Monitoring remote equatorial and tropical volcanoes using multi-sensor spaceborne imagery and in situ geophysical data

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Abstract

Volcanism impacts human activities on a variety of time and space scales. The risk entailed by volcanism on small island countries is particularly acute, as these populations can face important logistical difficulties in the event of a major eruption necessitating rapid evacuation. However, assessing hazard in volcanic islands represents a major challenge due to the remoteness of the environments.

In this project, we propose to exploit a panel of spaceborne sensors to monitor ground deformation in order to better understand the volcanic and magmatic processes driving volcanic activity. To do so, we will primarily exploit a new generation of radar sensors onboard the two Sentinel-1 satellites of the European Space Agency, using a technique called synthetic aperture radar interferometry (InSAR). Thanks to the new Sentinel-1 system capabilities, it becomes possible to monitor surface deformation of a large number of volcanoes simultaneously, with a short revisit time and a dense spatial coverage. This project will build upon recent processing methods developed at the Tectonics Laboratory of IPGP, dedicated to exploiting the unprecedented accuracy of Sentinel-1. In addition to InSAR, we will also use high-resolution satellite imagery (optical and radar) to track the evolution of topography as a function of time for a series of target volcanoes.

As deciphering the complex processes at play in the interior of a volcano requires a multi-parameter, we will also use complementary geophysical and geochemical observations. Gas emissions sensed from space by UV imagery techniques will be jointly interpreted with geodetic data to further improve our understanding of volcanic and magmatic activity. Finally, when available, ground-based geophysical data (GPS and seismology) will be integrated to improve the temporal resolution on activity and further constrain the main processes driving volcanic activity.

Two regions are primarily targeted by the present project. First, the North Molucca archipelago, in Indonesia, where a group of extremely active volcanoes yield frequent eruptions reported by local scientists. Liaising with local scientists, a prerequisite for access to ground-based monitoring data, is ensured thanks to an existing collaboration between IPGP, IRD (Institut de Recherche pour le Développement) and Indonesian CVGHM (Center for Volcanology and Geological Hazard Mitigation). Second, the Vanuatu islands in the SW Pacific, which is also characterized by an exceptionally high level of volcanic activity, will be another focus of this project. A third exploratory target will be the Lesser Antilles arc, where two volcanoes are under the responsibility of IPGP's Volcano Observatories.

1 Introduction

Volcanism is a major source of hazard threatening human activities. This is particularly true for communities living in remote volcanic islands due to the difficulty of rapidly relocating large groups of inhabitants away from the islands, especially if the slopes of the volcanoes are densely populated. The difficulty of a massive emergency evacuation in terms of economical impact and societal acceptability is well exemplified by the recent historical eruptions of La Soufrière de Guadeloupe (1975-77) and Soufriere Hills in Montserrat (1995-2013). As highlighted in the 2015 Global Volcano Model Network report (http://globalvolcanomodel.org/), all five sites most exposed to volcanic risk on Earth are located on volcanic islands.

Mitigating these hazards requires both an understanding of sub-surface volcanic and magmatic processes as well as a continuous observation of volcanic activity. While geological mapping of volcanic products helps characterize the type of volcanic activity that can be expected on a given volcano, keeping the volcano under constant scrutiny

