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Dacitic magma doming associated with shallow inflation and deep deflation sources
—An application to Mt. Usu, Japan

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Series of Mogi's single source model display characteristic family curves on the logarithmic graph of vertical displacement versus horizontal distance. The family curves on log-log plots are simply characterized by the flat part at short distances and constant decay at farther distances. The specific corner distances, which are defined by the bending corner of the curves, are mainly controlled by the source depth. The edifice scale deformation associated with the 2000 eruption of Mt. Usu is far from that predicted by Mogi's single source. The vertical displacement shows much more sharp decay with distance around 5－6 km and uplift-to-subsidence reversal at much farther distances on the logarithmic graph. This steep decay and a farther reversal can be well explained by a simplified twin spherical source model, with shallow inflation and deep deflation. It provides better fitness to the data, when the deflation volume at 10km is assumed to be nearly equivalent to the inflation volume at 2km. Similar result is also evident for the horizontal model. The combined twin source model of shallow inflation and deep deflation is also applied to the available leveling data for the historical 3 eruptions of Mt. Usu in 1910, 1943－45 and 1977－82. Edifice-scale deformations accompanied by 4 dome-building eruptions in 20th century can be also well explained by shallow inflation and deep deflation sources. Strong similarity between the 2000 and the 1910 eruptions is especially interesting considering the similarity of mutual surface eruptive activities and crypto-dome formations.

I. Introduction

Mt. Usu, which is located at the southwestern Hokkaido, is one of the most active volcanoes in the world. It has three lava domes and ca. 12 crypto-domes. Those are probably built by the intrusion of dacitic lava in a short time period since 1663 after its ca. 7000 year's dormancy. Among nine known eruptions, 4 occurred in 20th century and were luckily studied geodetically as well: Meiji-Shinzan crypto-dome (1910), Showa-Shinzan lava dome (1943－1945), Usu-Shinzan crypto-dome (1977－1982) and the 2000－Shinzan crypto-dome (2000). Omori (1911, 1920) described in details about 1910 eruption. Minakami et al. (1951) and Mimatsu (1962) reported about 1943－1945 eruption and Showa-Shinzan growth.

The 1977–1982 eruption is also well studied (e.g. Yokoyama et al., 1981; Okada et al., 1981). In the 2000 eruption of Mt. Usu various geodetic monitoring had been conducted and hitherto many papers are published. The 2000 eruption, which started on 3/31, is mostly characterized by intensive precursory earthquakes and enormous deformations as well as past 3 eruptions (e.g. Yokoyama and Seino, 2000). The enormous deformations are monitored by various geodetic observations, which including airborne laser survey as well as GPS and leveling surveys. The 60 % of the total volume of magma associated with the eruption intrudes to the summit besides the 30–40 % to the western flank in 2000 (e.g. Mori and Ui, 2000).

Ground deformation study is one of the most useful approaches for investigating shallow magma intrusion process. Mogi's single source model (Mogi, 1958) has been applied to many volcanoes in the world and gives us a fundamental understanding for the volcanic processes. Prior to complicate modeling, it is important to check basic features of total deformation field using a simplified deformation model as possible. In many cases, volcanic deformations can goodly be explained by the pressure source, which is inflation or deflation source in the shallow crust. In this study, the edifice-scale deformation associated with the 2000 eruption of Mt. Usu is mainly studied using logarithmic Mogi model, where new ideas of the model fitting and model evaluation are proposed, and then we applied the same method to the past 3 eruptions of Mt. Usu.

II. Logarithmic expression of Mogi model

1. Characteristics of the family curves

Mogi's vertical displacement pattern on the linear graph, which expression is conventionally used in many cases, showing strong model dependence (various gradients of the curves) near the source and model non-uniqueness (all little gradient) at the farther distances. In this case it is difficult to determine unique model using distal data set only. On the other hand, even using the data closer to the source, the data fitting sometimes may go wrong because data deviations might be large near the source, partly due to inelastic deformation. In such a situation, logarithmic data fitting might be useful tool for evaluating edifice-scale deformation (Okada, 2004b). This expression was also partly adopted by Swanson et al. (1976) and Fedotov et al. (1990). The formulations of the logarithmic Mogi model are follows:

Closer to the source $r \ll D$,

$$\log U_z = \log K - 2\log D \tag{1}$$

$$\log U_r = \log K - 3\log D + \log r \tag{2}$$

Farther from the source $r \gg D$,

$$\log U_z = \log K + \log D - 3\log r \tag{3}$$

$$\log U_r = \log K - 2\log r \tag{4}$$

where,

$$K = \frac{(\lambda + 2\mu)a^3 \Delta P}{2\mu(\lambda + \mu)},$$

U_z: *vertical displacement*

U_r: *horizontal displacement*

D: *depth of the source*

a: *radius of the source*

ΔP: *presure change*

r: *horizontal distance from the source*

$\mu(=\lambda)$: *Lame's constant*

Therefore, series of Mogi's single source models display similar pattern of family curves on the logarithmic graph of vertical displacement versus horizontal distance, showing nearly constant displacement near the source and constant decay at farther distances (Fig. 1). In the case of horizontal displacement, they show constant increase near the source and constant decay at the farther distances (Fig. 2). Here we defined the corner distance r^* which is the distance corresponds to the intersection point of the two equations, such as Eq. (1) and Eq. (3) for vertical, Eq. (2) and Eq. (4) for horizontal. Both of their specific corner distances characterize the bending of the curves on log-log plots that essentially corresponds to the source depth. The definition of this corner distance is similar to seismic scaling introduced by Brune (1970).

