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Deformation of New Trident volcano measured by ERS-1 SAR interferometry, Katmai National Park, Alaska

Z. Lu[1], R. Fatland, M. Wyss, S. Li, J. Eichelberger, K. Dean, and J. Freymueller

Geophysical Institute, University of Alaska, Fairbanks, Alaska

Abstract. Using Synthetic Aperture Radar (SAR) interferometry, we detect several centimeters of uplift that accumulated during two years (1993-1995) around the vent of the New Trident volcano in Alaska's Katmai National Park. The areas of image coherence correspond to fresh, blocky lavas, while coherence is lost in ash-covered areas. From the uplift gradient we estimate the depth of a pressure source under New Trident volcano to be approximately 0.8-2.0 km. Our results show that in spite of the difficult sub-arctic environment of southern Alaska, strain build-up can be monitored over a two-year period, showing the potential for global monitoring of volcano deformation using SAR interferometry.

Introduction

Many volcanic eruptions are preceded by pronounced ground deformation in response to increasing pressure in subsurface magma chambers, or the upward intrusion of magma beneath the volcano. Therefore, systematic geodetic surveillance and monitoring might enable eruptions to be forecast [e.g., *Swanson et al.*, 1985]. The logistical difficulties of surface-based measurements on Alaskan volcanoes make the application of satellite-based monitoring techniques such as SAR interferometry highly desirable. We chose the Katmai volcano group, located on Katmai National Park of the Alaska Peninsula, as the site for our investigation because several major eruptions have happened in this area this century, including the largest eruption of this century from Novarupta Dome in 1912 [*Simkin and Siebert*, 1994]. New Trident volcano (Figure 1) is part of the Katmai group of volcanoes, and is located 5 km from Novarupta Dome. The vent of New Trident volcano produced eruptions from 1953 to 1968 [*Ray*, 1967; *Simkin and Siebert*, 1994]. These eruptions have Volcanic Explosivity Indices of 2 to 3, and are termed as "moderate" to "moderate-large" eruptions [*Simkin and Siebert*, 1994]. The lavas produced by these eruptions have rugged surfaces comprised of 1-3 m blocks, and have not yet undergone significant weathering.

SAR interferometry measures the phase difference between two images taken on different satellite passes, corresponding to the change in the round-trip path length of radar waves to the same ground point. The phase differences are displayed in an interferogram, effectively a contour map of the change in distance to the ground surface along the look direction of the satellite. Each cycle of phase, or fringe, in the resulting interferogram (after removal of the "flat-earth" effects) corresponds to a change in range distance from the satellite to the ground surface equal to one-half of the radar wavelength (28.3 mm for ERS-1). We represent fringes in the interferograms shown here as red-green-blue (RGB) color bands. Each RGB band corresponds to a range change of 28.3 mm. SAR interferometry has been used to map displacements caused by earthquakes [e.g., *Massonnet et al.*, 1993; *Peltzer and Rosen*, 1995], and volcanic deflation following the eruption of Etna volcano [*Global Volcano Monitoring*, 1994; *Massonnet et al.*, 1995].

The interferometric phase difference is controlled by: a) topography, b) ground-surface deformation, c) atmospheric path delays, and d) noise sources including radar receiver noise, and environmental changes such as those caused by vegetation, snow accumulation and melting, and rain events. The topographic component of the interferogram scales with the baseline separation (the perpendicular distance between two satellite passes at the times of the radar observations), while the component due to ground surface movement is independent of the baseline. When the spatial baseline approaches zero, the fringes in an interferogram are completely controlled by ground movement and contain no information about the topography if noise sources are negligible, the ideal case for measuring surface deformation. When the baseline separation is not zero, the component of the phase signal contributed by ground movement can be obtained by removing the topographic component using a pre-existing DEM or another interferogram [e.g., *Massonnet et al.*, 1993, 1995].