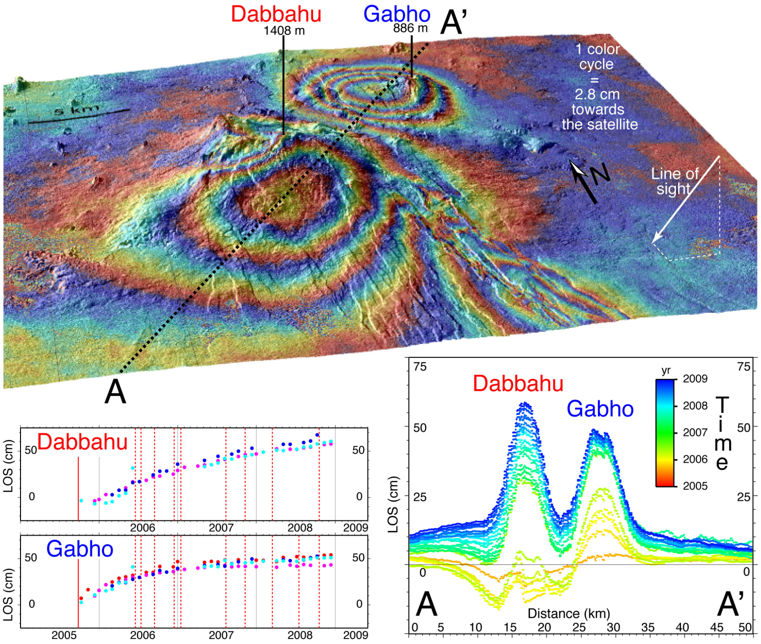

Figure 1: *Deformation of Dabbahu volcano (Ethiopia) from InSAR from 2005 to 2009. Lower left panels show displacement as a function of time above two magma reservoir showing uplift in the period of observation. After **Grandin** et al. [2010]*

using quantitative monitoring techniques provides crucial information about the state of the system in near real-time. Monitoring is usually achieved by combining three approaches: seismology, ground deformation and gas measurements. Unfortunately, maintaining ground instrumentation on a great number of active volcanoes is too costly for most countries impacted by volcanism, while being hazardous for the observatory teams in the event of a major eruption. Remote sensing of volcanism from space may fill part of this observation gap.

Recent progress in remote sensing has made it possible to measure subtle ground deformation over vast areas, and continuously detect gas and ash emitted by volcanoes into the atmosphere. Among the most promising of space-based observation tools, a technique called Synthetic Aperture Radar Interferometry (InSAR). This technique enables the measurement of ground deformation with an accuracy better than 1 cm, a coverage of tens to hundreds kilometers across, and dense spatial sampling (typically on the order of 100 meters) (Fig.1).

The recent launch of a new generation of spaceborne radars operating in a wide-swath mode has dramatically improved the temporal sampling of InSAR. The Sentinel-1 system of the European Space Agency is the most advanced sensor on the path toward operational monitoring of volcanic activity, allowing for regular acquisitions every 6 to 12 days. Whereas previous sensors could only focus on a small number of pre-chosen volcanoes, thanks to the wide and frequent coverage capability of Sentinel-1 it is now possible to provide regular observations of large regions with a large density of active volcanoes. This new methodology opens promising perspectives to better document, model and understand the activity of remote volcanoes, which represent the vast majority of active volcanic systems on Earth.

2 State of the art / Scientific context

The deformation of a volcano is mainly controlled by pressure changes within the edifice. The geometry of the pressure sources and the mechanical response of the edifice and host-rock control the amplitude and shape of deformation patterns [Pyle et al., 2013]. Deformation phenomena therefore convey information about the different components of a volcanic system, from the deeper magma reservoir, to the edifice and hydrothermal system at shallower depth [Dvorak and Dzurisin, 1997]. Most erupting volcanoes exhibit precursory deformation [Biggs et al., 2014]. Precursory deformation signals may be detected over time scales of months, weeks or days prior to eruption, depending on the type of volcanic activity (Fig. 2). Monitoring of deformation is therefore a powerful tool to warn local authorities ahead of the occurrence of an eruption.

Depending on the source process, deformation operates on a variety of temporal and spatial scales. To constrain and hierarchize these different processes on a given volcano, it is important to capture this deformation over vast areas, with dense spatial sampling and a short time interval [Segall, 2013]. This can now be achieved thanks to the InSAR technique, which was first applied to a volcano about 20 years ago, and has since made constant progress (Fig. 3). The all-weather, night-and-day capacity of InSAR makes it an appropriate tool to monitor volcanic activity. So far, InSAR has been mainly applied to individual volcanic eruptions, or to slowly-deforming volcanic