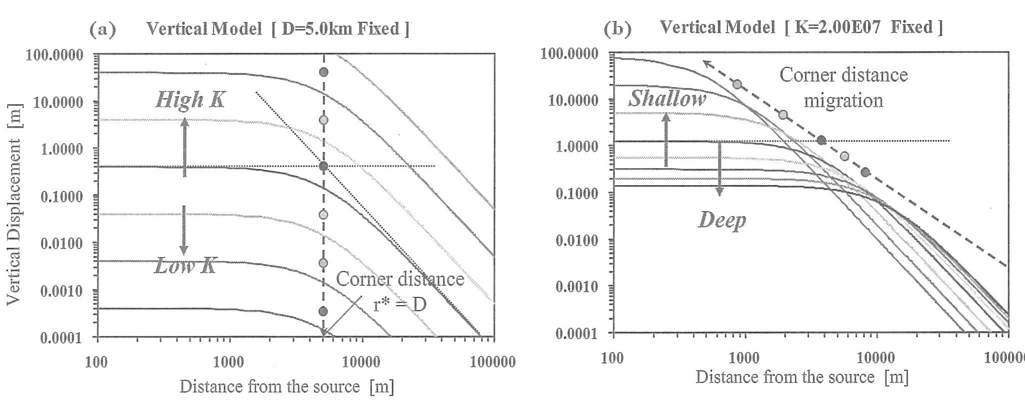


Fig. 1. (a) D-fixed family curves of Mogi's vertical model are characterized by the specific corner distance, which is given by the intersections of Eq. (1) and Eq. (3). (b) K-fixed family curves of Mogi's vertical model, where the specific corner distance changes with the source depth.

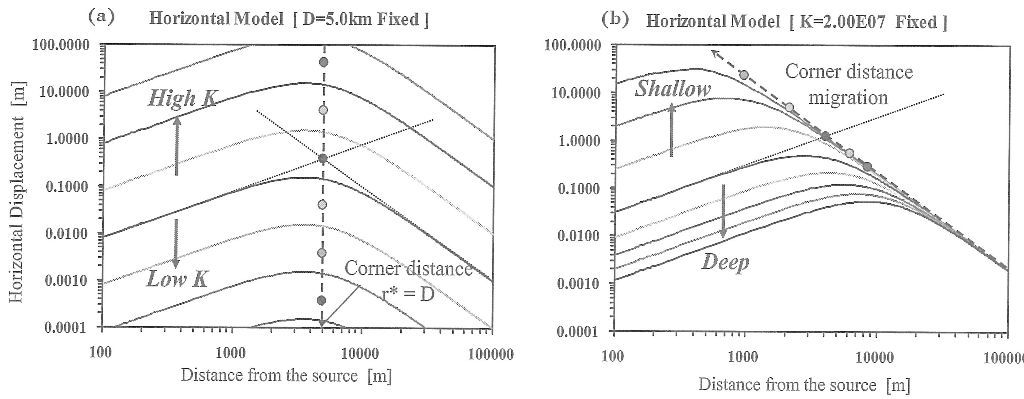


Fig. 2. (a) D-fixed family curves of Mogi's horizontal model are characterized by the specific corner distance, which is given by the intersections of Eq. (2) and Eq. (4). (b) K-fixed family curves of Mogi's horizontal model, where the specific corner distance changes with the source depth. At the farther distances, the models have nearly same value.

2. Logarithmic data fitting

Synthetic vertical displacement data plotted on the linear graph (Fig. 3a) with the different three models. Generally we have difficulty to have an accurate data near the source because where, center of deformation, is sometimes in the sea or by the craters. When we have to determine the valid model using the distal data only, we might encounter the problem of model non-uniqueness. Even when we have the data near the source luckily, their data might have larger deviations because of partly including the effect of inelastic deformation. Though we don't know how inelastic effect to the data is, the effect may be relatively larger than distal area. On the contrary, on the logarithmic graph (Fig. 3b), which is plotted the same synthetic data and the same models, there are smaller deviations near the source and the data deviations from Mogi model are much clear at the farther distances. Very small deformation data at the farther distances, play more important constraint for model fitting. Reversely saying, precise survey such as leveling and GPS, which should be installed as widely covering around the volcanic edifice, is very important for evaluating total deformation field. In the logarithmic data fitting, the data deviations

$$\sigma^2=\frac{1}{N}\sum_{i=1}^{N}(\log|d_{cal(i)}|-\log|d_{obs(i)}|)^2 \tag{5}$$

are minimized by grid search.

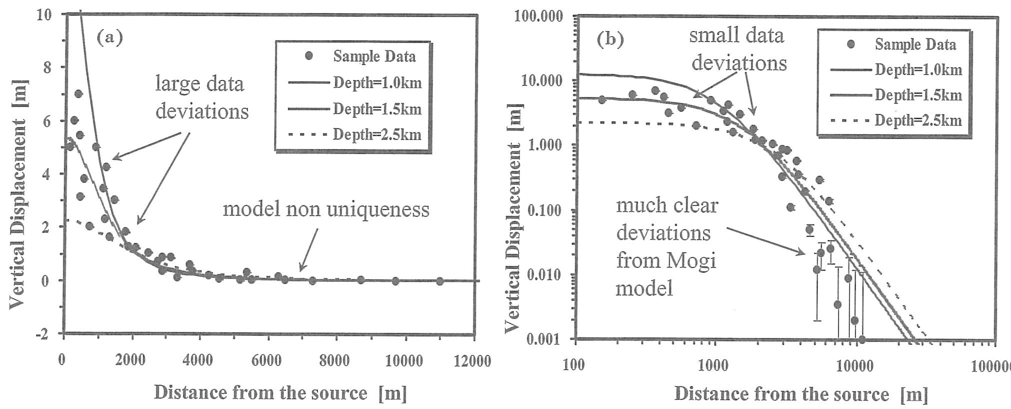


Fig. 3. (a) Linear expression of Mogi's vertical models with synthetic data (with 1 cm error bar), where the data deviations might be large near the source because of partly due to inelastic deformation and model non-uniqueness problem exists at the farther distances. (b) Logarithmic expression of Mogi's vertical models with same synthetic data (with 1 cm error bar), where small data deviations near the source and much clear deviations from Mogi model at farther distances are visually recognized.