Analysis

In order to measure the long-term deformation of volcanoes using SAR interferometry, it is necessary that phase coherence be maintained over a long period of time. This requires that the scattering characteristics of

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[1] Now at Hughes STX Co., EROS Data Center, Sioux Falls, South Dakota

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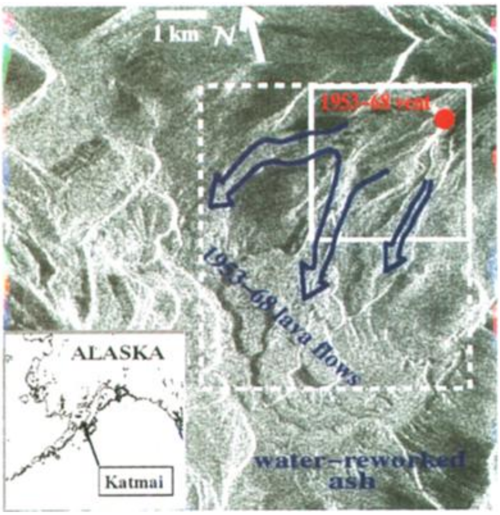

Figure 1. ERS-1 radar image of New Trident volcano and surrounding region. The location of the Katmai region with respect to Alaska is shown at the lower left corner. The location of the center of the figure is 58.20°N/155.17°W. The solid and dashed white polygons denote the area covered by Figures 2a and 2b.

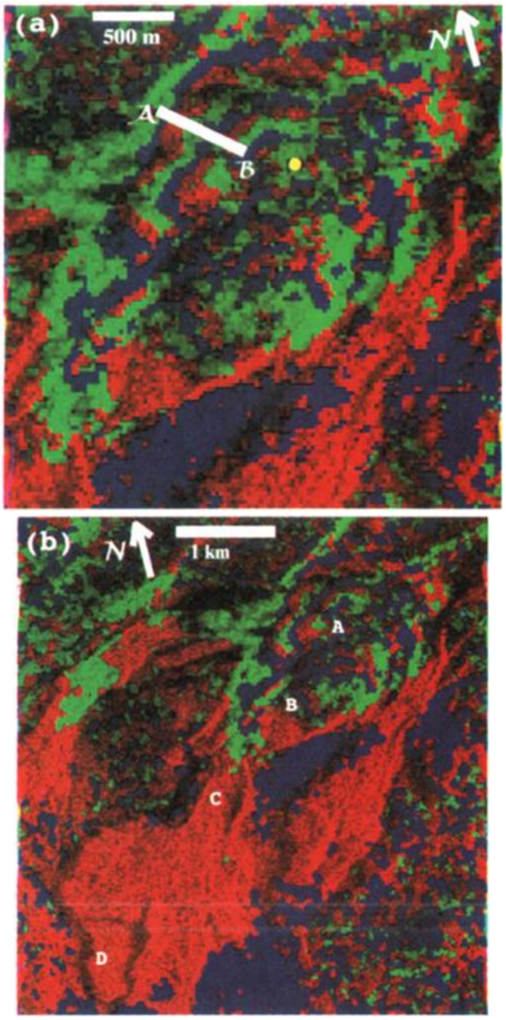

Figure 2. Interferogram around New Trident vent. One fringe is represented by three colors (red-green-blue). The interferogram was constructed using a pair of ERS-1 images recorded in the summers of 1993 and 1995 with baseline separation of 1 m. The locations and size of Figure 2a and Figure 2b are shown in Figure 1 by solid and dashed white polygons. The brightness scales with the amplitude of the radar image.

the ground surface remain the same over the time interval between SAR observations. Loss of phase coherence can be a problem for constructing interferograms on most of the world's volcanoes, which often are covered seasonally or permanently by snow and ice. Environmental changes reduce the coherence of the constructed interferogram [e.g., *Zebker and Villasenor*, 1992]. We have constructed dozens of interferograms from ERS-1 images which span from several days to three years at the Katmai National Park. Based on these interferograms, we can make the following general statements about the degradation of phase coherence of Katmai volcano group [*Lu et al.*, 1996]: 1) for the entire area, during the winter October to June, phase coherence is lost due to snow accumulation and melting, and other weather effects. This occurs randomly, with an average time to lose coherence of 9 days; 2) for areas covered by ash, acceptable phase coherence may be maintained over the three-month summer period from the early July to the end of September; 3) for the unweathered lava flows of New Trident volcano, coherence can be maintained for 3 years using images acquired in the summer. We present results based on images acquired by ERS-1 during the summers of 1993 and 1995.

