First Results from the UnderVolc High Resolution Seismic and GPS Network Deployed on Piton de la Fournaise Volcano

F. Brenguier,[1] P. Kowalski,[1] T. Staudacher,[1] V. Ferrazzini,[1] F. Lauret,[1] P. Boissier,[1] P. Catherine,[1] A. Lemarchand,[1] C. Pequegnat,[3] O. Meric,[1] C. Pardo,[2] A. Peltier,[2] S. Tait,[2] N. M. Shapiro,[2] M. Campillo,[3] and A. Di Muro[1]

INTRODUCTION

Recent advances in volcano seismology such as the measurement from seismic noise of subtle decreases of seismic velocities preceding volcanic eruptions (Brenguier *et al.* 2008; Duputel *et al.* 2009) or the precise localization of volcano-hydrothermal microseismic tremor sources (Taisne *et al.* 2011; Cros *et al.* 2011) have emerged from the analysis of long-term, continuous, and high-quality seismic data. There is thus an increasing need for high-resolution continuous seismic data in volcanic environments to improve our knowledge of fundamental volcanic processes such as deep magma transfers, volcanic unrest, magma transport, and eruptions.

With 30 eruptions since 2000, Piton de la Fournaise volcano (La Réunion Island) has been among the most active volcanoes worldwide. This volcano emits basaltic lavas with volumes ranging from less than 1 million cubic meters to hundreds of millions of cubic meters. Piton de la Fournaise volcano has been monitored since 1979 from a permanent observatory that since 1999 has recorded continuous seismic and deformation data. Since 2009, we have deployed new broadband seismic and GPS stations under the framework of the UnderVolc research project. Most of the temporary stations are being converted to permanent stations, and the continuous seismic waveforms are publicly available by standard *netdc* requests.

Within this paper, we will provide technical information about the deployed UnderVolc broadband seismic and GPS stations. We will also present data quality measurements from a noise spectral analysis using PQLX (McNamara and Buland 2004). We will show examples of seismic records during volcanic crisis and present novel results from the new seismic velocity monitoring method (Brenguier *et al.* 2008) using the new network. Finally, we will present some results of long-term displacement rates of the Piton de la Fournaise edifice flank using GPS data.

