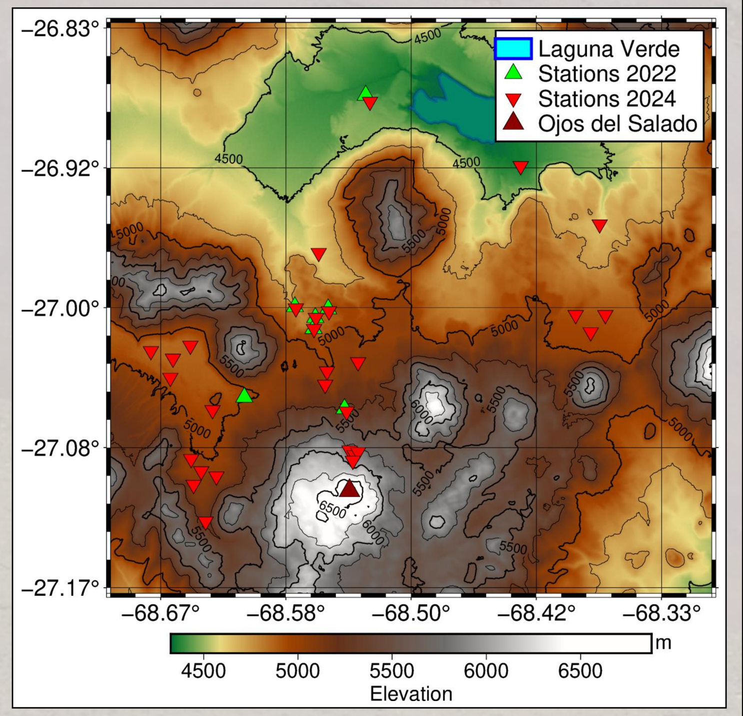
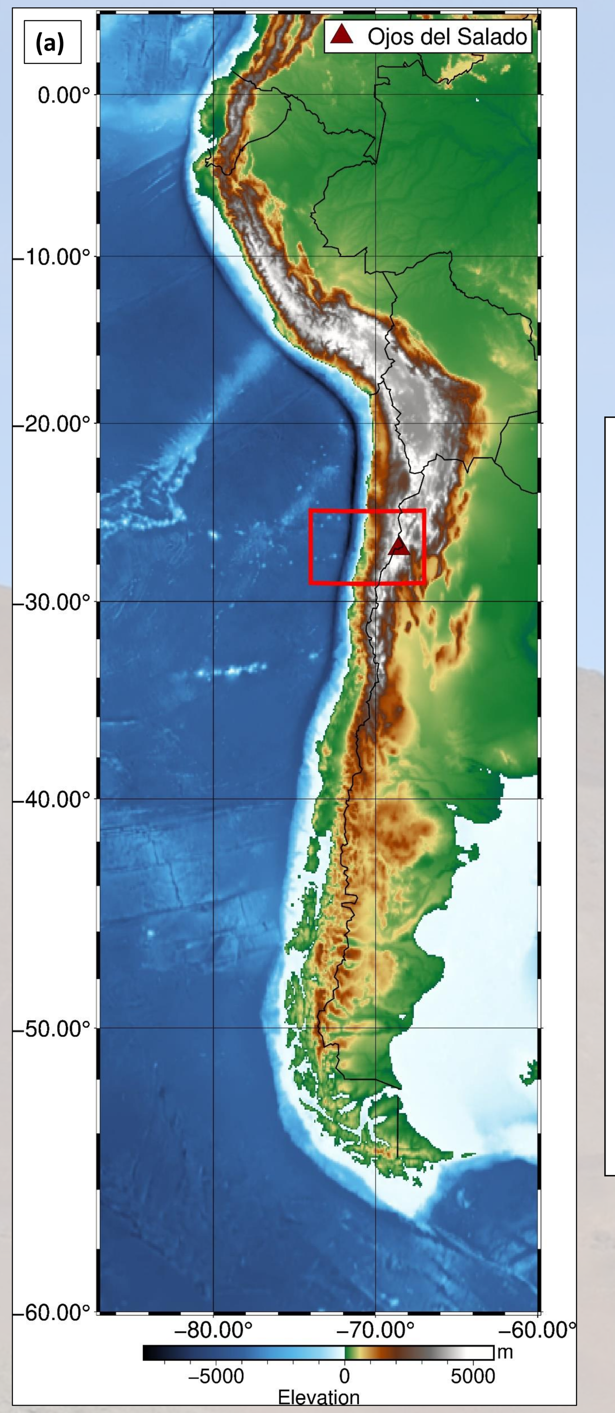


