HOKKAIDO UNIVERSITY

Title	The viscosity of Mt. Oyama, Miyakejima inferred from the caldera formation 2000
Author(s)	MAEDA, Itaru
Citation	Journal of the Faculty of Science, Hokkaido University. Series 7, Geophysics, 12(1), 1-8
Issue Date	2003-03-28
Doc URL	http://hdl.handle.net/2115/8869
Type	bulletin (article)
File Information	12(1)_p1-8.pdf

Instructions for use

Hokkaido University Collection of Scholarly and Academic Papers : HUSCAP

Jour. Fac. Sci., Hokkaido Univ., Ser. VII (Geophysics), Vol. 12, No. 1, 1-8, 2003.

The viscosity of Mt. Oyama, Miyakejima inferred from the caldera formation 2000

Itaru Maeda

Graduate School of Science, Hokkaido University, Kita-ku Kita10 Nishi8, Sapporo 060-0810, Japan

(Received December 25, 2002)

Abstract

A caldera formation was observed at the top of Mt. Oyama, Miyakejima from July to August, 2000. The caldera is more than 1 km in diameter and about 1/2 km in depth. The corresponding strain is of the order of 1. In this report, an apparent viscosity of this deformation is estimated. Although the viscosity does not means the molecular viscosity, it is important to be able to describe deformations of a volcano by a known continuum theory, i.e., in order not to be Ptolemaist.

As observations were not sufficiently frequent, a possible maximum value for the apparent viscosity was estimated to be 10^{12} Pa.s. This rather low value is consistent with the values obtained for Mt. Unzen and Mt. Usu through continuum models.

1. Introduction

Volcanic activities always accompany mechanical deformation of volcanos. The deformation is not limited within an infinitesimal one such as earthquake vibrations. This means that the deformation is not expressed within a linear elastic theory, so that we can not calculate force acting on a volcano from the observed strains using elastic constants deduced from seismic wave velocity. The motions of a volcanic body are frequently described by words such as ground slide which are simply descriptions of the phenomenon in terms of daily life words. Such a description cannot be a scientific analysis but ubiquitous.

To be scientific, we must describe the phenomenon in terms of mathematical and physical quantities and equations. It is not easy to construct equations with newly defined physical quantities having concrete bases adequate for the deformation such as the caldera formation. For want of better, we would approximate the deformation in terms of classical continuum having elastic constants and viscosity.

For a slightly non-equilibrium system, to which shallow crust is considered to be classified, we can describe it with a combination of springs and dashpots according to the theory of Onsager and Biot (Onsager, 1931a, 1931b ; Biot, 1955) That is to say, the system can be described by a visco-elastic model. Maeda (2000) showed, through a study of volcanic activity of Mt. Unzen began at the end of 1990, that the visco-elastic model is sufficiently good approximation to describe the deformations accompanying the volcanic episode.

It goes without saying that the viscosity which is a mechanism for diffusion process of linear moment of macroscopic motions does not necessarily means the molecular viscosity which may be a small part of the total. An example of this macroscopic moment diffusion is that caused by turbulent in fluid. We simply claim that in order to describe mathematically, a concept of viscosity may be useful.

The viscosity of dome lava of Mt. Unzen determined through observations of its flow (Sudo, et al. 1993) is much lower the value obtained experimentally (Goto, et al., 1994), which represents molecular viscosity, and the lower value is consistent with that obtained through a visco-elastic model for the eruption episode.

Although in-situ measurements on the viscosity of the upper crust or ground are desirable, there is no such measurements which directly relates to a volcano. Therefore, it is of great value if there is an observation or two from which the viscosity is deduced.

A caldera was formed at the top of Mt. Oyama, Miyakejima from July to August, 2000. Although the observations were not sufficiently dense in the sense of time resolution, it can give an estimate of the viscosity of this scale. In this report, the viscosity of Mt. Oyama, Miyakejima is deduced from data given by Japan Meteorological Agency and by The Geographical Survey Institute.

2. Model

Let us look at first the observed process of the caldera formation.

According to the data given by the Japan Meteorological Agency (JMA for short) (2000a, 2000b), the first observation of the collapse was made on July 9, 2000 at the top of Mt. Oyama, Miyakejima. At the time, the bottom of the collapse already reached to 200 m in depth. The downward speed at the central part of the collapse was 300 to 400 m per a week and after that the fall apparently stopped. It seems that the velocity of collapse was fast at first and then gradually decreased, though the data was too sparse to confirm it.

Synthetic photographs of the high-resolution multi parameter synthetic aperture radar by Communications Research Laboratory (2000) shows that the collapse had not yet taken place on July 6, 2000. These data suggest that the central part of the collapse went down 200 m over 2 days at the most. This shows that the possible maximum downward speed of the bottom is 100 m/day. Theoretically the maximum speed can be that of the free fall, i.e., 60 m/sec when it reached 200 m in depth, but it cannot make sense because the motion was nearly stopped at this level. These are the surface observations.

