2019

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PAPER · OPEN ACCESS

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To cite this article: R Kumalasari *et al* 2019 *J. Phys.: Conf. Ser.* **1321** 032120

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Location of Sinabung volcano magma chamber on 2013 using simulated annealing inversion scheme

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Abstract. Volcano has been monitoring using GPS after his eruption on August 2010. We Applied Simulated Annealing Inversion Scheme to GPS data on 2013, first we applied Simulated Annealing to velocity data on 23 January 2013 then we applied Simulated Annealing Inversion Scheme to data on 31 December 2013. From our analysis we got the depth of the pressure source modeling results indicate some possibilities that Sinabung has a deep magma chamber about 14km and also shallow magma chamber about 1km from the surface.

1. Introduction

1.1. Sinabung Vulcano

Before the eruption in 2010, the eruption of Sinabung volcano was never recorded in history. The first period of eruptive activity of Mount Sinabung began on August 27, 2010, which then turned into a classification Sinabung volcanoes type A is a solitary volcanic which has a single peak, where the activity before the eruption of Sinabung 2010 just a solfatara gas emissions and fumarole [1,2,4,5].

Figure 1. Sinabung volcano (PVBG)

Based on data and information from PVMBG, the period of the next eruption started on 15 September 2013, which is still a phreatic eruption, then turned into a magmatic eruption since 23 November 2013 and was followed by the emergence of a lava dome since December 16, 2013[10,11,12]. The Sinabung volcano picture can be seen in Figure 1.

1.2. Point Pressure source

Shape and size from the magma chamber is decided the surface deformation, the others factor that influence the surface deformation is the increment of pressure, and elastic properties of medium. From the Mogi models we described that deformation is ratio of the cavity pressure change to the half-space elastic modulus $\Delta P/G$, and Poisson's ratio [1,6,7,8]. Mogi model also assumes that the crust attribute is half-elastic medium and surface deformation at volcano caused by pressure source (magma chamber) in the form of a spherical which is locate data certain depth of its magma chamber. If there is a hydrostatic pressure on magma chamber, the deformation of the surface will occur symmetrically. The model needs to be input Mogi point pressure source are the depth (d), the radial distance to the source of magma chamber (r), and volume changes (ΔV).

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \alpha^3 \Delta P \frac{(1-\upsilon)}{G} \begin{pmatrix} \dfrac{x}{R^3} \\ \dfrac{y}{R^3} \\ \dfrac{d}{R^3} \end{pmatrix}, \tag{1}$$

Where υ = poisons ratio, G = shear modulus, and ΔP = Pressure change. u, v, w are surface deformation of positional the point $x, y, 0$ and $R = \sqrt{x^2 + y^2 + d^2}$ is the radial distance from a magma chamber point to the surface. It shown graphically in Figure 2. An example of surface deformation used Mogi model is shown in Figure 3 and Figure 4 in below shown a horizontal and vertical displacements. The input of our models are a = 1000 m, d = 1000 m, x-min= -1000, x-max = -1000, $\Delta P /G = 0.001$, and $\upsilon = 0.25$. The magnitude of displacement vector with radial direction is

$$U_r = \sqrt{u^2 + v^2 + w^2} = \alpha^3 \Delta P \frac{(1-\upsilon)}{G} \frac{1}{R^2}. \tag{2}$$