III. Edifice scale deformation associated with the 2000 eruption of Mt. Usu

1. Data compiling

Various geodetic observations were conducted during the recent 2000 eruption of Mt. Usu, which includes conventional precise leveling and photo survey, as well as new techniques such as GPS, air-borne lidar survey, and SAR. Preliminary results indicated an edifice-scale inflation, whose center is located beneath the western summit, and an additional inflation in the western flank due to the new crypto-dome growth (e.g. Mori and Ui, 2000). Most of the published reports hitherto, examined their own observational data. Previous studies of the edifice-scale deformation are listed in Table 1. In this study for the purpose of understanding total deformation field around Mt. Usu composite data were used, which includes not only the data by previous works but also additional new data as the data set. We have compiled and examined as many as possible data from the published or public released deformation data, which includes (i) leveling (Mori and Ui, 2000), (ii) GPS and triangulation (Japan Highway Pub. Co.), (iii) campaign GPS (Jousset et al., 2003), (iv) continuous GPS (GEONET) (Geographical Survey Institute), (v) angle-EDM (Mori and Ui, 2000), (vi) air photo-grametry (Suzuki, 2001), (vii) InSAR (Shimada, 2000), (viii) precise map analysis (Okada, 2004a). Compiled data set have wider coverage of distance and the amount of deformation. Over a few m uplifts at the summit, so the effect by the inconsistency of the reference points is relatively negligible at the summit. The long-term deformation before and after the 2000 eruption activity is also relatively small (e.g. Mori and Suzuki, 1998; Mori and Ui, 2000), so the differences of observation period are not so serious for the modeling.

Table 1. Previous studies on the edifice-scale deformation at Mt. Usu; the uplift which is concentric to the western summit is the most characteristic feature. Many kinds of geodetic observations had been conducted before and after the 2000 eruption in cooperation with the many organizations. There are many applications using Mogi model or Dike model (e.g. Okada, 1985). The deformation sources are estimated at various depths beneath the mountain. This study partly includes Churei and Kobayashi (2000), Mori and Ui (2000), Araki (2002) and Jousset et al. (2003) works.

Reference	Measurement	Time period	Model	Depth [km]
	leveling	1993 to 2000.5		
Mori and Ui (2000)	GPS (vertical)	1993 to 2000.5		
	AngleEDM	2000.3.30 to 2000.5		
Matsushima et al. (2000)	tiltmetry	2000.3.31 to	Mogi model	3
Murakami et al. (2001)	GPS (GEONET)	2000.3.27 to	Mogi model	10
			Dike	8 to 3
			Sill	2 to 3
			Dike	shallow
Okazaki et al. (2002a)	continuous GPS	2000.3.29.18h to 24h	Mogi model	4
			Dike	1.4
Okazaki et al. (2002b)	continuous GPS	2000.3.29.18h to 24h	Dike	0.5
		2000.3.31.00h to 06h	Dike	0.25
Takahashi et al. (2002)	continuous GPS		Dike	1
	GPS, gravity	1996.8,1998.7 to 2000.11	Mogi model	0.7 to 1.0
Jousset et al (2003)			Dike	0.5
			Okubo model	0.4 to 3.3
Furuya et al. (2001)	gravity	1993.6 to 2000.5	Mogi model	2
				3
Furuya et al. (2001)	gravity	1993.6 to 2000.5	Mogi model	2
Watanabe (2003)				2
				10
Churei and Kobayashi (2000)	GPS (GEONET)	2000.3.5 to 3.25	Mogi model	12
Sato et al. (2002a)	electric pole measurement	2000.4.18 to 2000.6.14	Mogi model	2 to 3
Matsumoto et al (2002)	ground water monitoring	before and after	Mogi model	0
Sato et al. (2002b)	ground water monitoring	before and after	Mogi model	to 4.3
			Line source	to 1.6
Sato et al. (2000)	ground water monitoring	before and after	Mogi model	4
Murakami (2003)	leveling	1985,86 to 1991,92	Mogi model	12
Araki (2002)	GPS (GEONET)		Mogi model	5.5
			Mogi model	10

2. New data supplement

We have found availability of some valuable supplemental data. For example, the data is very limited for the summit area where single data indicates upheaval of 6.4 m at the summit, while other few data indicated the order of 2−3 m. By using the repeated precise topography maps with the scale of 1/5,000, summit deformation data was supplemented successfully (Okada, 2004a). Some more important data also came from the precise survey for infrastructure maintenances, such as campaign GPS surveys along highways. Small deformations at the farther distances from the mountain are newly supplemented by GEONET data. We analyzed 36 dual-frequency GPS data around Mt. Usu (Fig. 4).

The resulted comprehensive data sets of vertical and horizontal deformations were then examined for model fitting. Sometimes volcano topography is often known to affect to the

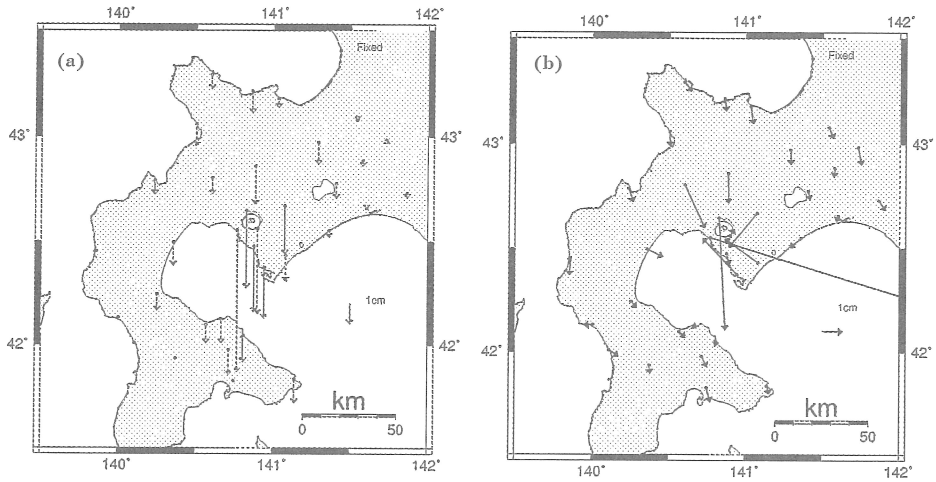


Fig. 4. Result of GEONET data analysis: (a) vertical displacement (b) horizontal displacement To detect large extent deformation around mountain, 36 GEONET data were analyzed in this study. Atsuta (950117) is fixed as a reference. Data periods are 3/1−3/11 to 4/15−4/25 in 2000. IGS precise ephemeris and Trimble Total Control Ver.2.7 software are used. Contraction vectors are seen in 35 km around Mt. Usu. Significant subsidence (more than 1 cm) is recognized around Mt. Usu.

source parameters in using a half space model (McTigue and Segall, 1988). Cayol and Cornet (1998), Williams and Wedge (1998, 2000), and Trasatti et al. (2003) investigated the topographic effects numerically or analytically. In the case of having a steep slope or large edifice, such as Mt. Etna which has 3km of height and 20km of radius of the edifice, it leads to not negligible errors of the source volume estimation. However, Mt. Usu has not so large edifice (6 km of the radius) and the average slope is about 7 degrees (Jousset et al., 2003), so topographic effect is supposed to be very small in this case.

