# Localized deformation at Miyakejima volcano based on JERS-1 radar interferometry: 1992–1998

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[1] Stacked radar interferograms at Miyakejima volcano (Japan) between 1992 and 1998 showed two localized significantly deforming areas with a magnitude of 4∼6 mm/yr in the radar line of sight. One area is close to the 1983 eruption vent, and, using a simple closed analytical formulation, the deformation is interpreted as due to a thermoelastic contraction of a formerly intruded magma. The other one detected in the previous caldera is explained by a depressurization source, whose depth (500 m) coincides with that of a low resistivity zone interpreted as a hydrothermal reservoir. Also, our computed $CO_2$ flux is consistent with in situ measurement data. The reservoir volume is significantly less than the collapsed volume in 2000, and its depth is much shallower than the void detected prior to the collapse. Hence, the depressurization would not directly induce the caldera collapse in 2000. *INDEX TERMS:* 1243 Geodesy and Gravity: Space geodetic surveys; 6924 Radio Science: Interferometry; 8419 Volcanology: Eruption monitoring (7280); 8424 Volcanology: Hydrothermal systems (8135); 8499 Volcanology: General or miscellaneous. **Citation:** Furuya, M. (2004), Localized deformation at Miyakejima volcano based on JERS-1 radar interferometry: 1992–1998, *Geophys. Res. Lett.*, *31*, L05605, doi:10.1029/2003GL019364.

## 1. Introduction

[2] Miyakejima volcano located in the Izu-Bonin arc has undergone a number of eruption episodes over the past centuries, and the recent three events before 2000 occurred in 1940, 1962 and 1983 (Figure 1). The most recent and still-ongoing unrest started in June 2000, and is particularly notable in the sense that a caldera collapse with a diameter of about 1.6 km has occurred [e.g., *Geshi et al.*, 2001].

[3] What was happening beneath the volcano before 2000? All baselines by four permanent GPS receivers showed a lengthening after their deployment in 1996. Using both the GPS and leveling data, *Nishimura et al.* [2002] inferred a source model consisting of a point inflation source at a depth of 9.5 km with a volume increase rate of 6.4 $\times$ $10^6$ $m^3$/yr in the south-western flank of the volcano (Figure 1). Furthermore, the secular decrease in total geomagnetic intensity data suggests an increase in temperature underneath the volcano [*Sasai et al.*, 2001]. While these observations show that magma was being accumulated before the 2000 unrest, it is also known that a couple of leveling benchmarks inside the Hatcho-taira caldera (Figure 1) were secularly subsiding [*Miyazaki*, 1990]. In this paper we will examine the ground displacements at Miyakejima volcano between 1992 and 1998 by radar interferometry, and interpret the observed deformation.

## 2. Data Analysis

[4] Interferometric synthetic aperture radar (InSAR) is capable of detecting mm- to cm-order ground displacements through differential measurement of the phase component of temporally separated SAR signals [e.g., *Massonnet and Feigl*, 1998; *Rosen et al.*, 2000; *Hanssen*, 2001]. It has been successfully applied to crustal deformation measurement at active volcanos [e.g., *Wicks et al.*, 1998; *Lundgren et al.*, 2001; *Lu et al.*, 2002; *Pritchard and Simons*, 2002]. In this study, we chose L-band (wavelength 23.6 cm) JERS data to overcome loss of interferometric coherence as most of the Miyakejima volcano is covered with vegetation. To remove topographic fringes, the 10-meter resolution digital elevation map derived by Geographical Survey Institute, Japan was used.

[5] Inaccuracy in the orbit data will generate a residual, long wavelength phase slope, which was taken out by fitting low order polynomials. Meanwhile, using the inflation model by *Nishimura et al.* [2002], we can predict a corresponding signal for InSAR. It turns out, however, that the inflating deformation looks like a long wavelength fringe over the island, because the island's surface area is small and the source depth is deep. Thus we were unable to detect the inflating deformation in this study, and focused upon a localized deformation.