Figure 2a shows an interferogram for the 3×3 km area around New Trident vent which spans the period from September 3, 1993 to July 23, 1995. Phase coherence was lost for most of the region surrounding this image, although there are other areas of coherence in the image. The pixel of the interferogram has dimension of 20 meters. The baseline separation for the two satellite passes is 1 m. One fringe in the interferogram represents a 28.3 mm change in distance from satellite antenna to ground surface between the two satellite passes. There are two fringes along the line from A to B (distance 650 m), and almost three fringes from A to the yellow dot (Figure 2a). The New Trident vent is about 500 m northeast of the yellow dot. The fringes cannot be attributed to topography because the relief from A to B is less than 200 m, corresponding to less than 1/40 of one fringe for this baseline separation. The order of color banding is green-blue-red from A to B, which implies increasing phase and corresponds to upward movement of B relative to A. The fringe pattern is quite clear on the west flank of the volcano, but it is disturbed on the east flank (east of the yellow dot). This is probably because the lava surface is disturbed on the east flank.

To demonstrate that fringes observed in Figure 2a are not contributed by topographic effect, we show an portion of the interferogram covered approximated all the lavas of New Trident vent (Figure 2b). The topographic relieves between A and B, B and C, and C and D are approximate 500 feet. However we observed much more fringes between A and B, and almost no fringe between C and D. Therefore, we conclude the fringes observed in Figure 2a are not controlled by topography.

The accuracy of ground deformation measurements made by SAR interferometry is limited by the error in estimating the baseline separation of the two satellite passes. The baseline separation is calculated based on the position and velocity vectors of satellites. The accuracy of the baseline is better than five meters based on a calibration study from altimetry [*Shum et al.*, 1996]. We further refine the baseline separation as follows: we change the baseline by 0.5 m at each step, produce an interferogram for each baseline separation, and then select the interferogram with no striped fringe pattern (the striped fringes are caused by errors in the baseline separation estimate). This procedure is time-consuming, but it provides an accurate estimate of the baseline to ±1 m. If we had made an error in estimating the baseline separation, and the perpendicular component of the baseline was 10 m instead of 1 m, the fringes contributed by the topographic relief would still be less than half of a fringe, far smaller than the 2 to 3 fringes observed in Figure 2a. Therefore, the observed fringes in Figure 2a are not caused by error in the estimation of baseline separation.

This change in phase, due to a shortening of the distance to the ground of 60 to 80 mm along the look direction of the satellite, took place between 1993 and 1995. Taking into account the radar's 23° incidence angle, this would correspond to about 70 to 90 mm of differential uplift over the two year period. The inflated region covers about 7 km^2. The boundary between the region of coherence and loss of coherence corresponds to the change in surface from rough young lava erupted between 1953 and 1968 to loose ash produced 1912.

To make certain the fringe patterns in Figure 2a are caused by deformation rather than by atmospheric effects or environmental changes, we analyzed three additional images. Two were acquired in August and October of 1995 with 35 days separation and one was acquired in July 1993. We constructed two interferograms, one for a 35-day (with baseline of 125 m) and another for a two-year interval (with baseline of 64 m). We use the 35-day interferogram as a DEM to remove the topographic effect in the two-year interferogram, assuming no deformation occurred during this 35-day pair image. This interferogram (http://www.asf.alaska.edu/step/insar/abstracts/zlu.html), constructed independently from the interferogram in Figures 2a and 2b, shows the same fringe patterns but with a higher noise level. Other interferograms not spanning the 1993-1995 time interval do not show this signal, so we conclude that it is unlikely that transient atmospheric propagation delays could be responsible for the observed signal.