PITON DE LA FOURNAISE VOLCANO OBSERVATORY AND THE UNDERVOLC PROJECT

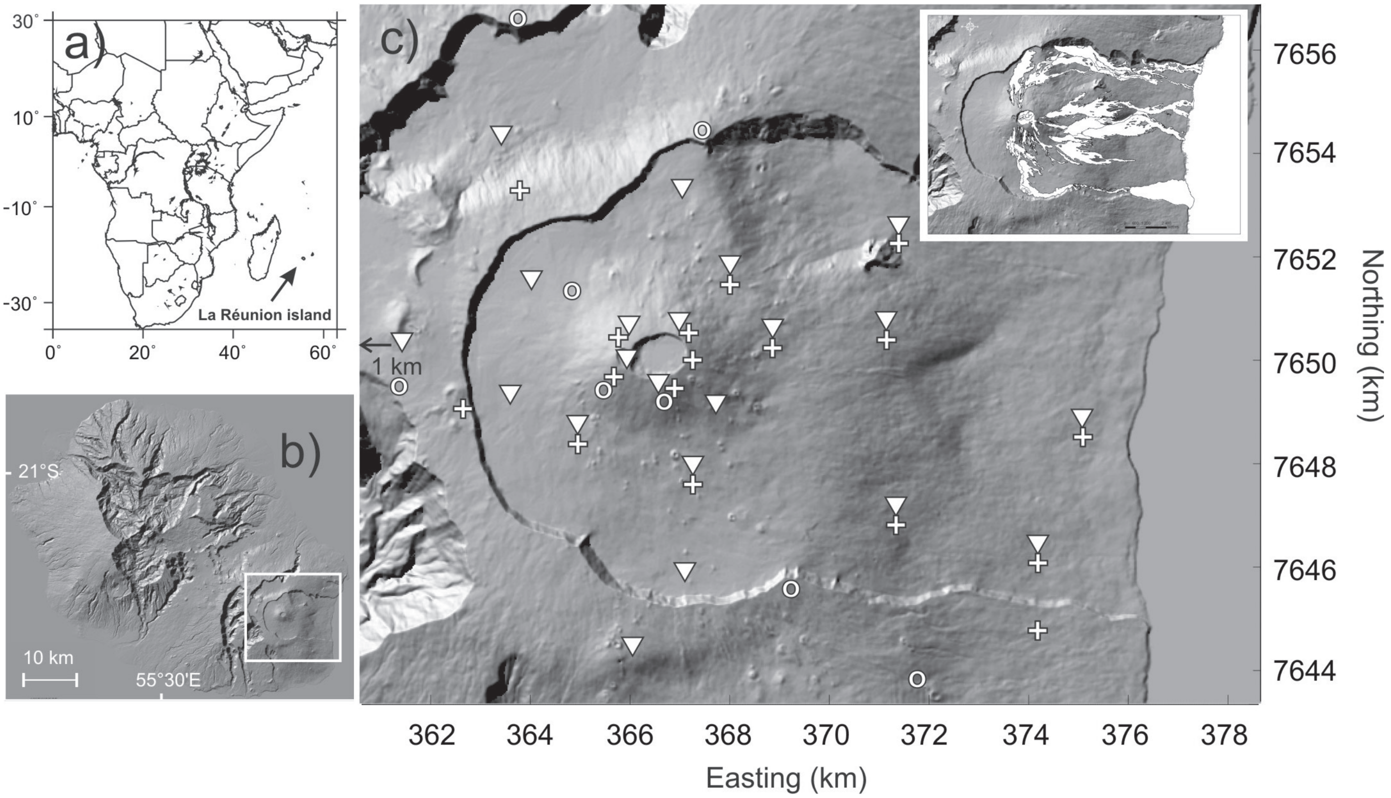
Piton de la Fournaise volcano is a hot-spot shield volcano located on La Réunion Island in the Indian Ocean (Figure 1). It erupted 30 times between 2000 and 2010. The eruptions last from a few hours to a few months and emit basaltic lava with volumes ranging from less than 1 million cubic meters to more than 200 million cubic meters (Peltier *et al.* 2009; Staudacher *et al.* 2009). Eruptions are mainly preceded by volcano-tectonic earthquakes located within the 7-km-high volcanic edifice or within the underlying oceanic crust.

Since 1999, the data from about 10 short-period 1-Hz seismometers have been continuously recorded at the Piton de la Fournaise Volcano Observatory (Observatoire Volcanologique du Piton de la Fournaise, OVPF). This unique dataset has been used to develop the method of high-precision seismic velocity monitoring from seismic noise (Brenguier *et al.* 2008). Since 2009, we have deployed 15 broadband, high-resolution seismic stations with differential GPSs (DGPS) in the framework of the UnderVolc (Understanding Volcanic Processes) research project (`http://undervolc.fr`) in addition to six pre-existing broadband seismic stations. The UnderVolc project brings together an international task force of more than 30 seismologists, volcano seismologists, and volcanologists. It is funded by the French Research Agency (2009–2012), and the officially associated research institutes are Institut de Physique du Globe de Paris (France), Institut des Sciences de la Terre (Grenoble, France), and the Bureau de Recherches Géologiques et Minières (Orléans, France). This project cooperates with the University College Dublin (C. Bean), the Earthquake Research Institute

---

1. Observatoire Volcanologique du Piton de la Fournaise/Institut de Physique du Globe de Paris, Sorbonne Paris Cité, Centre National de la Recherche Scientifique, France
2. Institut de Physique du Globe de Paris, Sorbonne Paris Cité, Centre National de la Recherche Scientifique, France
3. Institut des Sciences de la Terre, Université Joseph Fourier, Centre National de la Recherche Scientifique, France

doi: 10.1785/gssrl.83.1.97



▲ **Figure 1.** Location of (A) La Réunion Island, (B) Piton de la Fournaise volcano, and (C) the UnderVolc and observatory seismic and GPS networks. UnderVolc broadband seismic stations are shown as inverted triangles, GPS as crosses, and observatory short-period seismic stations as circles. The inset map shows lava flows from 2000 to 2010 (courtesy of OVPF, T. Staudacher, Z. Servadio).