[6] Since the GPS and leveling data at Miyakejima have indicated that the magnitude of secular displacements is on the order of 1 cm/yr or less, we selected such data pairs that can cover as much longer time period as possible so that derived signals can exceed a detection limit; even the shortest time period is 1.04 yr. Also, as suggested by GPS campaign measurements, atmospheric noise is rather large probably due to its humid climate [*Miwa and Kimata*, 1999], and can easily mask a deformation signal. Hence, we generated 13 independent interferograms (see auxiliary materials[1]), and, after normalizing by each time period, employed a stacking technique to suppress an atmospheric noise [*Fujiwara et al.*, 1998; *Strozzi et al.*, 2001], assuming a constant deformation rate over time during the 6 years of the analysis.

## 3. Results and Discussion

[7] Figures 2a, 2b and 2c show an average yearly rate of range changes, standard deviations of inferred rate and a

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2003GL019364.


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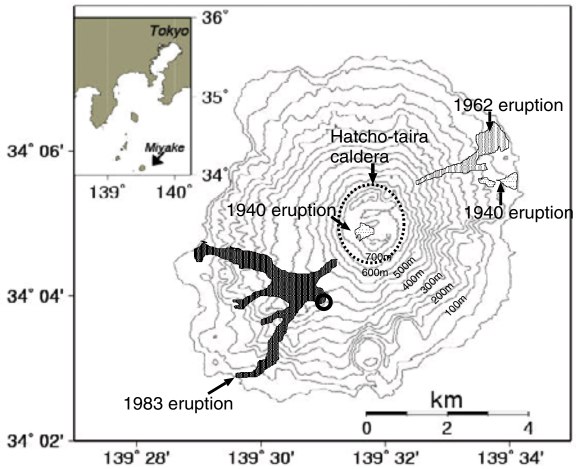


**Figure 1.** Location of Miyakejima volcano and the eruption deposits of 1940, 1962 and 1983 eruptions. Hatcho-taira caldera outlined with dashed line collapsed in 2000 unrest. An open circle shows the location of a point inflation source estimated by *Nishimura et al.* [2002].

number of unwrapped values for stacking at each pixel, respectively. Figure 2c indicates a good coherence at the 1940, 1962 and 1983 lava and scoria region as well as the Hatcho-taira caldera, where the density of vegetation is the least. Figures 2a and 2b show that the deformation amplitude is overall small and less than the standard deviation. However, maximum deformation can be recognized in the south-west flank nearby the 1983 lava (Figure 1), which amounts 5.5 ± 3.3 mm/yr in the range changes. Also, the southern part of the Hatcho-taira caldera shows a lengthening of range at a maximum rate of 3.8 ± 3.4 mm/yr; these range changes are with respect to the tide gauge station in the south-western coast, to which the leveling data is referenced. Because of large errors, it remains uncertain whether the whole Hatcho-taira caldera was undergoing subsidence. Though some signals can also be seen in the 1940, 1962 lava and 1983 lava near the coast, the standard deviation is too large, and we will focus our geophysical interpretations upon the two significantly deforming regions.

### 3.1. South-Western Flank Signal Nearby the 1983 Lava

[8] In view of the location, we can surely associate the signal in the south-west flank with the 1983 eruption, and the localized spatial extent also suggests its shallow origin. Assuming the signal as due to a thermoelastic contraction of the intruded magma in 1983, we compute an evolution of thermoelastic contraction and estimate the heat source; here we neglect a contribution from latent heat generated during a solidification which cannot last longer than the thermal diffusion. The solutions for displacement $u_i^{(\infty)}(\vec{x}, t)$ and strain $\epsilon_{ij}^{(\infty)}(\vec{x}, t)$ in an infinite elastic medium due to an instantaneous heat source of unit intensity at $\vec{\xi}$ are,

