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Magma Evolution of Lasem and Senjong Volcanic Complex: High-K Magmatism in Sunda Arc, Indonesia

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Abstract - Lasem and Senjong Volcanic Complex (LSVC) is one of four Quaternary volcanic complexes with high-K magmatism distributed in the northern coast of Central Java. This research aims to understand the magmatic evolution of the volcanic complex. Morphostratigraphy analysis and field observation show twelve pyroclastic density flow units in Lasem Volcano, distributed mainly in the northern to eastern flanks, but minor occurrences in the southern and western flanks. Meanwhile, nine lava flow units of Lasem are concentrated on the south flank of the volcano. Lasem stratovolcano is attributed to four lava domes distributed on the northern and southern flanks. Senjong Volcano comprises one lava flow and four lava domes. Rocks of LSVC are composed of plagioclase, K-feldspar, hornblende, clinopyroxene, and opaque minerals embedded in the groundmass of volcanic glass and microlite. These calc-alkaline rocks range from basaltic trachyandesite to trachyte in composition. The magma of LSVC can further be grouped into High K/Rb and Low K/Rb types, which dominate the Lasem and Senjong Volcano products, respectively. These two magma types consistently show divergent trends in K/Rb and Rb/Nb plots against increasing silica, indicating distinct differentiation processes of similar magma source.

Keywords: Lasem-Senjong Volcanic Complex, magma evolution, high-K magma, multiple magma

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Introduction

Lasem-Senjong Volcanic Complex (LSVC) isa high-K volcanic complex located on the northern coast of central part of Java Island (Calanchi *et al*., 1983; Leterrier *et al*., 1990). This complex is one of the back-arc side volcanoes of the Sunda Quaternary Arc resulted from Indo-Australian Plate subducted beneath Eurasian Plate (Hamilton, 1979; Setijadji *et al*., 2006). LSVC comprises of Lasem Volcano in the northern part and Senjong Volcano in the southern part of the volcanic complex (Figure 1).

Volcanoes of the northern coast of Java, such as Muria and Ringgit-Beser, have high-K magmatism character with multiple magma sources related to the presence of two end member magmas, which are subduction related magma and enriched magma from within-plate or mantle upwelling sources (Edwards *et al*., 1991; 1994).

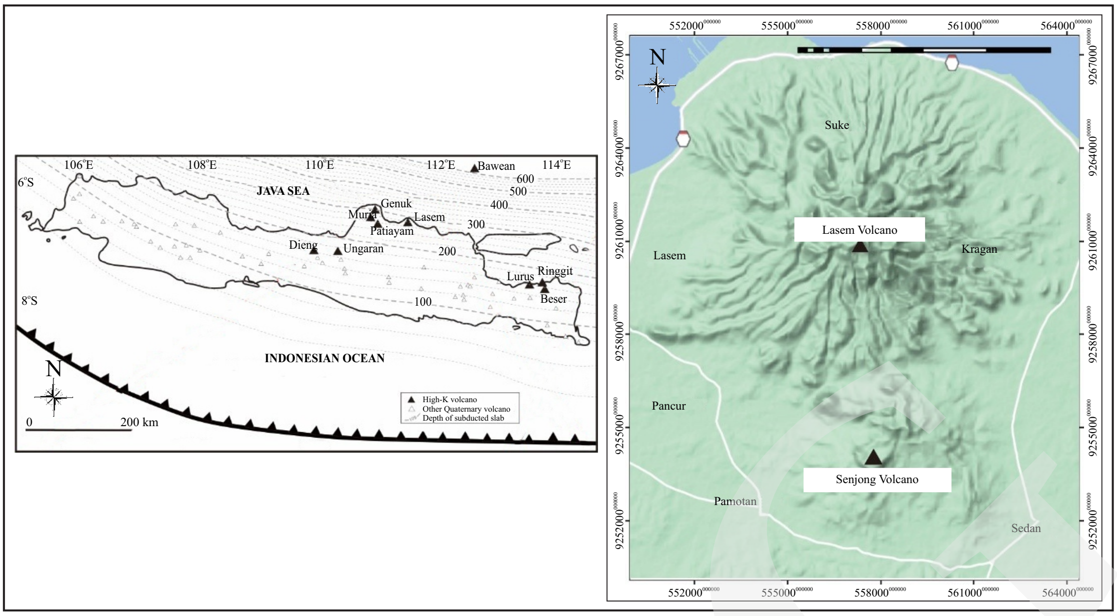

Figure 1. (a) Distribution of High-K volcanoes (black triangles) in Java Island mostly related to depth of subducted slab 160-600 km after Leterrier *et al*. (1990). Depth of subduction based on Hayes *et al*. (2018). (b) Lasem Senjong Volcanic complex consist of two adjacent volcanoes of Lasem in the north and Senjong in the south. Image taken from Google Maps (2018).

LSVC corresponds to the depth of Wadati-Beni off zone about 260-280 km (Hayes *et al*., 2018). This depth is within the range of Muria (260-300 km) and relatively deeper than that of Lurus and Ringgit-Beser (140-180 km). LSVC differs in magma characters than the neighboring volcanic complexes, reflecting heterogeneous mantle beneath north Java. Thus understanding the petrological characteristics of LSVC magma, which is located between Muria and Ringgit Beser, is the key to understand the back-arc side magmatism in the northern Java Arc.

