Tilt signals derived from a GEOSCOPE VBB Station on the Piton de la Fournaise Volcano

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Abstract. We report some very long period transients observed on a very broadband seismic station of the GEOSCOPE network, which is situated 8 km away from the summit of the Piton de la Fournaise volcano. We transform the ground velocity measured by the seismic station into tilt and test the result by comparing with data from Blum-type classical pendulum tiltmeters located in the same vault. The comparison validates the use of the horizontal seismometers for measuring tilt for periods shorter than 25 hours. The method is applied to the transients observed prior to several eruptions and magmatic intrusions since 1991. Because of the moderate distance between GEOSCOPE station and the summit of the volcano, the obtained tilt measurements provide information about eruptions and intrusions which complement the information on the geometry and location of the magmatic source provided by the summit tilt network.

Introduction

Piton de la Fournaise is a basaltic volcano located in the Indian Ocean, 700 kilometers east of Madagascar. It is one of the most active volcanoes in the world with a mean time between eruptions less than a year. Since 1980, the volcano has been monitored by an observatory. It has a network including about 20 permanent seismic stations, mainly short-period, which are digitally recorded by an event-triggering recorder. Signals from seven pairs of tiltmeters are also telemetered to the observatory. In addition to these devices directly related to volcano monitoring, a broadband seismic station of the global seismic network GEOSCOPE [*Romanowicz et al.*, 1991; *Montagner et al.*, 1998] was installed 8 km from the summit of the volcano in 1986. Following the recent development of broadband seismology on volcanoes [*Kawakatsu et al.*, 1994; *Neuberg et al.*, 1994] we took an interest in the data recorded at the GEOSCOPE station, which have not yet been used to study the volcanic activity.

Data from GEOSCOPE seismic station

A broadband seismic station of the GEOSCOPE global network (hereafter refered to as RER) is located at Rivière de l'Est about 8 km from the summit of the Piton de la Fournaise volcano (figure 1). Unlike the short period seismic stations of the observatory monitoring network which are not continuously recorded, RER station allows the continuous observation of low frequency seismic signals below 1 Hz. The station is equipped with a three component STRECKEISEN STS-1 seismometer [*Wielandt and Streckeisen*, 1982] located in a closed vault in the middle of a 4.7 km long tunnel. This environment provides high thermal stability, with diurnal variations of less than 0.1 ^oC [*Delorme*, 1994]. RER measures ground velocity at different sampling rates: continuous recording of the LP and VLP channels at 1.0 and 0.1 sps, respectively, and triggered recording of the VBB channel at 20 sps; since the beginning of 1998 VBB channel is recorded continuously. The instrument response of the station is well known and may be easily taken into account.

Since the installation of RER in February 1986, there were frequent eruptions until 1992. From 1992 until near the end of 1996, the seismic activity slowly decreased with no eruption or intrusion (seismic swarm without surface activity). Then, a seismic crisis occurred in November 1996 and the seismicity beneath the summit increased after July 1997 until the eruption on March 9, 1998. We checked the continuous raw VLP records obtained since the installation of the station in order to find any signal related to the eruptions or intrusions. We observed some unusual transients for the 3 eruptions that occured since July 1990 (19-20 July 1991, 27 August - 23 September 1992 and 9 March - 21 September 1998) and for the two seismic swarms without eruption (7 December 1991 and 26 November 1996). In one of those cases, the signals have very low amplitudes and are difficult to distinguish from the background noise or signals due to the earth tide. However, the transients recorded during the 1991,1992 and 1998 eruptions and the 1991 intrusion (figure 2), are clearly related to volcanic activity.

Prior to July 1991, no signals from eruption were observed, presumably because the sensitivity of the recording system was much lower: 12 bit gain-ranged from 1986 to July 1990 and 24 bits (VLP) since 1990. Other transients observed from time to time are mainly due to human interventions in the vault or nearby. We have not, so far, found any monochromatic long period tremors like those observed by *Kawakatsu et al.* (1994) for Aso volcano.

