Identifying Successive Eruption of Guntur Volcanic Complex Using Magnetic Susceptibility and Polarimetric Synthetic Aperture Radar (PolSAR) Data

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Abstract. Identifying distribution and stratigraphic of volcanic products are important not only for mitigating volcanic hazards, but also to know the characteristics of the successive eruptions. Guntur volcanic complex located in Garut, West Java, Indonesia was selected as study area because of the last eruption took place in 1847 and the volcanic activity has been dormant since then, however its seismicity is still active. During the period of July to October 2009, the hypocentre distribution of volcano tectonic earthquakes is mostly located at western flank of the volcano, beneath Guntur - Gandapura craters at the depth of less than 5 km. This study is aimed to identify distribution and succession of volcanic products based on their magnetic properties and backscattering signal of Polarimetric Synthetic Aperture Radar (PolSAR) data. The polarimetric decomposition method was used to identify the distribution of the volcanic products based on their scattering characteristics. Then, the field measurement using SM-30 magnetic susceptibility meter was performed to confirm the units of volcanic products and interpret their successions. According to the polarimetric decomposition method, we could identify fifteen successive eruptions formed Guntur Volcano Complex and termed as Khuluk and Gumuk in Indonesian standard. The successions were produced Gumuk Windu, Gumuk Malang, Gumuk Pulus, Gumuk Putri, Khuluk Meungpeuk, Gumuk Cakra, Gumuk Gandapura, Gumuk Putri, Gumuk Gajah, Gumuk Batususun, Khuluk Pasirlaku, Gumuk Agung, Gumuk Picung, Gumuk Pasirmalang, Gumuk Masigit, Khuluk Kabuyutan and Khuluk Guntur. The magnetic susceptibility confirmed that the variations of magnetic susceptibility of rocks at each gumuk agreed with their stratigraphy.

1. Introduction
The phenomenon of an ancient volcanic activities is relatively difficult to be investigated due to intensive erosion and weathering processes. To define a framework to improve early warning and hazard tracking of volcanic eruptions, the physics of volcanoes including what causes them, where they occur, and what hazards they pose must be addressed [1]. Volcanic eruptions could cause a great damage, so it is necessary to monitor periodically in order that losses caused can be reduced [2]. One of the monitoring was done by studying the rocks of the ancient volcanic products including identifying type and distribution of rocks. Surface volcanic rocks identification in active volcano is crucial not only to mitigate volcanic hazards, but also to characterize eruption, urban rehabilitation, and reconstruction especially after eruption [3].

Identifying volcanic rock distributions solely based on field investigation is not effective when applied under tropical condition such as Indonesia because of dense vegetation and intensive weathering. This condition caused a difficulty to find rock outcrops and boundary of volcanic products or geological structures. Therefore, the field observation requires a lot of time and cost. Utilization of
active remote sensing technology is a great advantage for mapping under large coverage area regardless time and weather conditions [3]. The change of volcanic rocks in one composite volcano might reflect the occurrence of magmatic evolution presented by variation in petrology and geochemistry of the rocks. The variation may serve as an indicator for characterizing the previous eruptions. Magnetic susceptibility of the rocks represented magnetization of the rocks when applied the magnetic field is a physical parameter to characterize and differentiate rock types [4]. Magnetic properties of rocks reflect the composition of the rocks minerals such as iron highly magnetic and other magnetic materials the weak such as silicates and carbonates. The difference of this magnetic property depends on chemical composition, ratio of iron oxide and petrogenesis of rocks. Magnetic susceptibility of rocks depends on composition of magnetic minerals in rock. Mafic rocks generally have higher magnetic susceptibilities than felsic rocks because mafic rocks are typically more abundant in strongly magnetic minerals such as magnetite [5]. According to the capability of magnetic parameter to characterize the rock type, we raised a combination method between magnetic susceptibility measurement at field with Polarimetric Synthetic Aperture Radar (PolSAR) image interpretations to delineate the boundary of volcanic groups and correlate with their successive eruptions.