This study aims to understand the stratigraphy, geochemical and mineralogical characteristics of LSVC volcanic products. This understanding will be used as a fundamental basis to achieve the primary goal of inferring the magma evolution of LSVC. The magma differentiation processes will be discussed that might correspond to both magma temporal and spatial evolutions of LSVC.

Geological Setting

Lasem-Senjong Volcanic Complex is a part of the Quarternary Volcanic Arc of Java (van Bemmelen, 1949). The volcanic arc formed due to the subduction Indo-Australian Plate below the Eurasian Plate (Hamilton, 1979; Tregoning *et al*., 1994; Hall and Smyth, 2008). The direction of convergence between the Indo-Australian Plate and Eurasian Plate in Java is calculated as N11°E with approximately 6.7±0.7 cm/yr in convergence rate (Tregoning *et al*., 1994). The depth of Wadati-Beni off zone beneath the LSVC is about 260-280 km (Hayes *et al*., 2018), though Abdurrachman *et al*. (2019) infer of about 450 km depth, while the subducted slab below Java Island reached up to 600 km depth. Situmorang *et al*. (1992) and Kadar and Sudijono (1993) interpreted that LSVC was situated above Tertiary calcareous and silicic sedimentary rocks. K-Ar radiometric dating shows that the age of Lasem volcanic rocks ranges from 1.6 - 1.1 Ma, or Lower Pleistocene (Letterrier *et al*., 1990).

LSVC volcanic products consist of basaltic andesite to dacitic lava flows, lava domes, and pyroclastic density current, within the range of Medium-K calc-alkaline to shosonitic magma series (Letterrier *et al*., 1990). Pumice fragments found within the Lasem pyroclastic flow deposits indicate explosive volcanism of andesitic to dacitic magma composition. Major and trace element patterns indicating a co-magmatic relation between Lasem and Senjong lavas (Disando and Abdurrachman, 2017).

Analytical Methods

A morphological analysis was conducted using topographic data from Digital Elevation Model to determine the morphostratigraphic order of LSVC products. Thirty eight rock samples representing each product for thin section observation, and twenty nine for geochemical analysis were collected.

Modal mineralogy composition was determined by point counting method involving 1000 points for each sample. The thin section preparation and observation were carried out in the Geological Engineering Department, Faculty of Engineering Universitas Gadjah Mada. We used Olympus CX-31 Trinocular polarized light microscope with 4x, 10x, 25x, and 40x objective lens magnification combined with 10x ocular lens magnification. The photomicrograph was taken using Canon EOS 700D camera.

The geochemical analysis was carried out in the commercial laboratory of ALS Geochemistry Lab, Canada. The Laboratory applies analytical methods of Inductively Coupled Plasma - Atomic Emission Spectroscopy (ICP-AES) for major elements and Inductively Coupled Plasma - Mass Spectrometry (ICP-MS) for trace elements and REE.The determination of major, trace, and rare earth elements was performed on a liquid sample prepared from the dissolution of powdered sample. As many as 0.1 g weight of the powdered sample is added to lithium metaborate and lithium tetraborate flux, combined well, and fused in a furnace at 1000-1025°C. The resulting melt is then cooled and dissolved in a mixture of nitric acid and hydrochloric acid.

Samples with LOI numbers of less than 2% were carefully selected to ensure the sample reliability in the discussion of magma differentiation, as suggested by LeMaitre (2002). Six out of twenty-nine samples have more than 2% LOI (Table 2), therefore considered unsuitable for analysis and not included in the discussion.

Data

Morphostratigraphy

The lava and pyroclastic deposit sobservation and morphostratigraphy analysis were performed to determine the stratigraphy and relative ages of Lasem and Senjong volcanic products. Morphostratigraphy analysis was carried out based on the principle of superposition and the cross-cutting relationship between the volcanic units, combined with field observations.

The research area includes two volcanic centers: Lasem Volcano in the north and Senjong Volcano in the south. The northern flank of Lasem Volcano is dominated by lahar and pyroclastic flow deposits, where as lava flows dominate the southern flank of Lasem Volcano. The explosive products of Lasem Volcano consist of 12 pyroclastic flow units, which are nine units of block and ash flow deposit (BAF 1-9), two units of lithic-rich ignimbrite (PF 1-2), and 1 unit of ash-flow deposit (AF). The contacts of each flow unit are marked by reworked volcaniclastic deposit, lava, and erosional boundary. The reworked volcaniclastic deposits were locally found in several locations, directly contacted with the primary deposits, to be used as the boundary layer between PDC units such as AF-BAF 1, BAF 3-BAF 4, and BAF 7-BAF 8.

The lava flow of Lasem Volcano can be divided into nine units (LL 1-9) interfingering with the PDC units. The lava flow units from Lasem volcano are extending up to 6 km from the volcanic center. The effusive eruption occurred overmultiple periods, marked by the over lapping lava lobes.Four lava domes (KLL 1-3, SLL) are distributed in the northern and southern flank of Lasem Volcano. Senjong Volcano comprises four lava domes (KLS 1-4) andone lava flow unit (LS 1).