***Figure 1**: A topographic map showing the station locations from the 2022 pilot study (green), the 2024 study (red triangles), and the summit of Ojos del Salado (dark red triangle).*

Tectonic Setting

Ojos del Salado is a stratovolcano at the southern end of **the Central Volcanic Zone (CVZ)**. Although the more active volcanism is further north in the CVZ there is **hydrothermal activity** with **surface water temperatures of up to 40 degrees around the nearby Laguna Verde**. To the south there is a **gap in volcanism** attributed to *shallowing of the subduction angle of the down-going Nazca plate*, this area is also called **the Pampean flat slab**. The transition from the CVZ to the Pampean flat slab coincides with the inception of the **Copiapó Ridge**, similarly the southern edge of the flat slab coincides with the **Juan Fernandez Ridge**, there is speculation that these ridges are responsible for the local shallow subduction angle [1].



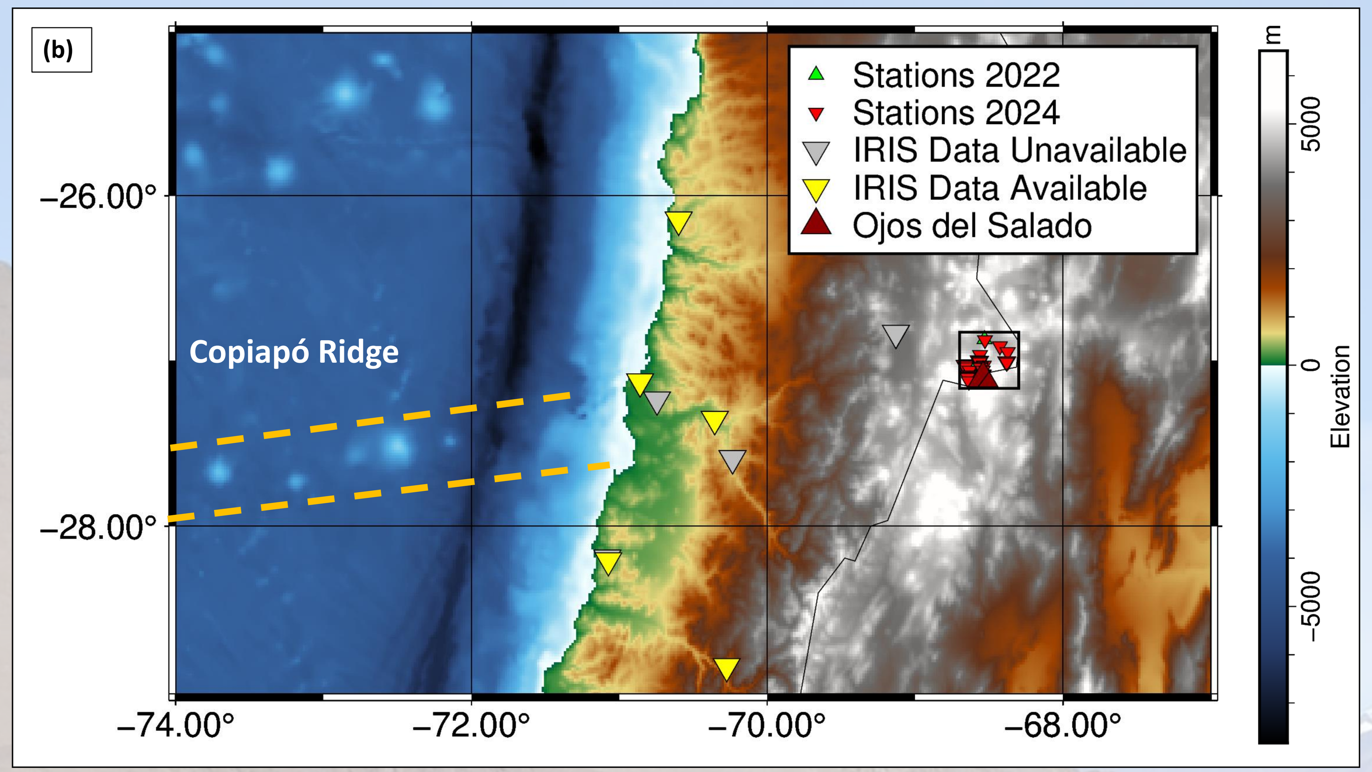