This research is aimed to identify successive eruption at the Guntur Volcanic Complex based on magnetic susceptibility and fully polarimetric SAR (PolSAR) data from PALSAR (Phased Array Type L-Band Synthetic Aperture Radar) onboard the Advanced Land Observing Satellite (ALOS). The magnetic susceptibility was used to interpret of the magnetic minerals within volcanic products. The PolSAR data was used to delineate boundary of volcanic groups following the Indonesian standard volcano stratigraphy.

The study area is located at Guntur Volcanic Complex in Garut, West Java, Indonesia (Figure 1). The first historical eruption of the volcano was occurred in 1690 and the last eruption was recorded in the 1847 [6]. The volcano-tectonic earthquake activity recently is still quite high more than 100 events in October 1997, May 1999, November 2002, and June 2005 [7].

![Map Index](image)

**Figure 1.** Study area located at Guntur Volcanic Complex, Garut District, West Java, Indonesia presented by pink square.

### 2. Data and Method

#### 2.1. ALOS PALSAR

ALOS PALSAR is one of the satellites are capable of sending and receiving electromagnetic waves with full polarization. Polarization is an index describing electromagnetic waves propagation and
relative orientation of the electric field. The electromagnetic waves propagate vertically and horizontally, they are termed as vertical (V) and horizontal (H) polarizations, respectively. Synthetic aperture radar satellite is usually designed to transmit and receive either horizontally or vertically polarized signals. For example, the Japan Earth Resources Satellite 1 (JERS-1) SAR utilized horizontally polarized signals. However, ALOS PALSAR can transmit and receive both horizontally or vertically polarized signals. Thus, a combined polarization radar image could be HH (horizontal transmitting, horizontal receiving), VV (vertical transmitting, vertical receiving), HV (horizontal transmitting, vertical receiving) or VH (the reverse of HV) as presented by Figure 2. Characteristics of scattering depend on the polarization properties of the target. The different scattering patterns among polarizations can be observed from ALOS PALSAR polarimetric image. PolSAR data of Guntur Volcanic Complex were derived from ALOS PALSAR level 1.1 with a spatial resolution 12.5 m and acquired on May 4, 2011. ALOS PALSAR operates using active microwave sensor with the L-band frequency by minimizing the atmosphere and canopy vegetation effects [8]. The acquired data are fully polarization types HH, HV, VH, and VV.

**Figure 2.** The full (left) and single (right) polarimetric SAR (PolSAR) images and illustration of their electromagnetic propagations.

The ALOS PALSAR data processing on this study is divided into two steps: processing of backscattering intensity and polarimetric decomposition. For processing of backscattering intensity, the ALOS PALSAR data Level 1.1 in Single Look Complex (SLC) were transformed into Multi Look Image (MLI) by splitting into four polarization modes HH, HV, VH, and VV of backscattering intensity. The polarized-backscattering intensity was quantified by a multi-look processing with 1×7 factor to keep the spatial resolution of image along the range and azimuth directions as 28 and 25 m, respectively. Finally, the MLI was corrected geometrically by transforming the slant to ground range
coordinate using a simulated DEM derived from the SRTM version 4 with spatial resolution 90 m. Yamaguchi decomposition method was applied to extract backscattering characteristics from object based on polarimetric decomposition [9]. Polarimetric decomposition of ALOS PALSAR data were performed by decomposing a single polarization into matrix scattering $[S] 2 \times 2$ followed by extraction of matrix coherency $[T3]$. In horizontal polarization (H) and vertical (V), the matrix scattering $[S]$ could be expressed by:

$$ S = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} $$  \hspace{1cm} (1)

Assuming the reciprocal condition $S_{HV} = S_{VH}$, the matrix coherency $[T3]$ could be expressed as follows:

$$ T3 = \begin{bmatrix} T_{11} & T_{12} & T_{13} \\ T_{21} & T_{22} & T_{23} \\ T_{31} & T_{32} & T_{33} \end{bmatrix} $$  \hspace{1cm} (2)

It should be noted that $T_{11}$, $T_{22}$ and $T_{33}$ are real-valued terms and that $T_{12}$, $T_{13}$, and $T_{23}$ are complex valued. Therefore there are 9 real-valued parameters in the matrix. The matrix $[T3]$ has advantages in the mathematical operations as well as in interpreting physical backscattering phenomenon [10].

