Tilt recorded by a portable broadband seismograph: The 2003 eruption of Anatahan Volcano, Mariana Islands

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[1] The horizontal components of broadband seismographs are highly sensitive to tilt, suggesting that commonly deployed portable broadband seismic sensors may record important tilt information associated with volcanic eruptions. We report on a tilt episode that coincides with the first historical eruption of Anatahan volcano on May 10, 2003. The tilt was recorded by a Strekheisen STS-2 seismograph deployed in an underground insulated chamber 7 km west of the active vent. An ultra-long period signal with a dominant period of several hours was recorded on the E-W component beginning at 06:20 GMT on May 10, which coincides with the onset of continuous volcano-tectonic (VT) seismicity and is one hour prior to the eruption time estimated by the Volcanic Ash Advisory Center. The signal is much smaller on the N-S component and absent on the vertical component, suggesting it results from tilt that is approximately radial with respect to the active vent. An estimate of tilt as a function of time is recovered by deconvolving the record to acceleration and dividing by the acceleration of gravity. The record indicates an initial episode of tilt downward away from the volcanic center from 06:20–09:30 GMT, which we interpret as inflation of the shallow volcanic source. The tilt reverses, recording deflation, from 09:30 until 17:50, after which the tilt signal becomes insignificant. The inflation corresponds to a period of numerous VT events, whereas fewer events were recorded during the deflation episode, and the VT events subsequently resumed after the end of the deflationary tilt. The maximum tilt of 2 microradians can be used to estimate the volume of the source inflation ($\sim$2 million m^3), assuming a simple Mogi source model. These calculations are consistent with other estimates of source volume if reasonable source depths are assumed. Examination of broadband records of other eruptions may disclose further previously unrecognized tilt signals. **Citation:** Wiens, D. A., S. H. Pozgay, P. J. Shore, A. W. Sauter, and R. A. White (2005), Tilt recorded by a portable broadband seismograph: The 2003 eruption of Anatahan Volcano, Mariana Islands, *Geophys. Res. Lett.*, *32*, L18305, doi:10.1029/2005GL023369.

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1. Introduction

[2] The horizontal components of a broadband seismograph are highly sensitive to tilt, since even very small changes in tilt affect the way that the acceleration of gravity is resolved by the horizontal components [*Rodgers*, 1968]. The contribution of tilt to the output of a typical broadband velocity force-feedback seismograph increases with period [*Wielandt and Forbriger*, 1999] and may become dominant at periods greater than 100 s in locations with significant changes in tilt. The tilt signal is not recorded on the vertical component, which facilitates the discrimination of tilt signals from ground displacement. Much of the literature concerning seismographs and tilt focuses on disentangling or removing the component of the signal due to tilt from broadband displacement records [*Wielandt and Forbriger*, 1999; *Crawford and Webb*, 2000; *Aster et al.*, 2003; *Chouet et al.*, 2003]. However, in some cases, tilt recorded by seismographs may be important data for understanding ground deformation. Tilt has been recorded by observatory-quality seismographs (Streckeisen STS-1) and confirmed by comparison with tiltmeters in several cases where such instruments are located near active volcanoes [*Ohminato et al.*, 1998; *Battaglia et al.*, 2000]. However, although these observatory-quality seismographs are sensitive to low frequencies out to DC, they require controlled environments and cannot be deployed in typical field enclosures. There have been no previous reports of useful ultra-long period tilt observations with portable broadband seismographs, which are much more commonly deployed near volcanoes.

[3] In this paper, we report observations of co-eruption tilt from a portable broadband seismograph during the first historical eruption of Anatahan volcano on May 10, 2003. Anatahan is a 9 km $\times$ 3 km volcanic island located about 120 km north of Saipan in the Commonwealth of the Northern Mariana Islands. The eruption was recorded by a portable STS-2 broadband seismograph fortuitously installed at $\sim$1 m depth and 7 km away from the crater four days prior to the eruption (Figure 1), as part of the Mariana Subduction Factory Imaging Experiment. This represents one of the first times that an initial eruption was recorded by a nearby broadband seismograph.