In applying Mogi model, we assume the position of the deformation source at the western summit. One reason for this assumption is that the vertical displacement pattern in the eastern half part of the mountain which was studied by Mori and Ui (2000) is nearly concentric to the western summit. The other reason is widely concentric deformation pattern recognized from Fig. 4. We used the data set at the only eastern-southeastern flanks and distal area in order to separating the effects of the localized deformation at the western flanks from edifice-scale deformation.

3. Shallow inflation and deep deflation sources

Uplift data and reversed plotted subsidence data are shown in Fig. 5 with Mogi models on the logarithmic graph. According to the single source model, the displacement in near distance became nearly flat, while that at farther distance decayed constantly in a logarithmic scaling diagram. It is easy to realize that the observed vertical deformation data set for the edifice-scale deformation fails to fit any constant decay curves, but shows much sharper decay and uplift to subsidence reversals with the distance of 4−9 km. This phenomenon surely indicates an existence of deep deflation source besides the shallow inflation source. Hence, we adapted multiple spherical source models, shallow inflation and deep deflation aligned vertically. Tomiya and Takahashi (1995) has proposed consistent model with the multiple sources from petrological research. Another independent support for deeper deflation source is the long-period seismic source deduced from broadband seismic study (Yamamoto et al., 2002). Murakami et al. (2001) and Watanabe (2003) also pointed the existence of multiple sources beneath the mountain.

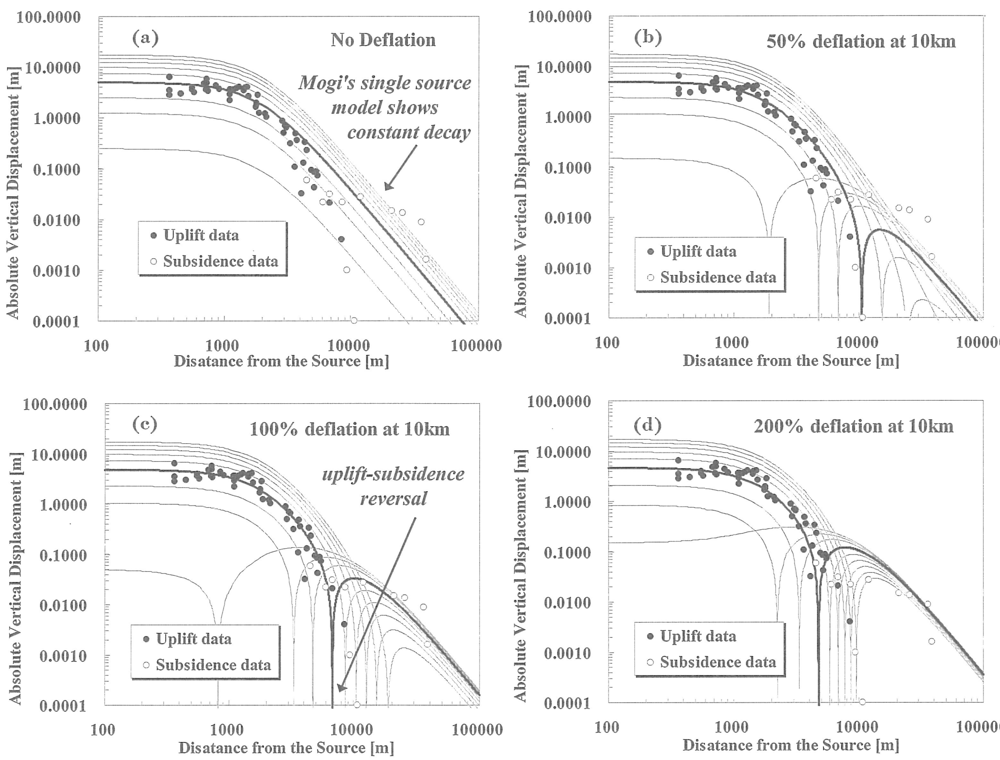


Fig. 5. The contributions of the deep deflation source to the shallow inflation source: (a) shallow inflation only (b) shallow inflation with 50% deep deflation (c) shallow inflation with 100% deep deflation (d) shallow inflation with 200% deep deflation. The family curves of the multiple source model display much sharp decay and uplift-subsidence reversals. It provides better fitness to the data when the deflation volume at 10km to the inflation at 2km is nearly equivalent.

The model parameters were derived from model fitting independently for each data set of vertical and horizontal deformation. The contributions of the deeper source to the shallower one are estimated as their relative volume change (Fig. 5). By considering deep deflation source the slope of the family curves became more sharp decay at farther distance. It is also shown constant decay of slopes at much farther distances. Vertical displacement can be better explained by the multiple source model, which is shallow inflation and deep deflation. It provides better fitness to the data when the deflation volume at 10km to the inflation at 2km is nearly equivalent (100% in Fig. 5c). Similar result is obtained for horizontal model. Best fit models are shown in Fig. 6. In short conclusion, edifice-scale deformation associated with the 2000 eruption of Mt. Usu could be basically explained by a simplified multiple source model, where the shallow inflation and deep deflation. However, problems also arise that the model parameters are different for the vertical and horizontal data sets. Similar results are well known for the single source model fittings (e.g. Swanson et al., 1976).

