A.1 Proposal Title

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

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Note that most space agencies require that each person using the data should sign a license agreement with specific rules on data use. (form/document to be prepared and added)

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Core science team as defined above could be expanded to other scientists upon request and after signing a simple MoU where open data sharing is acknowledged. We envision other research teams working on specific case-study (José Cembrano/Juan Carlos de la Llera at Pontificia Universidad Católica de Chile; Sergio Barrientos and Juan Baez at Centro Sismológico Nacional, among the others).

A.4 Region of Interest

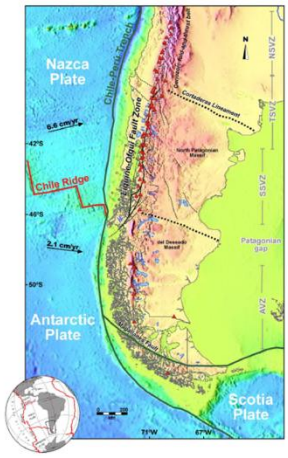
The region of interest extends from Copahue to Quetrupillán (Lanín) volcanoes over 220 km along the arc; in a swath of 50 km in width from 37.82ºS to 39.75ºS. Vertices are indicated in the figure and correspond to:

A: 37.76°S/70.97°W

B: 37.76°S/71.36°S

C: 39.75°S/72.15°W

D: 39.75°S/71.45°W



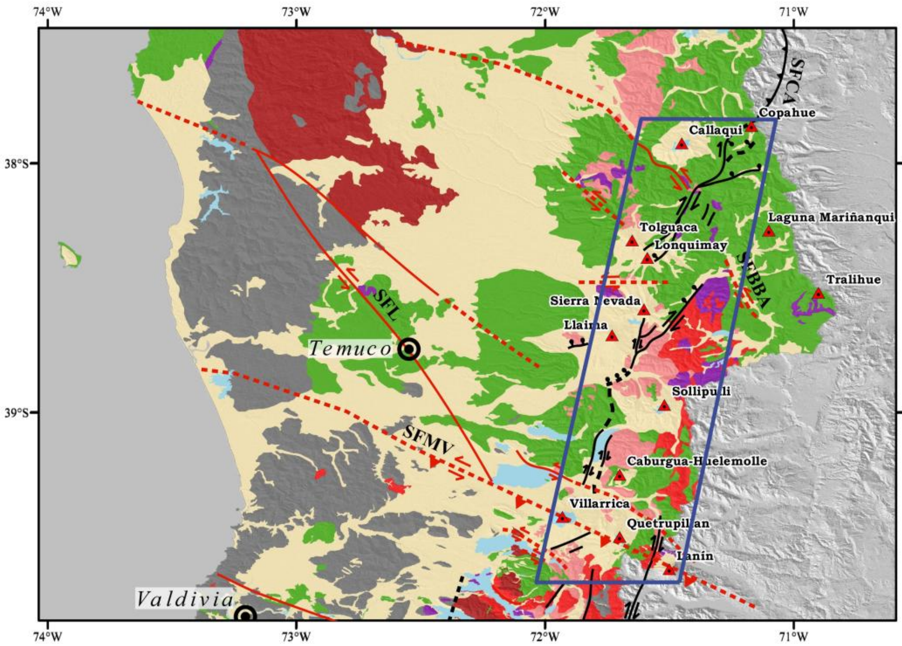


Fig. 1. Regional setting for the supersite proposed. The trapezoid (insert) on the left panel show the area defined by the coordinates.

A.5 Supersite (or Natural Laboratory) motivation (2-4 pages)

The Southern Andes (in a broad sense the region between the southern edge of the Pampean Flat Slab at 33°S and the Triple Junction of Nazca, Antarctica and South American plates at 46°S) are a young and active mountain belt where volcanism and tectonic processes (and those related to the hydrometeorological conditions controlled by this geological setting) pose a significant threat to the growing communities nearby. In fact, only recent eruptions caused evacuations of 250-3500 people each as managed by ONEMI (Chilean Civil Protection agency).