[4] Very little precursory seismicity was recorded by the seismograph in the four days preceding the eruption [*Pozgay et al.*, 2005]. Seismic activity commenced at 01:53 GMT

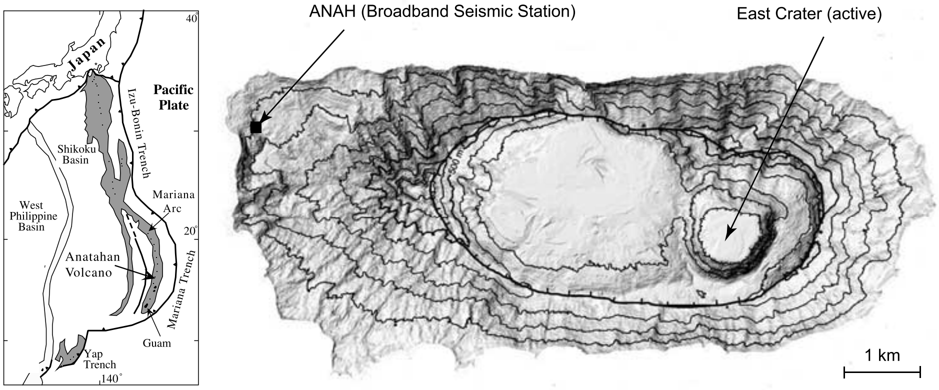

Figure 1. Inset map showing the location of Anatahan volcano (left) and topographic map of Anatahan island showing the location of the STS-2 seismograph (ANAH) 7 km west of the active East Crater (right). Topography is courtesy of Steve Schilling (NOAA) and island contour is from Bill Chadwick (NOAA).

on May 10, and volcano-tectonic (VT) events became nearly continuous at 06:20. The initial eruption was not observed since the island was uninhabited at the time, and the first detailed visual reports are from the seismograph installation team in the region aboard a small ship. However, the Volcanic Ash Advisory Council estimates the eruption time at 07:30. Long-period (LP) events and harmonic tremor did not occur during the first few hours, but these commenced at about 09:00. The eruption plume extended to heights of 10–13 km and the eruption had a volcanic explosivity index (VEI) of between 2 and 3. The initial eruption was largely a phreatic eruption, containing a high volume of a free vapor phase gas atop the column of magma [*Pallister et al.*, 2005]. A complete report on the seismicity associated with the eruption is given by *Pozgay et al.* [2005].

[5] Here we discuss an unusual long-period seismic signal observed on the horizontal component of the broadband seismograph at the same time as the eruption. We interpret this signal as a tilt signal induced by the inflation and subsequent deflation of the volcano.

2. The Tilt Signal

[6] A large, ultra-long period signal is observed on the E-W component beginning at about 06:20 GMT (Figure 2). The signal is much larger than the diurnal signal, which probably results from daily temperature cycling, and no similar signals are observed in the following months. A smaller signal is also present on the N-S component, but there is no signal on the vertical component, suggesting that the signal results from E-W tilt, approximately radial to the active crater.

[7] The tilt in radians [$\Theta(t)$] can be obtained from the output of a horizontal broadband seismograph using:

$$\Theta(t) = -a_X(t)/\mathbf{g} \tag{1}$$

where $a_X(t)$ is the apparent ground acceleration from the seismic record and **g** is the acceleration of gravity [*Weilandt and Forbriger*, 1999]. The tilt is defined as positive when it is downward in the positive x direction. We deconvolved the signal to acceleration in the passband of 500–50,000 s and divided by the acceleration of gravity to obtain the tilt as a function of time (Figure 3). Although the dominant period of the signal (~25,000 s) is well outside the nominal passband of the instrument, the acceleration falls off only linearly at periods beyond the corner frequency (as compared to quadratically for the velocity), so the main features of the tilt record are relatively insensitive to different deconvolution methods. However, we did observe that the maximum amplitude of the tilt has some dependence on the details of the deconvolution procedure.

[8] The initial apparent ground velocity and, thus acceleration recorded by the seismograph, is toward the east (Figure 2), so the initial tilt is downward towards the west

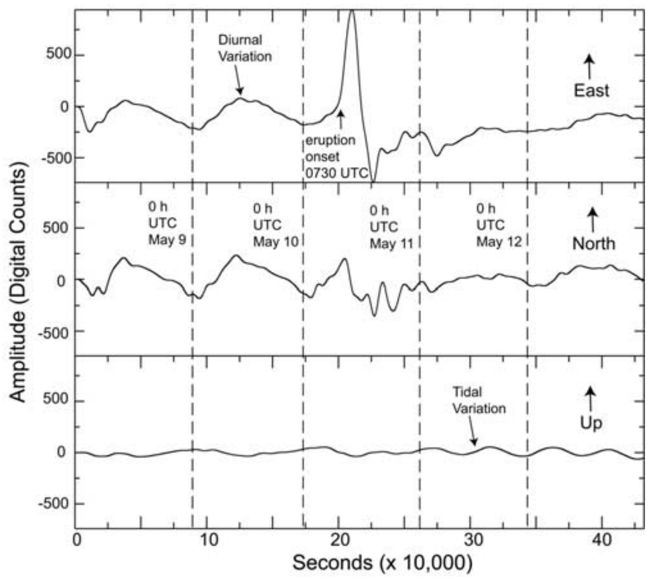

Figure 2. Seismograms from the Anatahan broadband station for the five-day period surrounding the eruption. The signals have been low pass filtered with a corner at 0.001 Hz. The strong signal on the E-W component coincides with the eruption time and is absent on the vertical component and weak on the N-S component, suggesting it results from tilt radial to the crater.