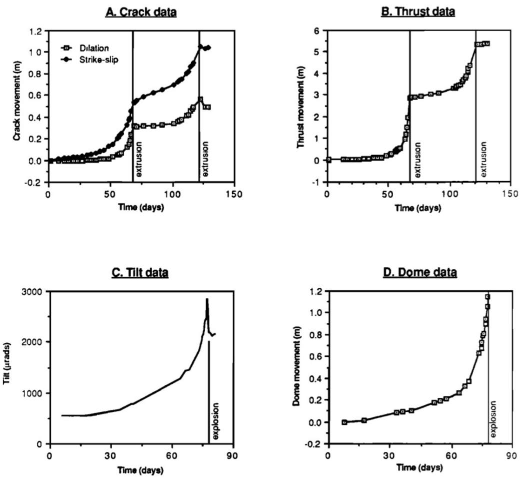

Figure 2: *Precursory deformation observations in the weeks prior to eruptions of Mount Saint Helens (USA). After [Chadwick et al., 1988].*

systems, in most cases at temperate latitudes. Application to remote volcanoes at equatorial and tropical latitudes has been significantly hampered by the insufficient temporal sampling of the acquisitions. As a result, the InSAR technique could not avoid coherence loss over densely vegetated areas.

The launch of the Sentinel-1A satellite in 2014 by the European Space Agency (ESA), followed by Sentinel-1B in 2016, acts as a game changer in the field. Thanks to a novel sensing mode and systematic acquisition capability, Sentinel-1 makes it possible to overcome many limitations of previous sensors. In the past four years, IPGP has developed dedicated processing strategies aiming at exploiting the full potential of these data. These methods were successfully applied to a number of recent case studies, from the measurement of extreme deformation due to great megathrust earthquakes [**Grandin** et al., 2015, 2016, Nocquet et al., 2016] to the sensing of subtle deformation signals induced by exploitation of shale gas in Oklahoma [**Grandin** et al., 2017].

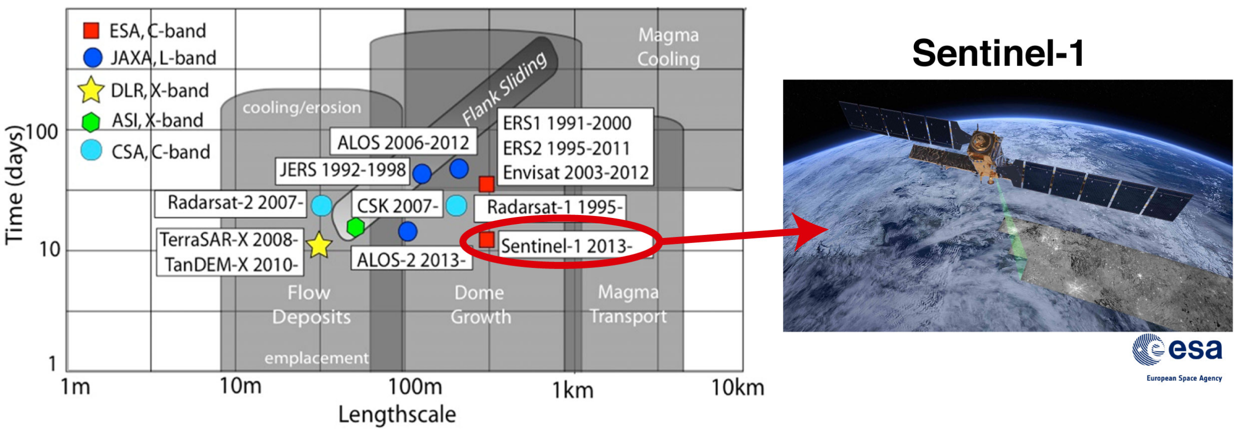

Figure 3: *Diagram showing the revisit time of successive generations of SAR satellites and the corresponding time and space scale of typical volcanic phenomena [adapted from Pyle et al., 2013]. Right panel shows an artist view of the Sentinel-1 satellite (source : European Space Agency).*

