Textural analysis and crystal size distribution of plagioclase from Ciremai’s a’ā lava: Interpretation magmatic processes and crystallization time

W N Hamzah1*, I A Kurniawan2, M Abdurrachman2, I G B E Sucipta2, and M E Suparka2

1Graduate School of Bandung Institute of Technology, Bandung, Indonesia
2Bandung Institute of Technology, Bandung, Indonesia

*corresponding author: Wildannurhamzah@gmail.com

Abstract. Ciremai Volcano is an active volcano in West Java, Indonesia. Based on geological observation, this volcano has erupted as central and flank eruptions. One of flank eruption products can be observed on Sukageri area. The products consist of ‘a’ā lava and pyroclastic fall deposits. This research is focus on ‘a’ā lava characteristics using petrology methods including textural analysis and crystal size distributions. The ‘a’ā lava of Sukageri area has ±11.5m thick and it spreads out into 4 km to the southward of Sukageri area. Section of the ‘a’ā lava can be divided into three sections; upper, middle, and lower part. The upper and lower part characterized by autobreccia, and middle part has sheet-like shear joint structure. Petrography analysis shows that the ‘a’ā lava consist of vesicular (16.04-47.85%), phenocryst of plagioclase (10.6-12.4%), pyroxene (1.66-2.78%), olivine (0.87-3.25%), and opaque mineral (0.3-0.42%). Groundmass (65.29-83.53%) of the ‘a’ā lava consists of microcrystalline of plagioclase, pyroxene, and glass. The differences of crystal size indicate the changing on crystallization time. Plagioclase texture of the ‘a’ā lava compose of fine-sieve, zoning, resorption surface, synneusis, glomerocrysts, and broken crystals. Those textures are indication of changing of magmatic system which caused by hotter and more primitive of magma injection or magma degassing. Crystal size distribution (CSD) analysis shows 2 trends and concave curve which indicate a progressive change in ∆T during magma ascent. One trend shows a steep slope (-21.05 – -27.61), with higher y-axis intercept (10.24–11.69), indicating of nucleation density, and smaller crystal size. The other trend shows phenocrysts with gentle slope (-2.22 – -4.25) and lower y-axis intercepts (1,4-4,25). Crystallization time was calculated from equation T=(-1/G*slope)/31536000), with assumption of growth rate (G) is 10-8 and the difference of trend between phenocryst and microcrystalline. Those calculation show that phenocryst crystallization time of the ‘a’ā lava is 0,75–1,43 years and whereas for microcrystalline is 41-54 days. The existence of microcrystalline indicates that before magma was erupted, it stayed on conduit for ±41 days. After the eruption, the ‘a’ā lava needs ±13 days for cooling and solidifying.

1. Introduction
Mt. Ciremai is an active volcano in West Java. The previous published was focused to study about volcano stratigraphy (Suradji, 1993; Situmorang et al, 1995; Al Rasyid, 2016), petrology and geochemistry of Ciremai’s volcanic rocks (Whitford, 1975; Sendjaja et al, 2009; Al Rasyid, 2016).
Based on volcano stratigraphy (Situmorang et al, 1995), Mt. Ciremai can be erupted as central and flank eruption. The flank eruption products can be seen as lava flow on Mt. Dulang, Mt. Buntung, Mt. Pucuk and Mt. Sukageri. This research is focused to study about magmatic processes and crystallization time of Mt. Sukageri’s lava as flank eruption products. It can be studied by textural analysis and crystal size distributions (CSDs) of Plagioclase (Cashman and Marsh, 1988; Mars 1988; Mangan, 1990; Higgins, 2000; Higgins, 2006; Morgan and Jerram, 2006; Vinet and Higgins, 2010; Melnik et al, 2011; Renjith, 2013; Preece et al, 2013 Spillar and Dolejs, 2013; Pourkhorsandi, 2015).

Mt. Sukageri’s lava can be found on Cigugur district, Kuningan. The lava spreads out into 4 km to the southward of Mt. Sukageri and it has ±11.5 m thick. It shows ‘a’ā lava characteristic which can be divided to three section as upper, middle, and bottom part. The upper and bottom section have roughly and sharp surface, high vesicular and red colour as oxidation processes. Their characteristic is known as autobreccia section (Lockwood and Hazlett, 2010). The middle section of ‘a’ā lava shows a coherent lava with low vesicular, but in transitional section has sheeting joint features which known as sheet like shear joint (Lockwood and Hazlett, 2010).