(Y. Aoki, Tokyo), and the University of Wellington (M. Savage, New Zealand).

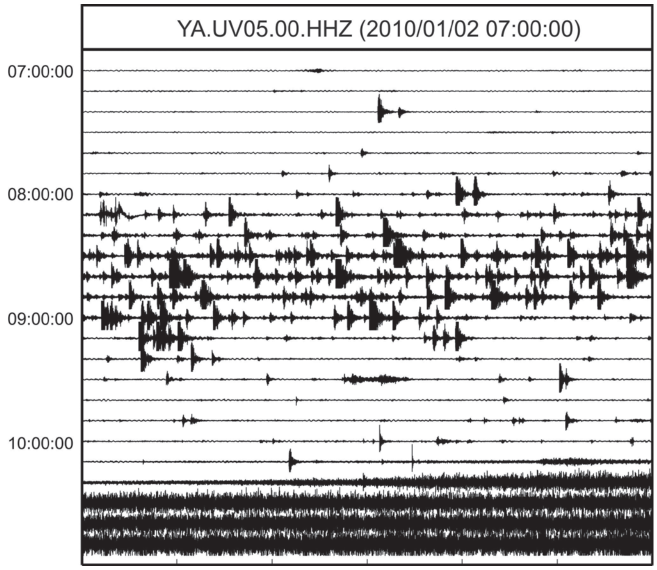
The research topics covered by the project are: high-precision seismic velocity monitoring from seismic noise (Brenguier *et al.* 2008), processes of dike injection (Taisne *et al.* 2011), dike-induced deformation (Peltier *et al.* 2011), microseismicity relocation (Got *et al.* 2008), shear-wave splitting monitoring (Gerst and Savage 2004), long-period event source inversion (De Barros *et al.* 2011), flank instability/rock fall processes (Hibert *et al.* forthcoming), and predictability of volcanic eruptions (Grasso and Zaliapin 2004). Since the beginning of the UnderVolc project station deployment (September 2009), five eruptions occurred at Piton de la Fournaise volcano (5 November 2009, 14 December 2009, 2 January 2010, 14 October 2010, and 9 December 2010). They were preceded by seismic swarms of volcano-tectonic and long-period earthquakes. Figure 2 shows a typical seismic swarm of mostly volcano-tectonic events preceding eruption tremor.

DATA ACQUISITION AND DISTRIBUTION

Piton de la Fournaise volcano, in particular its east flank, is barely accessible, and the on-site stations have thus been designed to be transportable by helicopter and fully autonomous. Within the framework of the UnderVolc project, we deployed 15 Nanometrics Taurus dataloggers from the French seismological network Sismob with 30-sec Guralp CMG-40T seismometers. The six additional permanent broadband seismic stations are Kinemetrics Q330 associated with Guralp CMG-3ESPC sensors. The seismometers are directly set on rock or on a cemented concrete plate and protected from temperature changes by polystyrene plates embedded within a rock-fixed plastic case.

One summit station is also equipped with a high-precision infrasound sensor sensitive to pressure changes with frequency from 0.0016 Hz (10 minutes) to 20 Hz. Data are sent in real time to the Piton de la Fournaise observatory using IEEE 802.11 b WiFi technology. Distances between stations and WiFi access points range from 1 to 10 km. We use two different acquisition systems at the observatory, either (1) earthworm or seiscomp to record the Q330 data or (2) Nanometrics Apollo system to record the Taurus data. All data are distributed to the UnderVolc scientific community by the Sismob data center by standard netdc requests. These data are distributed by standard netdc requests to netdc@fosfore.ipgp.fr, datacenter FOSFORE and network code YA. To join the UnderVolc scientific community, it is necessary to first send a request to Florent Brenguier (brenguier@ipgp.fr).

At the end of the two-year Undervolc data acquisition program (May 2011), the seismic sensors were returned to the French seismic network (Sismob). For that reason, to continue the high-precision seismic monitoring, this network is progressively being replaced since May 2011 by a permanent network



▲ **Figure 2.** Swarm of volcano-tectonic events preceding eruption tremor on 2 January 2010.

operated by the observatory. This permanent network is mostly composed of Quantera Q330S digitizers with CMG-3ESPC 60-sec broadband sensors. All data from the permanent network are publicly distributed using standard netdc requests to `netdc@fosfore.ipgp.fr`, datacenter FOSFORE and network code PF (`http://www.fosfore.ipgp.fr/`).

