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Using topographic signatures to classify internally and externally driven tilt anomalies at Merapi Volcano, Java, Indonesia

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[1] A 3-dimensional Finite-Element-Model of Merapi Volcano was developed to calculate the surface deformation field in response to internal pressure variations. The model geometry is based on a new Digital Elevation Model with a grid size of 15 m and an accuracy of 7 m. This allows an investigation of local effects due to radially striking features like deeply eroded canyons, separated by narrow ridges. Close to the ridge margins, topographic disturbances are invoked with amplitudes comparable to the expected signal on a smooth surface. Comparison of the model results with observed tilt records at four locations reveals that topographically induced tilts exhibit a certain pattern that differs systematically from the spatial characteristics of tilt disturbances induced by meteorology. We conclude that a monitoring of the difference of two instruments located at opposite ridge margins provides a simple test to discriminate externally from internally driven tilt anomalies. **Citation:** Westerhaus, M., J. Altmann, and O. Heidbach (2008), Using topographic signatures to classify internally and externally driven tilt anomalies at Merapi Volcano, Java, Indonesia, *Geophys. Res. Lett.*, *35*, L05310, doi:10.1029/2007GL032262.

1. Introduction

[2] Deformations of the volcano's edifice due to pressure changes within the internal system of magma chambers and conduits are among the most important volcanic activity parameters. A quantitative interpretation of deformation time series (displacement, tilt or strain records) requires an assessment of topographic disturbances that are effective on length scales from meters to kilometers. Changing surface slopes during phases of inflation or deflation induce considerable deviations from the expected, purely pressure related deformation field. Furthermore, topography promotes environmental disturbances as it initiates gravitationally driven ground water flow and determines the flow direction which in general follows the surface slope. Ground water induced soil movements constitute an important noise source that under unfavourable conditions may imitate the deformation field of an internal pressure variation.

[3] The potential similarity of deformation fields related to groundwater movements and internal pressure variations is easily illustrated for an axially symmetric cone with a central pressure source: the radial components of the displacement- and tiltvectors are aligned with a horizontal projection of the surface gradient vector (note, that tangential displacements and tilts are zero for a symmetric cone). The danger of misinterpretation is especially high for volcanoes such as Merapi that are continuously active on a certain pressure level with only small fluctuations. Thus, understanding the composition of deformation time series and a proper discrimination of volcanic and non-volcanic constituents of the signal is a prerequisite for using this information to assess volcanic hazard.

[4] The basic model used to interpret deformation data is a point source in a homogeneous half space [*Mogi*, 1958]. Corrections have to be taken into account, if the point source is replaced by a spherical, finite source [*McTigue*, 1987], or if the geometry deviates from the half space approximation. To avoid significant errors in the estimation of source depth and –volume, the full 3D topography of volcanoes with prominent relief is needed [*Cayol and Cornet*, 1998; *Williams and Wadge*, 2000]. *Beauducel and Cornet* [1999] adopted a 3D mixed boundary elements approach to model pressure induced tilts for a station located at the south-east flank of Merapi volcano. Near-field topographic effects on the tiltmeters were taken into account on the basis of a digitized topographic map (scale 1:50,000) from 1964. Their analysis revealed that tangential tilts vary strongly over short distances due to topography effects and may reach considerable amplitudes.

[5] In this paper, we model deformations of the edifice of Merapi Volcano due to an internal pressure variation by means of a 3D Finite-Element (FE) approach. We use a new Digital Elevation Model (DEM) with improved resolution and reliability. The modelled tilts are compared with observations at four tiltmeter arrays located at the south eastern, western, and northern flanks of Merapi Volcano at elevations ranging from 1300 m to 2062 m (Figure 1a). Our study emphasizes the importance of the tangential tilt component, and we propose a simple method to identify rain induced disturbances and to separate them from tilt signals caused by internal pressure variations.