Volcanic Products of Lasem and Senjong

The stratigraphy of the research area was arranged based on the integration of morphostratigraphy analysis and field observation. The compilation of these data is used to produce the geological map of LSVC (Figure 2). The

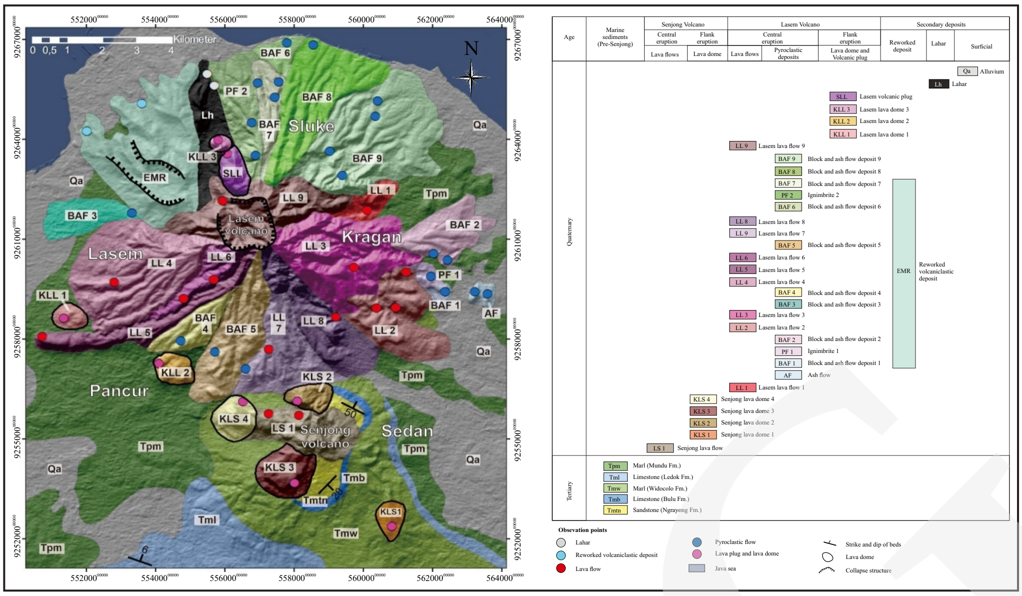

Figure 2. Geological map of Lasem-Senjong Volcanic Complex and the surrounding area overlain to DEM (modified from Moktikanana, 2019 and Abdillah, 2019). Senjong Volcano comprises one lava flow unit and four lava domes. The outcrops of Lasem lava are distributed in the southern flank, consist of 9 lava flow units, three lava domes, and one volcanic plug. The pyroclastic deposits of Lasem are concentrated in the northern flank, which are nine units of block and ash flow deposit, two units of lithic-rich ignimbrite, and 1 unit of ash-flow deposit. DEM data is freely downloadable through (http://tides.big.go.id/DEMNAS/).

characteristics of Lasem and Senjong volcanic productsare summarized as follows.

Lava flow

The lava flow unit can be divided into Senjong and Lasem lava flow units. Senjong Volcano consists of one lava flow unit (LS 1) located in the northwestern flank. Lasem Volcano comprises nine lava flow units (LL 1-9) concentrated on its southern part. LL1-3, LL 4-6, and LL 7 - 8 are distributed in the eastern, western, and southern flanks, respectively; while LL 9 is distributed in the central zone. These lava flows are mainly grey to dark grey-coloured, massive; varying from 2 to 25 m thick.

Thin section observation shows that the lava flow consists of hornblende andesite and pyroxene andesite, with ~50 vol% of phenocryst. The lava flow contains plagioclase, hornblende, clinopyroxene, K-feldspar, and opaque minerals as phenocrysts, with plagioclase microlite and volcanic glass as the groundmass (Figure 3). Plagioclase (10 - 32%) and hornblende (4 - 17%) are the most abundant component in hornblende andesite, while pyroxene andesite is dominantly composed of plagioclase (29 - 39%) and clinopyroxene (~15%). Opacitic rim texture is common in hornblende, while sieve and zoning texture are present in plagioclase. Porphyritic, vitrophyric, trachytic, pilotaxitic, hyalopilitic, and glomeroporphyritic textures are also found in the petrographic observation. Geochemical analysis of the lava flow samples indicates 52 - 63 wt.% silica, within the range of trachyandesite to trachydacite (Figure 4a).

Lava dome

Lasem Volcano has four lava domes (KLL 1-3, SLL), while Senjong Volcano also has four lava domes (KLS. 1-4). These units are characterized by dome morphology with grey to dark-grey colour and massive structure. Thin section observations show the KLL 1-3 and KLS 1-4 are hornblende andesite with ~70% phenocryst. The SLL unit is phaneritic inequigranular microdiorite. Trachytic, hyalopilitic, glomeroporphyritic, poikilitic, and vitrophyric textures are common in the hornblende andesite.