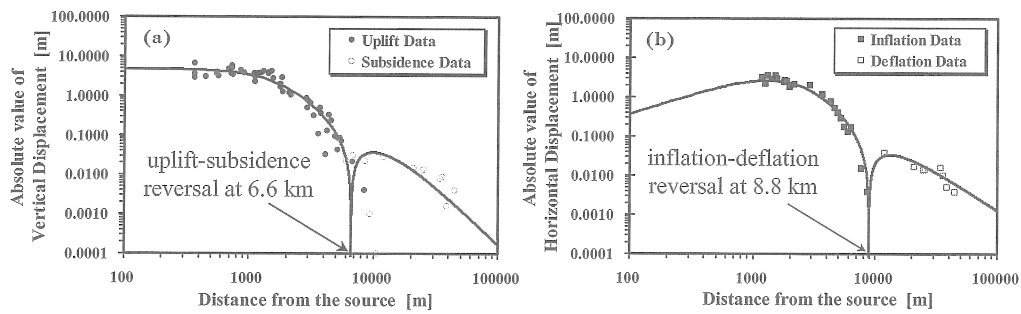


Fig. 6. (a) Best fit model for vertical displacement (D_1=2km, D_2=10km). Several m uplifts at the summit and a few cm subsidences at the distance could be explained by the multiple spherical source model. Uplift-subsidence reversal is seen at 6.6 km from the source. (b) Best fit model for horizontal displacement (D_1=2km, D_2=5km). Several m inflations at the summit and a few cm deflations at the distance could be explained by the multiple spherical source model. Inflation-deflation reversal is seen at 8.8 km from the source.

IV. Discussion

1. Model evaluation using the PMV

For the purpose of quantitative evaluation of data fitness, the residual misfit values (RMV) defined by the conventional linear data fitting are used for evaluating the edifice-scale deformation models of Mt. Usu. The RMV are given as

$$\frac{1}{N}\sum_{i=1}^{N}(d_{cal(i)}-d_{obs(i)}) \tag{6}$$

Using this Eq. (6), there are apparently little difference between the single source model and the multiple source model. This indicates the difficulties to estimate the deeper source when only RMV are considered. Then, in this study we proposed the proportional misfit values

(PMV) which means the ratio (%) of the RMV to the model. The PMV are given as

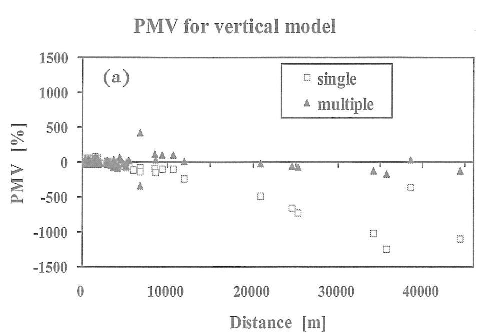
$$\frac{1}{N}\sum_{i=1}^{N}\frac{(d_{cal(i)}-d_{obs(i)})}{d_{cal(i)}} \tag{7}$$

The PMV of 49% by the multiple source model, which is much less than that of 130% by the single source model, is obtained for vertical. Similarly, the PMV of 22% by the multiple source model, which is much less than that of 62% by the single source model, is obtained for horizontal. In both cases, we could successfully distinguish multiple sources from single source by comparing the PMV (Table 2).

Table 2. Multiple source models for both of vertical and horizontal could be evaluated quantitatively using the proportional misfit values (PMV). Conventional model fitting using RMV can't distinguish multiple source models from single source model.

	VERTICAL		HORIZONTAL	
	Single	Multiple	Single	Multiple
RMV [m]	0.4656	0.4457	0.1999	0.1903
PMV [%]	129.46	**49.21**	61.96	**22.44**

Using conventional RMV, estimated model strongly depends on the large deformation data near the source, where data deviations generally might be large because of inelastic effects. It also happens to underestimate the small deformation data at the farther distances (sometimes over 30 km). On the contrary, using the PMV, very small deformation data play more important roles for elastic modeling. These small deformation data at the distances may be the key for precise estimation of the deeper source because the contributions by the deep sources are relatively large. Thus, the PMV is considered as useful value for evaluating the fitness of the elastic models, especially in the case over wide rage deformation (1mm to 1m deformation) data and edifice wide scale deformation data are discussed. The PMV



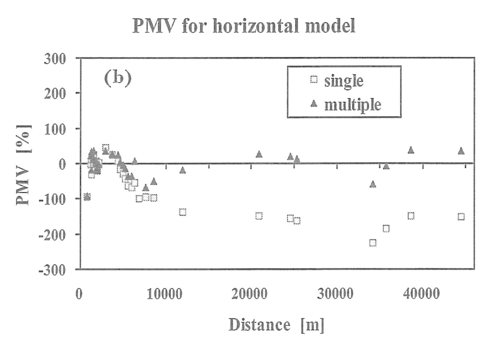


Fig. 7. (a) The comparison with the PMV of vertical models (b) The comparison with the PMV of horizontal models (squares: single source model, triangles: multiple source model)

of vertical and horizontal model are compared in Fig. 7. Multiple source models have smaller PMV and little moment of the data in contrast that single source models have larger PMV and large negative moment over wide distances.