2. The Model

[6] To incorporate the pronounced topography of Merapi Volcano we employ a new DEM developed by *Gerstenecker et al.* [2005]. The grid size is 15 m * 15 m; the mean circular and vertical accuracy was shown to be better than 7 m at the 95% confidence level. The full resolution of the DEM was used for 750 m * 750 m wide regions centered at the four tiltmeter arrays (Figure 1b). Outside this region the mesh size increases rapidly with increasing distance from a station. A sensitivity analysis verified that this kind of submodeling has negligible influence on the tilts in the center as long as a minimum size of 600 m * 600 m of the high resolution region is maintained. The size of the whole

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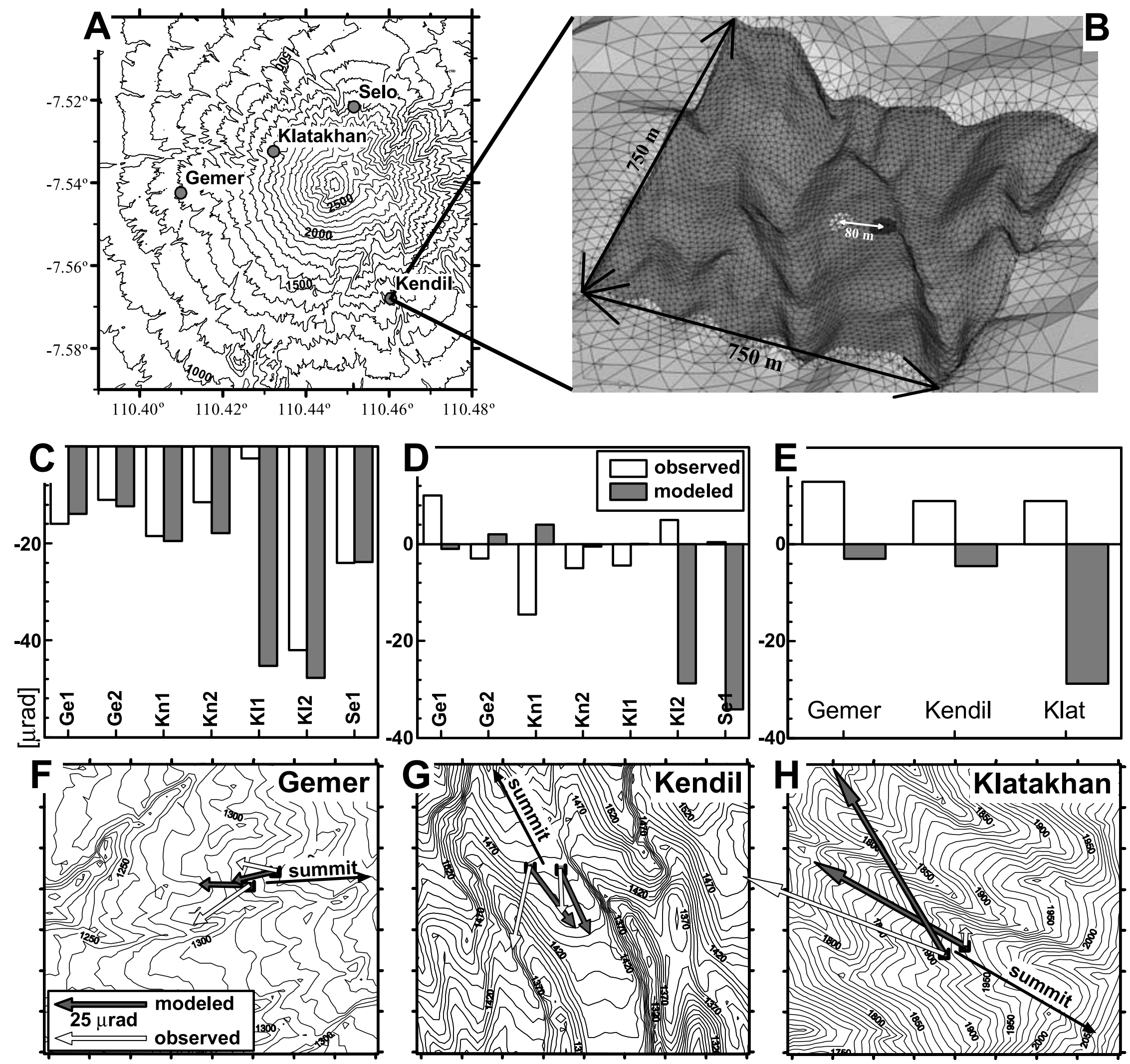

Figure 1. (a) Topographic map of Merapi Volcano showing the location of the tiltmeters. (b) Section of the Finite-Element-Model of Merapi Volcano. (c–h) Comparison of observed seasonal tilt variations and calculated tilt anomalies in response to an internal pressure increase. A best fitting model was obtained using the radial tilt components (Figure 1c). Six out of seven tilt anomalies are reasonably well modelled (Ge: Gemer; Kn: Kendil; Kl: Klatakhan; Se: Selo; 1,2: no. of instrument). No coincidence exists between the best fitting model and tilt observations in tangential direction (Figure 1d). Taking the differences between the two tangential tilt components at a certain station a clear anti-correlation between model and observations is proven (Figure 1e). The anti correlation is illustrated also by the tilt vectors plotted into topographic maps (Figures 1f–1h).