The hornblende andesites and microdiorite contain plagioclase, hornblende, clinopyroxene, K-feldspar, and opaque minerals as phenocryst

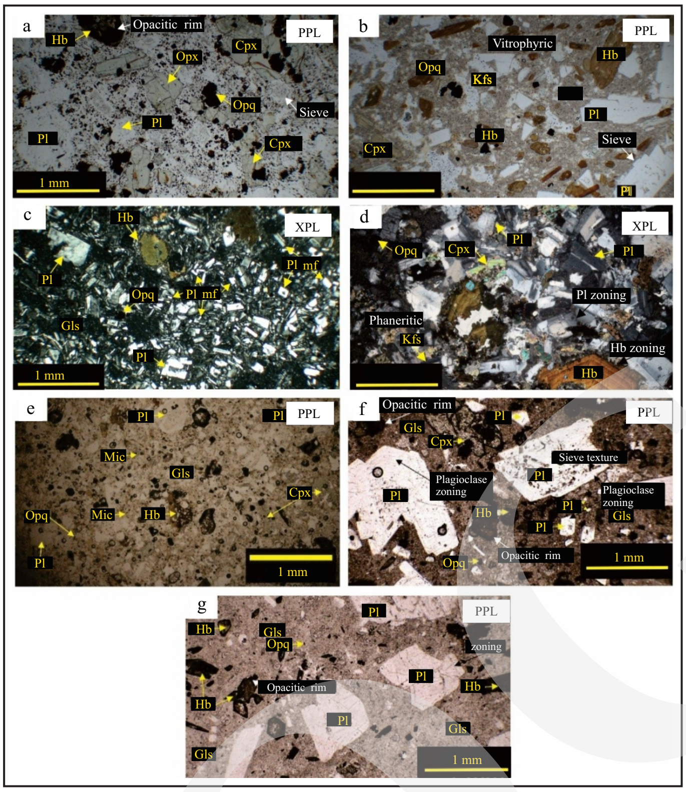

Figure 3. Photomicrograph of Lasem and Senjong volcanic products: (a) pyroxene andesite (lava flow), (b) hornbende andesite (lava flow), (c) hornblende andesite (lava dome), (d) microdiorite (lava dome), (e) andesite fragment (block and ash flow deposit), (f) andesite lithic (ignimbrite deposit), (g) crystal-vitric tuff (ash flow deposit). Photomicrograph a-d refer to Moktikanana (2019), e-g refer to Abdillah (2019). Cpx = clinopyroxene; Gls = volcanic glass; Hb = hornblende; Kfs = K-feldspar; Opx = orthopyroxene; Opq = opaque minerals; Pl = plagioclase; Pl mf = plagioclase microphenocryst.

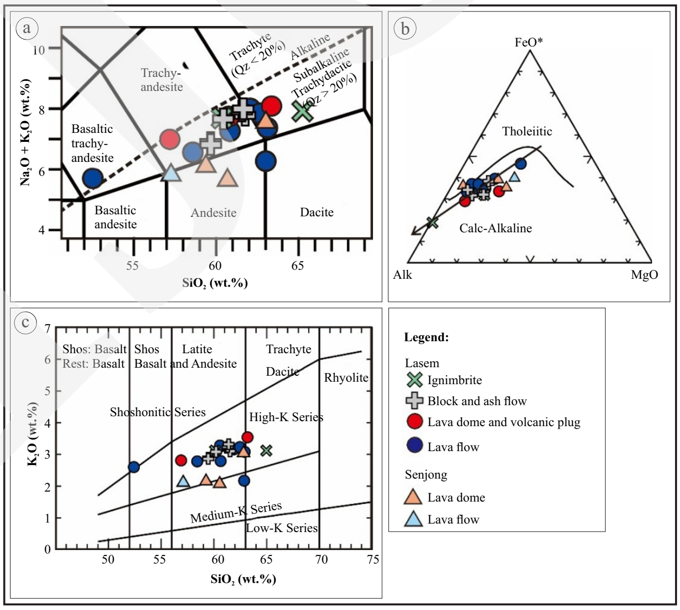

Figure 4. (a). Total Alkali-Silika classification (Le Bas *et al*., 1986) showing the composition of basaltic trachyandesite to trachyte, with SiO_2 ranges from 51% to 66%. The dividing line of alkaline and sub alkaline magma was taken from Irvine and Baragar (1971) (b) Geochemical data plot of Lasem and Senjong volcanic rocks within AFM. diagram by Irvine and Baragar (1971), showing calc-alkaline magma series. (c) Lasem and Senjong volcanic rocks data plot on magma series classification of Pecerillo and Taylor (1976), showing two distinct trends: (1) High K/Rb magma (dark blue circle) within the high-K series and (2) Low K/Rb magma (light blue circle) with shifting trend from high-K to medium-K series.

plagioclase microlite and volcanic glass as the groundmass (Figure 2). Zoning and sieve texture are also found in plagioclase, while hornblende has opacitic rim texture (Figure 2). Geochemical analysis indicates that the lava dome and volcanic plug have basaltic trachyandesite - trachydacite composition with 56 - 63 wt.% silica (Figure 4a).

Block and ash flow deposit

The Lasem Volcano block and ash flow deposits consist of nine units, BAF 1 - BAF 9. The units have grey to whitish-grey colour, massive, welded, with thickness ranges from 1 - 25 m. These deposits are dominantly composed of andesite fragments up to 90 cm in diameter, with volcanic ash as the matrix. Segregation gas pipe structure is found only in BAF 2.

Thin section observation shows that the fragment composing these units are andesite and hornblende andesite. The andesites contain phenocrysts of plagioclase, hornblende, clinopyroxene, K-feldspar, opaque minerals, in addition to plagioclase microlite, and volcanic glass as the groundmass (Figure 2). Plagioclase phenocryst has zoning and sieve textures, whereas hornblende phenocryst has opacitic rim texture. Trachytic, hyalopilitic, glomeroporphyritic, poikilitic, and vitrophyric textures are also identified in the petrographic observation.