In particular, the segment here considered corresponds to a low altitude orogen (<2000 masl on average) but characterized by a high uplift rate as a result of competing tectonic and climate forces (*e.g.*, Rosenau *et al.*, 2006). This area is also shaped by the northern segment of the Liquiñe-Ofqui Fault System (LOFS), a long-lived right-lateral strike slip fault running for ~1200 km (Cembrano *et al.*, 1996; Lavenu and Cembrano, 1999; Cembrano and Lara, 2009)(Fig.1).

This proposal focuses on a *ca*. 200 km long segment of the Southern Andes cordillera where 9 active stratovolcanoes (Copahue, Callaqui, Tolhuaca, Lonquimay, Llaima, Sollipulli, Villarrica, Quetrupillan and Lanín) and 2 distributed volcanic fields (Caburgua and Huelemolles) are located, just along a tectonic corridor defined by the northern segment of the LOFS (Cembrano and Lara, 2009). Volcanoes in this area take part of the central province of the Southern Andean Volcanic Zone (37-41°S) and run along the horse-tail array of the LOFS to the north (Rosenau *et al.*, 2006). Most of the stravolcanoes are located atop of the LOFS, commonly near the intersection with oblique (NW and NE-trendring) transverse faults. Activity of the LOFS has been detected prior to some eruptions and coeval with some others (*e.g.*, Lonquimay 1989)(Barrientos and Acevedo, 1992). There are several tectonic and volcanic models to be investigated: a strong two-way coupling between tectonics and volcanism has been proposed for the LOFS segment (Cembrano and Lara, 2009) but only recently detected by either geophysical techniques or numerical modeling (Jay *et al.*, 2014; Wendt *et al.*, 2017). In addition, recent network deployment allowed to detect subtle (silent) reactivation or seismic shadow (*e.g.*, Franco *et al.*, 2015) of local fault-fracture networks in specific volcanic domains after large earthquakes in the subduction zone, which suggest that besides the near field tectonic triggering there is an important component of remote tectonic trigger through static and dynamic stress transfer (*e.g.*, Lara *et al.*, 2004).

Hazards in the segment derive mostly from the activity of some of the most active volcanoes in South America (*e.g.*, Villarrica, Llaima), others with long-lasting but weak current activity (*e.g.*, Copahue, that caused evacuation in Chile,and Argentina of about 3,500 people during every major volcanic event) or some volcanoes with low frequency but high magnitude eruptions in the geological record (*e.g.*, Lonquimay). Since the beginning of the 20th century ~80 eruptions have been recorded in this area (Lara *et al.*, 2011). Volcanic hazards in this region are mostly related to debris flows triggered by ice/snow melting (lahars) and tephra fallout (Lara *et al.*, 2011). Ongoing modeling efforts allow a near real time forecast of ash dispersion and settling and new modeling tools (with local high resolution DEMs) allow a better constrain of lahar inundation zones. In addition, remote sensing techniques coupled with ground based seismic monitoring allowed a tracking of the effusive stage of the 2011-2012 Cordón Caulle eruption (Bertin *et al.*, 2015). These and other monitoring methods could be expanded to this area with direct impact in the quality of hazards assessment, estimating of their vulnerability and uncertainties that SERNAGEOMIN would provide to ONEMI and also to the scientific community.