All of the sections are composed of phenocrysts and microcrystalline of plagioclase. The differences of crystal size indicate the changing on crystallization time of plagioclase which formed in magma chamber and formed in conduit. Plagioclase texture of the ‘a’ā lava compose of fine-sieve, zoning, resorption surface, synneusis, glomerocrysts, and broken crystals. Those textures are indication of changing of magmatic system caused by hotter and more primitive of magma injection or magma degassing (Renjith, 2013). Both autobreccia and massive lava show that Crystal size distribution (CSD) analysis has 2 trends and concave curve. Those indicate a progressive change in ΔT during magma ascent. One trend shows a steep slope with higher intercept which indicate of nucleation density, and smaller crystal size. The other trend shows phenocrysts with gentle slope and lower intercepts. Crystallization time was calculated from equation $T=(-1/G \times \text{slope})/31536000)$, with assumption of growth rate (G) is $10^{-8}$ and $10^{-9}$ (Marsh, 1988; Brugger and Hammer, 2010; Preece et al, 2013; Pourkhorsandi, 2015).

2. Geology of Ciremai volcano

Mt. Ciremai is Quaternary volcano that included of rear arc volcano with calc-alkaline affinity (sendjaja et al, 2009) and it built on Tertiary sedimentary rocks (Budhitrisna, 1986; Suradji, 1993; Djuri, 1995; Situmorang et al, 1995; Silitonga et al, 1996; Al Rasyid, 2016). Beside of that, andesite intrusion can be found on Mt. Ciremai area which can influence of Ciremai’s magma chamber (Suradji, 1993; Djuri, 1995; Situmorang et al, 1995; Al Rasyid, 2016). The other possibility which can influence of magma chamber is structure that shown NE-SW trending. That structural pattern is strike-slip fault zone which known as Pamanukan-Cilacap fault zone (Armandita et al, 2011). Based on activity, Situmorang et al (1995) proposed that Mt. Ciremai has four periods of volcanism. The first period is Mt. Putri volcanism that the products are spread out on southern and eastern of Mt. Ciremai. The second period is Mt. Gegerhalang volcanism (40800 year ago). Those products can be found in Mt. Gegerhalang area. The third and fourth periods are Mt. Ciremai volcanism that was active in 13,350 year ago and built on Gegerhalang caldera. Volcano stratigraphy of Mt. Ciremai shows that Mt. Ciremai can erupt as central eruption and flank eruption. The flank eruption products can be found in Mt. Dulang, Mt. Buntung, Mt. Pucuk, and Mt. Sukageri. All of the flank eruption products are composed of basaltic lava and it lied of Mt. Ciremai volcanic products. It can be indicate that all of flank eruption products are produced by volcanic activity after the third period (Figure 1).
3. Methods

Fifth rock samples were selected from ciremai’s ‘a’ā lava that erupted as Sukageri flank eruption for textural and CSDs analysis. ES01 was sampled from middle section of ‘a’ā lava, and ES02, ES03, ES05, and ES07 was sampled from near of surface of ‘a’ā lava. After thin section preparation, the selected samples were observed by using polarization microscope with 40x magnification and the image was captured by optilab camera and optilab viewer 2.2 software. For textural analysis and CSD, we used plagioclase as observed and digitized minerals. Manual digitized (grain boundaries) was used by image J software and the results of digitizing was exported to CSD output plugins. Conversion of 3D shape and size distribution data from raw 2D data (from CSD output plugins) was done by using the CSDSlice5 excel spreadsheet (Morgan and Jerram 2006) and CSD corrections 1.55 software (Higgins, 2000).

CSDs is method which provide a quantitative measure of igneous textures and can be used to give information about the kinetics of magmatic crystallization, including estimates of cooling rate and crystallization time (residence time) (Cashman and Marsh, 1988; Mars 1988; Mangan, 2000; Higgins, 2006; Morgan and Jerram, 2006; Vinet and Higgins, 2010; Preece et al, 2013 Spillar and Dolejs, 2013; Pourkhorsandi, 2015). This concept was primarily developed in chemical engineering (Randolph and Larson, 1971). A theoretical basis of CSDs for igneous rocks was published (see Cashman and Marsh, 1988; Marsh (1988). Most of the CSD measurement was determined as 2D data raw, but the data used to analysis are 3D data. For solving that problem, Morgan and Jerram (2006) proposed a method for 3D conversion and made the excel spreadsheet which known as CSDSlice5 and to produce a characteristic aspect ratio, including short, S; intermediate, I; Long axis, L for knowing a 3D shape of crystals. CSDs deal with the size distribution of crystal populations. It is a function of the number of crystals of minerals per unit measured volume within a series of defined size intervals (Rannou and Caroff, 2010; Pourkhosandi, 2015). It represented by diagram which plot population density of ln (n) versus crystal length (L) and the histogram of volume fraction versus crystal size (Cashman and Marsh, 1988; Higgins 2000; Higgins 2006; pourkhorsandi, 2015). The shape of the CSD curve can be used to indicate of magmatic processes (Figure 2).