Utilizing these recent methodological advances, as well as the long experience accumulated at IPGP in the field of volcanology, we propose to use novel Sentinel-1 data for the study of active volcanoes in areas lacking previous geodetic observations. The objective of this project is to exploit the wide-swath capability to investigate simultaneously a whole volcanic region (a single Sentinel-1 image covers a 250 km wide area). This approach is especially powerful in Indonesia and Vanuatu regions where volcanoes are typically clustered along volcanic arcs (Fig. 4). The short revisit time of Sentinel-1 will allow for capturing short-lived deformation events, as well as long-term signals. This project will also pave the way for an operational exploitation of InSAR at the global scale. It will have application beyond the field of volcanology, as Sentinel-1 is the first radar satellite to warrant truly open access to data, in near-real time.

3 Concepts and objectives

3.1 Observational strategy

In recent years, IPGP has developed expertise in the exploitation of Sentinel-1 data for the measurement of ground deformation associated with large earthquakes [e.g. **Grandin** et al., 2015, 2016]. We will apply and adapt this existing methodology to the remote sensing of active volcanoes. In this thesis, large stacks of Sentinel-1 SAR data will be processed in order to enable the measurement of volcanic deformation in areas where deformation is highly suspected, but has never been measured due to remoteness of the environment and lack of data.

In addition to Sentinel-1, ALOS-2 data (Japan Aerospace Exploration Agency) will be used to improve the temporal coverage of observations and tackle the potential loss of coherence in densely vegetated regions. ALOS-2 operates in L-band, which yields a more robust detection ability in vegetated contexts, while providing several acquisition modes that can be selected according to the type of volcanic activity. Access to ALOS-2 data was secured in 2016 by Raphaël Grandin (JAXA project RA-6-3225).

InSAR data will allow for covering the period 2014-2020. In order to extend the study further back in time, we will also process archive radar and optical data to reconstruct the topography of volcanoes as a function of time. The objective is to map recent volcanic deposits, quantify their volumes and characterize potential flank destabilization.

A broader objective of this project is to better understand underlying volcanic/magmatic processes (both during pre-eruptive and eruptive periods) including magma intrusion and ascent, pressurization of the hydrothermal system from fluid injections, and edifice basal gravity spreading and flank instability. This will require a combination of ground deformation observations with complementary geophysical and geochemical data including:

- gas satellite imagery when degassing is sufficiently strong to be detected from space,
- in-situ ground data (GPS, seismology, continuous gas and temperature monitoring) whenever available.

3.2 Case studies

3.2.1 Primary target: frequently erupting volcanoes in Indonesia and Vanuatu

In this project, we will mainly focus on two groups of volcanoes exhibiting quasi-continuous activity (Fig. 4):

- (1) Northern Molucca area: (a) Dukono, which has been in a state of quasi-permanent eruption in the past eight years, and perhaps since 1933. Its summit is devoid of vegetation. (b) Ibu, which features a continuously growing dacitic lava dome and hosts regular explosions. (c) Gamalama, which overlooks the city of Ternate (200,000 inhabitants), a subject of concern for the pyroclastic flows and lahars that can be triggered by its activity. These volcanoes have been continuously active in the past decade, with at least one eruption every year. They are monitored by local scientists (CVGHM in collaboration with IRD) using a network of permanent instruments since 2014, including broadband and short-period seismometers and tiltmeters. GPS surveys have been carried out at Dukono since 2015, but lack the temporal resolution to capture its complex activity. Sustained SO2 degassing is regularly detected by space-based OMI and OMPS sensors as well as in situ gas continuous measurements. Sentinel-1 and ALOS-2 acquisitions are available since 2014 for these volcanoes.
- Vanuatu archipelago: Ambrym, Ambae and Yasur. In particular, Ambrym hosts a permanent lava lake, a rare feature for a volcano on Earth. (2) A few sparse GPS observations at Yasur suggest transient ground displacement exceeding 10 cm in amplitude, associated with inflation and deflation of an underlying reservoir [Brothelande et al., 2015]. Such deformation is consistent with the fact that Vanuatu volcanoes are also among the largest sources of volcanic SO_2 emissions on Earth and trigger nearly-continuous gas detections [Bani et al., 2012]. Sentinel-1 acquisitions have started in November 2016 for these volcanoes.