***Figure 2: (a)** Map of western South America, the red rectangle marks the area shown in **(b)** which shows stations from the permanent network (yellow triangles where data was available, grey where not), the black rectangle marks the area shown in **Fig. 1**, stations from the 2022 and 2024 deployments are marked with green and red triangles respectively, Ojos del Salado by the dark red triangle, and Copiapó Ridge is outlined by dashed orange lines.*

Comparison of GaMMA Locations with Geologic Features

The events associated in GaMMA are compared with maps of the elevation, fault density, and drainage patterns in **Figs. 5** and **7**.

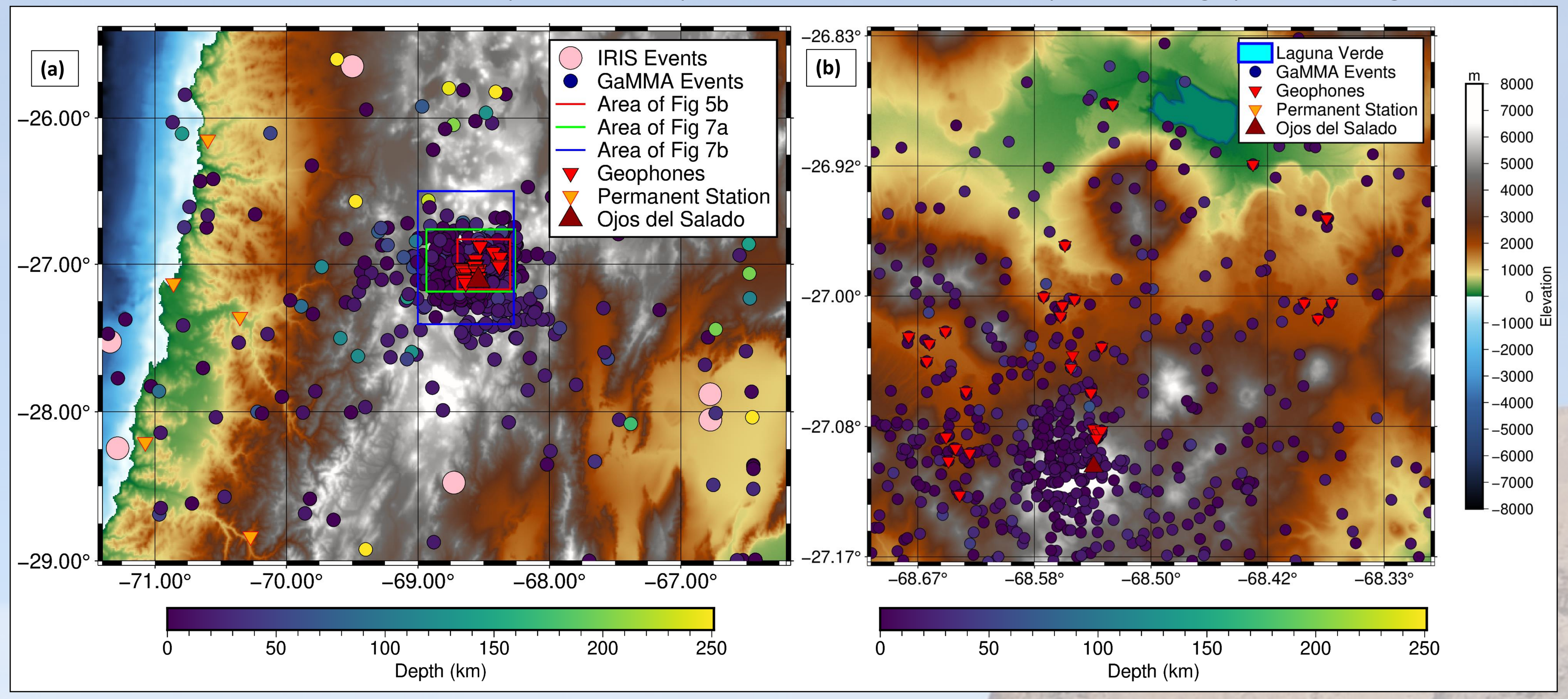


***Figure 5:** Preliminary event estimates are plotted on **(a)** a regional scale, and **(b)** in the area of the network. Events associated from this dataset using GaMMA are plotted as circles with colour corresponding to depth, events from the IRIS catalogue are shown as pink circles. Permanent stations are marked by orange triangles, geophone locations by red triangles, and the dark red triangle shows the summit of Ojos del Salado.*