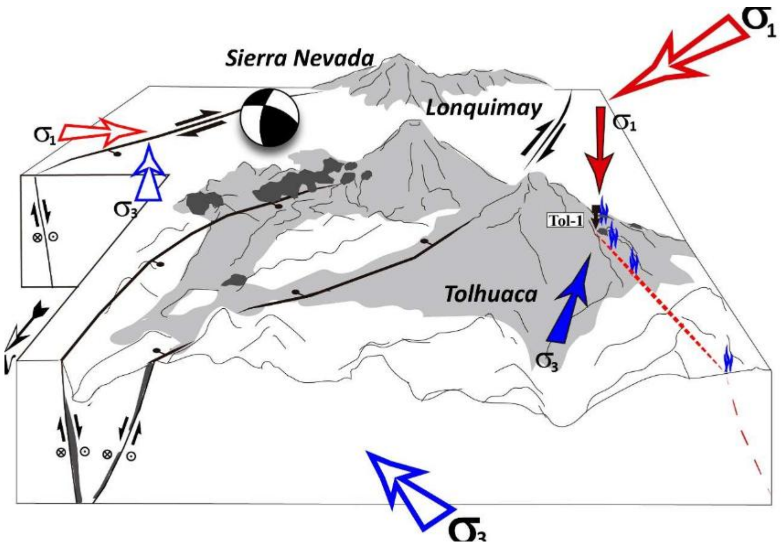


Fig. 2. Example of volcano-tectonic association for Lonquimay-Tolhuaca volcanoes (Pérez *et al*., 2017; Pérez *et al*., 2016), view to the north.

There is growing and interesting evidence of both magmatic and non-magmatic ground deformation in the volcanic areas of the proposed supersite, mainly from InSAR data (*e.g*., Fournier *et al*., 2010; Vélez *et al*., 2011, Lundgren *et al*., 2015; Delgado *et al.,* 2017)(Figs. 3 and 4), mostly in Copahue and more recently in Lonquimay, Llaima and Villarrica (Córdova *et al*. 2015). The first one seems to be related with a shallow source and its interaction with the hydrothermal system; the latter, Llaima and Lonquimay probably more related to processes on surface (Fournier *et al*., 2010, Remy *et al*., 2015). Based on RADARSAT-2 and COSMO-SkyMed images together with UAVSAR data, Copahue volcano has been under sustained inflation since 2012 at 10 cm/yr with a complex pattern until 2015 (Lundgren, 2015).

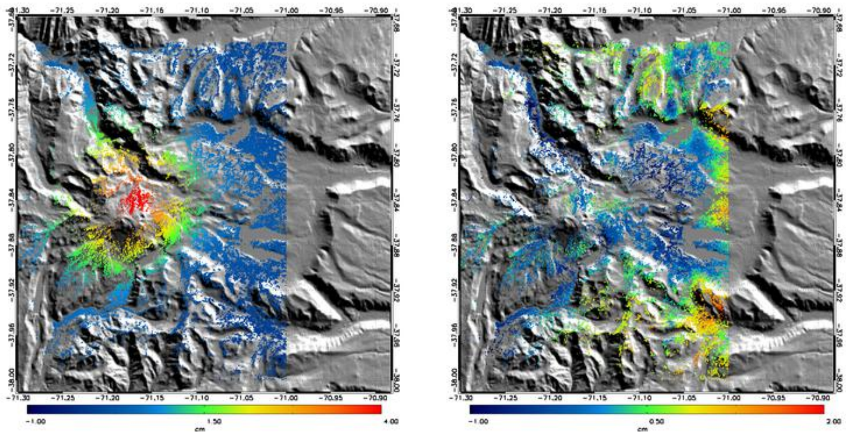


Fig. 3. Source model for Copahue volcano as proposed by Vélez *et al*. (2011)

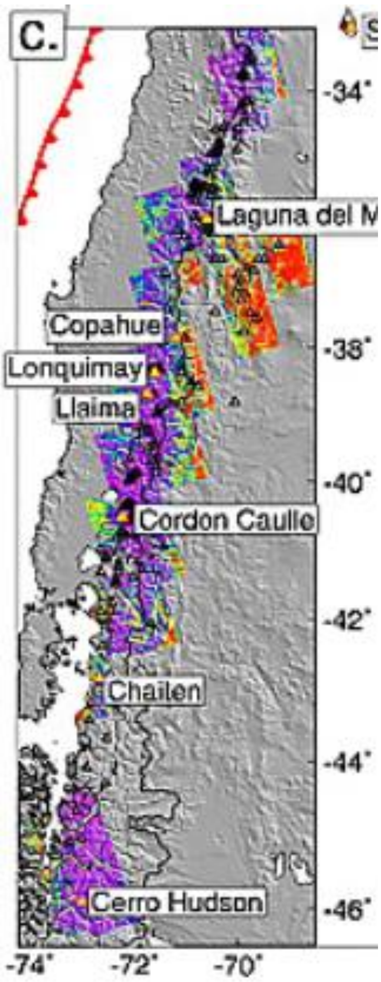


Fig. 4. Regional survey of active deformation of volcanoes in Southern Andes (Fournier *et al.*, 2010). Copahue, Lonquimay and Llaima appear with a signal, although with a different interpretation for related processes.

