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Monitoring a temporal change of seismic velocity in a volcano: application to the 1992 eruption of Mt. Merapi (Indonesia)

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Abstract. Multiplets, i.e. events with similar waveforms, are selected from shallow earthquakes recorded on Merapi volcano (Indonesia) before the eruption of February 2nd, 1992. Two multiplet families are found with their sources close to the summit. Their seismograms are analyzed using the Moving Window Cross Spectrum technique which measures the precise time delay between seismic phases in the entire seismogram. For both families of multiplets, a gradual decrease in the arrival times of coda waves is observed as a function of the date prior to the eruption: coda waves are becoming progressively faster (up to 1.2 per cent) as the time interval to the eruption shortens. This observation is interpreted as the consequence of an increase in the seismic velocity inside the volcano. The increase in velocity started in May 1991 and was observed until September 1991, 4 months before the eruption. This velocity increase may be related to an increase in pressure in the magma chamber or in the conduits and to the resulting closure of the surrounding cracks.

Introduction

The Merapi volcano (2965 m) is one of the active volcanoes in Central Java, Indonesia. It is characterized by the presence of an andesitic lava dome which forms during periods of enhanced activity. The volcano is intensely monitored by the Merapi Volcano Observatory (MVO), a department of the Volcanological Survey of Indonesia (VSI). The question of whether a high level of seismic activity is a precursor to an impending eruption is always in the mind of volcano observers. The study of the physical properties inside the volcano, for instance the measurement of a variable related to the pressure within the magma chamber, would help in assessing the danger of an eruption or of instability. Unlike a tremor, such a parameter would not be a short-term precursor to an eruption but a medium range precursor.

In this study, we use doublets, pairs of similar earthquakes, to monitor temporal velocity variations. Doublets or multiplets (more than two similar earthquakes) are frequently observed on volcanoes (Okada *et al.*, 1981; Okada, 1983; Frémont and Malone, 1987). Their similarity indicates that their sources are spatially near. The distance between sources is much smaller than the source-receiver distance. Due to this ray path similarity, doublets study is a precise method to detect small temporal changes in physical properties in the medium traversed by seismic waves.

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Data and Method

Selection of multiplets

Six seismic stations are installed on Merapi volcano (Fig.1) and the data are telemetered to the MVO in Yogyakarta. The seismometers are Mark Product L4C - 1 Hz. The seismic signals are digitized at frequency of 100 Hz and are recorded on a PC with PCEQ software (Lee, 1989). An independent clock signal is recorded as a pulse-per-second (PPS) signal in the same record.

Earthquakes are routinely localized by using the simplex method (Pruger and Gendzwill, 1988) which performs a grid search to find the minimum of the arrival time residuals. A homogeneous half-space, a P-velocity of 3 km/s and a V_P/V_S ratio of 1.86 were used (Ratdomopurbo, 1994). The hypocenters distribution of volcano-tectonic (VT) earthquakes recorded from January 1991 until the 1992 eruption are presented in Fig. 2. They can be divided into two groups: deep earthquakes (VTA) and shallow earthquakes (VTB). A gap in seismicity at a depth of 1 - 2 km beneath the summit separates both groups and can be interpreted as the expression of a superficial magma chamber.

The magnitudes of VTB events range from -0.6 to 1.8. In this analysis, we use the shallow events recorded at the summit station PUSV (2625 m), located less than 1 km away from the crater. The selection of shallow events and the choice of the station are based on the expectation that the corresponding source-receiver paths for coda waves are concentrated near the summit zone. Identification of multiplets was performed visually from their traces on seismograms. About 25 % of the 1991 events belong to multiplets. To know their average location, we stacked all traces in each station and determined the hypocenter of the stacked event. This technique improves significantly the S/N ratio and thus makes phase arrival picking easier. We are interested in doublets with a sufficient temporal gap: temporal doublets. From the 4 multiplets we found, multiplets-1 and multiplet-2 have a longer temporal coverage than the others. Seven events of each multiplet are selected in a way that each event occurs in a different month (Fig. 3). Multiplet-1 has a temporal coverage extending from January 1991 to September 1991, whereas multiplet-2 covers a period from January 1991 to October 1991.