3.2.2 Secondary target: volcanic unrest in Lesser Antilles

Exploratory investigations will be performed in a context characterized by a lower amplitude of deformation taking place at time scales of several years, and subject to dense vegetation and complex atmospheric conditions. For this second part, we will focus on the volcanoes of the Lesser Antilles Arc, which include Soufrière Hills in Montserrat, la Soufrière de Guadeloupe and Montagne Pelée in Martinique. The two latter volcanoes are located in the French territory, and are currently monitored by Volcano Observatories of IPGP. On the complex volcano of La Soufrière de Guadeloupe, deformation appears to be currently driven mainly by a complex and variable coupling of increased pressurization from the hydrothermal system, movement on a local oblique left-lateral fault as well as gravitational spreading along detachment planes inherited from previous partial collapse events [Rosas-Carbajal et al., 2016], although the contribution of deeper sources is also suspected [Villemant et al., 2014, Allard et al., 2014]. Flank instability is another major source of hazard in the Lesser Antilles [Boudon et al., 2007]. InSAR would provide

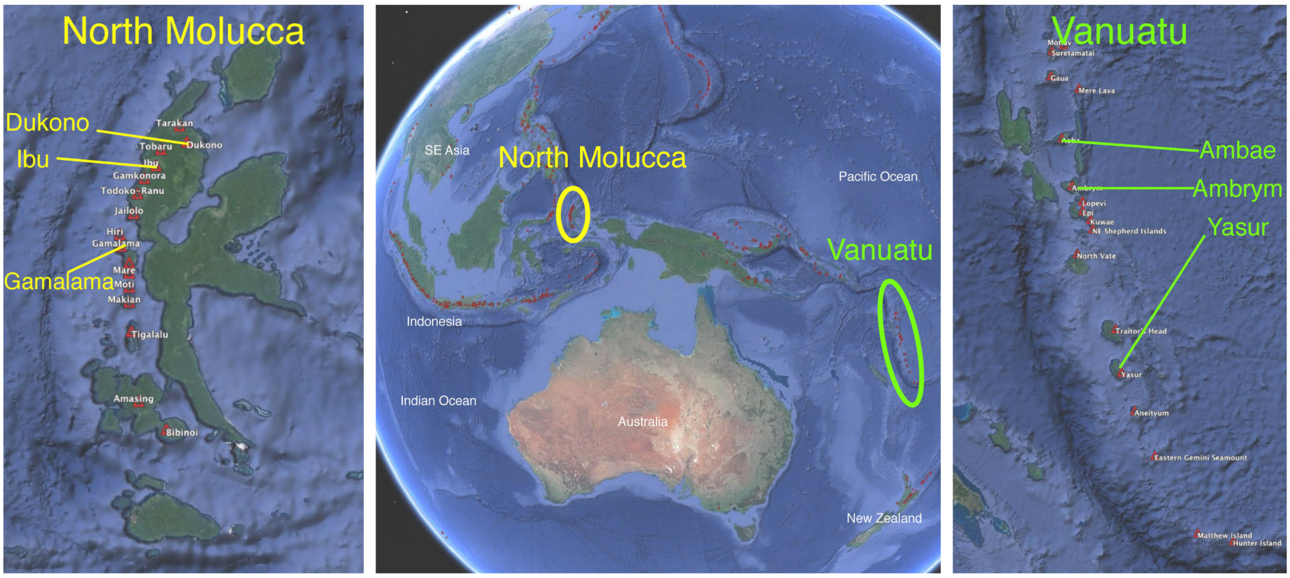

Figure 4: *Location map of the volcanoes targeted by the present project (source : Google Earth).*

information on both superficial and deeper sources, and help improve our understanding of variations in the volcanic system of La Soufrière, which is currently experiencing increased fumarolic and thermal unrest.