On the other hand, a large and growing network of continuous GNSS stations deployed along this segment is revealing interesting patterns of crustal deformation likely related to current activity the LOFS and its possible interaction with volcanoes. Figure 5 (after Tassara et al., 2016) shows a map of kinematic monoclinal vorticity (*i.e.*, the ratio between simple shear and pure shear deformation parallel to the LOFS, in this case) obtained from velocity vectors of campaign and continuous GNSS stations, averaged between 01/01/2008 to 31/12/2009 (couple of months before the Mw 8.8 Maule earthquake). Regions of large vorticity are nicely aligned with some segments of the LOFS demonstrating the localization of strike-slip motion there. A preliminary spatio-temporal analysis of vorticity from cGNSS stations suggests that the pattern of Fig. 5 has been rapidly evolving likely in response to the postseismic relaxation after the Maule earthquake. This process in turn could be driving disequilibrium of the volcanic systems as can be deduced by the apparent correlation between events of large concentration of vorticity and recent eruptive activity (Tassara *et al.*, 2016; García et al., 2017). This pattern is also related with the spatio-temporal evolution of crustal seismicity recorded by seismic networks, notably well observed along the proposed segment.

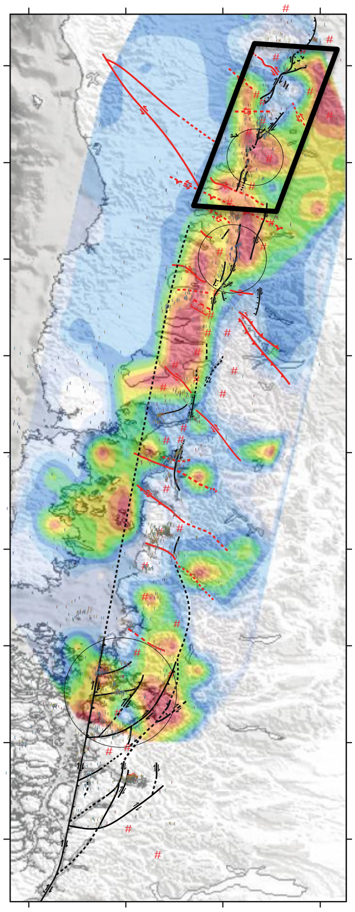


Fig. 5. Map of kinematic monoclonal vorticity of the Southern Andes from velocity vectors of GNSS stations averaged between 01/01/2008-31/12/2009 (Tassara et al., 2016). Hot colors marc regions of high vorticity, i.e. large dominance of strike-slip over pure shear deformation along a NNE axis (parallel to LOFS). Also shown are fault traces compiled from the literature. Black polygon shows the segment here proposed as Super Site.

Climate and tectonic forces shaped the steep relief of this region, which is a condition for frequent mass wasting (mostly low volume landslides and debris flows) triggered by heavy rains, shallow earthquakes, and/or volcanic activity (lahars). There is plenty of evidence for the first (worst in a scenario of climate change, which allow liquid precipitation at higher altitudes) and some outstanding examples for the latter in other places that share features with the proposed site (*e.g.*, Sepúlveda and Serey, 2009; Sepúlveda *et al*., 2010; Oppikofer *et al*., 2012).

In general, the modelling effort and other future research areas can be beneficial to the development of an early warning system for the evaluation of the geodynamic risk at a specific time and location. For example, predictive models that could relate the vorticity or ongoing Coulomb stress change to volcanic unrest or slope instability would be beneficial, including their uncertainties, to the local as well to the international communities, but have yet to be developed, which could be enhanced by the GSNL initiative.

Main scientific challenges

The connection between regional-scale tectonic processes and volcanic activity is poorly understood beyond the recent case-studies. Thus, early detection of tectonic unrest and its possible effect on volcanic systems require more comprehensive models that can be tested with near-real time data of surface deformation.