Moving-Window Cross-Spectral (MWCS) analysis

The purpose of this analysis is to detect any change in the waveforms of the seismograms of a doublet. First, the seismograms are aligned with a precision of one sample, i. e. 10

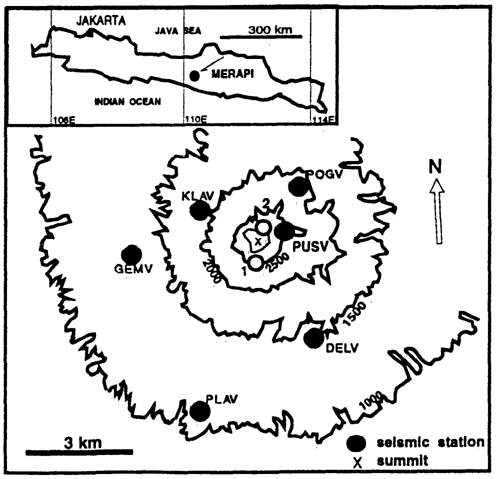

Figure 1. Seismic array operated on the Merapi by the VSI. Average epicenter position of multiplet 1 and 2 are indicated by open circles. Inset: position of Merapi volcano in Java island.

ms. For the processing, a window of 1.28 s is taken and tapered by a Hanning function. In a given window, the phase spectrum ϕ of the cross-correlation between two events is linearly proportional to the frequency f and to the time delay between the two signals Δt; $\phi(f) = 2\pi \Delta t f$. Thus the delay Δt between the two traces can be computed from the slope b of the phase of the cross-correlation (Poupinet *et al.,* 1984); $\Delta t = b/(2\pi)$. The phase error σ is estimated by:

$$\sigma^2 = \frac{1}{2 B_\omega T}\left(\frac{1}{C^2} - 1\right)$$

where C is the coherency, B_ω and T are the bandpass and the duration of the signal respectively. The slope b is estimated by a linear regression that takes into account the phase error σ as a weighting factor.

Relative relocation of multiplets

First for each station that recorded a doublet, we apply the cross-spectrum technique to compute the difference in P-wave arrival times. The first event was taken as the reference. For the absolute hypocenter position, we take that of the stacked seismogram. The relative location Δx, Δy, Δz is obtained by minimizing the square of the observed delays minus the delays computed on a XYZ grid. The coordinates relative to the first

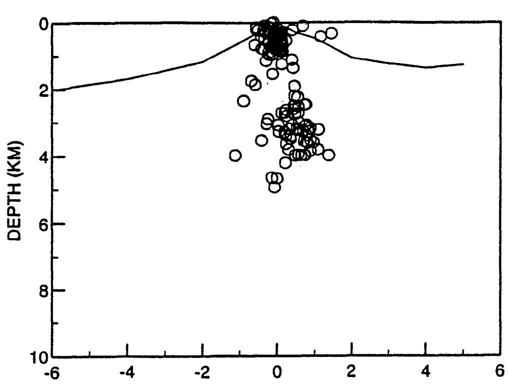

Figure 2. Cross-section of Merapi volcano showing the distribution of VT earthquakes. Events can be separated into two groups: VTA (depth > 2 km) and VTB (depth < 2 km). Both types of events seem to be separated by an aseismic zone at a depth of about 1.5 km.

