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Characteristic of Lokon Volcano Deformation of 2009 - 2011 Based on GPS Data

Karakteristik Deformasi Periode 2009 - 2011 Gunung Api Lokon Berdasarkan Data GPS

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Abstract

Precursor of Lokon Volcano eruptions in 2011 is believed to begin since December 2007 which was marked by increasing number of volcanic earthquakes and gas emission. To support this information, deformation method is used primarily to determine deformation characteristics of Lokon volcanic activity in the period of 2009-2011. The period of analysis is adapted to the presence of GPS data. Displacement rate of Lokon GPS observation points in the period of 2009 - 2011 ranged from 1.1 to 7 cm a year. Strain patterns that occur in the areas are compression surrounding Tompaluan crater and extension in the eastern slope. Location of the pressure source for August 2009 - March 2011 measurement was at a depth of 1800 m beneath Tompaluan crater. Deformation in the Lokon Volcano is characteristized by the compression zone in the summit and crater area caused by magma activity raised into the surface from a shallow magma source which is accompanied by a high release of volcanic gases. Accumulated pressure release and deformation rate as measured in the Lokon Volcano remain low.

Keywords: eruption, volcanic earthquakes, deformation, magma, Lokon Volcano, GPS

Sari

Tanda-tanda awal letusan Gunung Api Lokon tahun 2011 dipercaya dimulai sejak Desember 2007 yang ditandai dengan sejumlah gempa bumi vulkanis dan emisi gas. Untuk menunjang informasi ini, suatu metode deformasi digunakan, terutama untuk menetukan karakteristik deformasi kegiatan Gunung Api Lokon pada periode 2009 - 2011. Periode analisis disesuaikan dengan adanya data GPS. Kisaran pergeseran titik-titik observasi GPS Lokon pada periode 2009 - 2011 mempunyai rentang antara 1,1 sampai 7 cm per tahun. Pola tegangan yang terjadi pada daerah tersebut merupakan kompresi di sekitar kawah Tompaluan dengan perluasan di lereng sebelah timur. Lokasi sumber tekanan pada pengukuran Agustus 2009 - Maret 2011 berada pada kedalaman 1800 m di bawah kawah Tompaluan. Deformasi pada Gunung Api Lokon dicirikan oleh zona kompresi di daerah puncak dan kawah yang disebabkan oleh kegiatan magma yang muncul ke permukaan dari sumber magma dangkal yang diiringi oleh pelepasan gas vulkanis tinggi. Tekanan terakumulasi yang dilepaskan dan angka deformasi seperti yang terukur di Gunung Api Lokon tetap rendah.

Kata kunci: *letusan, gempa bumi vulkanis, deformasi, magma, Gunung Api Lokon, GPS*

Introduction

Lokon Volcano is part of the Sangihe volcanic arc system related to the Maluku Sea collision zone. The Maluku Sea collision zone lies in the area of the complex junction between Eurasia, Australia, Pacific, and Philipine-Sea Plates. Both Sangihe Arc, west of the collision zone, and

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Halmahera Arc in the east are active and convex toward the Maluku Sea (Figure 1). This collision formed complicated structure in the North Sulawesi area. The seismic activity of the Maluku Collision Zone has resulted in a double-dipping asymetrical subduction system. Seismicity along Benioff zone extends to a depth of 300 km beneath the Halmahera Arc. Beneath the Sangihe Arc, the Beniof Zone of the Maluku Sea Plate extends to deeper than 600 km, indicating a long - life subduction system. Most volcano chains in this area appeared in a seismic zone in a depth of about 100 km (Cardwell and Isacks, 1981).

Time intervals between eruptions were very long (400 years) before 1800, but eruption frequency suddenly increased after 1829. The intervals of eruptive activities were typically 1 - 4 years with variation of dormancy periods of 8 - 64 years. The last big eruption took place in 1991, while eruptions were relatively small in the last nine years. The recent eruptive activity at Tompaluan crater was initiated by ash/gas explosion and followed by magmatic eruptions. These activities were sometimes accompanied by pyroclastic flows. Distribution of pyroclastic flows reaching 3 km distance from the crater. Eruptions were usually preceded by emission of gas and increase in its height (450 - 500 m) above the crater rim. Eruptions with a sufficient intensity occured in 1991, which produced ash and pyroclastic flow to the Pasahapen River. The last major eruption taking place in October 1991, left a plug of lava (lava plugs 1991) at the bottom of the crater. In the period between 2000 to 2003 eruptions occurred almost every year and gradually eroded lava plugs (Wittiri, 1991).

The series of 2011 eruptions began with a phreatic eruption that occurred on February 22nd, 2011, 7:50 p.m. The ash column reached a height up to approximately 400 m and blowed to the southeast. The ash started to fall at Kakaskasen Village I, II, III, and IV (3.5 and 4 km from the crater, respectively) a few minutes after. The peak of the increased activity of Lokon occurred with the phreatic eruption on June