FE-model is 24 km * 24 km * 10.5 km; it has been checked that this is large enough to avoid boundary effects. Bottom and outside margins are fixed in normal direction, the surface is allowed to move freely.

[7] We use a simple spherical pressure source with a radius $a_L = 1.75$ km as the internal structure of the edifice is not known. With only four observation points at the surface there is not enough information available to constrain a more detailed source geometry. Furthermore, the volume of the source is of secondary importance as we are interested in spatial characteristics of the deformation field and not in an interpretation of absolute pressure values. A uniform pressure acting along the outward normal is assigned to each element of the surface of the source. The host rock is assumed to be homogeneous, isotropic and linear-elastic with a Young's modulus E = 20 GPa and a Poisson's ratio $\nu = 0.3$. The entire model comprises 738,202 linear elements and 136,358 nodes and the resulting numerical problem is solved with the commercial FE-software Abaqus.

[8] Constructing the FE-model geometry special attention has been paid to the fact that the borehole tiltmeters used in this study monitor the inclination of a vertical element. A superficial node was inserted at the place of each tiltmeter and a second one vertically below at a distance of Δz = 10 m. Tangential and radial displacements, u_i, are calculated at each node. The vertical tilt in a certain direction is given by:

$$t_i = \frac{\partial u_i}{\partial z} \cong \frac{\Delta u_i}{\Delta z}, \quad i = x, y$$

where $\Delta u_i = u_{i,top} - u_{i,bottom}$ is the difference of the displacements at the upper and lower node, and x, y define the local horizontal coordinate system with the +y-direction orientated towards a vertical line through the summit of Merapi (i.e. "radial" component). The results are given in terms of radial and tangential tilt, i.e. vertical elements tilted toward the summit or in the perpendicular direction, respectively. The strong topographic influence on short length scales can best be studied at the three locations where two tiltmeters are operated at a distance of about 80 m (Figure 1a: stations Gemer, Klatakhan, and Kendil). While only minor topographic effects are visible in the radial components, opposite signs and amplitude differences of up to 60% with respect to the radial amplitudes are observed for the tangential components of the two neighboring tiltmeters (Figures 1c and 1d; compare the dark bars for one and the same location).

3. The Data Base: Seasonal Tilts Observed at Merapi Volcano

[9] The tilt data we use for comparison with the model results have been recorded at four tiltmeter arrays as part of the Indonesian-German joint research project MERAPI [*Zschau et al.*, 2003]. The vertical design of the electronic tiltmeters (resolution 0.1 μrad) with a base length of 0.8 m allowed an installation in boreholes at depths of 2.5 m to 4 m in order to minimize meteorological noise, especially the influence of temperature variations. The boreholes are cased by a PVC-tube; the spacing between the casing and the soil is filled up with concrete. Each tilt station is equipped with sensors for local environmental parameters providing the possibility to recognise and to correct for the remaining meteorologically induced tilt disturbances.

[10] Between 1996 and 2002, five Merapi-type eruptions occurred that are occasionally accompanied by very small tilt anomalies at the flank stations. Using 2D FE-modeling, *Körner* [2000] explained the small anomaly amplitudes of up to 1 μrad by pressure variations due to magma fragmentation limited to the upper 500 m of the central vent. The tilt time series are dominated by seasonal variations, shifted by about 14 days with respect to the beginning of the wet season (Figure 2). A highly correlated negative tilt step is observed in the radial tilt components at all arrays with amplitudes of the order of 20–50 μrad for stations at high altitude and 10–20 μrad for stations at low altitude. The negative sign is indicative for a downhill tilting of the upper end of the instruments. A heterogeneous behavior is observed for the tangential tilt components; the amplitudes are somewhat lower than in the radial component. During the dry seasons the tilt returns slowly toward the old level.