Ignimbrite

The ignimbrite deposits can be divided into two units. Ignimbrite 1 (PF 1) is distributed in the eastern flank of Lasem Volcano, while Ignimbrite 2 (PF 2) is distributed in the northern flank. These deposits are mainly white-colored,minor are pink-colored, massive, with 4-15 m thick. These deposits are rich in andesite fragments up to 20 cm in diameter, and also contains pumice fragments with ~5 cm size, floating in the matrix of volcanic ash.

Thin section observation shows that the abundance of phenocryst in the ignimbrite fragments is less than the groundmass, with <5% vesicles. The ignimbrite fragments contain plagioclase, hornblende, clinopyroxene, K-feldspar, opaque minerals as phenocrysts, also plagioclase microlite, and volcanic glass as the groundmass (Figure 3). Plagioclase and hornblende are the most abundant component, composing more than 10% volume of the phenocryst. Plagioclase phenocryst has zoning and sieve texture, while hornblende has opacitic rim texture. Trachytic, pilotaxitic, hyalopilitic, glomeroporphyritic, poikilitic, and vitrophyric textures also present in the lithic fragments ofthe ignimbrites. Geochemical analysis of the lithic samples indicates that these ignimbrites have the most silicic composition among the volcanic products of Lasem Volcano, with 61-64 wt.% silica (Figure 4a).

Ash flow

The ashflow deposit comprises only 1 unit, located on the eastern flank of Lasem Volcano. Ash flow deposit thickness is about 6.5 - 8 m. This unit was grey in color, massive, dominantly composed of coarse volcanic ash, ~0.2 cm pumice fragments, and few prismatic mafic minerals. The ash flow is classified as crystal-vitric tuff (Cook, 1965) with mineralogical composition consists of plagioclase, hornblende, clinopyroxene, and volcanic glass. The plagioclase phenocryst has a zoning texture, while hornblende has an opacitic rim texture (Figure 3).

Mineralogy

Igneous rock textures such as porphyritic, vitrophyric, trachytic, pilotaxitic, hyalopilitic, and glomeroporphyritic are commonly found in the Lasem Senjong volcanic rocks. The modal compositions from point counting methods are summarized in Tables 1 and 2. The detailed mineralogical composition is described as follows.

Plagioclase

Plagioclase is the most abundant phenocryst present in the Lasem and Senjong volcanic products, with 10-60 vol.% as phenocryst, 25-55% as microphenocryst, and 4-60 vol.% as microlite. Microphenocryst plagioclase generally presents in lava dome, while plagioclase microlite is abundant in the lithic fragments of pyroclastic flow deposits. The plagioclase phenocryst is 0.3-10 mm in size,

Table 1. Modal Compositions of Lasem and Senjong Lavas (in vol.%)

Unit		Sample	Pl	Kfs	Hb	Cpx	Opx	Opq	Pl (mf)	Pl (mc)	Gls
LASEM	SLL	MLA22	61	8	20	10	<1	<1	-	-	-
	KLL3	MLA01	32	-	5	5	-	3	-	33	24
	KLL2	MLA04	17	2	11		-	<1	49	8	12
	KLL1	MLA07	16	4	13	4	-	5	-	32	27
	LL9	MLA05	23	2	8	7	-	3	-	14	44
	LL8	MLA18	28	3	6	2	-	4	-	23	35
	LL7	MLA17	39	1	2	17	5	3	-	22	12
	LL6	MLA08	29	3	5	16	6	2	-	24	16
		MLA09	29	1	2	15	8	5	-	22	17
	LL5	MLA03	21	-	15	4	-	<1	-	33	27
	LL4	MLA06	24	1	14	5	-	2	-	14	40
	LL3	MLA21	24	-	7	5	-	3	-	35	26
	LL2	MLA02	22	-	13	2	-	2	-	34	27
		MLA20	22	-	14	3	-	3	-	31	29
	LL1	MLA16	27	5	12		-	2	-	24	29
SENJONG	KLS4	MLA10	16	-	8	5	-	2	30	6	33
	KLS3	MLA15	15	1	4		-	<1	54	4	20
	KLS2	MLA12	14	2	17	2	-	3	44	5	14
	KLS1	MLA14	32	4			-	<1	25	19	19
	LS1	MLA13	15	-	10	5	-	2	29	7	33

Note: Pl = plagioclase; Kfs = K-Feldspar; Hb = hornblende; Cpx = clinopyroxene; Opx = ortopyroxene; Opq = opaque minerals; Pl (mf) = plagioclase (microphenocryst); Pl (mc) = plagioclase (microlite); Gls = volcanic glass.