To classify the backscattering characteristics of the ground surface, we used the four-component scattering power decomposition of the matrix $[T3]$ by dividing the polarimetric data in pixel area into scattering of surface, double bounce, volume, and helix with 4 expansion sub-matrices as follows:

$$ T3 = \left[ P_s \langle T \rangle_{Surface} + P_d \langle T \rangle_{Double} + P_v \langle T \rangle_{Volume} + P_h \langle T \rangle_{Helix} \right] $$  \hspace{1cm} (3)

**Figure 3.** Four mechanisms backscattering characteristics with coherence matrix [9].

Eq. (3) is an extension of the three-component decomposition to deal with non-reflection symmetry scattering case as illustrated by Figure 3. Figure 4 showed the classification steps based on Yamaguchi four component decomposition techniques [11].

In geology, the utilization of the decomposition characteristics of backscattering useful for detecting surface objects such as:

- **Surface scattering**: The scattering mechanism is mainly caused by rough surfaces such as bare soil, volcano summits, agricultural fields;
• **Double bounce scattering**: Right angle structures such as big fragmented boulder size, intrusive body, hill, and river surfaces;

• **Volume scattering**: eruptions centre, brecciate volcanic flow, and intensive fracture zone. Classification of object based on backscattering characteristics obtained from a combination of dual polarization signals, classification of characteristics

### 2.2. Magnetic Susceptibility

In addition to image processing, also check field and magnetic susceptibility measurement of rocks. Rocks that measured magnetic susceptibility this study focused only on igneous rock from volcanic products. Magnetic susceptibility measurement was performed using Magnetic Susceptibility Meter SM-30 with error measurement up to $1 \times 10^{-7}$ SI and maximum scale is 0.1 SI. Method of measurement can be performed directly on rock outcrops in the field as well as on samples of rocks, but in this study, measurements carried out directly on the outcrop in the field.

![Magnetic susceptibility measurement](image)

**Figure 4.** Flowchart of Yamaguchi SAR decomposition method modified from [11].

### 3. Result

The utilization of L-band SAR data with full polarization is effective for target detection under tropical regions. A technique adopted in this study is visual interpretation based on composite backscattering intensity and decomposition method. The technique was used to identify volcanic groups as well as stratigraphy termed as khuluk and gumuk. Khuluk and gumuk are Indonesian standard volcano stratigraphy to distinguish the groups of volcanic product based on their volcano origin. Khuluk is composed by groups of volcanic rocks from one or more eruption center and formed
large body of volcano. Gumuk is the smallest group of volcanic products originated from an eruption centre or single parasitic eruption [12]. Khuluk could be composed by several gumuks, but not in vice versa.

Based on the visual analysis of tonal pattern, texture, brightness, geomorphology and structure from SAR image, the composite backscattering intensity is useful to identify boundary of the gumuk. The optimum visual contrast was obtained by color composite for R=HH, G= HV, and B=VH (Figure 5A). On the other hand, the decomposition method showed a high detectability for the khuluk of the volcano. Result of the decomposition method is distinguished of backscattering characteristics from object on the surface in the form of surface scattering, double scattering, volume scattering, and helix scattering, that was then in the combined using RGB composite to R=double scattering, G=volume scattering, dan B=surface scattering (Figure 5B). This colour composite showed khuluk volcano with clear boundaries. Boundaries of khuluk volcano from decomposition results are shown with characteristics of the surface scattering (blue). Results analysis of the scattering intensity and decomposition characteristics, then on the location research complex consists of nine Khuluk that is formed by fifteen Gumuk.