Figure 2 displays clear variations of ground velocity on the north-south component. Some weak signals may also be observed on the east-west component but nothing anomalous appears on the vertical component. This basic difference between the 3 components is commonly observed for different eruptions or intrusions. In each case, the onset of the transients (dotted line A) may be correlated with the start of a swarm of volcano-tectonic earthquakes (seismic

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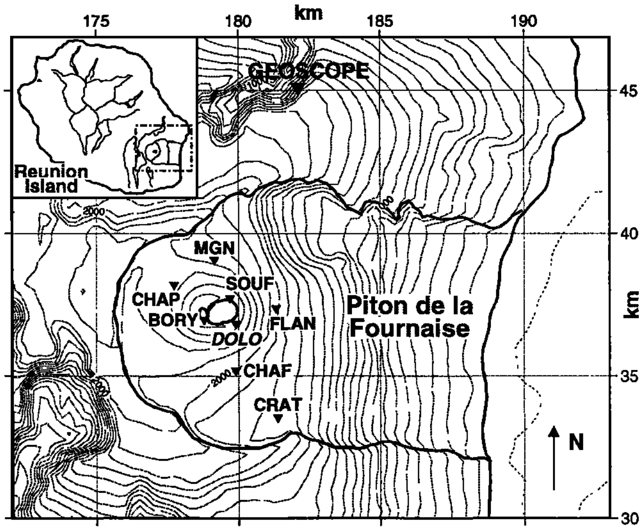

Figure 1. Map showing the location of the Piton de la Fournaise volcano on Réunion Island. Triangles represent the location of the tiltmeters of the monitoring network.

crisis) beneath the summit area and/or with some large tilt variations on the summit tiltmeters. This suggests that the signals are directly related to the volcanic activity.

Method

Because the observed long period pulses appear on only the horizontal components, we propose to interpret the transients as tilt variations [*Aki and Richards*, 1980], assuming that the horizontal ground acceleration is caused primarily by tilt at the recording site. We use the following relation (1) between the tilt variation Θ and the ground velocity measured by the seismograph:

$$\Theta = -\frac{1}{g}\gamma_{ground} = -\frac{1}{g}\frac{dv_{ground}}{dt}, \qquad (1)$$

where γ_{ground} is ground acceleration. Obtaining tilt from the recorded seismic data is done as follows. First, the ground velocity is obtained from the raw data after correcting for the instrument response. Differenciating the ground velocity, we obtain ground acceleration, which is then used in relation (1) to obtain the ground tilt. We use "RER_{tilt}" to refer to the ground tilt calculated from the seismic ground velocity recorded by the STS-1.

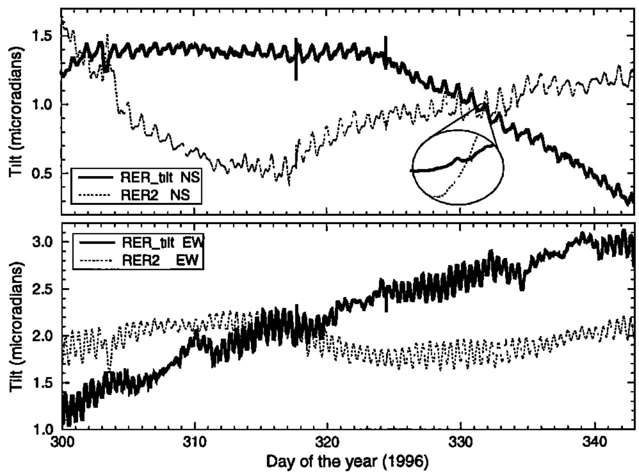

Figure 3. Tilt records from tiltmeter station RER2 and derived tilt records RER_{tilt} from the seismic ground velocity at the GEOSCOPE station RER. Top figure compares NS components; bottom figure compares EW components. Records are for a 43-day-long period in November 1996. The zoomed part on the NS curves shows the transient related to the 26 november seismic crisis, the signal is only observed on GEOSCOPE. Very long-term variations are different for the two kinds of instruments, but shorter-term variations are similar.

Comparison with records of tiltmeters

STS-1 seismometers (vertical component) were used for example by Pillet et al. (1994) outside their traditional spectral range (0.1-3600 s) for retrieving tidal signals near diurnal frequencies. Otherwise, earlier generation long period horizontal seismographs have been used to measure tilt [*Eaton et al.*, 1987] for very long period and modern seismographs have been used to measure tilt in the near-field of strombolian explosions [*Wielandt and Forbriger*, 1999] for periods between 20 and 200 seconds. In order to validate the use of horizontal STS-1 components for measuring tilt in subseismic bands we first compared tilt obtained from GEOSCOPE seismometers with the measurements obtained from classical tiltmeters.