SEISMIC DATA QUALITY CONTROL

We routinely monitor the quality of seismic data by searching for gaps or overlaps in the continuous waveforms and by filling these gaps by retrieving archived data directly from the station through radio links. We also check for polarity reversals, sensitivity changes, or acquisition issues by viewing time-series data with PQLII software. Finally, we analyze the data spectral content. We use the spectral analysis tool PQLX (McNamara and Buland 2004). In Figure 3, we compare noise spectrums from UnderVolc stations to those of the seismic Geoscope/FDSN station RER (STRECKEISEN STS1) located on La Réunion Island in a 200-m-deep and 2,000-m-long tunnel. We show the spectral analysis results for the stations with lowest and highest noise energies (respectively UV08 and UV05) for the month of May 2010. The low frequency (<1Hz) seismic noise at La Réunion is high and mostly associated with ocean-generated microseisms. Compared to Geoscope/FDSN station RER, we observe a high noise power for UnderVolc stations for periods higher than 20 seconds. We interpret this as being partly due to the intrinsic noise response of the CMG-40T compared to the STRECKEISEN STS1 sensor at low frequency. The bins of powerful energy at about 20 seconds of period correspond to the magnitude 7.2 northern Sumatra earthquake that occurred on 9 May 2010. Station UV05, with the highest noise energy level, is characterized by a strong noise with dominant frequency of 2 Hz, which probably corresponds to the seismic signal generated by oscillations of the radio mast induced by wind.

MEASUREMENTS OF CONTINUOUS SEISMIC VELOCITY CHANGES

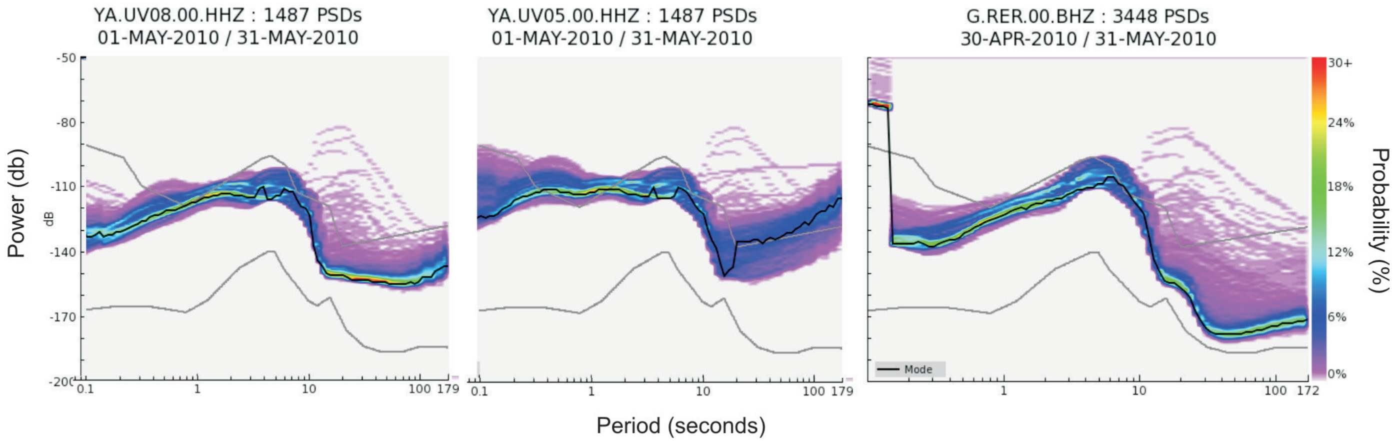
We have measured seismic velocity variations within the Piton de la Fournaise edifice from June 2010 to April 2011 following Brenguier *et al.* (2008). Because we have increased the number of stations and because we use broadband seismometers, compared to previous studies we are able to reduce the averaging time window from 10 to 5 days without increasing the associated error. Continuous seismic velocity changes as well as the daily seismicity rate are shown in Figure 4. We observe a strong velocity decrease starting about one month before the 14 October 2010 eruption. The velocity decrease correlates in time with an increase of seismicity and has been interpreted as the deformation of the edifice induced by magma pressure build-up and injection. Interestingly, seismic velocity increases during the eruption of October 2010 and after the short eruption of December 2010, indicating a possible mechanism of stress relaxation induced by the emptying of the magmatic reservoir.