[11] The seasonal tilt variations cannot be directly related to magmatic pressure variations because no obvious signs of volcanic activity phases are observed during these periods. The coincidence with the beginning of the rainy seasons suggests that there is a connection with the yearly water recharge to the ground. For the period subsequent to the initial tilt steps (cf. Figure 2, days 350 to 450), *Westerhaus and Welle* [2002] suggested that the increase in noise during the rainy season reflects local poroelastic deformation of the soil due to infiltration of rain water. The water related deformation effects are reasonably well modeled and corrected for by a convolution of local rain records with appropriate time functions [*Westerhaus and Welle*, 2002].

[12] This approach, however, fails to explain the amplitude and the shape of the dominating tilt steps at the beginning of the rainy season. Even though local soil deformation still cannot be ruled out as a source for the observed tilt anomalies, we cannot exclude a priori that the correlated tilt steps in fact are the consequence of a regional disturbance affecting each station simultaneously. For the latter a possible mechanism could be a pressure pulse within the hydrothermal system surrounding the central vent of Merapi due to ground water recharge (which, in fact, would be an internal pressure variation of hydrologic origin). As a basic test for this hypothesis we compare the observed signal with the results of our 3D FE-model to investigate if a central pressure source is sufficient to explain the spatial distribution of the seasonal tilt anomalies.

[13] This numerical experiment is of relevance also for volcanic hazard assessment. Each externally driven disturbance of an observation parameter that cannot be corrected for bears a potential danger of misinterpretation. This is especially valid if the parameter enters an automated system continuously monitoring the status of a volcano with respect to changes in the magmatic system. A problematic situation would arise if the spatial characteristics of the observed seasonal tilt variations resemble the effects of a volcanic pressure source. Comparison of the observations with our model results will help to assess the danger of misinterpretation.

4. Model Results

[14] The comparison of observed and predicted signals is done using the FE-model of Merapi with the pressure source fixed to 3500 m. Pressure and location of the source were varied on a regular grid with a step width of 300 m in horizontal and 250 m in vertical direction. The origin of the 3D-grid is centered at sea-level below the summit of Merapi. The best fit to the observed data was searched for by minimizing the weighted chi-square variable χ^2

$$\chi^2 = \frac{1}{n}\sum_{i=1}^{n}\frac{\left(t_{i,cal} - t_{i,obs}\right)^2}{\sigma^2}$$

where t_{cal} and t_{obs} are the calculated and observed tilt anomalies, respectively, σ is the uncertainty on the determination of the numerical values of the tilt steps from the time series in Figure 2, arbitrarily fixed to 3 μrad, and n is the number of anomalies used in the test.

[15] It turned out that the model is able to fit the radial tilt components reasonably well (Figure 1c). The common negative sign of the tilt anomalies confines the depth interval of the center of the pressure source to 600 m until −1000 m (a.s.l.). For larger depths the sign of the tilt anomalies at high altitudes changes. This is due to the fact that for volcanoes with a prominent edifice the shortest distance between the pressure source and the surface is found somewhere at the flanks, not directly above the source. Slopes are steepened at altitudes below this point, but flattened above. This behavior illustrates the potential of radial tilt components to resolve the depth of a pressure source.