Table 2. Modal Compositions of Lasem and Senjong Pyroclastic Deposits (in vol.%)

Unit		Sample	Pl	Kfs	Hb	Cpx	Opx	Opq	Pl (mc)	GLS	Vsc
LASEM	BAF 9	MYA10	33	6	4	1	-	3	54	<1	10
		MYA12	27	7	4	1	<1	4	53	2	12
	BAF 8	MYA21	10	<1	2	<1	-	21	63	2	21
	BAF 7	MYA18	21	10	<1	-	-	35	33	<1	18
	PF 2	MYA01	21	3	<1	3	-	7	67	-	1
		MYA02	15	3	3	<1	-	21	55	2	2
		MYA08	32	2	<1	<1	-	27	37	-	8
	BAF 6	MYA22	14	<1	1	1	-	15	65	3	22
	BAF 5	MYA23	22	4	1	<1	-	20	50	2	21
	BAF 4	MYA03	13	1	<1	1	<1	12	51	21	13
		MYA04	26	3	<1	<1	<1	7	59	4	26
		MYA16	22	2	7	<1	-	9	55	3	22
	BAF 3	MYA24	18	11	2	1	<1	47	19	<1	18
	BAF 2	MYA13	23	6	<1	<1	-	11	56	3	23
		MYA15	22	8	3	<1	-	12	52	2	22
	PF 1	MYA09	32	5	<1	1	-	8	53	<1	32
	BAF 1	MYA14	16	3	<1	<1	-	15	59	4	16
	AF 1	MYA17	32	7	<1	<1	-	9	53	<1	31

Note: Pl = plagioclase; Kfs = K-Feldspar; Hb = hornblende; Cpx = clinopyroxene; Opx = ortopyroxene; Opq = opaque minerals; Pl (mc) = plagioclase (microlite); Gls = volcanic glass; Vsc = vesicle.

colorless, has a euhedral-subhedral shape, polysynthetic twinning, with a sieve and zoning texture.

Hornblende

Hornblende also occurs as the most abundant phenocryst after plagioclase, from 1 to 20 vol.%. The hornblende phenocryst has an opacitic rim and zoning texture with brown color, 0.2-5 mm size, euhedral-subhedral shape.

Pyroxene

Pyroxene present as phenocryst in 1-17 vol.% for clinopyroxene and <1-8 vol.% for orthopyroxene. Clinopyroxene occurs almost in all lava samples, while orthopyroxene only present in the most basaltic lava (~53% SiO_2). The highest percentage of clinopyroxene also appears in the most basaltic lava. The clinopyroxene found in Lasem and Senjong volcanic products is aegirine commonly found in high-K silica undersaturated magma. The aegirine phenocryst has an intense green color, a concentration of 0.2-5 mm in the euhedral-subhedral shape and moderate pleochroism.

K-Feldspar

K-Feldspar occurs as phenocryst with 1-11 vol.%abundance.The phenocryst of K-Feldspar is

0.3-3 mm in size, colorless, and has a euhedral-subhedral shape with Carlsbad twinning.

Geochemistry

The rocks of LSVC are classified as basaltic trachyandesite to trachyte based on the Total Alkali-Silica diagram (Le Bas *et al*., 1986). Lasem and Senjong volcanic rocks are sub alkaline series and plotted as calc-alkaline type (Figure 4a-b). The affinity of these rocks ranges from medium-K to high-K according to diagrams of Pecerillo and Taylor (1976) and Gill (1981)(Figure 4c).

The Harker diagrams show positive trends for SiO_2 versus Al_2O_3, Na_2O, and K_2O but negative trends for FeO, CaO, MgO, TiO_2, and P_2O_5 (Figure 5). The distribution of trace elements including Large Ion Lithophile Elements (LILE) such as Rb, Ba, Sr, and High Field Strength Elements such as Zr, Nb, Hf, and Ta, and Rare Earth Elements (REE) were also analyzed using bivariate-diagrams against SiO_2. In general, LILE, HFSE, and LREE show positive trends, where as MREE and HREE show negative trends (Figure 6).

The REE pattern of Lasem and Senjong volcanic rocks normalized to chondrite (Sun and McDonough, 1989) shows a similar pattern with REE pattern from high-K calc-alkaline magma by Wilson (1989). Lasem and Senjong volcanic rocks have LREE enrichment compared to MREE and HREE (Figure 7a). The trace elements normalized to NMORB (Sun and McDonough, 1989) show that rocks of Lasem and Senjong volcanic rocks represent typical volcanic rocks related to subduction zone as indicated by LILE enrichment (Cs, Rb, K, Ba, Sr) and HFSE depletion (Nb, Ta, Zr, Ti) (Fig-