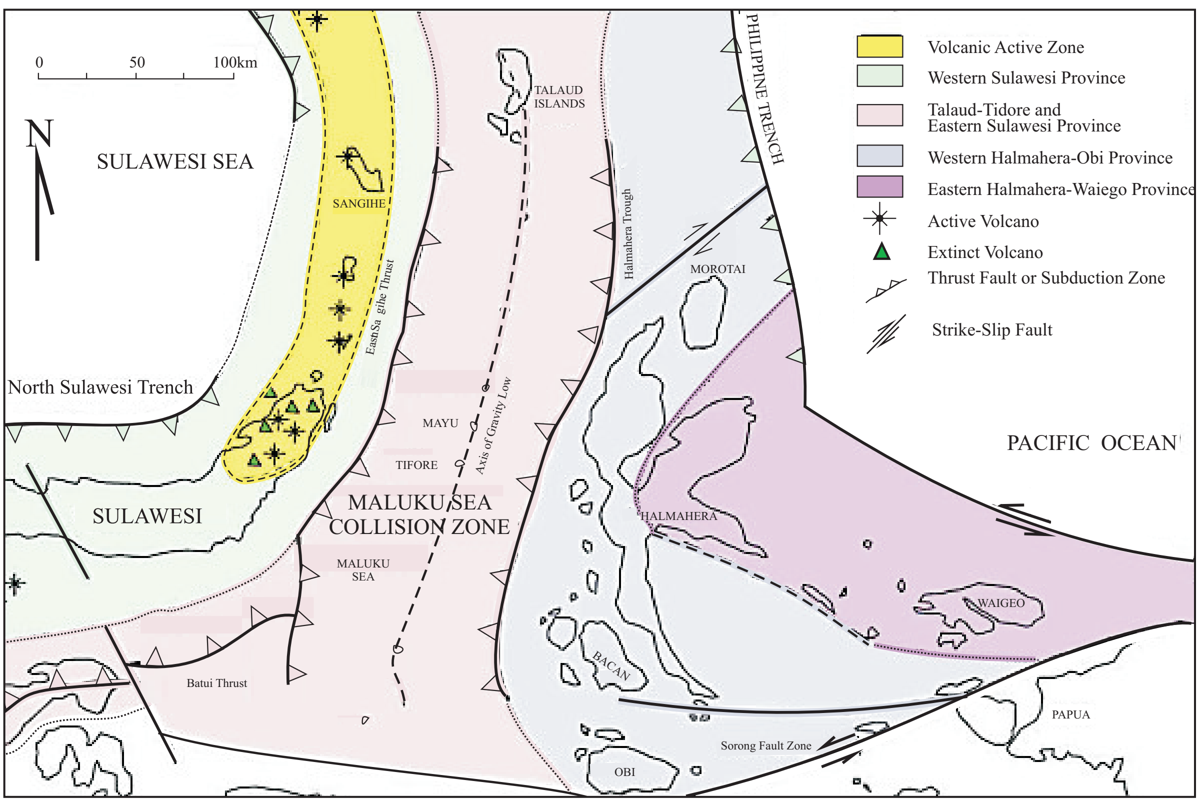

Figure 1. Geodynamic of Sulawesi with volcanic arc in northern part (http://www.earth-of-fire.over-blog.com/pages/The_Moluccas_1_tectonics-7808897.html).

26th, 2011 at 12:20 p.m., followed by the eruption on July 4th, 2011 and continuing until August 28th, 2011.

Precursor of 2011 Lokon eruption is believed to be initiated by the increased activity of Lokon Volcano since December 2007. The activity was marked by increasing volcanic earthquakes number and gas emission. Seismic crisis continues to fluctuate with a declining trend since 2008 until early 2011. Glowing material observed in the northern part of the crater wall since December 2009 is considered to be the result of degassing due to high pressure under the crater (PVMBG, 2011). In addition to seismic data, other geophysical data were required to determine the processes that occurred during the period of increased activity. In this paper, the deformation method was used to investigate the deformation characteristics of the Lokon Volcano in the period of 2009-2011 according to the presence of GPS data.

Methodology

Deformation characteristic of the Lokon Volcano determined using Global Positioning System (GPS) at 17 measuring points, that located around Tompaluan crater and on the slopes of Lokon-Empung (Figure 2) calculated displacement rate and strain analysis of GPS data in the periods of 2009 to 2011. Based on the displacement rate vector and strains that occur in the Lokon Volcano, supported by seismic and geological data, the deformation characteristics of the volcano can be better understood.

The GPS data were taken on August 2009, November - December 2009, March 2010, and March - April 2011. Geosystem Leica GPS 1200 series dual frequency was used for observations on August 2009, November - December 2009, March 2010 and March - April 2011 and Trimble GPS 4000SSI for observations on March 2011. The data were taken episodically with differential static observation. There are eighteen GPS observation points in the Lokon Volcano (Figure 2), those are POST, EMPG, LCA2, LCA3, LCAM, LCD1, LK01, LK02, LK03, LK04, LK05, LK06, LK09, LLRG, LSEA, KNLW, LTTW, and TDN1. POST observed with an interval of 3.5 - 24 hours, while for the other observation points, the measurements performed in the interval of 5.5 - 22 hours.

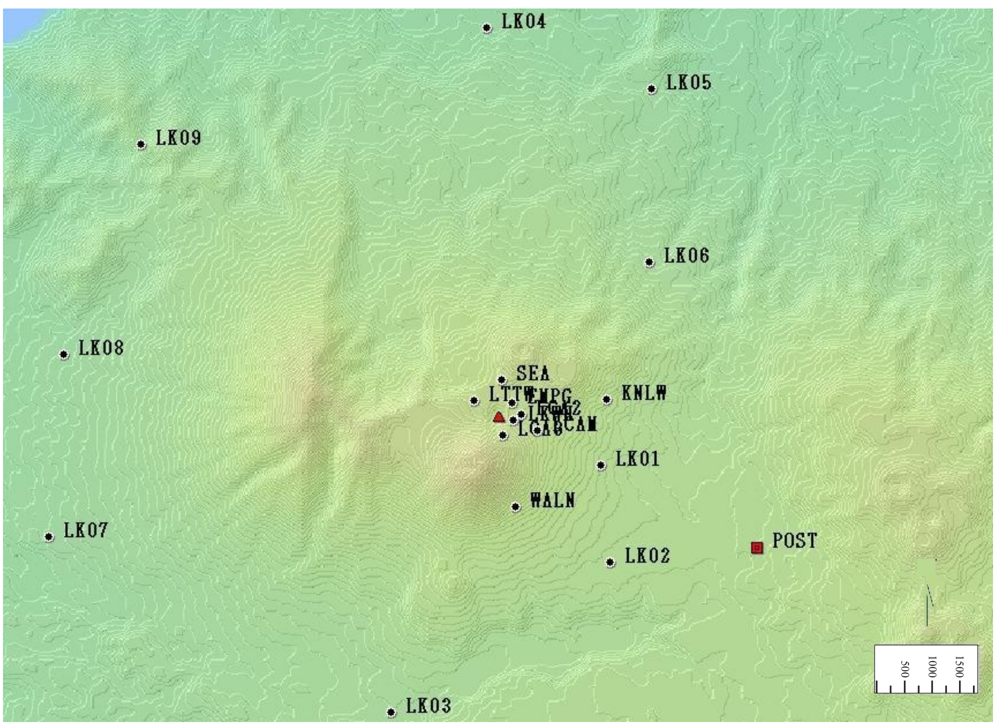

Figure 2. Distribution of GPS measuring points in the Lokon Volcano.