Deep in the ground, the precursory events had been taken place, though we have no proof of a causal relationship between these precursory events and the caldera formation. The proof strongly depends on models. Again, we follow the data (press release) by JMA. Earthquake activities just under the mountain top began on July 3, 2000 and on July 5, three earthquakes with the intensity of 3 at largest occurred, the depth of which was 2 to 3 km. At 2 p.m. on July 8, the amplitude of the volcanic swarm began to grow. At the same time, variations were detected in the geodetic data. And finally, Mt. Oyama erupted at about 6 : 43 p.m. on July 8, 2000. These observations suggest that some instability (fracture or dislocation) propagated upward and when it reached to the surface the eruption took place.

From these observations, we propose a model from which we will infer the viscosity of the materials forming the mountain. We assume that a cavity with the size of 1 km in diameter and 1/2 km or less in height in/under the mountain body was formed in advance. The cavity is filled with pressurized gas. It goes without saying that the upper part of the cavity is made of volcanic deposit, i.e., granular medium which is far from being a continuum of the same kind of stable man-made structural material. Even if it is supported by the pressurized gas, instability will occur at the ceiling of the cavity. Under gravity, the instability must propagate upward. It is very probable that, when the instability reached the surface, the pressurized gas having filled the cavity will escape through the instability path.

If it is the case, the pressure in the cavity will rapidly decrease and the collapse of the upper part of the cavity begins. We do not know if the collapse already began at the time of the eruption. But it is not the severe problem to infer the viscosity. The reduction of supporting pressure occurs over the ceiling at the same moment considering the nature of gas. What will happen next?.

Instabilities would take place at many points on the ceiling. These instabilities must propagate mainly upward but also diffuse horizontally which causes interactions between nearby instabilities to form larger scale motions. If the

the cavity is sufficiently shallow, the medium above the cavity is thin and the instabilities reach to the surface without sufficient interactions. This means that the collapse of the ground is very irregular and the surface region of the collapse corresponds to the cavity's horizontal extent. On the other hand, if the cavity is very deep compared with its size, the interaction between the instabilities will well develop and the horizontal extent of ground collapse is well over the diameter of the cavity and the vertical section of the collapse will be conic.

The variation of the vertical cross section of the collapse given by Geographical Survey Institute is reproduced in Fig. 1. The original data is a colored figure and more perspicuous. We reproduced in Fig. 2 three sections, the original, the ones observed on 7/9 and on 7/22 and also added two parabola curves with the same edges (or rims in three dimensions) assuming axial symmetry with vertical axis. It is recognized that, up to July 22, 2000, the cross sections are sufficiently well approximated not by conics but parabolas.

The data indicates that the depth of the cavity is intermediate, neither too shallow nor too deep. Taking into account of the depths of earthquakes occurred just before the eruption, the top of the cavity may be several kilometers in depth. Because parabolas well fit to the cross sections, we can assume that the motion of the medium just above the cavity is expressed as a viscous flow in a pipe. If it is the case, the extent of the ground collapse reflects the size of the cavity ; the diameter be about 1 km and the height of the cavity may be 400-500 m as assumed above,

As shown in Fig. 1, the horizontal expansion of the ground collapse took place well after the downward motion of the bottom had nearly stopped. This fact is consistent that at first the motion is limited just above the cavity and the direction is vertical. Horizontal expansion of instabilities may need time to take effect. We will discuss this point later.

Not only the geomorphological evidences given above, the extremely large strain of the order 1 during the formation of the caldera suggests that the viscous motion is dominant even within a visco-elastic theory given in Introduction, as far as we limit the motion in the region of the caldera.

Now we approximate the motion forming a caldera as a Poiseuille flow in a vertical pipe. This means that the motion reaches to its steady state immediately after the start of falling, may be because of high "viscosity" of the ground. To be able to take into account of non-steady motions, we need data with sufficient resolution of time, which is not the case.