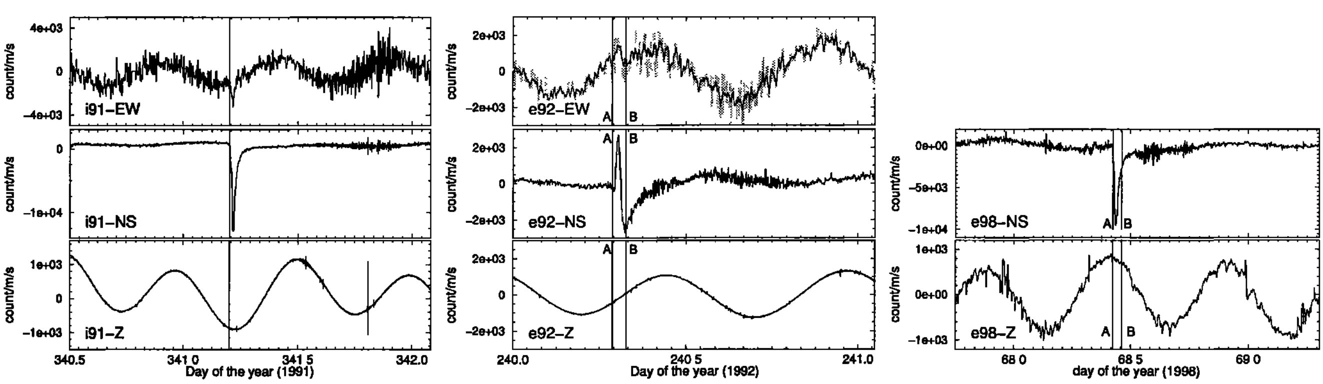

Figure 2. Seismic velocity signals (VLP) observed at RER station for 2 eruptions in 1991 (e91) and 1992 (e92) and an intrusion in 1991 (i91). Data are not corrected from the instrument response and presented in count/m/s. The first dotted lines (labelled A) indicate the approximate beginning of the seismic crises and the second ones (B) in the case of the eruptions corresponds to the beginning of surface activity.

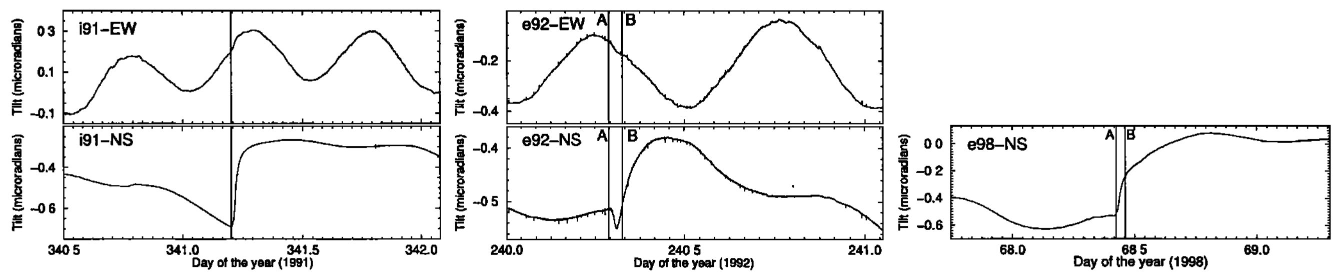

Figure 4. Tilt records derived from the VLP seismic signals observed at RER station for the 1992 and 1998 eruptions and for the 1991 intrusion (figure 2). Time scales are the same as on figure 2 and the dotted lines have the same meaning.

Two Blum-type tiltmeters [*Blum et al.*, 1991] are located in the same vault as the GEOSCOPE seismometers. Those instruments (hereafter refered to RER2) are astatic mechanical pendulums with a short base [*Agnew*, 1977] and are made of fused silica. In the present case, each tiltmeter (radial and tangential) is fixed on a silica base with two levelling screws and is simply lying on the concrete floor. Data from those tiltmeters are recorded at a rate of one sample per two minutes. Since the two tiltmeters are approximately oriented radially and tangentially to the summit of the volcano, we rotate RER2 data to north-south and east-west axis before comparison.