GPS data were processed with Bernese 5.0 software using a rigorous orbit (precise ephemeris). The method used to conduct baseline processing is radial method by determined coordinates of GPS observation points relative to the POST. POST is regarded as a stable point considered to be a reference point for the others. After data processing, there were only seventeen observation points that could be processed properly. LK02 point could not be processed due to a large cycle slip in the measurement.

Displacement Rate

Deformation of a volcano can be seen from the displacement of observation point vector. Velocity parameter was calculated using least squares method as follow:

$$S = vt + C$$

where:
S : displacement
v : rate/velocity vector
t : time interval
C : constant

Figures 3, 4, and 5 show displacement of LCD1, where the displacement are represented by the trend-line with linear assumption.

The displacement rate was tested statistically using t-student test as follow:

$$t = \frac{Vr}{StdVr}$$

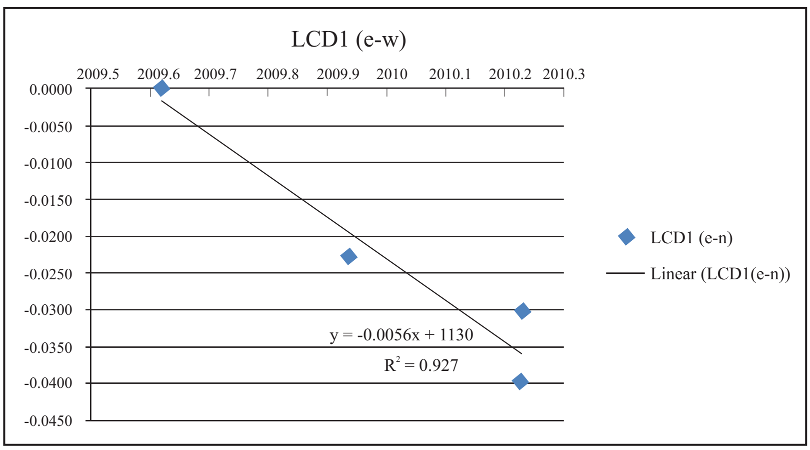

Figure 3. Displacement rate of EW (east-west) component of LCD1.

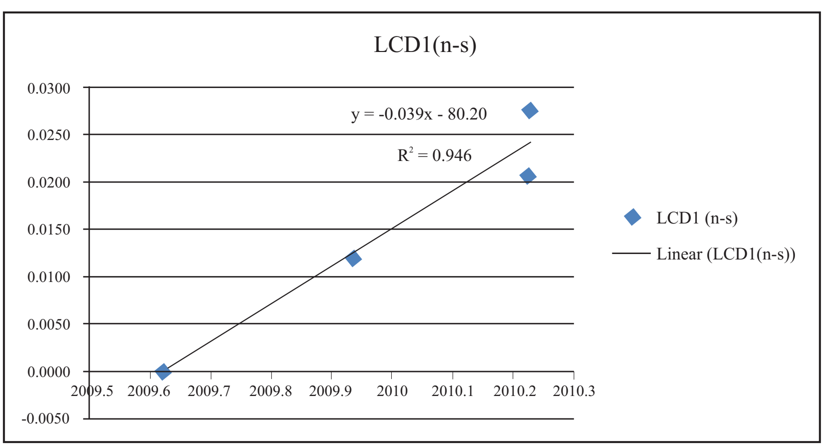

Figure 4. Displacement rate of N-S (north-south) component of LCD1.

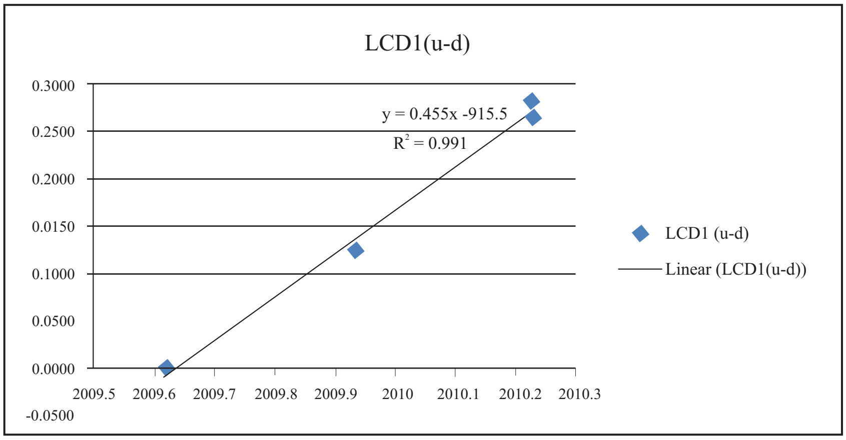

Figure 5. Displacement rate of U-D (vertical) component of LCD1.

Significant displacement or the null hypothesis is rejected if:

$$t > t_{v,\alpha/2}$$

$$v = n - 2$$

explanation:

Vr : horizontal displacement resultan
StdVr : deviation standard of Vr
t : significant quantity that determines whether or not the shift points
v : degrees of freedom
n : number of observation.