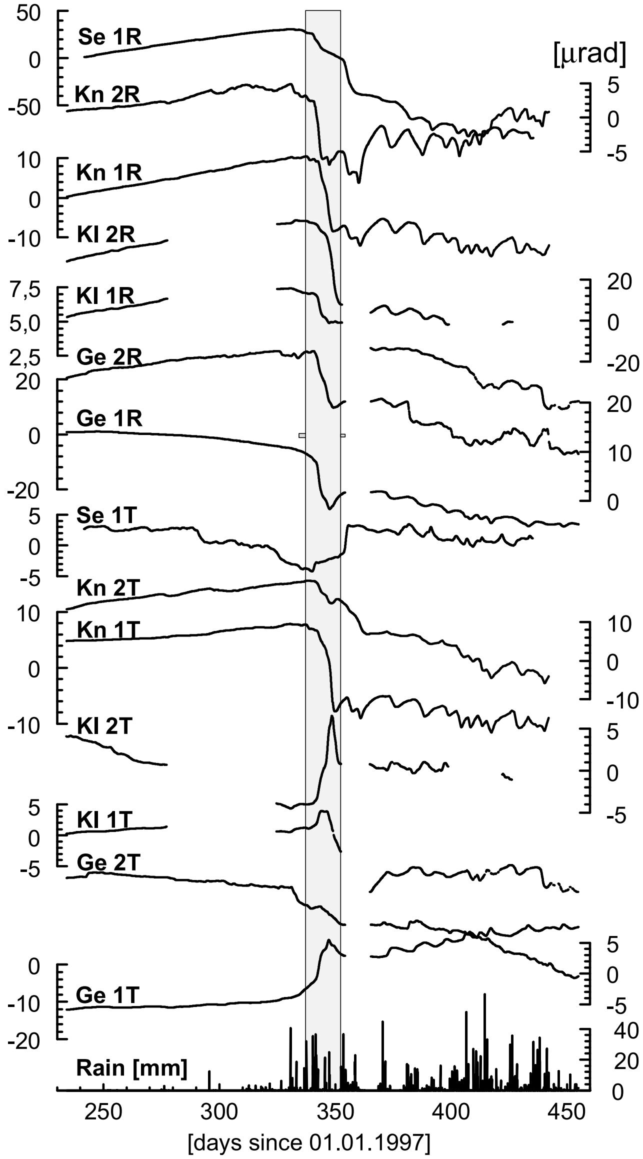

Figure 2. Data base of this study. A sharp tilt signal is observed about 14 days after the beginning of the rainy season. In radial direction ("R", upper half of the figure) the tilt variation is highly correlated at the four stations. The negative sign indicates a downhill tilt of the upper end of the instruments along the general slope of the edifice. The tangential components ("T", lower half) behave irregularly reflecting an influence of local topography. A similar situation is met every year.

[16] The best fit of the radial tilt signal is obtained for a pressure source with 3.5 MPa located at 250 m a.s.l. (i.e. 2750 m below the summit) and 300 m north–west of the summit (Figure 1c). At four stations out of seven, the difference between model and observation is less than 2 μrad; at two other stations it is 7–10 μrad. A special situation is found for tiltmeter 1 at Klatakhan station; the model is not able to explain the unusually small tilt amplitude recorded at this site. In the context of the proposed model, this discrepancy could be attributed to small scale heterogeneities not included in the FE-model, or some instabilities of the borehole. Discarding this observation reduces the χ^2–value from 32.18 to 2.83. We conclude that the radial tilt field is compatible with a pressure variation in a volume that is located near to the center of Merapi's edifice.

[17] In contrast to this the tangential tilt cannot be reproduced by the best fitting model for the radial tilt. A comparison between model and observations does not show any agreement; in fact there is an anti correlation (Figure 1d). This general behavior does not change with any other model tested throughout this study.

5. Discussion

[18] Closer inspection of Figure 1d reveals some systematic behavior in the tangential component. Neglecting the amplitudes for the moment, it is found that the sign of the modeled and observed tilt disturbances differs for 6 out of the 7 instruments. The anti correlation becomes immediately clear if the difference is taken between the two tiltmeters running at a certain station (Figure 1e). The difference of the observations is remarkably similar for the three stations; the positive value means that the upper ends of the instruments are tilted away from each other. In contrast to this, the modeled difference is negative in all cases, indicating an inward tilting, and there seems to be a tendency toward larger differences at higher altitudes. The systematic discrepancy between model and observation is seen in more detail if the separation between radial and tangential components is dropped and the complete tilt vectors are plotted into a topographic map. At each station, there is a clear downhill tilting; however, the tips of the observed tilt vectors diverge, while the modeled vectors converge (Figures 1f–1h).

[19] This systematic behavior emphasizes the importance of the tangential component for an interpretation of observed deformation signals. An internal pressure increase necessarily leads to an inflation of the edifice. Depending on the depth of the pressure source, an inflation phase leads to steeper slopes at lower parts of the edifice and a flattening at high altitudes. If all tiltmeters are situated at moderate altitudes, a general downhill tilt will be the result. The radial components of the observed seasonal tilt signal at Merapi match this pattern, implying that a potential danger of misinterpretation exists.