Igneous textures can be classified into three categories based on main processes which related to forming the textures. The categories including 1) kinetic textures resulting from nucleation and growth processes, 2) mechanically modified textures resulting from sorting and compaction processes, 3) equilibrium textures which produce a coarsening effect on pre-existing textures (Cashman and Marsh; 1988; Higgins, 2006; Rannou and Caroff, 2009). Those texture presented on CSD curve which indicate magmatic processes such as increasing under cooling, crystal fractionation, increasing growth rate (residence time) coarsening, and magma mixing (Cashman and Marsh, 1988; Higgins 2000; Higgins 2006; pourkhorsandi, 2015). From the the CSD curve, we can get the slope and intercept value which used to
estimating of crystallization time (or residence time). Marsh (1988) proposed that formula can be used to estimating crystallization time is \( T = \frac{(-1/G \times \text{slope})}{31536000} \) with assumption of growth rate \((G)\) from Brugger and Hammer (2010b) is \(10^{-8}\) and from Marsh (1988) is \(10^{-9}\).

![Figure 2. Schematic examples of processes which can influence of the CSD shape (Higgins, 2006; Vinet and Higgins, 2010). a) Increasing undercooling (saturation), b) Increasing growth rate or residence time, c) Accumulation and crystal fractionation crystal, d) Coarsening, e) mixing of two crystal populations or magma mixing.](image)

4. Results

**Petrography and textural analysis of plagioclase phenocrysts**

Lava from Mt. Sukageri has ±11.5 m thick with ‘a’ā lava characteristics and it can be divided into three section as upper, middle and bottom part (Figure 3). It spread out into 4km to the southern from Mt. Sukageri, involving Cisantana, Mayasih and Cigugur quarry. The complete section of ‘a’ā lava can be seen on ES01, ES02, and ES07 sites. The upper and bottom part are characterized by autobreccia texture with roughly and sharp surface, high vesicular and red colour as oxidation processes. Petrographic analysis from the upper and bottom part are vitrophyric texture with phenocrysts and groundmass (microcrystalline and glass). Phenocrysts of plagioclase (10.6-12.4%), pyroxene (1.66- 2.78%), olivine (0.87-3.25%), and titanomagnetite (0.3-0.42%) are present. The groundmass (65.29- 83.53%) is composed of microcrystalline plagioclase, pyroxene, titanomagnetite, and glass. The vesicular of this part is more than middle part and has various shape and size.

The middle part of ‘a’ā lava section has coherent, but in transition area shows sheeting joints features. Characteristics of that section has dark colour, low vesicular, and aphanitic texture. Petrographic analysis of this part show vitrophyric texture composed of phenocrysts of plagioclase, pyroxene, olivine and titanomagnetite with groundmass of microcrystalline plagioclase, pyroxene, titanomagnetite, and glass. Vesicular of this part is a little and the size of crystal more coarse than upper or bottom part of ‘a’ā lava section. All of the sections are composed of phenocrysts and microcrystalline of plagioclase which indicates the changing on crystallization time. Plagioclase texture of the ‘a’ā lava compose of fine-sieve, zoning, resorption surface, synneusis, glomerocrysts, and broken crystals (Figure 4). Those textures are indicating of changing of magmatic systems.
Figure 3. The complete section of Sukageri’s ‘a’ā lava of ES01 outcrop. The upper and lower parts are characterized by autobreccia, the middle part is massive texture and the transition is sheeting joint features.

Figure 4. Photomicrograph of plagioclase texture of Sukageri’s ‘a’ā lava, a) fine sieve texture, b) fine oscillatory zoning, broken crystal, c) resorption surface, d) synneusis, e) glomerocrysts, f) broken crystal.