In Chile early-warning system for volcanic eruptions is now mostly based on seismic data. A major challenge is to integrate seismicity with other proxies like deformation (both based on cGPS and InSAR) and degassing in near real time. These geodynamic data integration, through GSNL and the present GeoHaZSA initiative, would allow to develop new products and services that would be very beneficial to local and international communities and agencies, such as SERNAGEOMIN, ONEMI and others.

Once eruptions begin the ability to track the evolution providing reliable forecast about the possible duration and eruptive magnitude (or erupted volume) is limited. Near real time survey of the effusion/emission rate from space borne data could provide key information to understand first-order behaviour of an eruptive cycle.

For long-lasting eruptions, eruptions of very short duration or those occurring in remote areas, tracking of the thermal anomalies is a very useful tool that allow estimation of eruption rates (Coppola *et al*., 2016) and lava-lake dynamics (Medina *et al*., submitted). Tracking ash clouds is well accomplished using aerial images and could be used in back analysis of forecast models and uncertainties.

Once eruptions begin the need for specific hazards assessment is limited for the availability of background data (*e.g.*, <5 m resolution topography). High resolution (*ca*. 1 m) DEMs and other aerial images, if available, could be rapidly set to run numerical models for a number of processes, which could lead to new products portfolio of information services (*e.g.*, maps of arrival times, etc.) beneficial to everybody from first responders to civil population and scientists.

Specific goals of the supersite will be:

- To establish regional source models (faults and volcanoes), mostly based on ongoing research at Universidad de Concepción/Fondecyt.
- To develop a rapid strategy for deformation monitoring along the LOFS based on InSAR.
- To develop and early warning for volcanic unrest system based on InSAR and other aerial images.
- To set and integrated early-warning system coupling seismicity with deformation (InSAR) and degassing from space-borne, and other data.
- To improve capability to track effusion/emission rates based on optic, radar and other aerial image products.
- To improve capability to generate high resolution hazards maps for lahars and other debris flows.
- To develop new products and services based on collaboration within GSNL, for first responders, civil and scientific communities.

Data required and applied research opportunities envisioned

SAR and other image data will be fundamental for systematic InSAR analysis and long to short-term forecast of activity at faults and volcanic systems. In addition, some SAR products would be useful for preparing DEMs, which are a critical input for numerical modeling of gravity flows (lahars, pyroclastic density currents and lavas). High resolution optical sensors could be useful to observe evolving situations during unrest periods in some specific volcanoes. We do not mention here images or web-based services already freely available that certainly will continue to serve for this task. Details in next section.

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A.6 In situ data

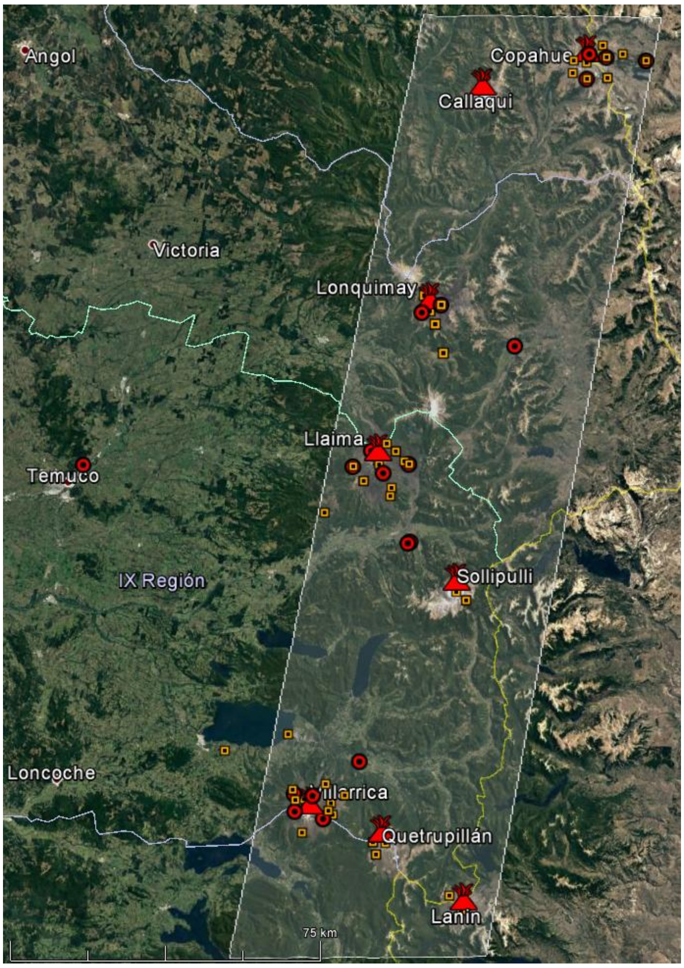
This section should provide a detailed description of the in situ data available to the Supersite participants, at the time of proposal submission as well as following Supersite implementation. Please address here criteria 4,9 of section 5.1.1