2. Dacitic magma intrusion process

It is quite interesting to consider volcanological meaning of the estimated multiple deformation sources (e. g. Ishihara, 1997). Deep deflation process associated with the great eruption is widely known in many volcanoes, such as Sakurajima in 1914, Kilauea in1924, Komagatake in 1929 and Miyakejima in 1940. It is generally considered that these deflation phenomena are caused by out-flow of lavas from a depth in a shallow crust (Mogi, 1958). Though the 2000 eruption of Mt. Usu is not great eruption but small eruption in volcanology, quite similar deep deflation process has been recognized. In Fig. 6 enormous uplift and sharp decay of the curve indicate the effect of not only deep deflation but also shallow intrusion of dacite magma. Simplified deformation pattern and sketch of magmatic intrusion process of the 2000 eruption of Mt. Usu is shown in Fig. 8, where we can see 3 major deformation sources (i.e. a deep deflation source and a shallow inflation source beside the local shallow intrusion that allows crypto-dome growth in the western flanks). This proposed model can be

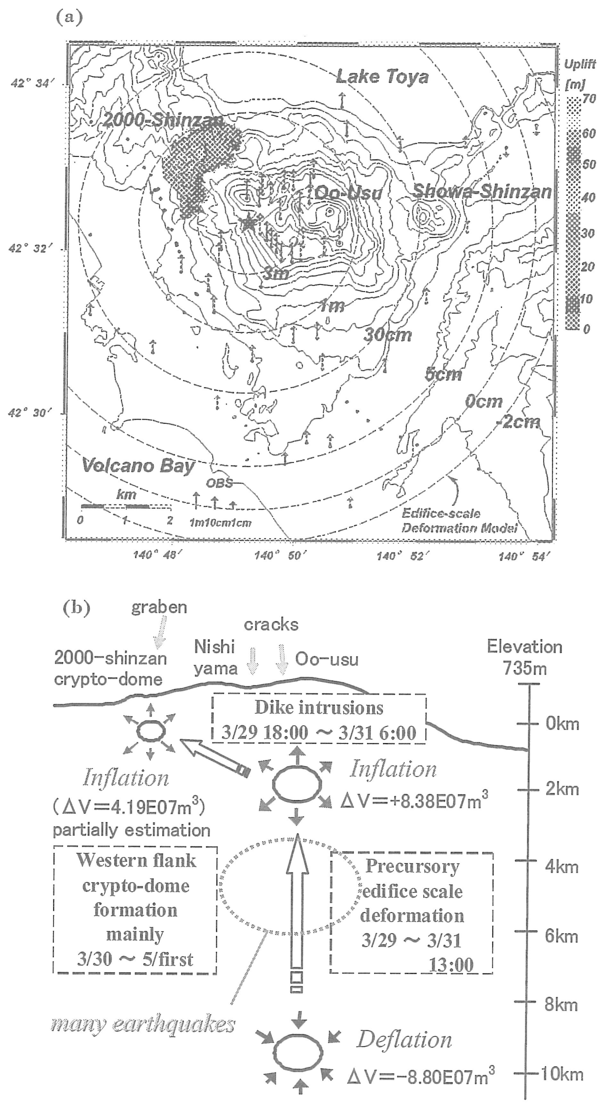


Fig. 8. (a) Total deformation map (DEM data from air-borne rider measurement by Aero Asahi Co.) (b) a simplified sketch of magma intrusion process of the 2000 eruption of Mt. Usu. Three major deformation sources are visible. Most of precursory earthquakes concentrate at 4−6km depth, where just between deflation and inflation sources.

interpreted as follows: (i) deep deflation causes magma intrusion to the shallower depth (not to happen magma drain back to deeper crust). Then, (ii) the intruded magma increases its volume by confining pressure decreasing at shallow depth. (iii) Nearly equivalent volume of magma to deep deflation is consumed for shallow inflation at 2 km, and the residuals happen to 2000−Shinzan crypto-dome formation. Dacitic magma of Mt. Usu is inclined to the intrusions and following doming activities in the shallow crust.

3. Comparison with past 4 eruptions of Mt. Usu in 20th century

Once simplified multiple source model is accepted for the edifice-scale deformation in 2000, it is very interesting to apply the same model for the three past geodetical data sets of dome-building activity in 1910, 1943−1945, and 1977−1982 at Mt. Usu. We used available precise leveling data set which is compiled by UVO (2003). Those 3 cases also could be basically explained by a combined model with shallow inflation (=1.2 km to 2 km) and deep deflation sources (=10 km). Inflation and deflation volume were nearly equivalent in any cases. Their uplift-subsidence reversals are seen at 4.3 to 6.6 km from the source (Fig. 9). It was found that extremely similar model fitting could explain the vertical deformations in 1910 and 2000. Similarities of precursory seismic activity, surface deformation and following eruptive activity are already well known among them. Our results imply that the magma intrusion process might be also very similar among them.

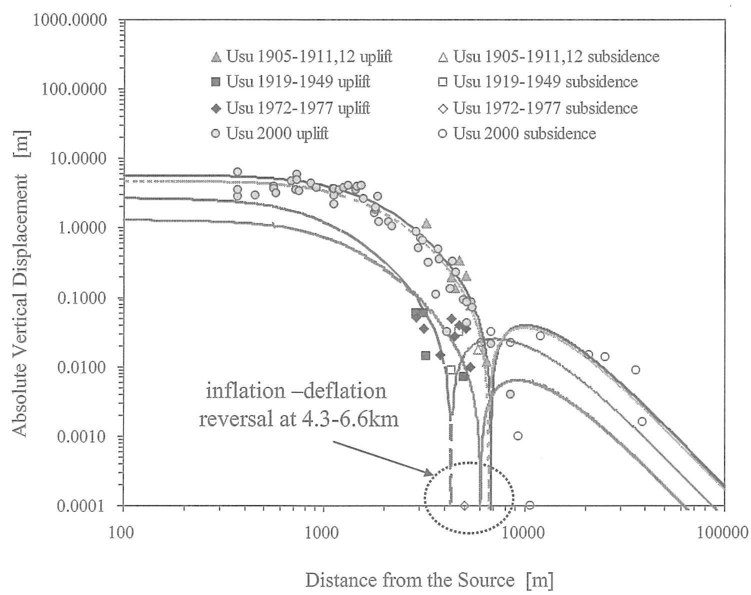


Fig. 9. Edifice-scale deformations associated with last 4 eruptions in 20th century of Mt. Usu. Any cases could be all characterized by the shallow inflation and deep deflation sources. A strong similarity is recognizable between the 1910 and the 2000 eruption.