The magnitude of displacement vector depends on inverse of squared distance from the center cavity. We can calculate the location of the source and the depth of magma chamber using $\left(w/U_r \right) r$ where $U_r = \sqrt{u^2 + v^2}$. We can calculate the Pressure changes using the relationship between volume of surface deformation and discharge time of the lava. Relationship between surface deformation $\left(\Delta V_{uplift} \right)$ and the change of volume magma chamber $\left(\Delta V_{injection} \right)$ shown in equation $V_{uplift} = 2(1-v)\Delta V_{injection}$ with v is poisons' ratio. Mogi equation has been used in many applications by Murray *et al* [7].
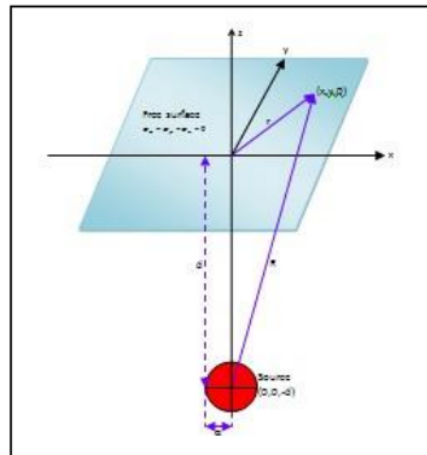
Figure 2. Geometry of source in elastic half space (redrawn based on Lisowski [3])
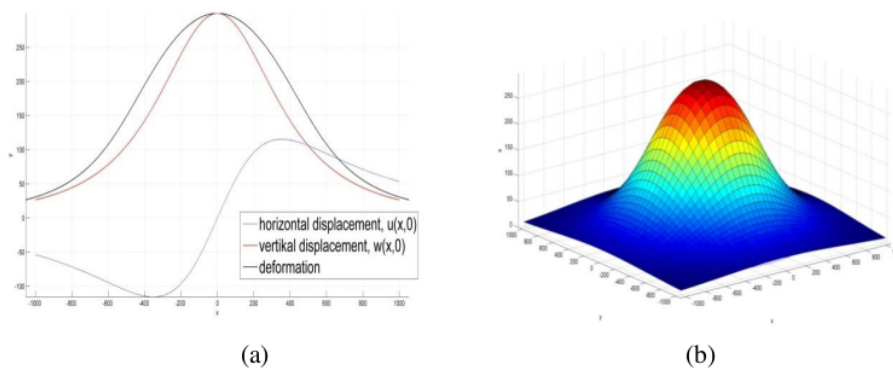

(a)

(b)

Figure 3. (a) Horizontal and vertical displacements using Mogi model. (b) 3D surface displacement
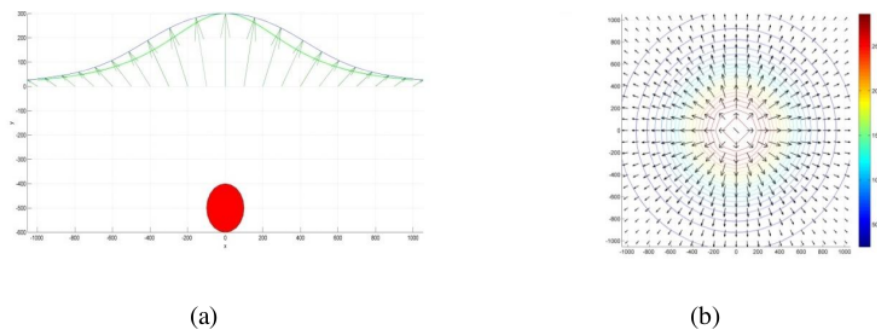

(a)

(b)

Figure 4. (a) Surface deformation. (b) displacement vectors using Mogi model.

2. Methods

The Simulated Annealing (SA) method progressively deforms the shape of the pdf from prior pdf to posterior pdf by decreasing a parameter known as temperature. When the temperature is high (initially), all models are selected, even those with a larger misfit. As the temperature decreases in steps, fewer and fewer models are selected, only those which give a lesser misfit. Hence, it does not get trapped in the local minima like Metropolis. The expression for $P(\text{dobs}|m)$ is modified as

$$P(d^{obs|} \mid m) = \exp\left(-\frac{1}{2}\frac{\left\| d^{obs} - d \right\|^2}{\sigma^2 T}\right),$$

(3)

Where T, the temperature is decreased from high to low [13,14]. (See the Algorithm of SA in Figure 5)

```
Algorithm SIMULATED-ANNEALING
Begin
        temp = INIT-TEMP;
        place = INIT-PLACEMENT;
        while (temp > FINAL-TEMP) do
                while (inner_loop_criterion = FALSE) do
                        new_place = PERTURB(place);
                        ΔC = COST(new_place) - COST(place);
                        if (ΔC < 0) then
                                place = new_place;
                        else if (RANDOM(0,1) > e^{-(ΔC/temp)}) then
                                place = new_place;
                temp = SCHEDULE(temp);
End.
```

Figure 5. Algorithm of simulated annealing

3. Results and Discussion

PVMBG has placed several GPS stations at Sinabung volcano since 2010. The locations of these stations are shown in Figure 6, Figure 7, and Figure 8. We use data of deformation recorded at these stations in 2013 published by PVMBG because in this period we have condition that Sinabung being inflation and deflation and we can observe shallow magma chamber and deep magma chamber on this period by applying simulated Annealing inversion scheme.