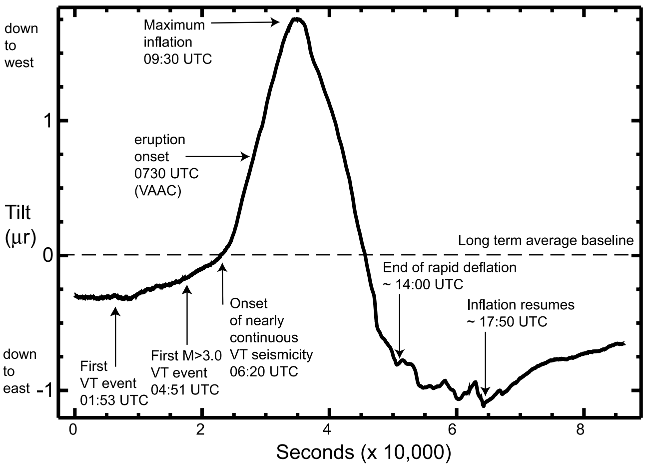

Figure 3. East-West tilt determined from the Anatahan seismograph for May 10 by deconvolving the EW record to acceleration and dividing by g within a passband from 500–50,000 seconds. The time of significant events in the sequence are indicated by arrows.

(Figure 3). This suggests uplift of the center of Anatahan and inflation of the volcano immediately prior to the estimated first eruption time of 07:30. Maximum inflation occurred at 09:30 reaching ~2 microradians, after which rapid deflation occurs until 14:00. Following this large-scale deflation, there is some suggestion of a second minor episode of inflation at about 17:00. Although the seismograph is not sensitive to a DC offset, the amount of deflation on May 10 exceeds the amount of inflation, suggesting that some long-term precursory inflation of the crater may have been relieved. The tilt signal is well correlated with the seismicity record (Figure 4) [*Pozgay et al.*, 2005]. The initiation of the tilt at 06:20 corresponds with the start of near-continuous VT activity, probably representing the pressurization of the system. The maximum inflation at 09:30 follows shortly after the estimated eruption time of

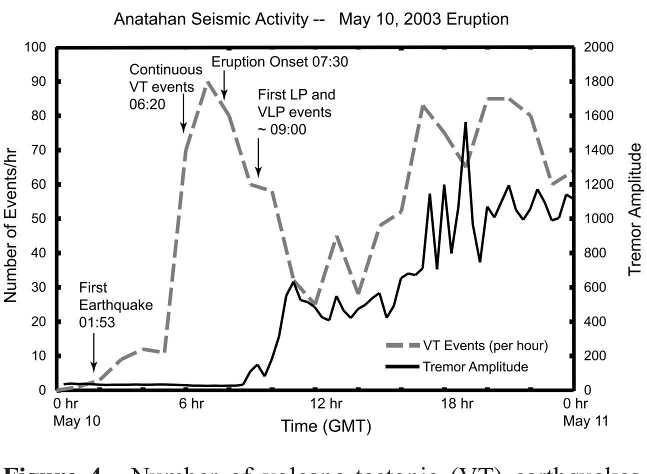

Figure 4. Number of volcano-tectonic (VT) earthquakes (dotted line) and amplitude of harmonic tremor (solid line) as a function of time during May 10. Significant events are indicated by arrows. Seismicity characteristics are correlated with tilt (Figure 3), consistent with episodes of inflation, deflation, and reinflation.

07:30 and corresponds to the onset of LP events and harmonic tremor, representing the movement of magma. The deflation period from 11:00–17:00 corresponds to a minimum in the occurrence of VT events due to the depressurization, and the resumption of minor inflation at 17:50 corresponds with another peak in VT activity.