[20] Simultaneously, with increasing perimeter of the edifice the base of the radially striking ridges is stretched and the lateral slopes become less steep. A formerly vertical element would be tilted towards the ridge crest, in accordance with the model results (Figure 3). In contrast to the radial direction, the spatial characteristics of the observed tangential components deviate considerably from the model. Thus, we are able to reject the hypothesis that the observed seasonal tilt steps are caused by an internal hydrologic pressure pulse. It seems plausible to assume that the seasonal tilts are instead caused by a local but deterministic soil effect related to the filling of empty pore space in upper soil layers at the beginning of the rainy seasons. Gravitationally driven ground water flow in the uppermost soil layers usually following the sloping surface could explain a downhill tilt in both radial as well as in tangential direction (Figures 1f–1h).

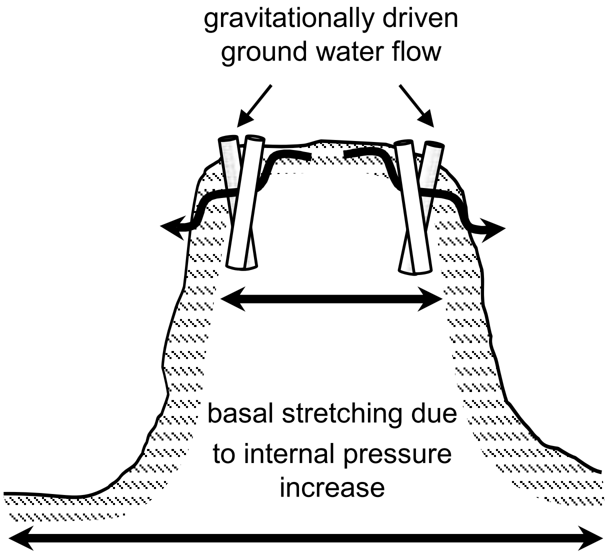

Figure 3. Cut through a radially striking ridge and a qualitative illustration of possible tilting mechanisms in tangential direction. The lower ends of the tilt meters are moved away from each other due to a stretching of the base of the ridge during a phase of volcanic inflation. The opposite is observed during the rainy season. Surface near runoff induces a downhill tilt of the upper ends of the instruments due to friction between the mobile pore fluid and the immobile soil matrix.

[21] These results suggest a simple way to separate volcanic signals from a certain class of non-volcanic disturbances along the flanks of Merapi-type volcanoes: monitor the difference between two tiltmeters located near to both margins of a radial ridge and compare it with the expected tilt difference due to an internal pressure source for a suitable reference model. If the signs of the observed and expected differences do agree, the case has to be investigated in more detail; if not, a change in the status of the volcanic system is less probable. This test is easily implemented in any automated monitoring scheme and does not rely on environmental information or complex processing of correction functions. However, while providing a quick and useful check in most cases, our procedure is ambiguous when internal and external deformations occur simultaneously. It has to be emphasized that this test would not be possible for volcanoes without pronounced lateral topographic structures, where no significant tangential tilts would be invoked. If only radial tilts are observed a separation of external and internal signals in this way is not possible.

6. Conclusions

[22] We employed 3D FE-modeling to investigate the spatial characteristics of tilt anomalies due to an internal pressure source at Merapi Volcano. A DEM with an accuracy of 7 m was used to incorporate the complex topography of Merapi into the model geometry that is characterized by radially striking erosional canyons and ridges. Distortions induced by these topographic features reach amplitudes similar to purely pressure induced signals on a smooth surface. A second major source of conflicting signals are local poroelastic deformations of the ground due to rain and ground water movements. Comparing tilt anomalies related to the seasonal ground water cycle with the expected signature of an internal pressure source, it was found that the radial topographic features provide an easy means to classify tilt anomalies: the differences of the tangential tilts of two tilt meters located at both margins of a ridge have opposite signs for externally (i.e. rain induced) and internally driven signals. If this systematic behavior, observed for three stations along the flanks of Merapi, is confirmed by additional case studies from Merapi and other stratovolcanoes, a corresponding test could be easily implemented in any automated monitoring system. This would help to classify tilt anomalies and to flag disturbances of possibly external origin. We conclude that (i) a high resolution DEM is required, and (ii) the operation of tilt arrays substantially supports an interpretation of observed tilt anomalies with respect to changes in the status of a volcano.

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