As the number of each observations point is different, the degrees of freedom (v) is also different. With the confident level is 90%, then $\alpha = (1- 0.9)/2 = 0.05$. The $t_{v,\alpha/2}$ is also called t nyquist. Tabel 1 shows the t-student result.

The t-student test shows that all observation point is passed. There are two points which are not qualified, LK03 and LTTW, indicating that the points were not shifted. The point that passes means that the null hypothesis is rejected, indicating a displacement at that point. The statistical test can not be done in two observational data, LK05 and LSEA, so the total analyzed points were twelve.

Displacement values of Lokon GPS points from 2009 - 2011 were obtained with the range of 1.1 - 7 cm/year. Displacement vector rate of twelve observation points are plotted as shown in Figure 6.

Displacement vector of GPS observation points tends to be in the same direction towards northwest which varies in magnitude, while GPS observation point is around the Tompaluan crater shifted eastward except LCD1 point which leads to the northwest. The strain analysis performed is to show the stress pattern of Lokon Volcano and to clarify the deformation characteristics of Lokon Volcano.

Strain Analyses

The strain value of Lokon GPS points calculated by the strain model consists of 9 parameters, 6 strain parameters, and 3 rotation parameters. In the method, the functional relationship between the vector displacement and deformation parameters in the coordinate toposentric is expressed as follows (Ma'ruf, 2001):

$$dn = \varepsilon_{nn}\, n + \varepsilon_{ne}\, e + \Omega_{ne}\, e$$
$$de = \varepsilon_{ne}\, n + \varepsilon_{ee}\, e - \Omega_{ne}\, n$$

on matrix :

$d = Bc$

$d = [dn\ de]^T$

where:

dn = northing displacement
de = easting displacement
σn = deviation standard of dn
σe = deviation standard of de
d = displacement vector

$$B = \text{matrix design} = \begin{pmatrix} n & e & e \\ n & e & -n \end{pmatrix}$$

$$c = \text{parameters of deformation} = \begin{pmatrix} \varepsilon_{nn} & \varepsilon_{ne} \\ \varepsilon_{ne} & \varepsilon_{ee} \\ \Omega_{ne} & \Omega_{ne} \end{pmatrix}$$

Tabel 1. Result of t-student Test (Suhartaman, 2011)

No	Point	2	Latitude (N)	de	dn	σe	σn	Vr	StdVr	t	v	Term	Statistic Test
1	EMPG	124.801484	1.366327	0.0257	-0.0344	0.0015	0.0016	0.042977	0.002172	19.783	5	2.571	Qualified
2	KNLW	124.816507	1.366824	0.0525	-0.0018	0.0015	0.0015	0.052554	0.002122	24.768	1	12.706	Qualified
3	LCA2	124.805551	1.361950	-0.0235	-0.0008	0.0016	0.0016	0.023551	0.002228	10.572	2	4.303	Qualified
4	LCA3	124.800106	1.361131	0.0231	0.0157	0.0015	0.0016	0.027951	0.002192	12.750	5	2.571	Qualified
5	LCAM	124.805551	1.361950	0.0021	0.0106	0.0016	0.0017	0.010851	0.002334	4.650	2	4.303	Qualified
6	LCD1	124.803047	1.361269	-0.0581	0.0395	0.0015	0.0016	0.070233	0.002175	32.291	2	4.303	Qualified
7	LK01	124.815605	1.356267	0.0506	0.0435	0.0018	0.0018	0.066714	0.002588	25.778	3	3.182	Qualified
8	LK03	124.782344	1.316763	-0.0087	-0.0389	0.0020	0.0021	0.012429	0.002877	4.320	1	12.706	Not Qualified
9	LK04	124.797492	1.426517	-0.0169	0.0152	0.0016	0.0017	0.022714	0.002299	9.879	2	4.303	Qualified
10	LK05	124.795477	1.366673	-0.0126	0.0106	0.0016	0.0018	0.016447	0.002371	6.936	-	-	-
11	LK06	124.823301	1.388959	-0.0219	0.0094	0.0018	0.0019	0.023791	0.002616	9.093	3	3.182	Qualified
12	LK09	124.725793	1.374536	-0.0122	0.0109	0.0017	0.0018	0.016353	0.002504	6.532	3	3.182	Qualified
13	LLRG	124.808195	1.410511	-0.0313	0.0240	0.0016	0.0017	0.039477	0.002287	17.258	4	2.776	Qualified
14	LSEA	124.798875	1.369489	-0.0356	0.0108	0.0016	0.0016	0.037159	0.002228	16.681	-	-	-
15	LTTW	124.795477	1.366673	0.0054	-0.0022	0.0016	0.0016	0.005794	0.002249	2.576	3	3.182	Not Qualified
16	TDN1	124.910226	1.294738	-0.0414	0.0072	0.0019	0.0020	0.042018	0.002723	15.433	2	4.303	Qualified

Explanation: σn: deviation standard of dn, σe: deviation standard of de

The parameters of strain and deformation calculated by the least squares method, c = (BT Σdd B)$^{-1}$ (BT Σdd d) and standard deviation of strain and rotation were determined by Σpp = (BT Σdd B)$^{-1}$. Based on these parameters, the value of principal strain ε_1 and ε_2 can be derived. The ε_1 is a scale that shows the value of extension, while ε_2 is the value of compression. Both are obtained through equation (Ma'ruf, 2001):

$$\varepsilon_1 = \varepsilon_{ee} \cos^2 \theta + 2\, \varepsilon_{ne} \sin \theta \cos \theta + \varepsilon_{nn} \sin^2 \theta$$

$$\varepsilon_2 = \varepsilon_{ee} \cos^2 (\theta + 90^o) + 2\, \varepsilon_{ne} \sin (\theta + 90^o) \cos (\theta + 90^o) + \varepsilon_{nn} \sin^2 (\theta + 90^o)$$

$$\tan 2\theta = (2\, \varepsilon_{ne}) / (\varepsilon_{ee} - \varepsilon_{nn})$$

Strain values in Lokon area were calculated using software Grid_Strain. The value of principal strain extensions ε_1 and principal strain compression ε_2 occurring in Lokon can be seen in Figures 7 and 8.