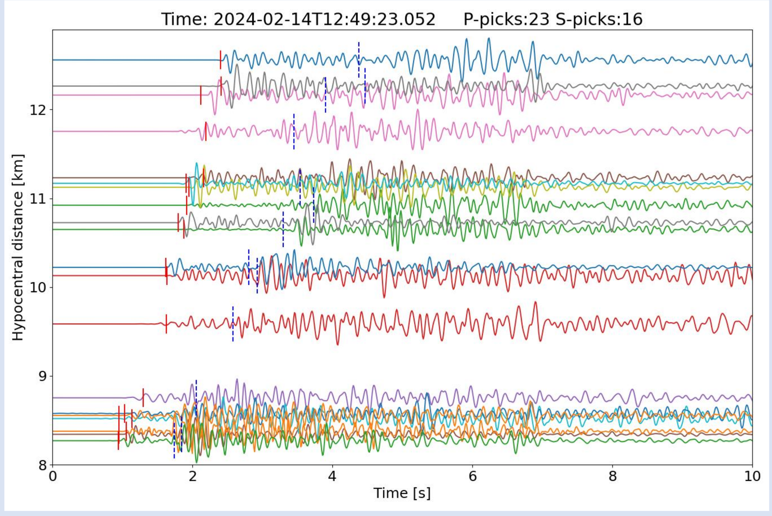
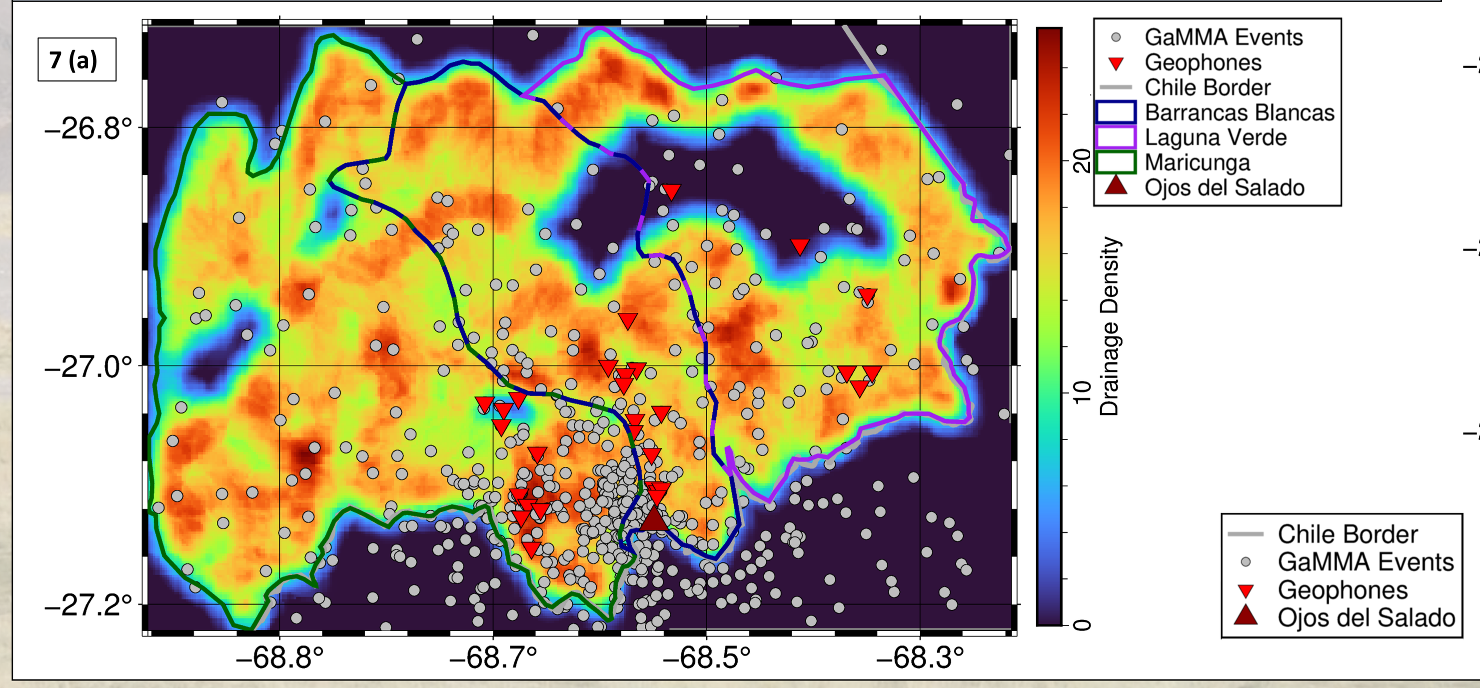