CSDs of plagioclase
The measured crystal size data are presented in table 1 and shown as histogram which represent of frequency versus crystal size (Figure 5). It shows the difference between crystal sizes of autobreccia with sheeting joint section. The autobreccia section is dominated by 0.019 - 0.048 mm and it shows the distribution pattern into the left. The sheeting joint section has crystal sizes which dominated by 0,
04 – 0.1 mm. The aspect ratio value from CSDSlice5 spreadsheet (Morgan and Jerram, 2006) is used to get S/I and I/L ratio. The S/I versus I/L diagram show that shape 3D shape of plagioclase of ‘a’ā lava is bladed (Figure 6) (Zingg, 1935) with the base fit is shown in Figure 7. All of sample of ‘a’ā show that the CSDs diagram have curved line than kinked (Figure 8). Although the CSDs are curved, the pattern can be divided to two trends. The first trend has steep slope and high intercept value which represent mikrolite and the second trend has gentle slope and low intercept value which represent phenocrysts. Those data are presented in table 1.

Table 1. CSD data and crystallization time of sukageri ‘a’ā lava.

| Sample | Number of Measured Total area (mm²) | Score (R²) | Aspect ratio | S/I | I/L | Crystal shape | Regression line | Crystallization time |
|--------|-------------------------------------|------------|--------------|-----|-----|---------------|-----------------|---------------------|
|        |                                     |            |              |     |     |               | Slope           | Intercept           |                     |
| ES01   | 2500                                | 12.1147    | 0.8191       | 1 : 3.4 : 7 | 0.29 | 0.49 | Bladed        | -2.5             | 3.1                 | 12.82 years         |
|        |                                     |            |              |     |     |               | -21.05          | 11.7               | 55 days             |
| ES02   | 1700                                | 36.7926    | 0.8735       | 1 : 4.5 : 7 | 0.22 | 0.64 | Bladed        | -2.22            | 1.4                 | 14.28 years         |
|        |                                     |            |              |     |     |               | -26.88          | 10.25              | 43 days             |
| ES03   | 1200                                | 9.0393     | 0.8192       | 1 : 2.8 : 4.5 | 0.36 | 0.62 | Bladed        | -2.65            | 2.4                 | 11.95 years         |
|        |                                     |            |              |     |     |               | -27.61          | 11.52              | 42 days             |
| ES05   | 1600                                | 15.89      | 0.5958       | 1 : 2.5 : 5 | 0.40 | 0.50 | Bladed        | -2.3             | 2.27                | 13.76 years         |
|        |                                     |            |              |     |     |               | -23.63          | 11.11              | 49 days             |
| ES07   | 1600                                | 14.205     | 0.8741       | 1 : 3.6 : 5.5 | 0.28 | 0.65 | Bladed        | -2.61            | 2.74                | 12.16 years         |
|        |                                     |            |              |     |     |               | -27.28          | 11.35              | 42 days             |

Figure 5. Frequency versus length histogram of the measured plagioclase crystal of Sukageri a’ā lava. It show that plagioclases size is dominated by mikrolite. 0.03-0.06 mm.

Figure 6. S/I versus I/L diagram show that shape 3D shape of plagioclase of ‘a’ā lava is bladed (Zingg, 1935).
Figure 6. The position of average aspect ratio of plagioclase in igneous rocks on I/L versus S/I diagram (Zingg, 1935). All of Plagioclase of sukageri a’ā lava are bladed shape.

Figure 7. Frequency versus 2D Short axis/Long axis histogram of measured plagioclase crystals of sukageri a’ā lava with base fit shape output by CSDs slice and the propose aspect ratios.
5. Crystallization time and magmatic processes of Sukageri 'a'ā lava

The sukageri 'a'ā lava is an effusive volcanic products that produced as flank eruption of Ciremai volcano. That lava can be divided into 3 sections into upper and lower part as autobreccia texture, and middle part as massive texture. Petrographic analysis of sukageri 'a'ā lava has vitrophyric texture with euhedral olivine, pyroxene, and plagioclase as phenocrysts and microlite of plagioclase, pyroxene and glass as groundmass. The mineral associations indicate that magma of Sukageri 'a'ā lava is basaltic. Vitrophyric texture indicates a two-stage cooling history of magma. An initial episode of slow cooling rate yields few nuclei of olivine, pyroxene, and plagioclase just below liquidus temperatures in a thermally insulated plutonic environment (magma chamber) beneath Ciremai volcano. These grow produced relatively large phenocrysts with euhedral shape. When the magma ascent to the surface, it environment and systems was changed into rapid cooling conditions. Those change produced microlite of plagioclase with bladed shape.