Result

Deformation characteristics of the Lokon Volcano have been seen clearly in the displacement pattern. Displacement pattern in Tompaluan slope follows the pattern that most likely if influenced by the regional activity. In a limited area around the summit and the active crater, the displacement has a different pattern, showing only a deformed area around the crater and the evidence of a shallow pressure source. The pressure source in the Tompaluan crater was then determined using a Model Point Source (Mogi, 1958). The data used were horizontal displacement data in the area around the Tompaluan crater. Pressure source is at a depth of 1700 below the Tompaluan crater (Figure 9).

The location of this pressure sources corresponds to a predetermined by the vector changes horizontal GPS data obtained from March 2010 to December 2009 measurements (Haerani *et al*., 2010). The difference is in the time interval measurement, but it produces a relative similarity; so the pressure source location can be interpreted that the deformation in the period 2009 - 2011 is linear with respect to time.

Strain analysis can obtain the data that describes the compression and extension in Lokon Volcano. The extension pattern shows that the compression strain occurred in the crater and on the slopes southwest clearly. The pattern compression at the maximum and minimum strain showed a pattern of reverse fault in the crater (Kato, 2011, Figure 10).

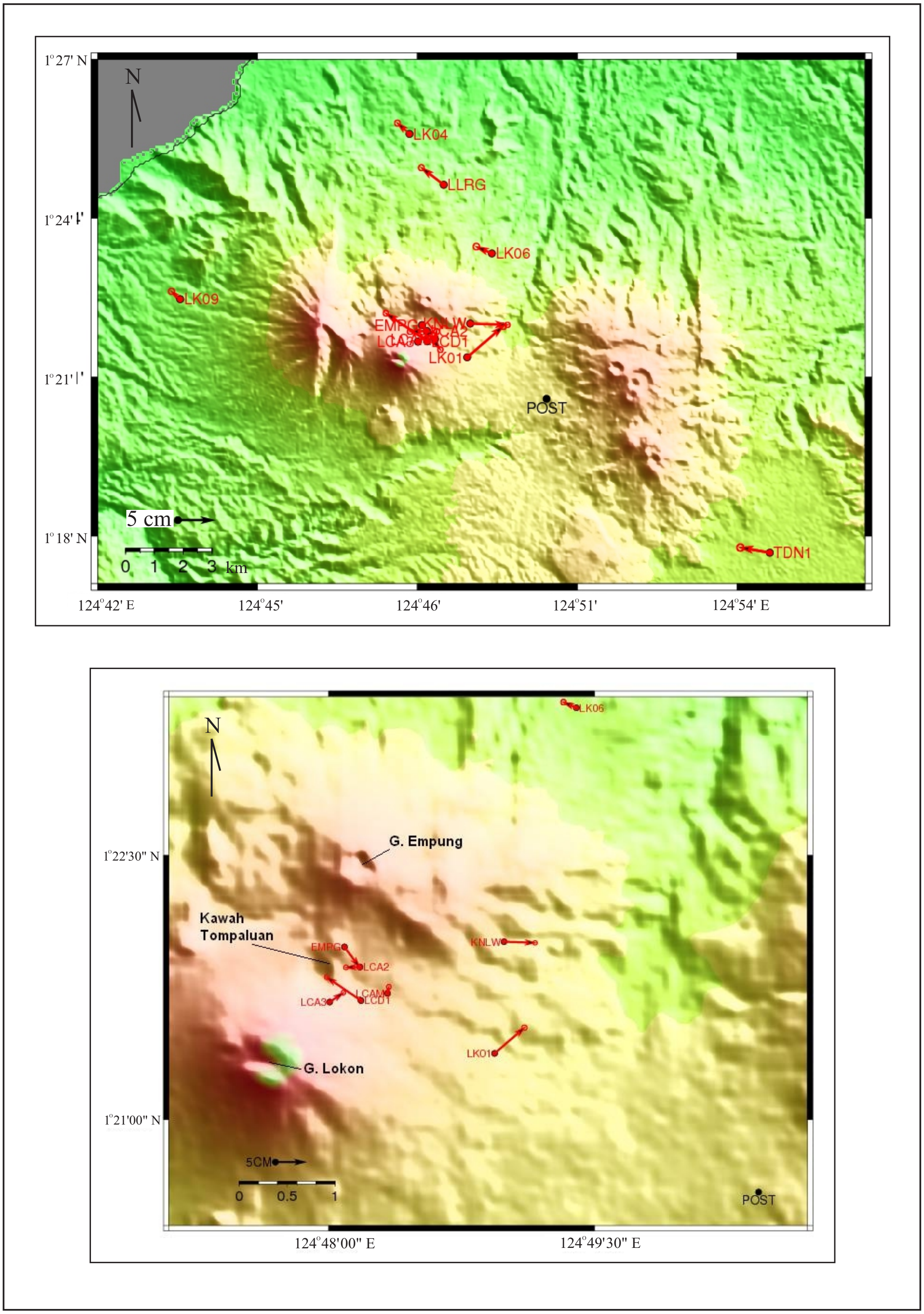

Figure 6. Vector of horizontal displacement in Lokon slope (above) and around the Tompaluan crater (bottom) for the period of August 2009 - March 2011.