***Figure 6:** Example seismograms from an event on February 14th 2024. Red vertical lines show P-picks and blue dashed lines show S-picks.*



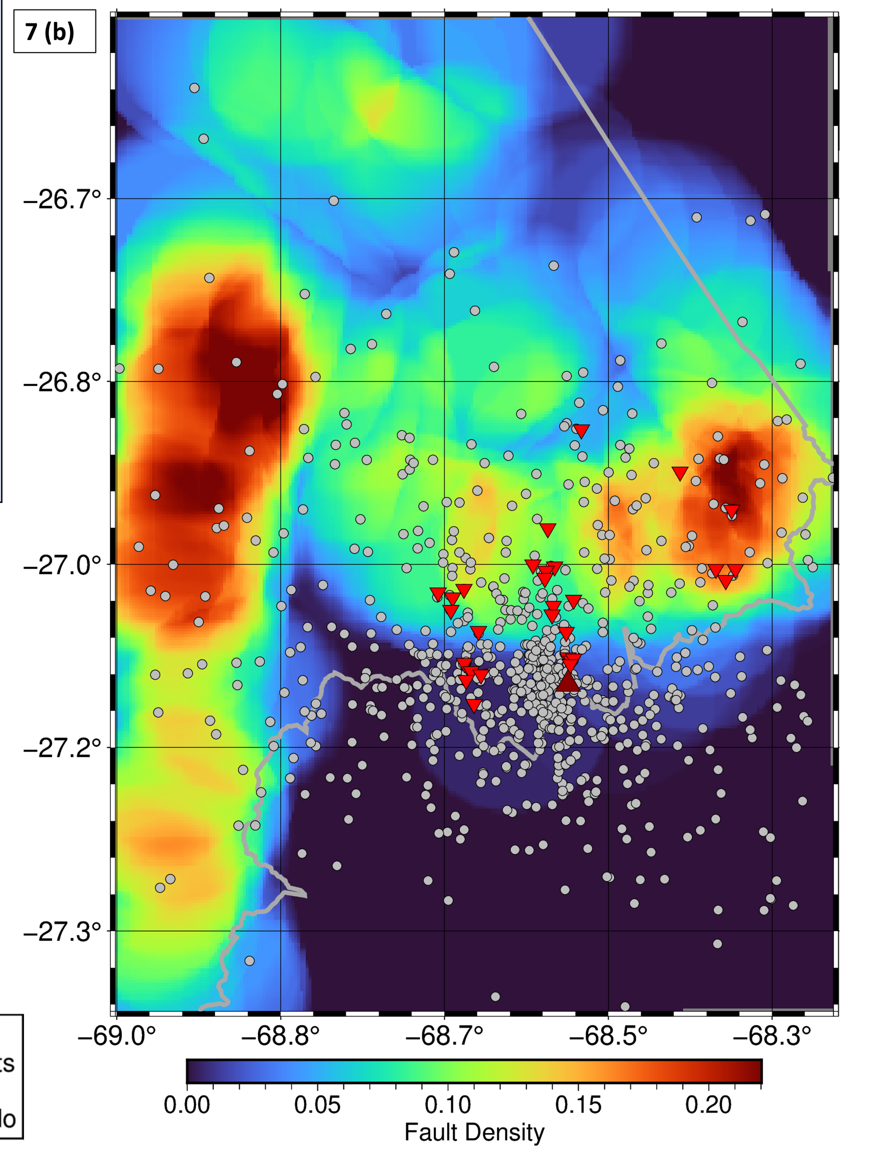
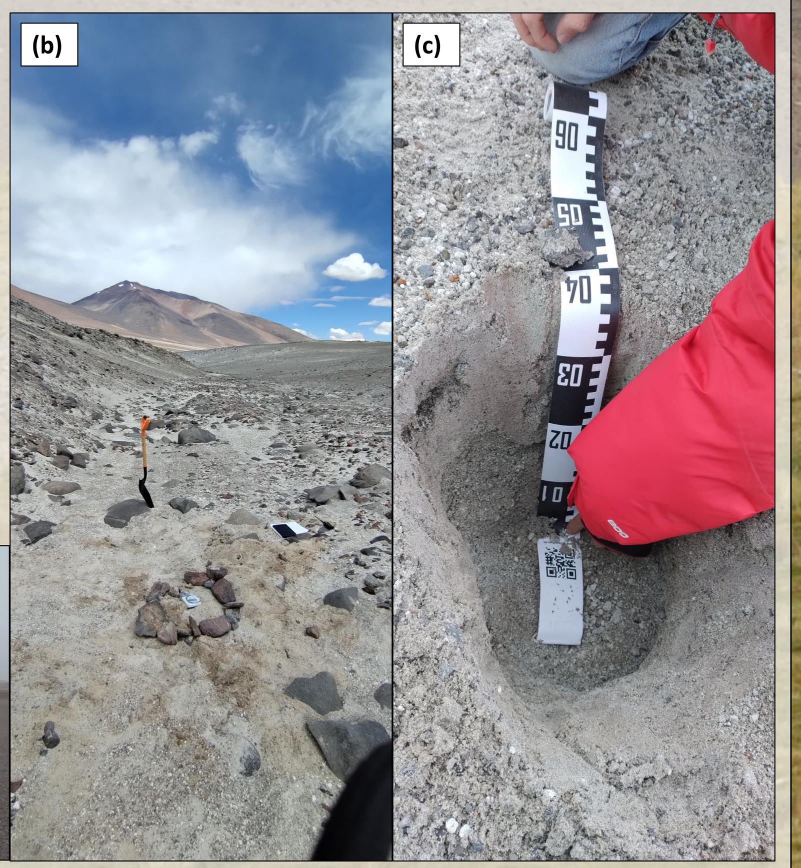