The Simulated Annealing was applied to GPS deformation data at Sinabung volcano in 2013, first we tried to apply Simulated Annealing on GPS data on 23 January 2013, we choose that time because at 23 January 2013 condition of Sinabung is tend to be stable, from our inversion we get deep magma chamber about 1km with volume of magma chamber about $3x10^9$ m^3 . Then we applied Simulated Annealing inversion on velocity data on 31 December 2013, on this period we get shallow magma chamber about 1 km and volume of magma chamber about $0.8 x10^9$ m^3. From tha calculation we predict that the magma sources in 2013 migrated from deeper part to shallower beneath summit of Sinabung before the lava dome appearance in December 2013.
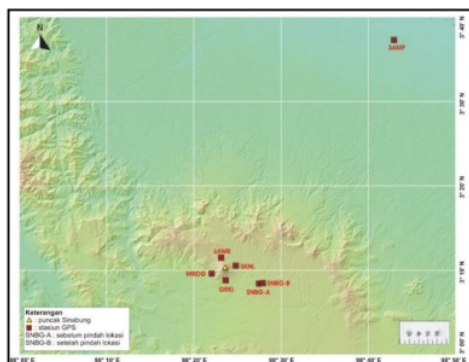
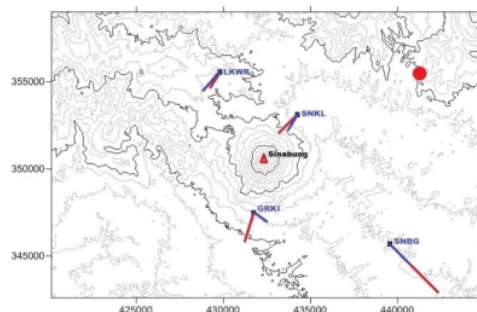**Figure 6.** Global Positioning System (GPS) stations at Sinabung volcano in 2013

Figure 7. Source inversion on phase 1 (23rd January 2013), and we get deep magma chamber about 12 km
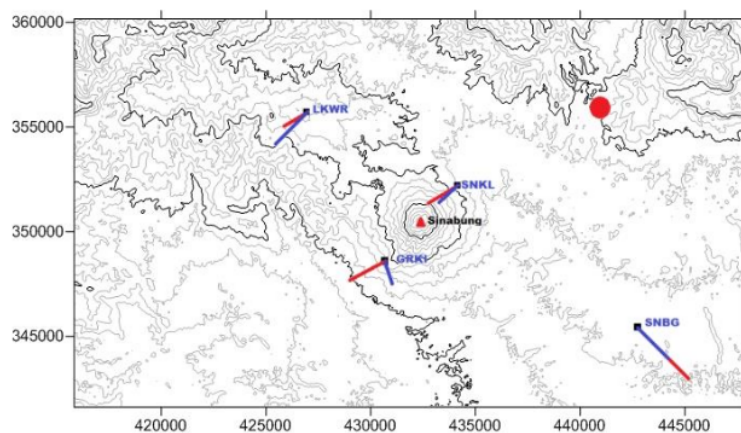

Figure 8. Shallow magma chamber about 1 km from the surface (on 31st December 2013)

4. Conclusion

From our analysis using Simulated Annealing Inversion Scheme, we get prediction that the magma sources in 2013 migrated from deeper part to shallower beneath summit of Sinabung before the lava dome appearance in December 2013, from our inversion we got deep magma chamber about 14 km and also shallow magma chamber about 1 km under the surface.

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