V. Concluding remarks

Logarithmic expression of Mogi's deformation model provides better quantitative evaluation for the edifice-scale deformation of Mt. Usu. The specific corner distances for the single source model characterize the bending of the curves on log-log plots that are strongly depending on the depth of the single source. The edifice-scale deformation which accompanied with the 2000 eruption of Mt. Usu can be successively explained by a multiple spherical source model, with shallow inflation and deep deflation. It provides better fitness to the data when the deflation volume at 10km is taken nearly equivalent to the inflation volume at 2km. The combined models of shallow inflation and deep deflation are also applied to the past 3 eruptions in 1910, 1943–45 and 1977–82. Edifice-scale deformations accompanied by 4 dome-building eruptions in 20th century can be also well explained by shallow inflation and deep deflation sources. For the purpose of quantitative evaluation of data fitness, proportional misfit values (PMV) are newly proposed. The PMV is a useful measure for evaluating the fitness of the models. It became clear that very accurate deformation data at farther distances is very important to understand deep magmatic process. For further understanding of dacitic magma intrusions of Mt. Usu, future works should be considered time-series analysis for the magma movements using more realistic model together with high resolution data sets in time and space.

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References

Araki, H., 2002. The wide-areal crustal movement caused by the Usu 2000 eruption and it's implication by Mogi-model, Graduation thesis, *Fac. Sci., Hokkaido Univ.*, pp.38 (in Japanese).

Brune, J., 1970. Tectonic stress and the spectra of seismic shear waves from earthquakes, *J. Geophys. Res.*, **75**, 4997–5009.

Cayol, V., and F. Cornet, 1998. Effects of topography on the interpretation of the deformation field of prominent volcanoes – Application to Etna, *Geophys. Res. Lett.*, **25**, No.11, 1979–1982.

Churei, M., and A. Kobayashi, 2000. Crustal movement in the south-western part of Hokkaido associated with the 2000 eruption of Usu volcano, *Volc. Soc. Japan* (Japanese abstract).

Fedotov, S., N. Zharinov and V. Gorel'Chik, 1990. Deformation and seismicity at Klyuchevskoi, a model for its activity, *Volc. Seis.*, **10**, 165−225.

Furuya, M., Y. Ohki, S. Okubo, T. Maekawa, H. Oshima and H. Shimizu, 2001. Urgent gravity measurements for the eruption of Usu volcano in 2000, *Bull. Earthq. Res. Inst., Univ. Tokyo*, **76**, 237−246 (in Japanese with English abst.).

Ishihara, K., 1997. Researches on the mechanism of volcanic eruption with geophysical observation, *Bull. Volcanol. Soc. Japan*, **42**, 445−458 (in Japanese with English abst.).

Jousset, P., H. Mori and H. Okada, 2003. Elastic models for the magma intrusion associated with the 2000 eruption of Usu Volcano, Hokkaido, Japan, *J. Volcanol. Geotherm. Res.*, **125**, 81−106.

Matsumoto, N., T. Sato and N. Matsushima, 2002. Hydrological anomalies associated with crustal deformation before the 2000 eruption of Usu volcano, Japan, *Geophys. Res. Lett.*, **29**, No.5, 1−1−1−3.

Matsushima, T., H. Shimizu, A. Watanabe, K. Yamashina and Y. Nishimura, 2000. Tilt changes observed during the 2000 eruption of Usu volcano, *Volc. Soc. Japan* (Japanese abstract).

McTigue, D., and P. Segall, 1988. Displacements and tilts from dip-slip faults and magma chambers beneath irregular surface topography, *Geophys. Res. Lett.*, **15**, No.6, 601−604.

Mimatsu, M., 1962. Diary of the growth of Showa-Shinzan, *Sobetsu*, pp.202.

Minakami, T., T. Ishikawa and K. Yagi, 1951. The 1944 eruption of Usu Volcano in Hokkaido, Japan, *Bull. Volcanol.*, **11**, 45−117.

Miyazaki, T., 1990. Recent crustal movements of active volcanoes in Japan as revealed by leveling survey, *Bull. Earthq. Res. Inst., Univ. Tokyo*, **65**, 665−807 (in Japanese with English abst.).

Mogi, K., 1958. Relations between the eruptions of various volcanoes and the deformations of the ground surfaces around them, *Bull. Earthq. Res. Inst., Univ. Tokyo*, **36**, 99−134.

Mori, H., and A. Suzuki, 1998. Volcanic ground deformation at Mt. Usu − a perspective of the deformation in the last twenty years −, *Geophys. Bull., Hokkaido Univ.*, **61**, 275−285 (in Japanese with English abst.).

Mori, H., and T. Ui, 2000. Crustal deformation and eruptic activities of Mt. Usu in 2000, *J. Japan. Soc. Nat. Disaster Sci.*, **19**, 383−390 (in Japanese with English abst.).

Murakami, M., S. Ozawa, T. Nishimura and T. Tada, 2001. A model of magma movements associated with the 2000 eruption of Usu Volcano inferred by crustal deformation detected by continuous GPS and other geodetic measurements, *J. Geograph. Surv. Inst.*, **95**, 99−105.

Murakami, M., 2003. Magmatic process of Usu volcano before 2000 eruption inferred from precise leveling, *Geod. Soc. Japan* (Japanese abstract).

Okada, H., H. Watanabe, H. Yamashita and I. Yokoyama, 1981. Seismological significance of the 1977−1978 eruptions and the magma intrusion process of Usu Volcano, Hokkaido, *J. Volcanol. Geotherm. Res.*, **9**, 311−334.

Okada, J., 2004a. Ground deformation associated with the 2000 eruption of Usu Volcano − an application by multiple spherical sources −, M.S.Thesis, *Fac. Sci., Hokkaido Univ.*, pp.122.

Okada, J., 2004b. Edifice scale deformation due to shallow inflation and deep deflation sources − an application to the 2000 eruption of Usu Volcano, *IAVCEI General Assembly 2004* (English abstract).

Okada, Y., 1985. Surface deformation due to shear and tensile faults in a half-space, *Bull. Seismol. Soc. Am.*, **75**, 1135−1154.

Okazaki, N., H. Takahashi, S. Nakao and M. Kasahara, 2002a. *CHIKYU MONTHLY*, **39**, 22−28 (in Japanese).