4 Methodology / Materials and methods

4.1 InSAR processing

Sentinel-1 and ALOS-2 data will be processed using state-of-the-art methods. Sentinel-1 data will be pre-processed according to the methodology of **Grandin** [2015]. The ROI_PAC processor will be used to generate timeseries of interferograms, which will be further combined using the NSBAS software, recently adapted for the processing of Sentinel-1 data [**Grandin** et al., 2015, 2016, 2017]. Topographic corrections will be carried out using TanDEM-X high-resolution DEM (access to these data was secured in January 2017 by Raphaël Grandin, DLR project number DEM_GEOL1244). The high resolution of the 12 m TanDEM-X data will be a significant improvement for the quality of final products, compared to previously available DEM data, whose best resolution is 30 m. Atmospheric corrections will be performed using meteorological data according to the method of Jolivet et al. [2011]. Topographic errors will be corrected using the method developed by Ducret et al. [2014].

In addition to InSAR, optical satellite images will be used to reconstruct the eruption history of the volcanoes since the mid-1990s. Sentinel-2 and Landsat-8 imagery, whose acquisitions encompass the timeframe of the project (2014–2020), will be exploited systematically to provide a synergy with Sentinel-1 and ALOS-2 radar data. As optical and radar imagery have similar temporal resolution ($\sim$ 1 image every 15 days), the most recent activity of the volcanoes will be tightly constrained. This will be particularly crucial for Dukono and Ambrym, which experience quasi-continuous volcanic activity. The Landsat archive (1972–2017) will be used to map and determine the timing of the ash deposits and lava flows evident in today's images.

4.2 Generation of high-resolution digital elevation models

In addition to sensing deformation using InSAR, we will also reconstruct digital elevation models (DEM) as a function of time using optical and radar imagery. Studying the evolution of topography will be important in case of major resurfacing of the edifices (for instance due to ash deposits, pyroclastic flows, lava flows or lahars) that can induce a loss of the InSAR coherence. Topography will be reconstructed at different epochs, first by processing spaceborne optical imagery using photogrammetric techniques developed at IPGP, in collaboration with IGN (MicMac software). We will use high-resolution SPOT-5 archive data for past topography, and/or programmed SPOT-6-7 and Pléiades very-high-resolution imagery for present-day topography. Secondly, synthetic aperture data acquired by the dedicated radar mission TanDEM-X will be requested from DLR (German Space Agency). TanDEM-X data allow for mapping topography with a very high accuracy ($\sim$ 1 m in z) and high-resolution ($\sim$ 5 m pixel size). These latter radar data may be crucial to study equatorial volcanoes which are often covered with clouds (such as Dukono) and hence difficult to observe using optical imagery.

4.3 Other remote sensing imagery

Furthermore, additional data will be exploited to provide a multi-parameter overview of activity of targeted volcanoes:

- Gas and ash imagery : SO2 emissions in the atmosphere can be tracked using UV-sensors, such as OMI and OMPS, which are adapted to the humid equatorial conditions. They can also detect degassing in the lower troposphere (below 5 km of altitude, as in Molucca and Vanuatu). These data will be systematically collected to build a time-series of detected volcanic gas, a proxy for eruptive activity. Total gas load and deformation will be jointly interpreted according to the approach of McCormick et al. [2016].

- Thermal infrared imagery (MODIS): will allow for unambiguously documenting eruptions triggering thermal alert.

- Geostationary orbit imagery (SEVIRI): will provide ash dispersal snapshots and help constrain eruption dynamics.

4.4 In situ observations

Finally, in situ data, where available, will be combined with remote sensing.

For the Molucca volcanoes, seismological data acquired continuously since 2015 at Dukono, Gamalama and Ibu will be exploited jointly with the geodetic results produced during this project. These data will allow for understanding how modulations of seismic activity can be related to behavior of the volcanic system as seen by remote sensing data. Fieldwork will be carried out to re-survey GPS networks at Gamalama during the course of the thesis.