We employ standard assumptions ; the flow v is purely vertical (z-direction) and it varies only in radial direction r, i.e., $v=v(r)$. We take the down-

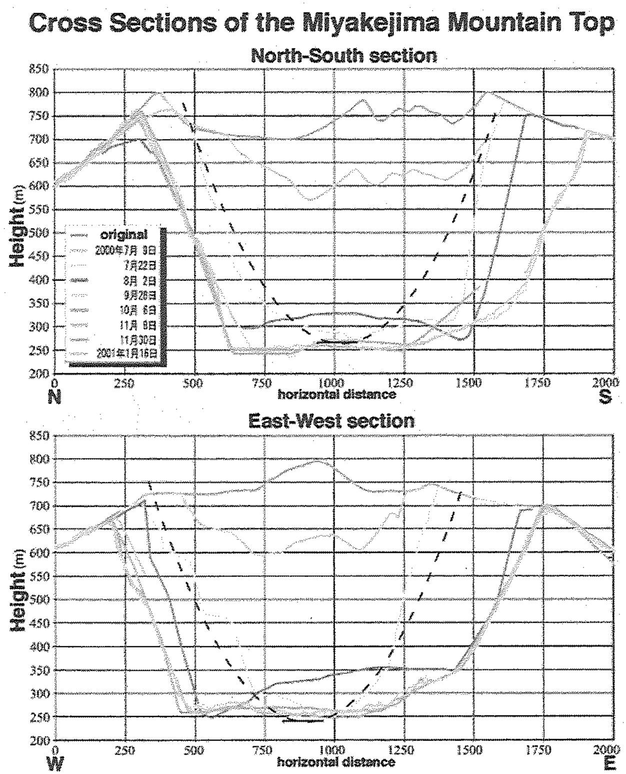

Fig. 1 N-S (upper fig.) and E-W (lower fig.) cross sections of the Miyakejima caldera observed and uploaded on http://www.gsi.go.jp/WNEW/LATEST/MIYAKE/tochijoken/kanbotsuryou2.gif by Geographical Survey Institute and parabola expected from the viscous model. This figure is poor reproduction of the much more perspicuous original figure.

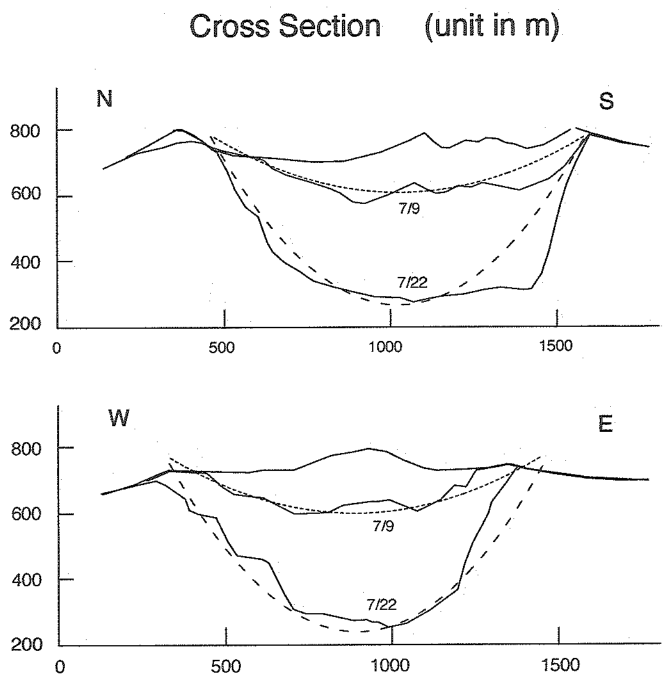

Fig. 2 Original geomorphological cross section of the top part of Mt. Oyama and the ones observed on July 9, and on July 22, 2000. They are reproduced from Fig. 1. And also depicted two parabolas expected from viscous deformation. In this figure, vertical to horizontal axis ratio is 1 : 1

ward direction positive in z. The well known formula gives, with the radius of the pipe R and the boundary condition $v(R)=0$,

$$v(r)=\frac{1}{4\eta}\left|\rho g-\frac{dP}{dz}\right|(R^2-r^2), \tag{1}$$

where η is the viscosity of the moving medium, dP/dz the pressure gradient, ρ the density, and g the gravitational acceleration.

To form a caldera, we assume for simplicity that the pressure in the cavity suddenly drops, though we do not know how sudden it is actually. Then the medium above the cavity begins to fall. Because we know nothing about actual values of the pressure drop, depth of the cavity, and speed of the pressure reduction, what we can do is to determine the maximum of possible viscosity. To this end, we neglect the factor dP/dz which may be small. Then maximum viscosity is given by

$$\eta=\frac{\rho g R^2}{4v(0)}, \tag{2}$$

where we substitute for $v(0)$ the values of falling speed of the caldera bottom inferred above.

3. Viscosity for caldera formation and discussion

We already inferred a maximum velocity of 100 m/day. As we know almost nothing about viscosities of ground or volcanos subjected to a large strain with spacial extent of kilometers and time span of weeks. It is well known from geological evidences that geological bodies having a size of tens of kilometers can deform without break over millions of years but no one knows of its viscosity. Equation (2) shows viscosities are inversely proportional to the falling speed. All these factors indicate that we need not precise falling velocity. It is sufficient to be able to estimate the order of magnitude of the viscosities.