The progressive change from slow cooling into rapid cooling rate is shown as in CSD curve pattern. The slow cooling rate is indicated as gentle slope of CSD curve with low intercept, but the rapid cooling rate is indicated as step slope of CSD curve with high intercept. From CSD curve, we divided it into two segments which represent crystallization time (Figure 8). The first segment is slow cooling which formed large phenocrysts and euhedral shape. It needs 11.95 – 14.28 years for crystallize and we interpreted as time when magma moved from magma chamber into conduit. The second segment is rapid cooling rate which formed microlite of plagioclase with bladed shape. The crystallization time of that segment is 42-43 days which represented as ES02, ES03, and ES07 sample of autobreccia. It can be interpreted as time when magma in conduit ascent to the surface. We suggested that, the time when lava solidifying is the difference crystallization time of autobreccia sample (ES02, ES03, and ES07) with massive lava sample (ES01 and ES05). It needs ±13 days for solidifying.

Igneous textures can be classified into three categories based on main processes, including 1) kinetic textures resulting from nucleation and growth processes, 2) mechanically modified textures resulting from sorting and compaction processes, 3) equilibrium textures which produce a coarsening effect on pre-existing textures (Cashman and Marsh; 1988; Higgins, 2006; Rannou and Caroff, 2009). In volcano, the system is open-system contained mixed crystal populations of xenocryst, antecryst, phenocryst, and microlite (Renjith, 2013). Renjith (2013) proposed that micro-textural analysis of plagioclase can indicate of magmatic processes beneath volcano. Those texture are included, coarse-sieve, fine-sieve, fine-oscillatory zoning, rounded zone corner, resorption surface, synneusis, glomerocrysts, swallow tail, microlites, and broken crystal.

Plagioclase texture of the Sukageri 'a'ā lava compose of fine-sieve, fine oscillatory zoning, resorption surface, synneusis, glomerocrysts, microlite and broken crystals. Renjith (2013) suggested that fine sieve, fine oscillatory zoning, resorption surface, synneusis and glomerocrysts can be used to interpret of magmatic processes in shallow magma chamber, but microlite and broken crystal texture can be used to interpret magmatic processes in conduit. Shallow magma chamber is dynamically active by the new magma injection or by convection or combination of both. It processes made the phenocrysts undergoing repeated dissolution-regrowth process. It is represented as fine sieve, fine oscillatory zoning, resorption surface and synneusis of plagioclase texture (Renjith, 2013). During the self-mixing processes, it might was undercooling condition, controlled by degassing or water ex-solution and resulted of microlite and broken crystal plagioclase.
Figure 8. CSD diagram of Sukageri ‘ā’ā lava has kinked curve with two segments which represent plagioclase as phenocrysts and as groundmass.

6. Conclusions
Sukageri ‘ā’ā lava has ±11.5 m thick and it can be divided into three section as upper, middle and bottom part (Figure 9). The upper and bottom part are characterized by autobreccia texture with rough and sharp surface, high vesicular and red colour as oxidation processes. Sample which represents autobreccia section is ES02, ES03, and ES07. The middle part of ‘ā’ā lava section which represent as ES01 and ES05 sample has coherent, but in transition area shows sheeting joints features. Characteristics of that section has dark colour, low vesicular, and aphanitic texture. Vesicular of this part is a little and the size of crystal more coarse than upper or bottom part of ‘ā’ā lava section. CSD analysis shows a concave curve with difference of slope value. It can be interpreted as progressive change of cooling rate and crystallization time of phenocryst and mikrolite of plagioclase, or interpreted as magma mixing processes. The crystallization time of phenocrysts is interpreted as initial stage when magma started to ascend to the surface, but the mikrolite crystallization time is interpreted as magma in conduit. The difference crystallization time between autobreccia and massive sample is interpreted as solidifying time of Sukageri ‘ā’ā lava after eruption. Micro-textural analysis of plagioclase shows a shallow magma chamber processes involve magma mixing and heating which influence to dissolution-regrowth process. Those texture include, fine sieve, fine oscillatory zoning, resorption surface, synneusis and glomerocrists. When magma moved in conduit, the environment and
system was changed, controlled by degassing or water ex-solution. The texture which represents that condition is broken crystal and mikrolite of plagioclase.

![Figure 9. Sample position of Sukageri' a’ā and CSDs characteristics of each sample.](image)

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