Figure 5. (A) Composite RGB backscattering intensity image R=HH, G=HV, B=VH; (B) Composite decomposition polarimetric image R=Double Bounce Scattering ($P_d$), G=Volume Scattering ($P_v$), and B=Surface Scattering.

Magnetic susceptibility rocks characteristics are controlled by mineralogy of rock. The characteristic of the concentration is an indicator of magnetic minerals in rocks. For Guntur Volcanic Complex, magnetic susceptibility values range from $16.17 \times 10^{-3}$ to $30.2 \times 10^{-3}$ SI. The stratigraphic of each Khuluk were arranged based on PolSAR image interpretation and magnetic susceptibility measurement at field, except for Khuluk Pasirlaku. The khuluk has a lowest magnetic susceptibility about $19.7 \times 10^{-3}$ SI, but the stratigraphy is older than Khuluk Gajah with magnetic susceptibility about $21.18 \times 10^{-3}$ SI. The discrepancy of the magnetic susceptibility at Khuluk Pasirlaku was interpreted from magmatic phenomena during ascend from the deep to the shallow reservoir such as magma differentiation or mixing with surrounding rocks (Table.1). The highest magnetic susceptibility is about $30.2 \times 10^{-3}$ SI for the Khuluk Guntur. The magnetic susceptibility shows an agreement with the stratigraphy of volcanic groups in general, and also with their absolute age. The magnetic susceptibility of the rocks at the study area increased from the old to the young volcanic products in general (Table.1).
Table 1. Comparison of magnetic susceptibility with their absolute age following [13] of Guntur Volcanic Complex.

| Khuluk   | Gumuk | Age (Ma)  | Susceptibility (× 10⁻³ SI) | Rock Type |
|----------|-------|-----------|-----------------------------|-----------|
| Guntur   | Guntur| 0.05±0.38 | 30.2 Basalt                 |           |
| Kabuyutan| Kabuyutan| 26.76 Basalt|                       |           |
| Masigit  | Pasirmalang| 24.53 Andesit|                     |           |
|          | Picung  | 0.07±0.02 | 23.73 Andesit               |           |
|          | Agung   | 0.08±0.4  | 22.07 Andesit               |           |
| Pasirlaku| Pasirlaku| 19.7 Andesit|                     |           |
| Gajah    | Batususun| 21.18 Andesit|                     |           |
|          | Gajah   |           |                            |           |
| Putri    | Putri   | 0.14±0.08 | 21.03 Andesit               |           |
| Gandapura| Gandapura| 0.33±0.02 | 20.9 Dacite                 |           |
|          | Cakra   |           |                            |           |
| Meungpeuk| Meungpeuk| 19.87 Andesit|                     |           |
| Windu    | Windu   |           |                            |           |
|          | Malang  |           |                            |           |
|          | Pulus   |           |                            |           |
|          | Putrri  |           |                            |           |

Figure 6. The cross-plot between stratigraphy of Guntur Volcanic Complex and magnetic susceptibility showed an agreement, except at Khuluk Pasirlaku.

4. Discussion
Several Polarimetric SAR processing methods have been widely used in the study of volcanoes and very useful and effective to observe ground surface. Compared with optic remote sensing data, Fully Polarimetric SAR is suitable to detect and classify the characteristics of the geometric of ground surface. As in Figure 7 directed Gumuk Guntur dominated by Surface Scattering (blue portion in Figure 7) that shows the characteristics of smooth surfaces such as soil until gravel sized rocks.
However some places at Khuluk Guntur show the double scattering characteristics the resulting by scattering of blocks boulder rocks sized and of residential building at Guntur volcanic foot (Figure 8A). Double bounce characteristics (red portion in Figure 7) dominated at residential areas that formed by scattering from the building. These characteristic can be used for mitigation of eruption because it can classify the residential areas well, so it is useful for the evacuation of residents and also relocation of affected areas after eruption. While on the khuluk or gumuk volcanoes, characteristic double bounce dominated on Khuluk Pasirlaku that formed by scattering from the blocks of lava flows (Figure 8B). The rocks were mined by local people. Volume scattering originated from dense vegetation at the old volcanic products and presented by green portion in Figure 7. An intensive weathering of the old volcanic products caused decomposition of the rocks into the soil layers. Therefore, the vegetation has growth densely at this zone. These characteristics dominate almost the entire old volcanic products as seen on the Gumuk Picung, Agung, and Masigit (Figure 8C).