Ground-based monitoring networks for both volcanism (the so-called Red Nacional de Vigilancia Volcánica at Sernageomin) and tectonics (Centro Sismólogico Nacional at Universidad de Chile) allow a good complement with space-borne data. Figure 6 shows the present network run by Sernageomin.

Type of data	Data source	Data access
e.g. seismic waveforms, GPS time series, gas measurements, etc.	*……*	*Please describe how to access the data, type of access (unregistered, registered, limited to GSNL scientists, etc.), and future developments in the Supersite framework.*
Seismic wave form	*SERNAGEOMIN (OVDAS) network (35 stations)*	*Open access with registration form; server to remote download scheduled. Time-series for registered scientists under specific agreements*
Geodetic data from 18 cGPS--GNSS	*SERNAGEOMIN (OVDAS) (16), IGM(1) and CSN (1) network and GPS Campaigns*	*Open access to GNSL scientists*

DOAS and Gas measurements	*SERNAGEOMIN (OVDAS) network (5 continious stations) and Campaigns*	*Open access to GNSL scientists*
Infrasounds (2)		*Open access to GNSL scientists*

In detail, the present network in the area of interest is distributed as shown in figure 6 and the table below. In addition, temporal campaign stations have been deployed by Universidad de Concepción and Pontificia Universidad Católica de Chile as part of research Fondecyt projects.



Volcano	Seismic stations	GNSS stations	DOAS	Infrasound
Copahue	7	4	2	1
Callaqui	2	0	0	0
Lonquimay	5	3	0	0
Llaima	9	5	1	0
Sollipulli	2	0	0	0
Villarrica	7	5	2	1
Quetrupillán	2	0	0	0
Lanin	1	0	0	0
OVDAS- Temuco	0	1	0	0

Fig.6. Present distribution of GPS (red dots) and other type of stations (seismic and DOAS, in orange squares) used for monitoring by Sernageomin

A.7 Supersite activity work plan

This section should describe the work plan (including timeline) of the Supersite implementation, e.g. in terms of scientific activities, in situ and EO data provision to the community, infrastructures for data and products storage and distribution (implementation of supersite specific ones as well as utilization of existing ones), benefits for end-users, etc.
Please address here criteria 4,6,9,12 of section 5.1.1

Year 1: Planning and launching. Building of a national capability for InSAR and other aerial image analysis. First systematic survey on target areas (those with high vorticity or evidence of surface deformation based on GNNS stations).

Year 2: Preliminary source model; plan for development of products and services for early warning systems and first response to emergency.

Year 3: Advanced source model and prospectus of early warning system and first response to emergency.

Year 4: Operational source model. Tests and try-outs for predictive models, early warning system and first response to emergency.

A.8 Available Resources

Describe resources and funding available to carry out the Supersite objectives.

Sernageomin and its Volcano Monitoring Network run a network of 18 GNSS stations in the area of interest. A 3 staff team is in charge of the processes and analysis of this data at OVDAS (Observatorio Volcanológico de los Andes del Sur). Other senior scientists take also part of the analysis. Annual budget for this task is *ca*. US$100,000. Total funding for the Chilean Volcano Monitoring Network run by SERNAGEOMIN (45 volcanoes with local networks at present) is *ca.* US$585,615.