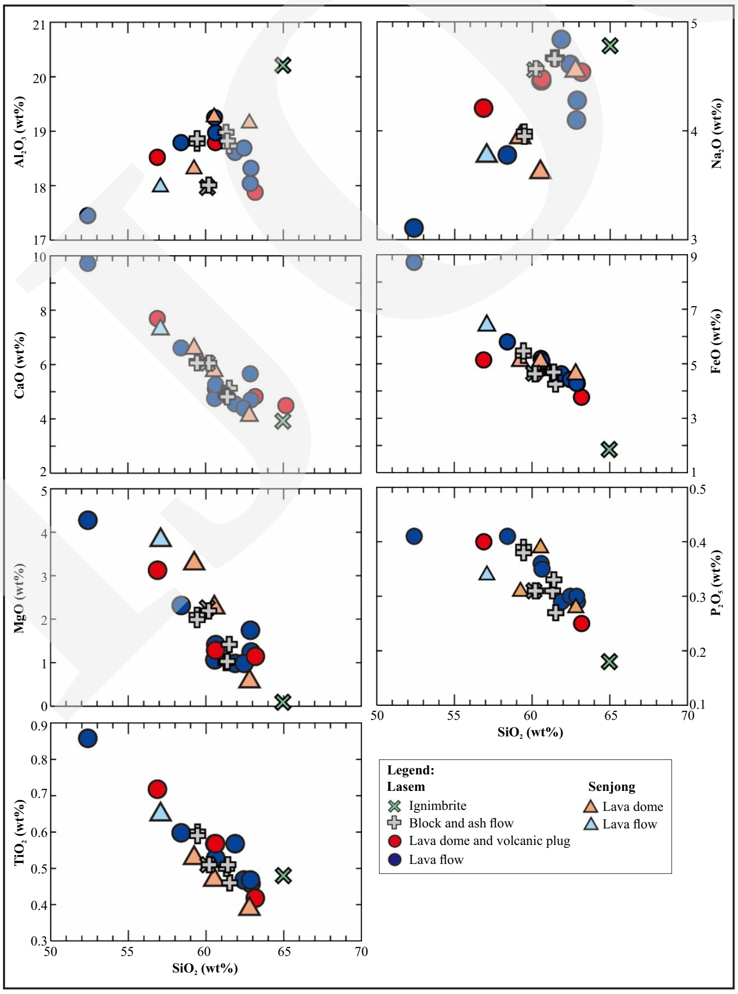

Figure 5. Bivariate plot of major oxides *vs*. SiO_2 showing the differentiation pattern of Lasem and Senjong volcanic rocks.

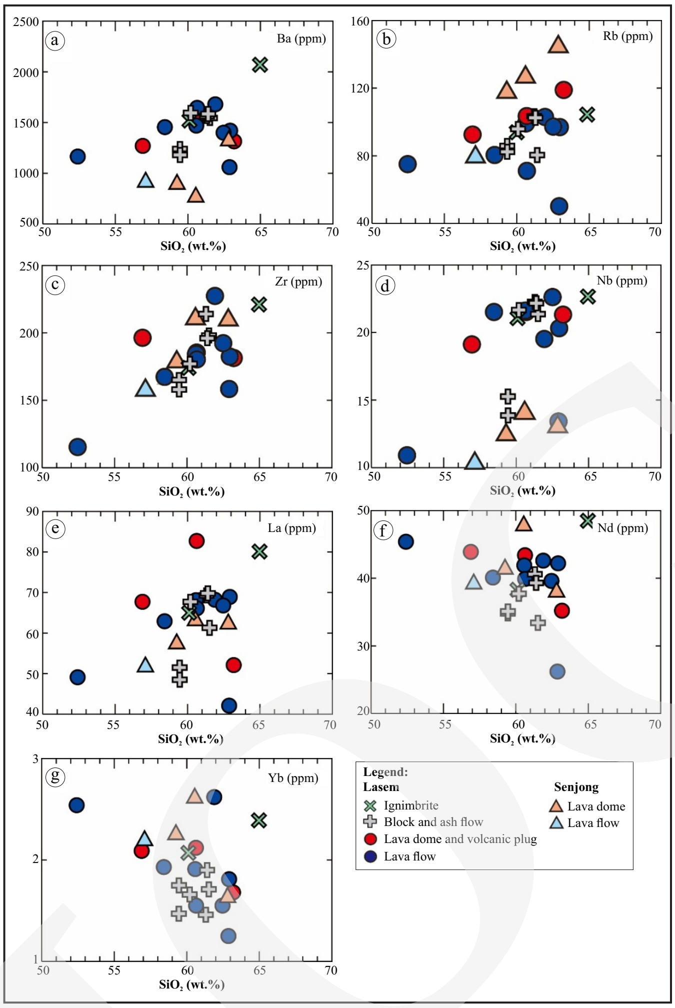

Figure 6. Bivariate plot of trace elements and REE *vs*. SiO_2 showing the differentiation pattern of Lasem and Senjong volcanic rocks. a-b) LILE, c-d) HFSE, e) LREE, f) MREE, g) HREE.

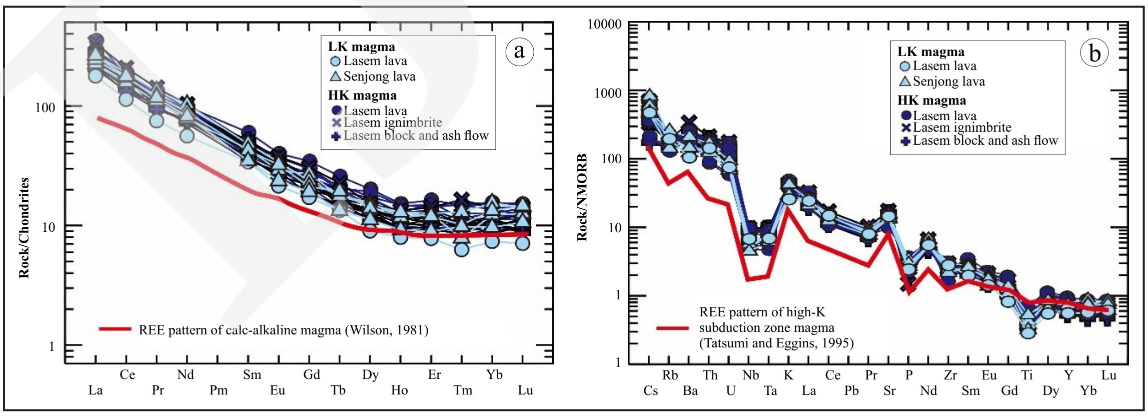

Figure 7. Trace elements and REE patterns of Lasem and Senjong volcanic rocks, normalized to (a) chondrite and (b) NMORB (Sun and McDonough, 1989). The trace elements and REE patterns represent a high-K subduction zone magma character.

ure 7b). The REE and trace element behavior from the spider diagram reflects a similar and inseparable pattern between the two volcanoes. However, plots of SiO_2 against K/Rb and Rb/Nb ratios show distinct trends of Lasem and Senjong volcanic rocks (Figures 8a-b).