This method is now used routinely at the Piton de la Fournaise observatory to improve eruption forecasting.

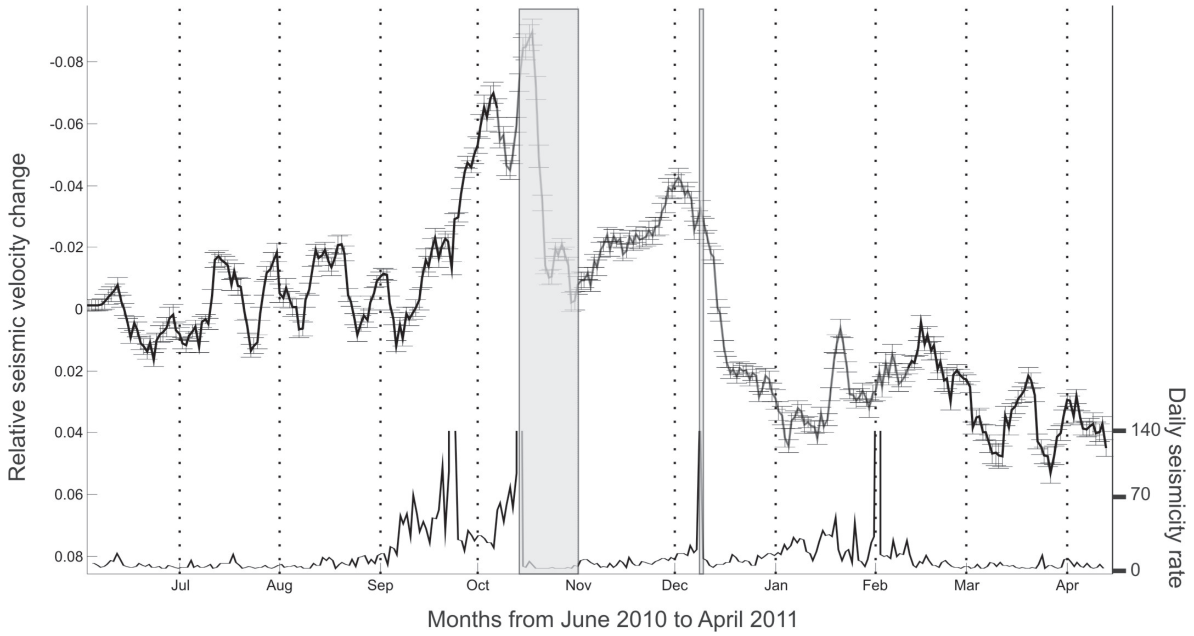
LONG-TERM TRENDS OF FLANK DISPLACEMENT INFERRED FROM GNSS (GPS and GLONASS)

Before 2009, only the summit cone was monitored by permanent GPS stations, preventing follow-up of the deformation outside this area. Only the study of the deformation associated to the dike injected close to the summit cone was possible (Peltier *et al.* 2008, 2009). One of the main goals of the UnderVolc project was the installation of seismic and GPS stations on the eastern flank of the volcano, which was not previously monitored. An eastward preferential flank motion was expected to explain the asymmetric deformation pattern associated with lateral dike injection (Peltier *et al.* 2009). Moreover, the previous GPS network did not allow recording the large flank displacement detected by InSAR of up to 1.4 m to the sea associated with the April 2007 large eruption. This large eastern flank displacement was probably triggered by a pre-eruptive magmatic intrusion (Massin *et al.* 2011; Clarke *et al.* 2011) and seems to be going on to a minor degree. Figure 5 shows the horizontal displacement measured by permanent DGPS since April 2010. Over one year a constant shift of up to 3.4 cm to the east is observed in the “Grandes Pentes” area. This is in agreement with InSAR displacement rates between 2009 and 2010, the figure of which is superimposed. Each InSAR fringe here corresponds to ~1.5 cm of displacement toward the satellite, which was roughly located east of La Réunion Island. DGPS and InSAR data are thus consistent and show a clear eastward displacement of the Piton de la Fournaise eastern flank by a maximum of more than 3 cm/year.