3. Tilt Magnitude and Source Volume

[9] Since we have tilt records from only a single location, a detailed calculation of the source volume and depth is obviously impossible. However, we made a simple highly-idealized calculation of the source volume to see if the measured tilt is reasonable relative to other estimates of the erupted volume. We assume the tilt is caused by a pressurized spherical cavity at depth (Mogi source). For a sphere with an injection volume of ΔV at depth d, the surface tilt (Θ) at a distance r is given by *Mogi* [1958] and *McTigue* [1987]:

$$\Theta = 9/4\ \Delta V/\pi d\ r\left(d^2 + r^2\right)^{-5/2} \qquad (2)$$

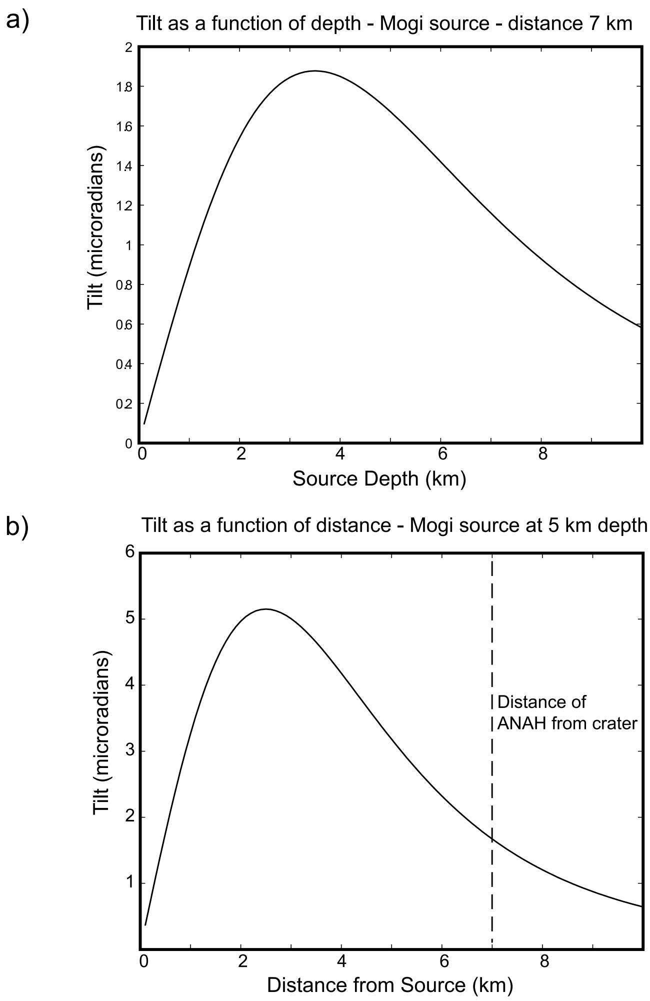

Figure 5. (a) Calculation of tilt at the distance of the Anatahan seismograph (7 km) for different source depths. The injection volume ΔV is set to produce the observed tilt (~2 microradians) for the optimum source depth (3.5 km). (b) Tilt as a function of distance for a source depth of 5 km.

Figure 5a shows the calculation of tilt at the distance of the Anatahan seismograph (7 km) for different source depths. Significant tilt on the order of that observed is generated for source depths of 1–8 km. Extremely shallow (<1 km) or deep (>10 km) sources are unable to generate significant tilt at the observed distance. Figure 5b shows the tilt as a function of distance for a source depth of 5 km. Shallow sources do not generate tilt at this distance since the tilt is concentrated immediately above the source, and deep sources generally produce only small amounts of tilt.

[10] The minimum injection volume required to generate the tilt, assuming the optimum source depth (3.5 km, ref. Figure 5a), is 2 million m^3, or the equivalent volume of a sphere 160 m in diameter. Deeper or shallower sources require a larger source volume; for example, depths of 1 km or 8 km require an injection volume of 4 million m^3. This compares to an estimate of 10 million m^3 for the total volume output (solid rock equivalent) estimated from ash mapping [*Pallister et al.*, 2005; *Trusdell et al.*, 2005]. For most eruptions, the injection volume is less than the total volcanic output [e.g., *Dvorak and Dzurisin*, 1997], so this calculation shows that the observed tilt obtained from the STS-2 seismograph is compatible with other estimates of the volume of the Anatahan eruption.

4. Discussion

[11] The Anatahan observation suggests that useful records of volcanic tilt can be obtained from portable broadband seismographs even when the instruments are deployed in typical temporary field deployment housings. Such seismograph installations are increasingly a part of volcano monitoring deployments and may record major eruptive episodes. This study suggests that such records should be examined for tilt. Tilt episodes such as reported here are not obvious from the raw seismograph records and are only apparent when long time series of many hours are filtered with long-period filters. This suggests that valuable seismograph records of ground tilt may be going unnoticed. Such records may contribute considerable additional information about the eruption mechanics, particularly in cases where tiltmeters and other geodetic equipment have not been deployed.

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