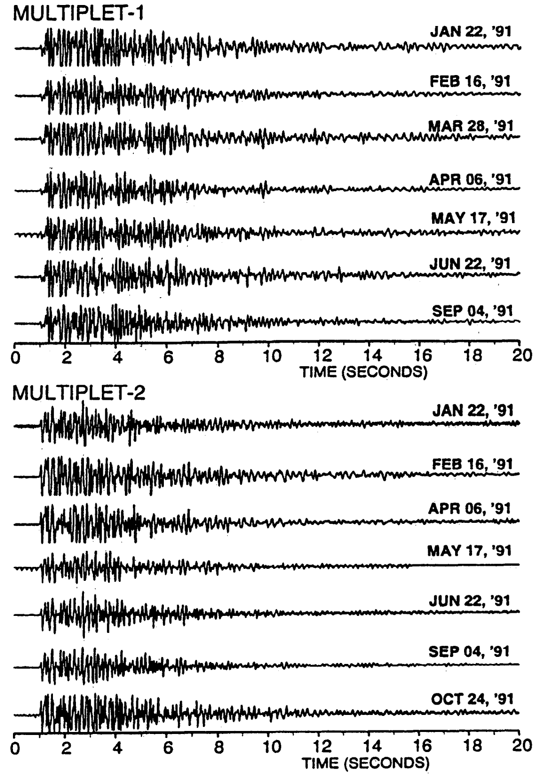

Figure 3. Seismograms of the two multiplets recorded at PUSV. They have been aligned on the arrival time of P-wave.

hypocenter are given in meter in table 2; their precision is of the order of 10 meters. The hypocenters of multiplet-1 are plotted on a horizontal and vertical cross-sections in Fig. 4. All the epicenters are concentrated within 10 meters for seven events in multiplet-1.

Analysis of temporal variations in the coda of multiplets

The MWCS analysis is applied to the entire seismograms recorded at PUSV to find velocity variations. We compute the time delay between the two seismograms for each window starting from the P-wave arrival until the end of the coda with a step of 0.1 second. Fig. 5 shows an example of the computation of the delay between the seismograms of two events belonging to multiplet-1 which occurred in June 22, 1991 and in September 4, 1991, respectively.

The coda is the superposition of scattered S waves that are radiated from the earthquake source and that travel through an heterogeneous medium before they are recorded at a seismic station (Aki and Chouet, 1975). The longer the path travelled by the scattered wave, the later this wave is recorded on a seismogram. Let us consider a doublet, i.e. two earthquakes

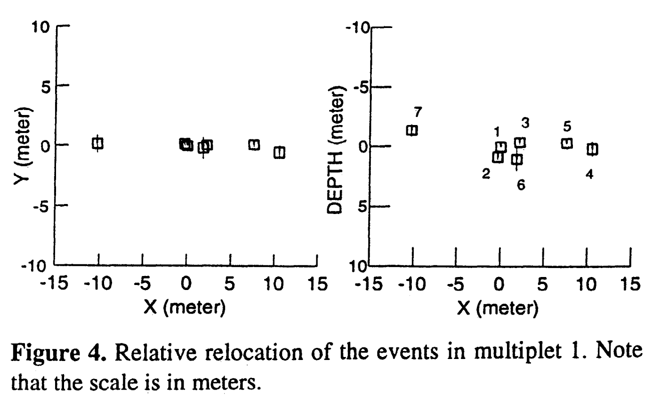

Figure 4. Relative relocation of the events in multiplet 1. Note that the scale is in meters.

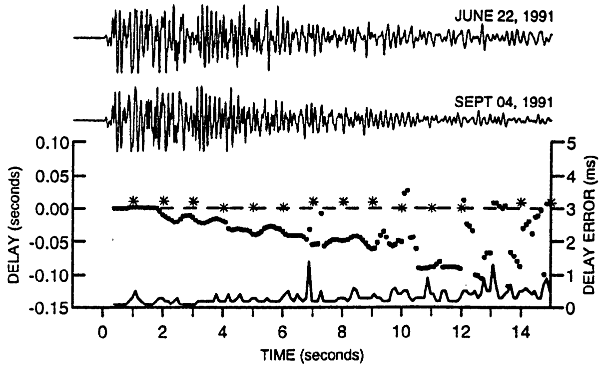

Figure 5. Processing of two seismograms, aligned on the P-wave arrival time, from a doublet recorded at PUSV. The time delay is computed all the way along the seismogram. The slope of the time delay is proportional to the S-velocity change $-\Delta V/V$. Stars are the delay of the PPS clock signal. Errors in delay calculation are presented in the lowermost line graph (right scale).

occurring at different dates and at the same hypocenter. For a wave from the first event the time t used to travel a distance L is equal to L/V, where V is the average velocity along the ray path. For the second event of the doublet, the travel time $t+\Delta t$ for the same wave travelling the same path with a new velocity $V+\Delta V$ is $(t + \Delta t) = L/(V + \Delta V)$, where Δt is the difference in travel time. Combining the last two equations and assuming that $(\Delta V.\Delta t)$ is negligible, we find $\Delta t = -(\Delta V/V).t$. This relationship means that the fractional change in velocity is equal to the slope of the time delay in the coda. A decrease in delay time along the seismogram indicates an increase in velocity. The slope is calculated using a coherence weighted linear regression. The delay pattern between the direct body waves is different from the delay pattern in the coda: for the direct waves, within a 2 second interval following the first arrival, the delay time is constant and then it gradually decreases along the coda.