As discussed in Clarke *et al.* 2011, this deformation could be related to the relaxation of the massive flank instability that occurred in April 2007. In such a case the eastward movement should decrease with time. However, the eastward displacement rate observed by DGPS is quite constant over one year (Figure



▲ **Figure 3.** PQLX spectral analysis results for one month of seismic data for UnderVolc stations UV08 and UV05 and for seismic Geoscope/FDSN station RER located at La Réunion Island.



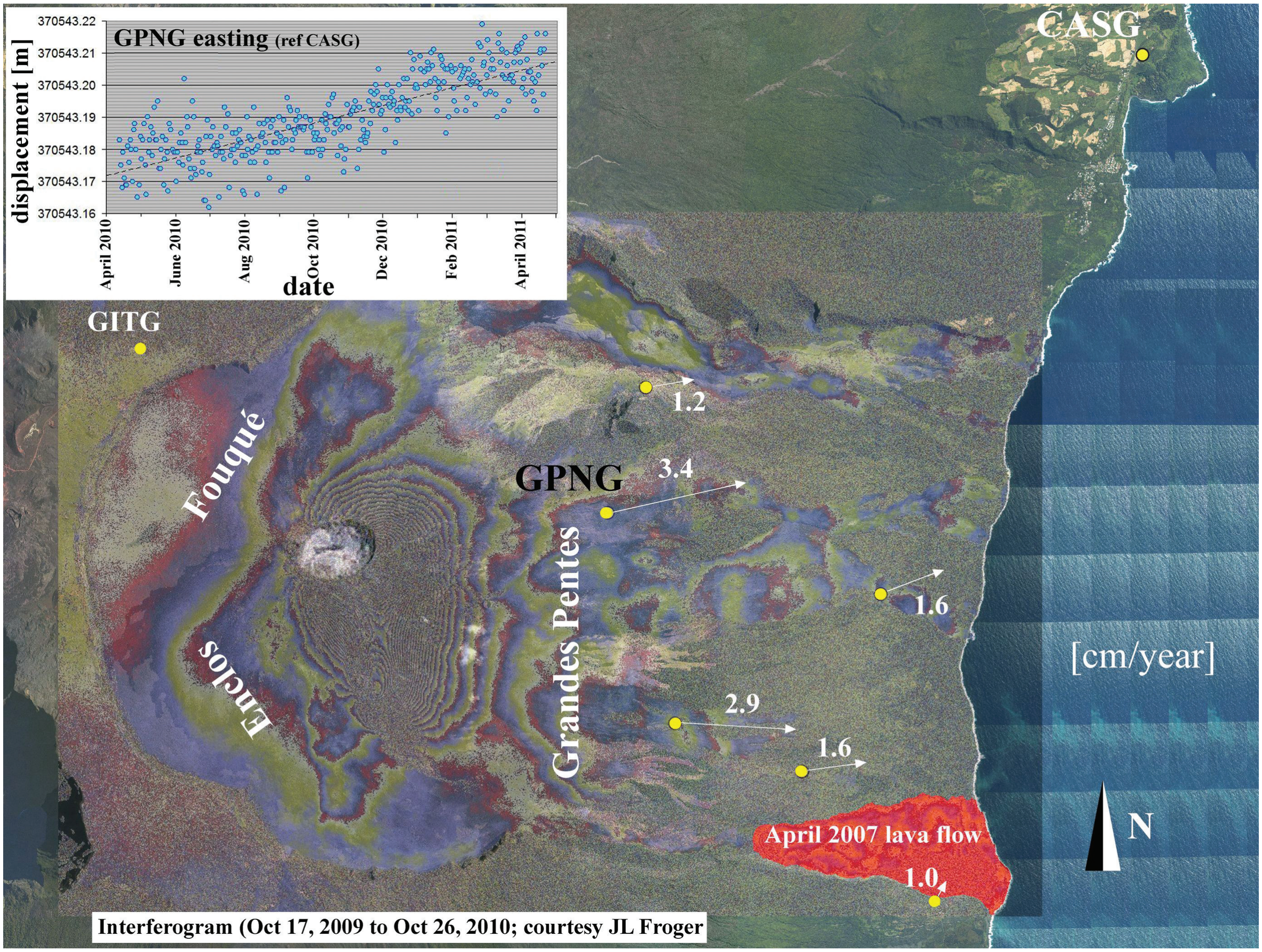
▲ **Figure 4.** Relative seismic velocity changes with error bars and daily seismicity rate between June 2010 and April 2011. Eruption periods are shown as gray rectangles.