$$u_i^{(\infty)} = m\left(\frac{x_i - \xi_i}{R^3}\right)\left[\mathrm{erf}\left(\frac{R}{\sqrt{\theta}}\right) - \frac{2R}{\sqrt{\pi\theta}}\exp\left(-\frac{R^2}{\theta}\right)\right], \quad (1)$$

$$\epsilon_{ii}^{(\infty)} = \frac{m}{R^3}\left[1 - \frac{3(x_i - \xi_i)^2}{R^2}\right]\left[\mathrm{erf}\left(\frac{R}{\sqrt{\theta}}\right) - \frac{2R}{\sqrt{\pi\theta}}\exp\left(-\frac{R^2}{\theta}\right)\right] + \frac{4m}{R^2}\frac{(x_i - \xi_i)^2}{\sqrt{\pi}\theta^{3/2}}\exp\left(-\frac{R^2}{\theta}\right), \quad (2)$$

$$\epsilon_{ij}^{(\infty)} = \frac{3m(x_i - \xi_i)(x_j - \xi_j)}{R^5} \cdot \left[\frac{2R}{\sqrt{\pi\theta}}\left(1 + \frac{2R^2}{3\theta}\right)\exp\left(-\frac{R^2}{\theta}\right) - \mathrm{erf}\left(\frac{R}{\sqrt{\theta}}\right)\right] \quad (i \neq j), \quad (3)$$

where $m = \alpha(1 + \nu)/(4\pi(1 - \nu))$, $R = [(x_1 - \xi_1)^2 + (x_2 - \xi_2)^2 + (x_3 - \xi_3)^2]^{1/2}$, $\theta = 4\kappa t$, and erf($x$) is the error function [*Nowacki*, 1962]: $t$ is the time elapse since the emplacement of the heat source. Three material properties enter through a thermal expansivity $\alpha$, a thermal diffusivity $\kappa$ and Poisson's ratio $\nu$. Taking advantage of the solutions above, we can derive in a straight forward way a closed analytical solution in a semi-infinite medium, since the rationale of *Davies*

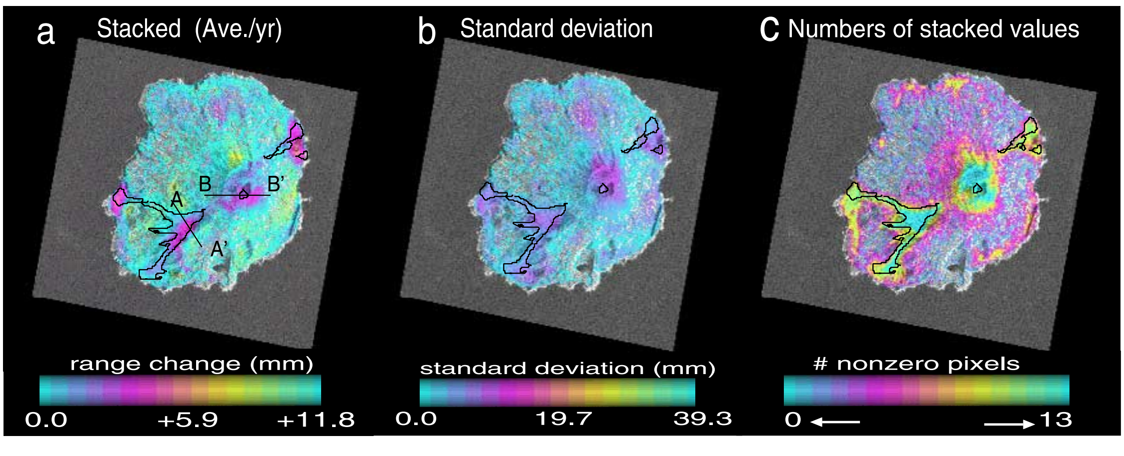


**Figure 2.** (a) Stacked interferogram, showing averaged range change rate in mm/year. Two cross-sections, A-A′ and B-B′, are shown in Figures 3 and 4, respectively. (b) Standard deviation at each pixel in the stacked interferogram. (c) Total number of unwrapped phase values at each pixel in the stacked interferogram. Larger numbers indicate better coherence.