At La Soufrière de Guadeloupe, deformation is monitored by GPS and extensometry. Furthermore a long database consisting in a great variety of in situ observations is available. It includes gas composition and emission rates, fumarole temperature, thermal spring, water geochemistry, microseismicity, seismic tomography, muon tomography and electrical conductivity tomography [e.g. Jourde et al., 2016, Rosas-Carbajal et al., 2016].

5 Feasibility / Timetable (approx. timetable in a calendar format over 3 years: 2017-2020)

- 2017 Q1: during Tara Shreve's M2 internship, first tests exploiting of Sentinel-1 and ALOS-2 data archive on Molucca volcanoes. Evaluation of coherence from interferograms spanning different time intervals. Processing using ROI-PAC/NSBAS and ISCE (Sentinel-1) and GMTSAR (ALOS-2) softwares.

- 2017 June: Tara Shreve Master's thesis report and defense.

- 2017 Q3: time-series processing of Sentinel-1 and ALOS-2 data archive on Molucca volcanoes using NSBAS software.

- 2017 Q4: fieldwork in Molucca islands. GPS survey of Gamalama. Depending on accessibility, fieldwork at Dukono and Ibu.

- 2017 Q4 / 2018 Q1: Raphaël Grandin HDR report and defense. RG becomes official PhD advisor.

- 2018 Q1: joint exploitation of InSAR data and in situ data for Molucca volcanoes. First tests on Vanuatu volcanoes and Lesser Antilles volcanoes.

- 2018 Q2: publication of results on Molucca volcanoes.

- 2018 Q3-Q4: publication of results on Vanuatu volcanoes.

- 2019 Q1-Q2: publication of results on Antilles volcanoes.

- 2019 Q3 / 2020 Q1: synthesis of results.

- 2020 Q3: Tara Shreve PhD thesis report and defense.

6 Financial sources for carrying out research, and if required visits to laboratory of collaborators

- Financial support requested from French Embassy in Indonesia (request made in December 2016, decision pending) ; PI: R. Grandin
- PNTS grant PNTS-2015-09, 29k€ (2015-2017); PI: R. Grandin.
- CNES-TOSCA grant ("Mesure des déformations par imagerie optique") ; PI: Y. Klinger.

7 Impact : scientific, potential applications, societal

The present project will provide crucial information to characterize poorly understood volcanoes in Indonesia and Vanuatu. Significant impact on the volcanology community is expected from this work. Results will be shared with local scientists, especially as part of the collaboration between IPGP, IRD and CVGHM. This exchange of expertise, data and results will allow for improving the recognition of the impact of volcanism on the fast-growing population living on the slopes of Indonesian volcanoes.

The results acquired on La Soufrière de Guadeloupe will complement the vast multi-parameter (geophysical, geochemical, geological) database maintained by IPGP since the establishment of the observatory in 1950, and help improve the understanding of the behavior of the volcano and the assessment of volcanic hazard related to future eruptive activity, especially given the current increasing degassing and thermal unrest at the volcano.

The processing algorithms developed during this project will be used for the study of other remote volcanoes, as the ever-growing Sentinel-1 data archive will allow for increasingly more challenging cases to be tackled. The methods will also benefit to other research areas that share the same data processing methodology, in particular applications of InSAR to tectonics (earthquakes, interseismic strain), landslides and land subsidence. Finally, this study paves the way for automatic surveys, exploiting the near-real time capacity of Sentinel-1.

8 International collaborations

Collaboration between IPGP, IRD (Institut de Recherche pour le Développement) and CVGHM (Center for Volcanology and Geological Hazard Mitigation) will help share geophysical data acquired on the ground. François Beauducel, formerly head of La Soufrière volcano observatory at IPGP, is currently visiting CVGHM for a duration of 2 years, and will play an active role of relay between the present project and our indonesian counterparts. Thanks to this collaboration, access to in situ data sharing of results to end-users will be facilitated.

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