5, inset). This observation would be interpreted as an ongoing instability that would affect the eastern flank and that could be associated with processes of creep and/or slow slip along a fault plane. The creep could be emphasized by stress accumulation on the unbuttressed eastern flank due to the successive intrusions and accumulation of magma in the reservoir (Peltier *et al.* 2009). Such permanent eastern flank instability would explain the asymmetric magma-induced pattern of deformation observed since the first geodetic measurements at Piton de La Fournaise (Letourneur *et al.* 2008; Peltier *et al.* 2009).

CONCLUSIONS

Piton de la Fournaise volcano is among the most active volcanoes worldwide. The UnderVolc project initiated a comprehensive, long-term seismo-volcanic research experiment based on high-resolution seismic and GPS data to shed light on complex volcanic processes. Our first results of improved continuous seismic velocity monitoring show a clear decrease of velocity one month prior to the October 2010 eruption. This observation indicates a longer pre-eruptive phase than what was reported before (Brenguier *et al.* 2008; Duputel *et al.* 2009), possibly related to the change in the edifice mechanical properties associated with the large 2007 eruption and crater collapse. Also, the long-term GPS measurements on the volcano's eastern flank show an eastward displacement of as much as 3.4 cm/year. A careful analysis of the data seems to indicate that this edifice flank instability is constant in time and thus possibly related to an ongoing process of creep and/or slow slip along a fault plane.

Finally, our aim is to provide extensive and public access to seismic data to foster collaborative research on a common active



▲ **Figure 5.** Comparison between DGPS (arrows) and InSAR (fringes) yearly displacement rates. Each fringe corresponds to approximately 1.5 cm of displacement eastward. The inset figure shows the eastward displacement of the GPS station GPNG over one year. InSAR figure is courtesy of J. L. Froger (LMV/OPGC).

target. We remind readers that the continuous waveforms are available using *netdc* to datacenter FOSFORE (netdc@fosfore.ipgp.fr) with network codes YA and PF for, respectively, the temporary and the permanent networks. In the near future, our goal will also be to develop and distribute novel operational routines for volcano monitoring such as real-time seismic velocity change monitoring using seismic noise cross-correlations.

ACKNOWLEDGMENTS

The data used for the analysis were collected by the Institut de Physique du Globe de Paris, Observatoire Volcanologique du Piton de la Fournaise (IPGP/OVPF), and the Institut des Sciences de la Terre (ISTerre) within the framework of ANR_08_RISK_011/UnderVolc project. The sensors are property of the French transportable seismic network, Sismob (INSU-CNRS). Data from broadband station RER are provided by the FDSN/Geoscope network. We are grateful to Jean-Luc Froger for providing the InSAR interferogram and to an anonymous reviewer whose comments greatly improved the manuscript. This work has been supported by Agence Nationale de la Recherche under contract ANR-08-RISK-011 (UNDERVOLC). This is IPGP contribution no. 3216.

REFERENCES

Brenguier, F., N. M. Shapiro, M. Campillo V. Ferrazzini, Z. Duputel, O. Coutant, and A. Nercessian (2008). Towards forecasting volcanic eruptions using seismic noise. *Nature Geoscience* **1** (2), 126–130.

Clarke, D., F. Brenguier, J. L. Froger, and N. M. Shapiro (2011). Remote observation of volcanic slope instability associated with magmatic injection.

Cros, E., P. Roux, J. Vandemeulebrouck and S. Kedar (2011). Locating hydrothermal acoustic sources at Old Faithful geyser using matched field processing. *Geophysical Journal International* doi:10.1111/j.1365-246X.2011.05147.x.