***Figure 7:** Events associated using GaMMA (grey circles) plotted on maps of **(a)** the drainage density, with watersheds outlined by coloured borders, and **(b)** fault density. Stations are shown by red triangles, and Ojos del Salado is marked by an upright dark red triangle.*

Station Installation

- **29 stations** were deployed at the locations shown in ***Fig. 1***
- Stations were composed of a geophone, external battery pack, and DataCube recorder, which includes a GPS for time signals
- To reduce noise levels **the geophones were buried** to between 50cm and 1m depth
- Battery packs were also buried to maintain a more constant temperature
- Most stations were in loose sand, but at higher elevation **permafrost was reached,** the highest elevation station was only buried at ~35cm depth due to permafrost

***Figure 3: (a)** Station installation near Laguna Verde, **(b)** a high altitude station is marked with rocks for visibility and to shield cables from the wind, **(c)** measuring permafrost depth at one high altitude station site before deploying the geophone in the hole.*



Picking and Association

The data was processed using **Seisbench** and **Obspy**:

1. The raw data had **400Hz** sampling rate, this was **resampled to 100Hz** which is required for **PhaseNet**
2. The data was **bandpass filtered to between 0.1 and 30Hz** and the Seisbench tool **DeepDenoiser**, pretrained on the "original" benchmark data set, was used to reduce noise
3. The pretrained model weights from the **INSTANCE** [2] data set were used to pick the denoised data with the **pre-trained Seisbench model PhaseNet**
4. The seismic phase associator **GaMMA** [4] was used to associate events and provide initial estimates for the event time and location