Universidad de Concepción is running Fondecyt-funded research projects in this subject (a PhD student working on a numerical model). Annual budget for this task is *ca*. US$100,000, part of it is used to improve the network of continuous GNSS stations.

Pontificia Universidad Católica de Chile is running Fondecyt-funded research projects in this subject (active tectonics of LOFS and oblique to the arc fault systems). Annual budget for this task is *ca*. US$15,000.

A.9 EO data requirements

This section should provide details on the EO data requirements for each mission. It should also provide justification for the requested EO data with respect to the Supersite objectives.

MISSION NAME *(e.g. COSMO-SkyMed, TerraSAR X, Radarsat 2, etc.)*

Scenario 1 (High Priority): during unrest periods as detected by any mean, ongoing volcanic eruptions (including weak sustained activity) or waning stages after peak eruptions

	Information	Notes
Image mode	SAR (ALOS-2, COSMO SkyMed, TerraSAR X) Optical (Pléiades)	ALOS-2 and COSMO SkyMED are intended for near real time monitoring with InSAR; TerraSAR X is for DEMs production at selected sites. Optical images are intended for detection of morphological changes (e.g., variations of craters and lava lakes, glacier response to subglacial ice-melting; slow slope failure, etc.)
Orbit pass		
Look direction	Ascending, but mostly descending	
Beam or incidence angle (range)		
Polarization		
Type of Product	(i.e. SLC, RAW)	
Number of archive images requested	SAR images as defined in moderate priority scenario; optical depending on the site	
Number of new images requested, per year	ca. 48-432 SAR images (every 2 weeks from each satellite; 3-27 optical (e.g. Pleiades) every 4 months or every 2 days during peak eruptions	*For each 9 of 11 volcanic centres(stratovolcanoes) but especially for those with signals of unrest (under yellow or higher alert level; areas where clustered seismicity or surface deformation recorded by cGPS; or areas under evident slope instability*

Repeat table above for each sensor/system

Scenario 2 (Moderate Priority): during quiescence periods

	Information	Notes

Image mode	ALOS-2 ScanSAR Envisat, COSMO SkyMED, TanDEM X TerraSAR X
Orbit pass	
Look direction	descending
Beam or incidence angle (range)	
Polarization	
Type of Product	(i.e. SLC, RAW)
Number of archive images requested	*ca.* 200 Envisat for Copahue (2002-2012); *ca*. 1000 COSMO SkyMED (2011-present, descending): Llaima (276), Villarrica (270), Copahue (284); *ca*. 30 TanDEM X
Number of new images requested, per year	See high priority scenario

A.10 Declaration of commitment

In Chile there is a law that mandates public agencies to disseminate the information. Internal procedures in Sernageomin put some restrictions to the data access during ongoing crisis (red and orange alert levels) but the general policy is to share rough data as open as possible (only limited by the capability in terms of staff if some procedure is required; and internal IT security issues). At present, rough data is shared upon request through a requisition form and depending on the volume transfer is made by hardware or using a dedicated ftp server.

A.11 Further comments

The investigator(s) may provide additional comments or information to ensure that the request is properly understood.

This proposal is a first step in Chile aimed to connect space-based technology with ground-based techniques for monitoring and research of geological hazards (mostly volcanic hazards) in near real time. It would be also the first exercise of massive sharing data acquired by SERNAGEOMIN networks at global scale. We expect to contribute to both an improvement of the monitoring capability (merging data and taking advantage of the experience in the global

scientific community) and a better knowledge of some key geological processes. Rough data as indicaed in section A6 will be available upon request or in a dedicated, along with regular upload to international databases (e.g., IRIS, UNAVCO GSAC, WOVOdat, etc.
) and possibly a Chilean GSNL at http://www.sernageomin.cl/)Spanish and English) and GSNL website. GeoHaZSA is intended as a research network rather than an institution-hosted program and thus funding for regular activities would be obtained from active research projects/programs leaded by the core scientists at the first stage. When more stablished, funding from other sources could be explored.