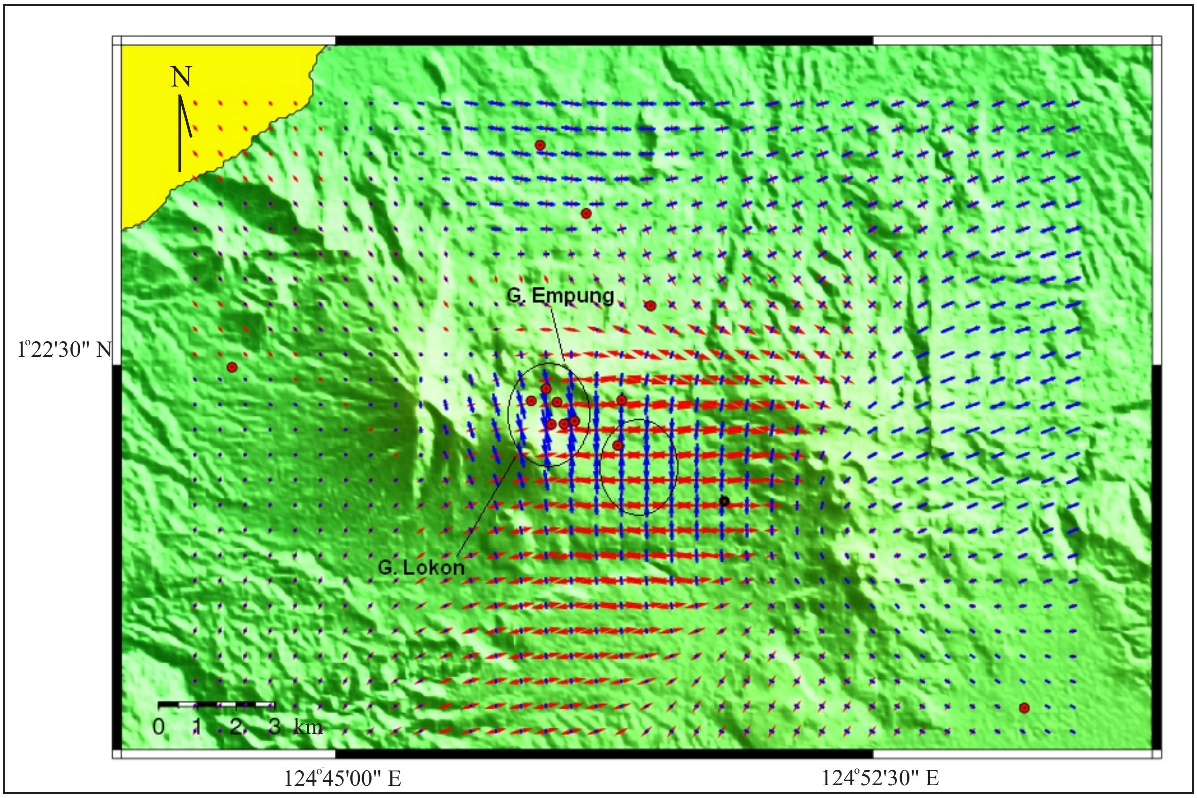

Figure 7. The value plot of principal strain using displacement data of all observation points.

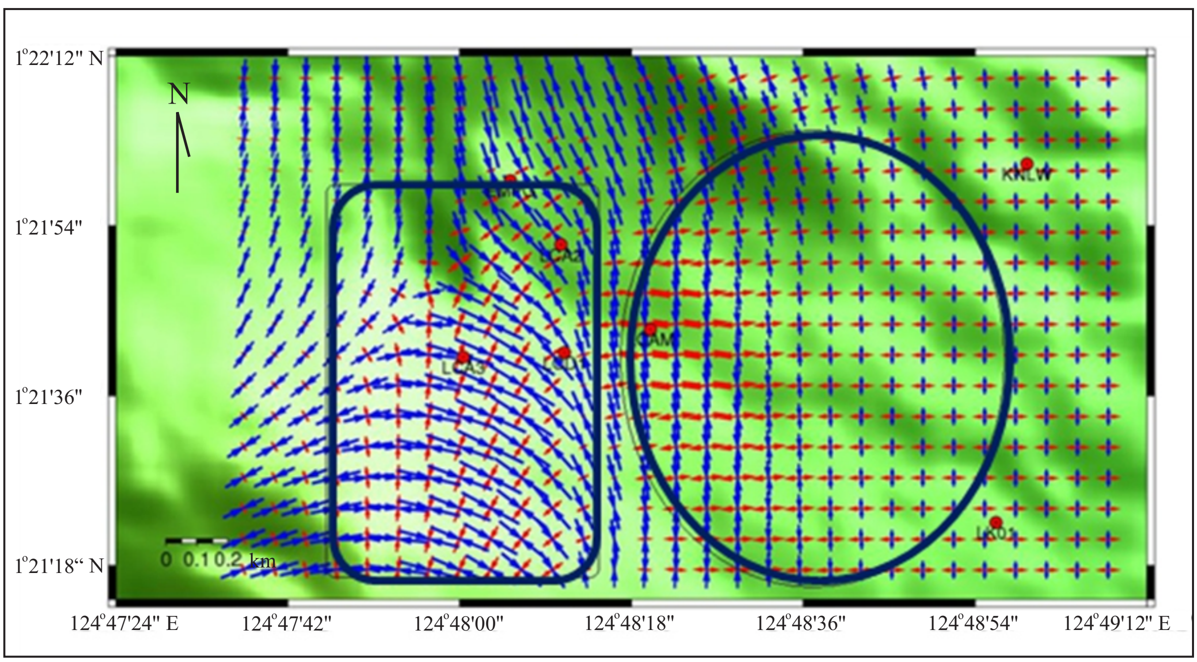

Figure 8. The value plot of principal strain using a displacement of observation points around the Tompaluan crater. The area inside the box is Tompaluan crater, showing a compression strain pattern, of the circle is the area of the eastern slopes of Lokon Volcano which shows a pattern of extension-compression. : compression, : extension.