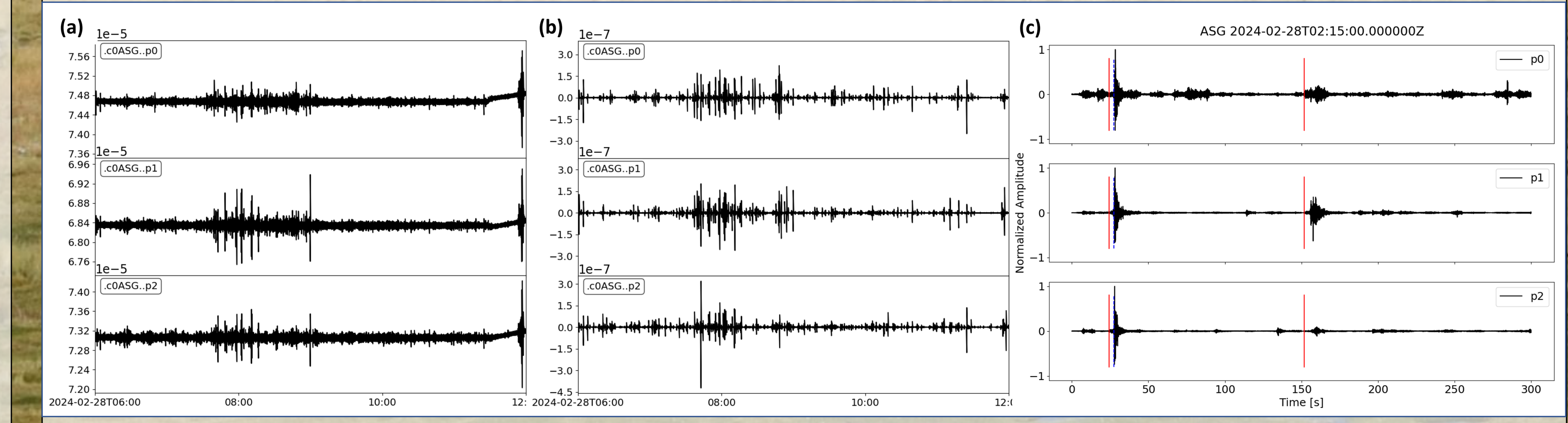


***Figure 4:** Example seismograms from station ASG, February 28th from 6:00am to 12:00 **(a)** low-pass filtered to below 50Hz and **(b)** after applying **DeepDenoiser** to reduce noise levels, **(c)** shows a zoom in to 5 minutes of the denoised stream with picks from **PhaseNet** plotted, P-wave arrival picks are marked with a solid red line, and S-wave picks with a dashed blue line.*

Project Outlook

This expedition produced ~20 days of dense data with hundreds of detected events. The next steps will be to characterize the seismicity by determining **event magnitudes** and **focal mechanisms**. As well, **the frequency content will be analyzed** which can help distinguish signals from different seismic sources.

This will help to divide the events into sources in the **crust related to the magma chamber and geothermal-cryospheric sources**, and the **deeper events related to the down-going slab**.

This data provides an exciting opportunity to better understand **high altitude volcanism, its implications for the cryosphere, and the transition from the Central Volcanic Zone to the Pampean flat slab**.

References

[1] Álvarez, O., Gimenez, M., Folguera, A., Spagnotto, S., Bustos, E., Baez, W., Braitenberg, C., 2015. New evidence about the subduction of the Copiapó ridge beneath South America, and its connection with the Chilean-Pampean flat slab, tracked by satellite GOCE and EGM2008 models. Journal of Geodynamics 91, 65–88. https://doi.org/10.1016/j.jog.2015.08.002
[2] Michelini, A., Cianetti, S., Gaviano, S., Giunchi, C., Jozinović, D., Lauciani, V., 2021. INSTANCE – the Italian seismic dataset for machine learning. Earth Syst. Sci. Data 13, 5509–5544. https://doi.org/10.5194/essd-13-5509-2021
[3] Woollam, J., Münchmeyer, J., Tilmann, F., Rietbrock, A., Lange, D., Bornstein, T., Diehl, T., Giuchi, C., Haslinger, F., Jozinović, D., Michelini, A., Saul, J., & Soto, H. (2022). SeisBench - A Toolbox for Machine Learning in Seismology. in *Seismological Research Letters* https://doi.org/10.1785/0220210324
[4] Zhu, Weiqiang et al. (2021) "Earthquake Phase Association using a Bayesian Gaussian Mixture Model."

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