The value 100 m/day means that the process is nearly quasi-static. Therefore, the motion is consistent with our steady flow model. Take values for $R=$ 500 m, $\rho=2\times10^3$ kg/m^3 and $g=10$ m/s^2, we obtain 10^{12} Pa.s for the upper limit of the viscosity coefficient. Actually, the residual pressure in the cavity might impede the falling, so that the real viscosity may be much (possibly order of magnitude) less than 10^{12} Pa.s. What is the lower bound of the value? If we take the average value of free fall, 30 m/sec, the coefficient becomes of the order of 10^7 Pa.s.

The value of 10^{12} Pa.s is extremely small compared to the values of the crust but not largely different from the value deduced through the analysis of the recent eruption of Mt. Unzen (Maeda, 2000). An analysis for the eruption 2000 of Mt. Usu indicates its ground viscosity to be 10^8–10^9 Pa.s. These low values indicate that for shallow and large strain deformation with spacial extent of order of kilometers and duration of a week can be treated as a rather low viscosity medium. As stated earlier, these deformations are not driven as a viscous flow with viscosity caused by molecular diffusion.

The deformation may consist of many small scale dislocations in the sense of granular materials. Because the size distribution and form of grains consisting the real ground are extremely wide and irregular, a systematic theory is not available. But we can say something about this type of media. At least, grains exert frictional forces to nearby contacting grains with each other. In general, a frictional system has a threshold stress under which the deformation is elastic and above which it slide. For a granular system, the average of relative grain slide over many grains may be considered as flow (coherent large scale grain motion).

Sudden forcing may not result in a sudden flow. At first, frictionally week coupling points will slide and accumulation of stress will occur at stronger portions. It takes some time to develop. When spatially averaged slide motions reaches at some amount, a transition from elastic deformation to plastic flow will occur. For a classical granular medium, random forces to activate the slides is not the thermal agitation but external random classical forces. This means that the actual activations sparsely occur compared to the thermal activation. Therefore the transition may takes long time.

This transition period may depend on the intensity of stress acting on the system ; if the stress is low, the probability of sliding at a contact point is low and the transition period becomes long and vice versa. This may explain the observed variation of the cross section (Fig. 1). Synchronized with the pressure reduction in the cavity, elastic stress relaxation must occur. After that, for grains above the cavity, acting force and its relaxation motion are in the same direction (vertically downward) in the average but, for the grains at the side of the cavity, they are perpendicular. This imply that the transition period to inelastic relaxation, i.e., flow, may be short for the medium just above the cavity. That is to say, firstly the vertical flow occurred then, well behind the first, the collapse of the cavity wall followed.

References

Biot, M.A. 1955. Variational principles in irreversible thermodynamics with application to viscoelasticity., Phys. Rev., **97**, 1463-1469.

Goto, A., H. Ohshima, Y. Nishida, and H. Okada, 1994. Viscosity measurements of dome lava and volcanic ejecta of Unzen volcano, Kazan, **39**, 267-271 (in Japanese)

Goto, A., Ohshima, H., Nishida, Y., and Okada, H. (1996) An experimental study on the rheological property of the dome lava of Unzen volcano., in Proc. '95 Int. Workshop Volc., 45.

Japan Meteorological Agency, 2000a, On the activities of Miyakejima, 7/18/2000 (press release), http://www.kishou.go.jp/press/miyake/18_1800/index.html.

Japan Meteorological Agency, 2000b, On the volcanic and seismic activities around Miyakejima, Niijima and Kouzusima, 8/8/2000 (press release), http://www.kishou.go.jp/press/0008/08a/index.html.

Geographical Survey Institute, 2001. Geomorphological cross sections of Miyakejima moutain top., http://www.gsi.go.jp/WNEW/LATEST/MIYAKE/tochijoken/kanbotsuryou2.gif.

Maeda, I. 2000. Nonlinear visco-elastic volcanic model and its apprication to the recent eruption of Mt. Unzen., J. Volcanol. Geotherm. Res., **95**, 35-47.

Onsager, L. 1931a. Reciprocal relations in irreversible processes. I., Phys. Rev., **37**, 405-426.

Onsager, L. 1931b. Reciprocal relations in irreversible processes. II., Phys. Rev., **38**, 2265-2279.

Suto, S., K. Sakaguchi, K. Watanabe, E. Saito, Y. Kawanabe, K. Kazahaya, S. Takarada, and T. Soya, 1993. Dynamics of flowage and viscosity of the 1991 lava of Unzen volcano, Kyushu, Japan., Bull. Geol. Surv. Japan, **44**, 609-629 (in Japanese with English abstract).

Communications Research Laboratory, 2000. Synthetic images of Miyakejima obtained by the high-resolution multi parameter synthetic aperture airborne radar, CRL/NASDA, http://www.crl.go.jp/ck/ck521/PI-SAR/J/izu/Miyake.html.