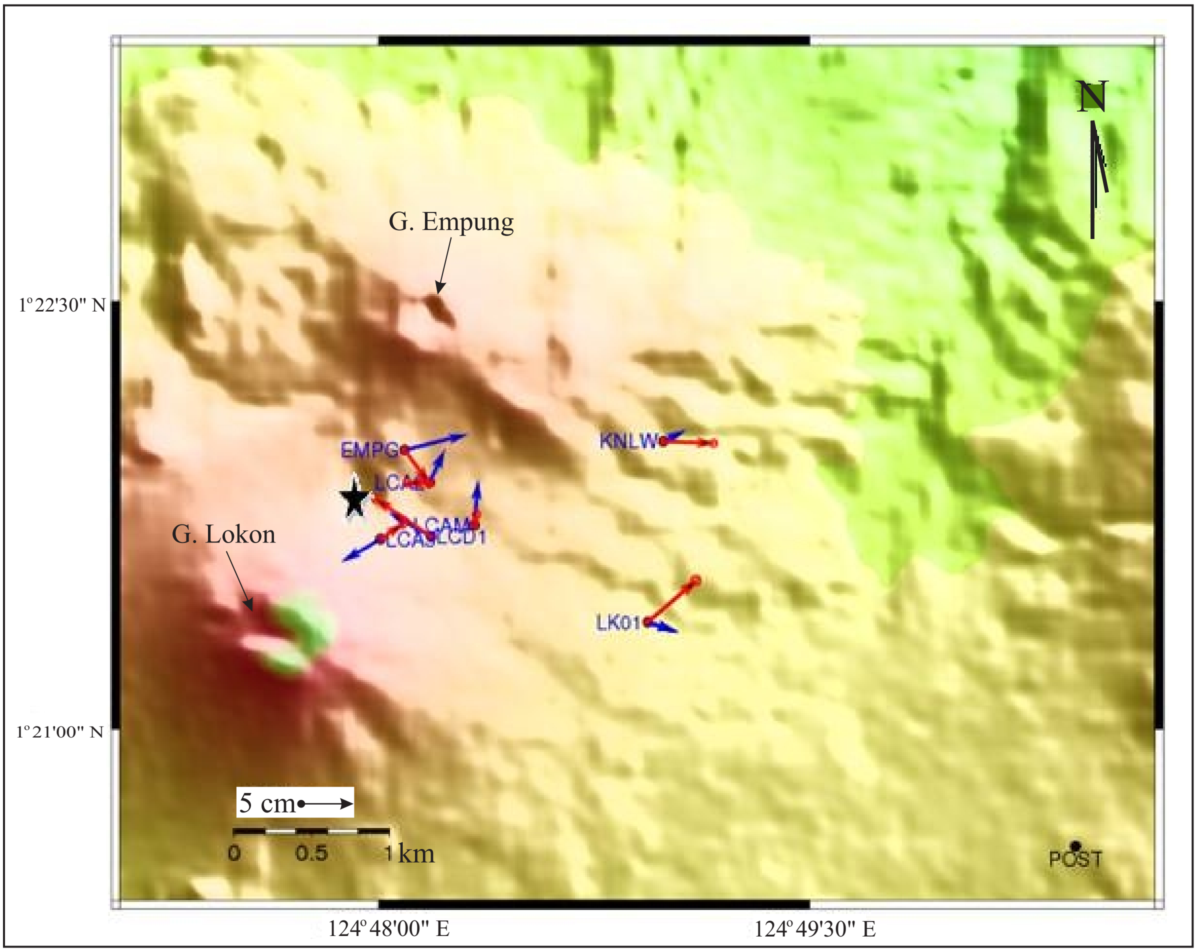

Figure 9. Estimation of pressure source (denoted by star) at Tompaluan crater on the period of August 2009 – March 2011.

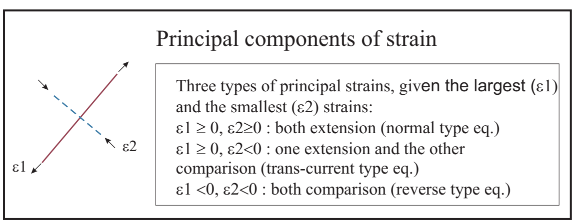

Figure 10. The strain component and constituent mechanisms (Kato, 2011).

Focal mechanism of VTA and VTB is normal fault in normal conditions, while during the period of increased seismic activity it is normal fault for VTA and reverse fault for VTB (Suparman, 2010). Extention mechanism of VTA is possibly related to the accumulation of magma at 4-6 km depth below the crater. Wittiri (1991) interpreted a seismic zone in the depth as a magma chamber/pocket. Inflation of magma pockets causes tensional stress at depths shallower than the magma pockets. The accumulation of magma at a depth of 4-6 km causes the increase of horizontal extension, and generates normal fault type of VTA. Magma moves upward and accumulates in the shallower magma pockets and triggeres a reverse fault type of VTB that occurs when volcanic gas discharges (Figure 11). Extension pattern shows inflation or rising magma to the surface, as shown by the extension pattern of deformation and extension mechanism (normal fault) in VTA. Meanwhile, the compression in the shallow parts and around the Tompaluan crater are interpreted as a gas release and confirmed with the reverse fault mechanism of VTB. The release of pressure in the shallow area below the crater caused deformation in this area not become large because of the accumulation of pressure release when volcanic activity increased.