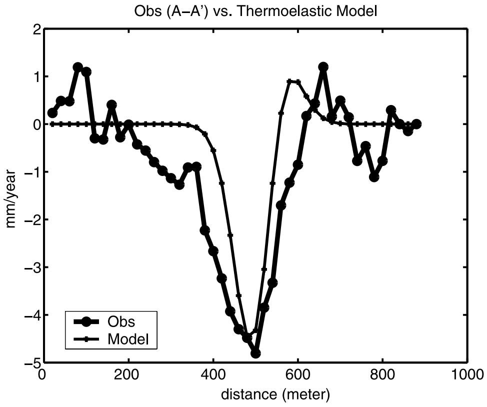


**Figure 3.** Observed (thick) and computed (thin) range change profile along A-A′ in Figure 2a.

[2003] holds true even in the case of quasi-static response (J. H. Davies, personal communication, 2003):

$$\mathbf{u} = \mathbf{u}^{(\infty)} + (3 - 4\nu)\bar{\mathbf{u}}^{(\infty)} - 2x_3\left(\bar{\epsilon}_{13}^{(\infty)}, \bar{\epsilon}_{23}^{(\infty)}, -\bar{\epsilon}_{33}^{(\infty)}\right), \quad (4)$$

where the overbar-ed quantities are derived by simply replacing $x_3$ in the infinite solution with $-x_3$; there were no previous literatures, to my knowledge, that applied this simple analytical solution to a thermoelastic deformation at the volcano.

[9] Figure 3 compares the observation and modeled deformation rate along the profile A-A' in Figure 2a. A good agreement between the observation and model can be achieved with a model heat source at a depth range of 50–200 m and a volume of $0.2–3.0 \times 10^6$ m$^3$. Considering that the total lava flow on the surface in the 1983 eruption is 5–7 $\times$ 10$^6$ m$^3$ [*Suto et al.*, 1984], we may regard the estimated volume of the heat source as those that could not outflow on the ground in the 1983 eruption. Here, since the 1983 lava was mainly basaltic, we assumed a temperature offset of 10$^3$ K. Other material parameters were assumed as $\kappa = 10^{-5}$ m$^2$/s, $\alpha = 2 \times 10^{-5}$, and $\nu = 0.3$, which are standard values except that the thermal diffusivity is appreciably large. If we take a $\kappa = 10^{-6}$ m$^2$/s [e.g., *Turcotte and Schubert*, 2002], the temporal evolution of ground deformation is greatly slowed down. We speculate that, since the actual cooling process involves not only a pure thermal diffusion but also a forced cooling by meteoric and/or ground water, magma can be cooled down more efficiently, and that a thermal diffusivity can be effectively lowered than a laboratory-derived value.

### 3.2. Secular Subsidence in the Hatcho-Taira Caldera

[10] It was the 1940 eruption which most recently deposited a lava and scoria on the summit of the volcano (Figure 1). Triangulation survey after the 1940 eruption allowed to infer a subsidence of as much as 15–50 cm near the coast and about 60–70 cm around the summit caldera [*Miyazaki*, 1990]. Total volume of the 1940 deposits was estimated to be 1.9 $\times$ 10$^7$ m$^3$ [*Japan Meteorological Agency*, 1996], and the deflation volume should have been of similar magnitude.