Error on each delay calculation is less than 0.002 second, much smaller than the sampling period. To check the possibility that it results from sampling drift, we apply the MWCS technique to the PPS signal which is recorded in parallel with seismic signals. The delay time of the PPS signal is about constant along the seismogram (stars in Fig.5): it fluctuates around one sampling period. The slope of the delay in the coda is much bigger than the delay in clock pulses so it is not an instrumental drift.

To know if there was a temporal velocity variation before the 1992 eruption we applied the MWCS technique on the selected multiplets (Fig. 3). To maintain a high coherency level, instead of using the first event as a reference, the MWCS analysis was done on pairs of successive events. Every event is compared to the event that precedes it. Velocity changes were then reconstructed as if we were using the first event as a reference.

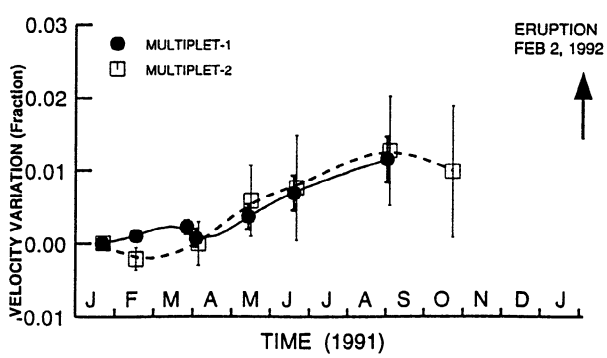

Figure 6. Plot of the S-velocity change measured at PUSV as a function of date. The onset of the eruption is marked by the arrow.

Table 1. Coordinates of the hypocenters of multiplet 1 and 2. The reference (0,0,0) is the summit of the volcano.

	Numbers of events stacked	E - W (km)	N - S (km)	Depth (km)
Multiplet-1	10	.089	-.658	.590
Multiplet-2	41	.176	.210	.930

We applied the same procedure to the events of multiplet-2. The variation pattern is similar for both multiplets. The velocity started to increase in May 1991 and it changed by up to 1.2 per cent in September 1991 (Table 2 and Fig. 6). Events in multiplet-1 are situated in a zone less than 30 meters wide (Fig 4). There is no systematic relationship between event position and the measured time delay.

Interpretation

Our results show that in the Merapi volcano, the precursory period can be divided into two periods: first between January 1991 to April 1991, the velocity was stable. Then from April 1991 to September 1991, the continuous increase in seismic velocity was of the order of 1.2 per cent for a period of 150 days. About half the velocity change occurred in May 1991-June 1991, about 8 months before the eruption.

We have analyzed coda waves which are essentially composed of scattered S-waves, thus what we have measured is the change in S-velocity in the region around the source-receiver region. The velocity change is probably related to a pressure change within the magma chamber and in the conduits.

An eruption usually results from an increase of pressure inside the magma chamber; pressure is at least higher than lithostatic pressure. This increase in pressure results either from a transfer of magma from below (Blake, 1984) or from fractional crystallization and over-saturation of volatiles in the magma chamber (Tait *et al.*, 1989). Changes of pressure of the order of 10 - 50 MPa are necessary to open a conduit and to provoke an eruption (Bardintzeff, 1992). The edifice of a volcano whose

Table 2. Velocity changes measured from seven events of multiplets 1 and 2. The event position relative to the first event is presented as Δx (W-E), Δy (S-N), Δz (Depth). The velocity change (column 6) and its errors (column 7) are in fraction.

Multiplet-1.