An example of comparison is shown for the data collected during a period of 43 days around November 1996. The choice of this time period was due to the good quality of data during this period, all sensors were working properly and there wasn't any interruption or technical problem. Figure 3 presents the unfiltered tilt signals measured by RER2 tiltmeters (after rotation) and those deduced using relation (1) from RER signals (RER_{tilt}); both components (east-west and north-south) are shown. Very long-term (several days) variations are clearly different for both directions (NS and EW) and may be due to the different instrumental drift characteristics between the tiltmeters and the STS-1. However, a very good cross-correlation is obtained between the signals from the two instruments when supressing periods longer than 25 hours: both instruments show tidal signals with similar amplitude (0.1-0.2 μRd) and shape. Some remaining differences may be attributed to the different characteristics of the instruments and to some possible errors in instrumental calibrations. GEOSCOPE seismometers seem to be more sensitive for periods around an hour and shorter as it appears on figure 3 where a slight signal related to the 1996 magmatic intrusion may be observed on the NS component while nothing appears on the Blum-type tiltmeters. At this point we have no explanation for this difference of sensitivity except for the difference of installation: broad band seismometers were installed carefully (e.g., Urhammer et *al.*, 1998) while tiltmeters were simply placed on the concrete floor.

Tilt transients associated with eruptions and intrusions

The application of our method to the seismic transients presented in Figure 2 leads to the tilt records presented in figure 4. All tilt variations have amplitudes of a few tens of microradians or less, and appear mainly on the north-south component which is in a nearly-radial direction from the summit of the volcano.

The signal obtained for the 1991 intrusion is similar to the one obtained for the 1998 eruption. In each case, tilt suggests a monotonic inflation of a source situated under the volcano. For the 1991 intrusion, the tilt signal at RER starts at about the same time as the seismic swarm originating under the summit of the volcano and the large tilt transients observed on tiltmeters in the summit area. The March, 1998 eruption has been studied in detail [*Staudacher et al.*, 1998]. The pre-eruptive volcano-tectonic swarm lasted for about 35 hours, starting at focal depth of 5 km below sea level (7.5 km below the summit). However, the main deformation at RER, as well as at tiltmeters located in the summit area, started only one hour before the beginning of eruption. Using Okada's formulas [*Okada*, 1985] for an opening rectangular dislocation in a homogeneous half space, we are modelling the derived tilt (RER_{tilt}) and tiltmeter data in the summit area (stations on figure 1); results indicate a shallow inclined dyke extending north of the summit along an almost NS direction with a total volume of about 2×10^6 m^3. The characteristics of this dyke are similar to those of the model deduced from interferometry by Sigmundson et al. (1998) for the same eruption of the Piton de la Fournaise. Summit tiltmeters provide constraints on the geometry and location of the dyke while the tilt ar RER provides complementary constraints, particularly on the total volume of magma intruded into the dyke. The location of the seismic station at a moderate distance from the summit (8 km), makes it less sensitive to the geometry and location of the source than the tiltmeters located much closer to and right above the source.

For the 1992 eruption the signal observed on RER is different from the 1998 eruption. It starts with deflation that coincides with the beginning of the pre-eruptive volcano-tectonic swarm. This deflation is confirmed by the tiltmeter CHAP (figure 1), located about two kilometers NW of the summit. On the other hand, tiltmeters located at the summit (SOUF, DOLO and BORY) are already dominated by effects related to dyke injection at this time. Following the initial deflation on RER_{tilt} is an inflation that continues until the beginning of eruptive activity (dotted line B). A signal of the same characteristic was also observed for the eruption that occured in july 1991 suggesting a common eruptive mechanism for those two eruptions. This difference between the signals observed for the 1991 and 1992 eruptions and the 1998 eruption is probably due to different eruptive mechanisms. According to geochemistry [*Bachèlery*, 1999], the small amounts of lava emitted during the 1991 and 1992 eruptions were emplaced in the superficial magmatic system during the 1977 eruption, while the 1998 eruption was triggered by an income of magma coming from deeper areas of the volcano.

Conclusions

We show in this paper that the horizontal components of continuous seismic velocity data recorded by the very long period (VLP) channel of the GEOSCOPE seismic station RER, located 8 km from the summit of the Piton de la fournaise volcano, can be transformed to tilt. Furthermore, we show that for periods less than 25 hours, the derive tilt is comparable to the Blum-type tiltmeters records recorded in the same vault. The observation of the seismic signals recorded at RER indicates the presence of transients directly related to the volcanic activity. In the case of the eruption that occured in March 1998, derived tilt records are consistent with inflation of a dyke north of the summit of the volcano. Recent modelling indicates that, due to the moderate distance between the station and the source of deformation, these records provide strong constraints on the intrusive process (e.g., intrusive volume) which are not provided by summit tiltmeter data.

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