Based on the correlation coefficient around the New Trident vent (http://www.asf.alaska.edu/step/insar/abstracts/zlu.html) and the relationship between phase error and correlation coefficient [e.g., *Rodriguez and Martin*, 1992, Equation 25], we estimate the standard deviation of the interferometric phase to be about 40°, corresponding to about 3 mm precision in detecting ground deformation.

Discussion

Using ERS-1 SAR interferometry, we detect several centimeters ground surface movement around the vent of New Trident volcano. We do not attribute the ground deformation to earthquakes, because no earthquakes large enough to produce such deformation were located in the region during the observation interval. The largest earthquake recorded has a magnitude of 2.2 [*A. Jolly*, pers. comm., 1997]. We therefore conclude that the fringe patterns most likely reflect ground deformation due to volcanic inflation.

We interpret this inflation as being caused by shallow intrusion of magma and/or pressurization of the hydrothermal system under the vent. Based on the uplift gradient, and assuming a simple model of pressure change in a sphere located in an elastic half-space [*Mogi*, 1958], the depth of the source body could be in the range from 0.8 km to 6.0 km. This model is consistent with the observed lack of horizontal deformation in the Novarupta EDM/GPS network [*Kleinman et al.*, 1996]. There are four reliable benchmarks, all located about 5 km NE of New Trident vent. Based on the Mogi source model, any source depth shallower than 2 km would predict no measurable deformation at any of the sites. Therefore depth of the pressure source is about 0.8-2.0 km. Such a shallow depth would correspond approximately to the location of a volume of intense microseismicity [A. Jolly, pers. comm., 1996]. The volume of the increased seismicity is located 2 km NW of the New Trident vent, and spans about 8 km^2. These earthquakes ranges from 1 to 4 km in depth. Their magnitudes are smaller than 2.2 [*A. Jolly*, pers. comm., 1997].

At New Trident, the inferred inflation rate is 30 to 40 mm/year and the strain rate is 20 to 30 ppm/year. This rate is twice the long-term strain rate at Sakurajima volcano, Japan (10 to 15 mm/year) [*Organizing Committee*, 1988] before the 1915 and 1946 eruptions. The inflation rate is also higher than those at Yellowstone caldera (1 ppm/year) [*Dzurisin and Yamahita*, 1987], Long Valley caldera (1~25 ppm/year) [*Hill et al.*, 1991], and Campi Flegrei caldera, Italy (20 ppm/year) [*Berrina et al.*, 1984], and is comparable with that observed at Kilauea volcano (20~50 ppm/year) before eruptions [*Decker*, 1981]. However, at New Trident the area undergoing inflation seems smaller than at the above-mentioned volcanoes, and the New Trident volcanic system differs from those silicic caldera systems.

Seismological evidence and gravity measurements also suggest the existence of a shallow fluid body under the study area. Seismic travel time delays of up to 0.9 sec have been measured at a station near New Trident vent [*Ward et al.*, 1991], which were explained by the presence of a large low-velocity magma body or plexus of magma bodies beneath the Trident volcano. The hypocenters of earthquakes beneath Trident volcano range from 2 to 6 km depth. Gravity measurements [*Saltus et al.*, 1991] showed a large bowl-shaped Bouguer gravity anomaly of -42 mgal centered at a point 3 km west of New Trident vent and spanning an area of 400 km^2. These authors developed a model of an anomalous body centered at about 6 km with a top that could be as shallow as 2 km.

Conclusion

We suggest that at least 70 mm of recent uplift has occurred at the New Trident vent and that it reflects expansion of a shallow magma body or hydrothermal system. Based on our observations and previous supporting work, we envision a large magma body under the study area with a localized area of shallow expansion.

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K. Dean, J. Eichelberger, R. Fatland, J. Freymueller, S. Li, and M. Wyss, Geophysical Institute, University of Alaska, Fairbanks, AK 99775.

Z. Lu, Hughes STX Co., EROS Data Center, Sioux Falls, SD 57198. (e-mail:lu@edcsnw15.cr.usgs.gov)

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