Okazaki, N., H. Takahashi, M. Kasahara, S. Ishimaru, H. Mori, S. Kitagawa, K. Fujiwara and M. Churei, 2002b. Crustal deformation associated with the 2000 eruption of Usu Volcano as observed by a dense GPS array, *Bull. Volcanol. Soc. Japan*, **47**, 547−557 (in Japanese with English abst.).

Omori, F., 1911. The Usu-san eruption and earthquake and elevation phenomena, *Bull. Imp. Earthq. Inv. Com.*,

5, 1−38.

Omori, F., 1920. The Usu-san eruption and earthquake and elevation phenomena III. *Bull. Imp. Earthq. Inv. Com.*, **9**, 41−76.

Sato, T., H. Ohta, F. Akita, A. Suzuki and N. Matsushima, 2000. *CHISHITSU NEWS*, **551**, 20−26 (in Japanese).

Sato, T., K. Kazahaya, A. Suzuki and N. Matsumoto, 2002a. Estimation of amplitude of crustal movement by measurement of intervals between poles, *Bull. Volcanol. Soc. Japan*, **47**, 699−704 (in Japanese with English abst.).

Sato, T., N. Matsumoto, F. Akita, T. Shibata, A. Suzuki, N. Matsushima and M. Takahashi, 2002b. Anomalous groundwater-level changes in Date City associated with the 2000 eruption of Usu volcano, *Bull. Volcanol. Soc. Japan.*, **47**, 171−176 (in Japanese with English abst.).

Shimada, M., 2000. Temporal terrain change at Mt. Usu by SAR, In *The Eruption of Mt. Usu −Heisei 12 (2000) − Observation and analysis from space (NASDA/RESTEC)*, 36−41 (in Japanese).

Suzuki, H., 2001. The change of elevation around Nishiyama area caused by the volcanic activity of Mt. Usu − Comparison between a tentative result by a single model measuring and precise result using aerial triangulation, *J. Geograph. Surv. Inst.*, **95**, 49−55.

Swanson, D., D. Jackson, R. Koyanagi and T. Wright, 1976. The February 1969 east rift eruption of Kilauea volcano, Hawaii, *U. S. Geol. Surv. Prof. Paper*, **891**, 1−30.

Takahashi, H., N. Okazaki, S. Ishimaru, H. Mori, T. Matsushima, A. Watanabe, S. Miura, S. Nakao, T. Kato, F. Kimata and M. Kasahara, 2002. Geodetic observation of the 2000 eruption of Usu volcano using dual frequency GPS receivers, *Bull. Volcanol. Soc. Japan*, **47**, 161−166 (in Japanese with English abst.).

Tomiya, A., and E. Takahashi, 1995. Reconstruction of an evolving magma chamber beneath Usu volcano since the 1663 eruption, *J. Petrol.*, **36**, 617−636.

Trasatti, E., C. Giunchi and M. Bonafede, 2003. Effects of topography and rheological layering on ground deformation in volcanic regions, *J. Volcanol. Geotherm. Res.*, **122**, 89−110.

Usu Volcano Observatory, 2003. Estimation of the upheaval volumes for the past 4 eruptions of Mt. Usu.

Watanabe, H., 2003. Magma-pluming system and doming processes of dacite volcano Usu (2), *Japan Earth and Planetary Sci. Joint Meeting* (English abstract).

Williams, C., and G. Wedge, 1998. The effects of topography on magma chamber deformation models: Application to Mt. Etna and radar interferometry, *Geophys. Res. Lett.*, **25**, No.10, 1549−1552.

Williams, C., and G. Wedge, 2000. An accurate and efficient method for including the effects of topography in three-dimensional elastic models of ground deformation with applications to radar interferometry, *J. Geophys. Res.*, **105**, 8103−8120.

Yamamoto, M., H. Kawakatsu, K. Yomogida and J. Koyama, 2002. Long-period (12 sec) volcanic tremor observed at Usu 2000 eruption: seismological detection of a deep magma pluming system, *Geophys. Res. Lett.*, **29**, 10.1029/2001GL013996.

Yokoyama, I., H. Yamashita, H. Watanabe and H. Okada, 1981. Geophysical characteristics of dacitism volcanism − the 1977−1978 eruption of Usu Volcano, *J. Volcanol. Geotherm. Res.*, **9**, 335−358.

Yokoyama, I., and M. Seino, 2000. Geophysical comparison of the three eruptions in the 20th century of Usu Volcano, Japan, *Earth. Planets. Space*, **52**, 73−89.

浅部膨張・深部収縮源によるデイサイトマグマ貫入
－有珠山への適用－

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圧力源からの水平距離を横軸，垂直変位を縦軸とした両対数グラフ上での茂木モデルの振る舞いが調べられた．単一圧力源モデルの振る舞いは非常に特徴的かつシンプルであり，圧力源近傍では一様な変位を，そして遠方では一定率の変位減衰を示す．モデル曲線はいずれもある距離で１つの屈曲点（corner distance）をもち，その距離は圧力源の深さに最も依存する．しかしながら，有珠山 2000 年噴火に伴う全山規模の地殻変動はこの傾向とは異なり，水平距離 5 － 6 km 付近での隆起量の急減，更に隆起から沈降への反転，遠方での沈降を示す．この変動は浅部膨張源と深部収縮源の重ね合わせによる複合圧力源モデルによって統一的に説明されうることがわかった．その際，深部収縮源の浅部膨張源に対する影響は定量的に検討され，最適解として，体積変化が互いに等価な深さ 2 km の膨張源と深さ 10 km の収縮源の組合せが推定された．水平モデルについてもほぼ同様の結果が得られた．また，有珠山の過去の噴火(1910 年，1943－45 年，および 1977－82 年)に伴う全山規模の地殻変動を調べるため，既存の水準測量データに対して 2000 年と同様のモデルを適用した結果，いずれの噴火も浅部膨張・深部収縮モデルによってデータがよく説明されることが示された．特に，2000 年と 1910 年のモデルには強い類似性が見られた．このことは両者の活動において地表での噴火様式や潜在ドームの形成過程などの強い類似性を考えると極めて興味深い結果である．このような圧力源モデルの類似性は，有珠山におけるデイサイトマグマの貫入様式が過去 4 回とも相互に非常に似ていることを示唆する．