De Barros, L., I. Lokmer, C. J. Bean, G. S. O'Brien, G. Saccorotti, J.-P. Metaxian, L. Zuccarello, and D. Patane (2011). Source mechanism of long-period events recorded by a high-density seismic network during the 2008 eruption on Mount Etna. *Journal of Geophysical Research* **116**, B01304; doi:10.1029/2010JB007629.

Duputel, Z., V. Ferrazzini, F. Brenguier, N. M. Shapiro, M. Campillo, and A. Nercessian (2009). Real time monitoring of relative velocity changes using ambient seismic noise at the Piton de la Fournaise volcano (La Reunion) from January 2006 to June 2007. *Journal of Volcanology and Geothermal Research* **184** (1–2), 164–173.

Gerst, A., and M. K. Savage (2004). Seismic anisotropy beneath Ruapehu Volcano: A possible eruption forecasting tool. *Science* **306**, 1,543–1,547.

Got, J.-L., V. Monteiller, J. Monteux, R. Hassani, and P. Okubo (2008). Deformation and rupture of the oceanic crust may control growth of Hawaiian volcanoes. *Nature* **451** 453–456.

Grasso, J. R., and I. Zaliapin (2004). Predictability of volcanic eruption: Lessons from basaltic volcanoes. *Geophysical Research Letters* **31**, L05602; doi:10.1029/2003GL019022.

Hibert, C., A. Mangeney, G. Grandjean, and N. M. Shapiro (forthcoming). Slopes instabilities in the Dolomieu crater, la Réunion island: From the seismic signal to the rockfalls characteristics. *Journal of Geophysical Research*.

Letourneur, L., A. Peltier, T. Staudacher, and A. Gudmundsson (2008). The effects of rock heterogeneities on dyke paths and asymmetric ground deformation: The example of Piton de La Fournaise (Réunion Island). *Journal of Volcanology and Geothermal Research* **173** (3–4), 289–302.

Massin, F., V. Ferrazzini, P. Bachèlery, A. Nercessian, Z. Duputel, and T. Staudacher (2011). Structures and evolution of the plumbing system of Piton de la Fournaise volcano inferred from clustering of 2007 eruptive cycle seismicity. *Journal of Volcanology and Geothermal Research* **202**, 96–106.

McNamara, D. E., and R. P. Buland (2004). Ambient noise levels in the continental United States. *Bulletin of the Seismological Society of America* **94** (4), 1,517–1,527.

Peltier, A., P. Bachèlery, and T. Staudacher (2009). Magma transport and storage at Piton de La Fournaise (La Réunion) between 1972 and 2007: A review of geophysical and geochemical data. *Journal of Volcanology and Geothermal Research* **184** (1–2), 93–108.

Peltier, A., P. Bachèlery, and T. Staudacher (2011). Early detection of large eruptions at Piton de La Fournaise volcano (La Réunion Island): Contribution of a distant tiltmeter station. *Journal of Volcanology and Geothermal Research* **199**, 96–104.

Peltier, A., V. Famin, P. Bachèlery, V. Cayol, Y. Fukushima, and T. Staudacher (2008). Cyclic magma storages and transfers at Piton de La Fournaise volcano (La Réunion hotspot) inferred from deformation and geochemical data. *Earth and Planetary Science Letters* **270** (3–4), 180–188.

Staudacher, T., V. Ferrazzini, A. Peltier, P. Kowalski, P. Boissier, P. Catherine, F. Lauret, and F. Massin (2009). The April 2007 eruption and the Dolomieu crater collapse, two major events at Piton de la Fournaise (La Réunion Island, Indian Ocean). *Journal of Volcanology and Geothermal Research* **184**, 126–137; doi:10.1016/j.jvolgeores.2008.11.005.

Taisne, B., F. Brenguier, N. M. Shapiro, and V. Ferrazzini (2011). Imaging the dynamics of magma propagation using radiated seismic intensity. *Geophysical Research Letters* **38**, L04304; doi:10.1029/2010GL046068.

Observatoire Volcanologique du Piton de la Fournaise
14 RN3–Km 27
97418 La Plaine des Cafres
La Réunion, France
brenguier@ipgp.fr
(F. B.)