No	Date of event	Δx (m)	Δy (m)	Δz (m)	$\Delta V/V$ fraction	Error
1	21-01-1991	0.00	0.00	0.00	0.0000	0.0000
2	16-02-1991	-0.29	0.15	0.81	0.0011	0.0003
3	28-03-1991	2.21	0.02	-0.37	0.0023	0.0009
4	06-04-1991	10.5	0.48	0.14	0.0008	0.0013
5	17-05-1991	7.59	0.06	0.32	0.0037	0.0017
6	22-06-1991	1.84	0.17	1.01	0.0069	0.0024
7	04-09-1991	-10.3	-0.17	-1.34	0.0116	0.0031

Multiplet-2.

No	Date of event	Δx (m)	Δy (m)	Δz (m)	$\Delta V/V$ fraction	Error
1	21-01-1991	0.00	0.00	0.00	0.0000	0.0000
2	16-02-1991	2.74	-0.10	0.15	-0.0021	0.0015
3	06-04-1991	7.77	0.68	0.85	0.0000	0.0030
4	17-05-1991	-2.58	0.10	-0.03	0.0059	0.0049
5	22-06-1991	1.29	1.53	-1.59	0.0076	0.0072
6	04-09-1991	-24.9	12.7	24.63	0.0127	0.0075
7	24-10-1991	-74.1	7.90	11.26	0.0099	0.0090

activity is almost uninterrupted is certainly very fractured and fluids are pervasive in the summit area. Seismic velocity and anisotropy in cracked rocks is dependent on stress (Birch, 1960; Nur and Simmons, 1969). Velocity increases when the effective crack density in the medium decreases (O'Connell and Budiansky, 1974). A decrease in crack density can be caused either by an increase of pressure, without any fluid participation, or by a migration of fluids into the cracks. We think that the second possibility is more likely the case, especially before an eruption when the role of magma fluid becomes important. Using data for granulite samples (Manghani *et al.*, 1974), a change of pressure of 50 MPa (0.5 kbar) from 50 MPa to 100 MPa would induce an average change in S velocity of 0.044 km/s or 1.2 per cent.

Another possibility is that the coda is composed of several reflected waves. Thus, time delay variation could result from a velocity change in a restricted zone located between source-receiver and the reflectors, i.-e. below the station because the source-receiver distance is about only 1 km. The time delay starts to vary 2 seconds after the P-arrival. For instance, the phase arriving 2.5 seconds after the direct P-wave has a time delay of about 0.02 second. If this phase is a single reflection, the depth of the reflector would be about 2.5 km, for a S-velocity of 2.0 km/s and the zone above that depth should undergo a velocity change of less than 0.02 km/s. There might be a relationship between our observation and the aseismic zone separating VTA events from VTB events (see Fig.2).

We can suppose that the velocity increase is essentially located inside and close to the magma chamber. Thus, the velocity variation might be due to the change in the state of the magmatic fluid from equilibrium to a compressive caused by a new magma supply the deeper crust. Some VTA events have been recorded before the eruption of 1992 so that replenishment of the magma chamber is a possibility. Multiple reflections which travel through the zone of increasing velocity would give gradually decreasing time delays along the seismograms.

A limitation in applying this technique is that we need doublets occurring sequentially in time before an eruption. We did not find any doublet after October 1991 until the onset the eruption in February 1992. Error in the calculated velocity variation depends strongly on the degree of similarity between events in a multiplet. Multiplet-1 has a higher similarity than multiplet-2 so that its error is only about one third that of multiplet-2 (Fig. 6). The degree of event similarity in the multiplet is an important point that should be considered in the data selection to find a robust result in monitoring velocity variation.

Conclusion

The processing of temporal multiplets by the MWCS technique provides a means to measure temporal variations of seismic velocity inside a volcano. The result shows that S-velocity in the Merapi volcano had changed since eight months before the 1992 eruption and increased by about1.2 per cent. We infer that it results from a pressure increase in the magma chamber and in the surrounding medium. This variation is much larger than that detected in an active tectonic region like California (Poupinet *et al.*, 1984; Ellsworth *et al.*, 1992). Because the velocity started to vary eight months before the eruption, it may be useful as a long term precursor to an eruption. Doublet analysis has a potential to monitor the variation of internal pressure and to assess the impending probability of an eruption. Controlled experiments using artificial sources could complement natural doublet studies to improve the measurement of possible velocity variations.

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