Samples of rocks on the Guntur Volcanic Complex show changes the value of the higher magnetic susceptibility toward younger rock as listed in Table 1. Change the value of magnetic susceptibility indicates that the level and stability of magnetisation are dependent on the quantity and composition of the magnetic minerals (which are controlled by the composition of the original liquid magma), their oxidation states and grain sizes [14]. If the change on the composition of magma derived from original magma then it can be interpreted as differentiation occurred and produced different type of rock with different magnetic susceptibility values, which is also reflection of changes in rock type, but this needs further analysis on rock geochemistry.

Figure 7. Delineation of volcanic groups at Guntur Volcanic Complex based on PolSAR image interpretation and magnetic susceptibility measurement following geological field observations presented by white lines.

According to [6], rock type of young Guntur Volcano are generally basalt (result of the eruption in 1840), this is confirmed with high magnetic susceptibility that is $30.2 \times 10^{-3}$ SI and rock sampling when field check. The correlation between the absolute age of rocks and magnetic susceptibility data also show changes of the magnetic susceptibility higher towards the age of younger rocks. As shown in the Gumuk Gandapura, Putri, Agung, Picung and Guntur (Table 1). Therefore, if the data is correlated with magnetic susceptibility, then change the magnetic susceptibility is higher towards
younger rocks reflect changes of rocks from acidic to basic. These changes are also visible from rock samples in the field as in the old aged rocks tend to andesitic and basaltic tend towards older.

![Figure 8. Field photographs of volcanic products at Guntur Volcanic Complex with their locations presented in Figure 7.](image)

5. Conclusions
Utilization of magnetic susceptibility and Polarimetric SAR (PolSAR) data to the geological field observation is effective to delineate the boundary of volcanic units under tropical area. The colour composites of backscattering characteristics such as PolSAR intensity images and decomposition of the full polarized data were useful for identifying part of the volcanic stratigraphic units in the form of Khuluk and Gumuk. In addition, the geomorphologic and structural features could be used for basis interpretation. The geomorphology and structural features influenced to the interpretation process because the distribution of volcanic products followed the morphology and structure. Yamaguchi decomposition could show characteristics of ground surface such as soil, loose sediment, and gravel. They were identified by surface scattering (soil and loose sediment), double bounce scattering (building and boulder to block sized of rocks), and volume scattering (dense vegetation). Magnetic susceptibility was also useful to confirm the occurrence of the magnetized minerals in the rock type of volcanic complex. The changes of magnetic susceptibility value reflected the changes in mineralogical composition of rocks. We obtained that volcanic products in the same gumuk have similar susceptibility value. Then, the significant different was interpreted that the volcanic rocks were produced by the other gumuk. Successive eruptions of Guntur Volcanic Complex based on PolSAR and magnetic susceptibility data from an old to young volcanic products are as follows: Gumuk Windu, Gumuk Malang, Gumuk Pulus, Gumuk Putri, Khuluk Meungpeuk, Gumuk Cakra, Gumuk Gandapura, Gumuk Putri, Gumuk Gajah, Gumuk Batususun, Khuluk Pasirlaku, Gumuk Agung, Gumuk Picung, Gumuk Pasirmalang, Gumuk Masigit, Khuluk Kabuyutan and Khuluk Guntur. The causes of the change of magnetic susceptibility with mineral composition of the successive eruptions were aimed to the next step of this study.

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