[11] Although the 1940 deposits over a non-elastic porous substrate would cause a consolidation, which may last over decades, it does not play a primary role because the deforming area is obviously wider than the 1940 deposits on the summit (Figure 1). As another possibility, we might associate the subsidence with a thermoelastic contraction as shown in the previous section. The broader spatial extent of the subsiding area as well as the long time elapsed after 1940, however, impose us to put a source at a depth of as deep as 500 m with a volume greater than 5 $\times$ 10$^9$ m$^3$. This is more than two orders of magnitude greater than that of the 1940 deposits, and we need to consider a similar amount of deflation in order to close a budget of magma flow as well as to explain the subsidence in 1940. However, it is impossible to explain the subsidence by a deflation source with a volume change of greater than 10$^9$ m$^3$ at a depth of 9–10 km. Hence, explaining the caldera subsidence in terms of a thermoelastic contraction model is unrealistic. Most likely mechanism can be inspired by the nearby fumarole activity, which suggests an intimate connection between ground displacement and hydrothermal system beneath the ground as suggested in other volcanos [e.g., *Dzurisin et al.*, 1994; *Lundgren et al.*, 2001; *Lu et al.*, 2002; *Mann and Freymueller*, 2003]. Using a deflation source [*Mogi*, 1958] whose volume change rate is $-5 \times 10^3$ m$^3$/yr at a depth of 500 m, we can explain the observed profile (B-B′) as in Figure 4. This depth coincides with a central depth of a low resistivity zone beneath the caldera shown by *Zlotonicki et al.* [2003], who interpreted it as a hydrothermal reservoir. Assuming a spherical volume with a radius of 250 m in light of *Zlotonicki et al.* [2003] and shear modulus of 10 GPa, we can convert the volume change rate into a pressure change rate of 1.6 MPa/yr. The equation of state for ideal gas allows us to compute a discharging rate of volcanic gas [*Mann and Freymueller*, 2003]. Assuming that the gas composition from the fumarole to be 98 mol% $H_2O$ and 2 mol% $CO_2$ and that the gas temperature to be 353K [*Hirabayashi et al.*, 1984], we find that $\sim$600 kt/yr $H_2O$ and $\sim$30 kt/yr $CO_2$; there was virtually no $SO_2$ and $H_2S$ unlike other volcanos, and indeed there used to be no sulfur smell. In the meantime, *Hernández et al.* [2001] surveyed an emission of $CO_2$ at Miyakejima in 1998, and their estimates are found to be 36 $\sim$ 55 kt/yr. Considering the uncertainties in the parameter values of this simple deflation model, these two independent $CO_2$ flux estimates can be regarded as quite consistent, and support a plausibility of the deformation mechanism.

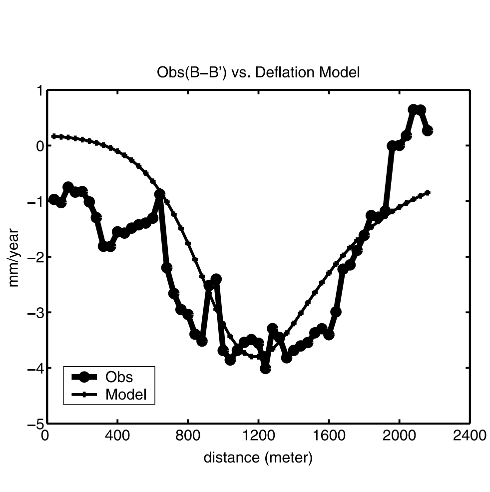


**Figure 4.** Observed (thick) and computed (thin) range change profile along B-B′ in Figure 2a.

[12] The volume of the estimated hydrothermal reservoir is an order-of-magnitude smaller than that of the newly formed caldera in 2000, and thus, even if the depressurization continued for a sufficiently long time, this process cannot explain the formation of the new caldera. Also, the depth of hydrothermal reservoir is significantly shallower than the void at a depth of 1.7 km found by microgravimetry prior to the collapse [*Furuya et al.*, 2003]. Hence, the subsidence at Hatco-taira caldera detected before 2000 is unlikely to be a precursor of the caldera collapse in 2000.

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