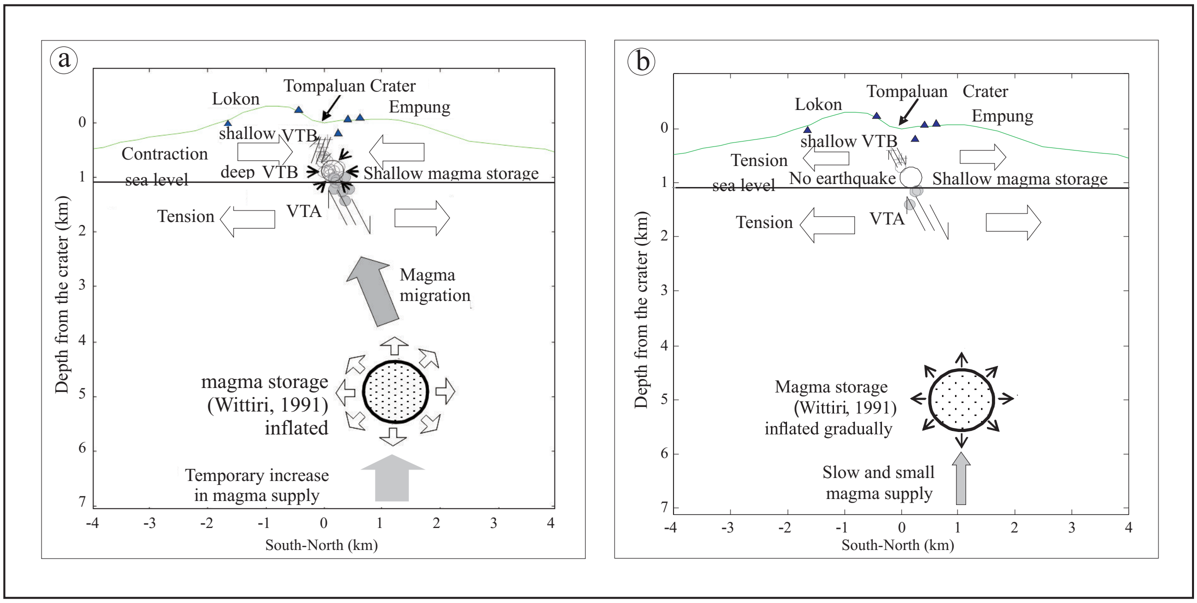

Figure 11. Sketch of Lokon magmatism system: (a) an increase in activity during December 2007 and (b) under normal conditions on May 2008 (Suparman, 2010).

Strain pattern on the eastern slope at Lokon-Empung is compressed for the maximum strain and extension for the minimum strain, and the pattern characterizing the shear faults in the area. According to Lecuyer (1998), the fault that developed in the southern and eastern slopes of Lokon-Empung is sinistral strike slip fault (Figure 12). The strain data demonstrate that the mechanism of deformation on the area was affected by the activity of the geological structure. Orientation axis T (tension) of the VTA in The Lokon Volcano is dominated by a north-south direction. The direction is almost the same as the

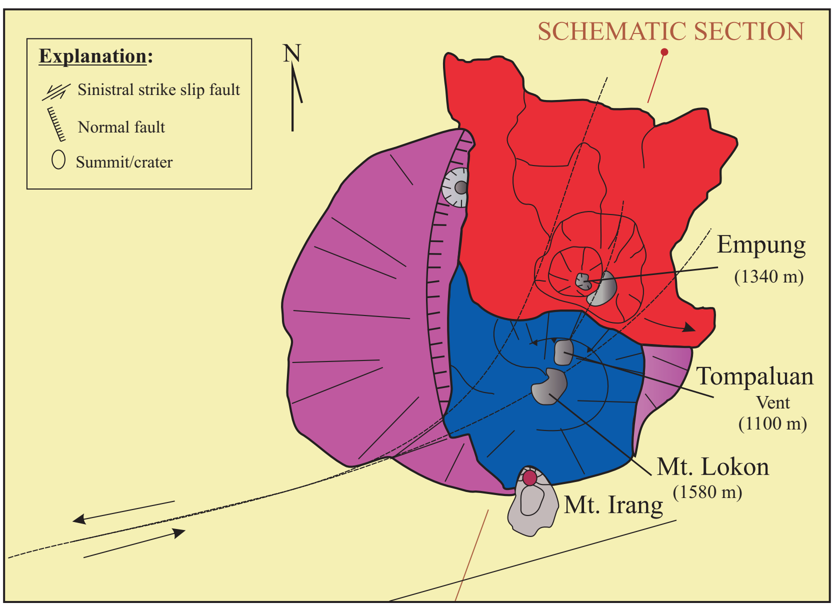

Figure 12. Geologic structure of Tompaluan crater and surrounding area (Lecuyer, 1998, simplified).

direction of geological structures that develop in the area of research, especially due to normal fault that occurs between the Lokon-Empung and Tatawiran. While the contraction of VTB has a direction relatively east-west which is not the same as the regional tectonic tensional stress (Suparman, 2010). Thus, defined mechanism of shallow earthquakes in the Lokon Volcano is caused by a volcanic activity.

On the slope areas, the regional tectonic/structure influence is larger, while the area close to the summit of Tompaluan crater is more affected by the volcanic activity. Then it can be concluded that the pressure source on the Lokon Volcano is located at shallow depths.

Conclusions

The deformation of Lokon Volcano was characterized by:

1. Displacement rate of GPS observation points at the Lokon Volcano from 2009 - 2011 was linear with respect to time, ranging from 1.1 to 7 cm a year.
2. Displacement pattern near the crater indicated the presence of volcanic activity while the farther area coincided with regional patterns. The distribution of displacement pattern around the crater indicated a shallow pressure source. Magma source location using Mogi model on observations on August 2009 - March 2011 is estimated to be at a depth of 1700 m below the Tompaluan crater.
3. Strain pattern that occurs in the Tompaluan crater is compression and extension on the eastern part of the crater. The maximum value of the extension is -0.0338 μ strain and minimum 0.0018 μ strain. The maximum value of compression is -0.0031 μ strain and minimum is 0.0313 μ strain.
4. Compression zones in the crater were caused by magma ascent from a shallow pressure source accompanied by a high release of volcanic gases.
5. The displacement pattern and strain show that there are two sources affecting the deformation in the Lokon Volcano. The first source is the tectonic activity; either local or regional, and the second one is volcanic activity. Deformation caused by the volcanic activity is limited in the area close to the crater as a consequence of the pressure source in the Lokon Volcano which is located in a shallow depth.

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