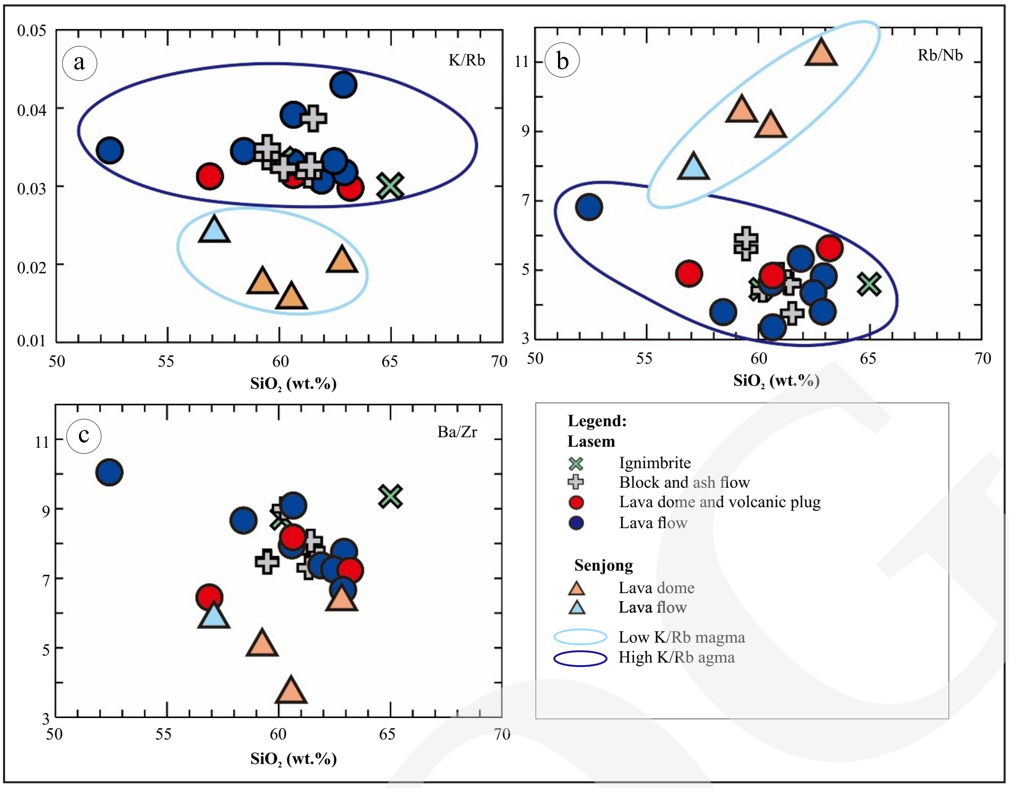

Figure 8. Bivariate plots of a) K/Rb, b) Rb/Nb, and c) Ba/Zr to SiO_2. Ba/Zr plot does not show any differences in trends between Lasem and Senjong samples. However, the prominent separated trends of Low K/Rb and High K/Rb magma spotted in the K/Rb and Rb/Nb pattern confirms the presence of two different magma types.

Discussion

Magma Type

Two different patterns trends are identified in plots of K/Rb *vs.* SiO_2 (Figure 8a) in which Lasem samples have a higher K/Rb ratio than Senjong samples. A separated pattern is also observed in the Rb/ Nb *vs.* SiO_2 plot (Figure 8b), where Lasem products have a low Rb/Nb ratio and show negative trends with increasing SiO_2. On the contrary, Senjong products have a higher Rb/Nb ratio and positively correlate with SiO_2. The separation of K/Rb and Rb/Nb trends indicate that Lasem and Senjong magma are different. Lasem magma is then grouped as High K/Rb magma, while Senjong magma is classified as Low K/ Rb magma.

Magma Differentiation

Mineralogical compositions of Lasem and Senjong phenocryst are plagioclase, K-feldspar, hornblende, clinopyroxene, orthopyroxene, opaque minerals, with plagioclase microlite and volcanic glass as the groundmass. The phenocryst component in the lava dome is generally more abundant (~70 vol.%) than lava flow (~50%) and pyroclastic deposit (~30 vol.%). Microphenocryst dominantly presents in the lava dome, while microlite is dominant in the lava flow and pyroclastic deposit. The higher proportion of phenocryst within the lava dome is related to the lava viscosity. More viscous lava tends to form a lava dome with a slower cooling rate than the lava flow. Crystallization becomes more intensive in the lava dome and produces more abundant phenocryst.

Almost all samples have dominant hornblende content up to ~20 vol.%. Some hornblende show opacitic rim texture (Figure 9). Opacitic rim texture was formed when magma reached the surface and came into contact with oxygen so that the hornblende became unstable and replaced with Fe-Ti oxide in the rim. Pyroxene are more abundant in the rocks with <59% SiO_2 than those with >59% SiO_2. The highest content of orthopy-

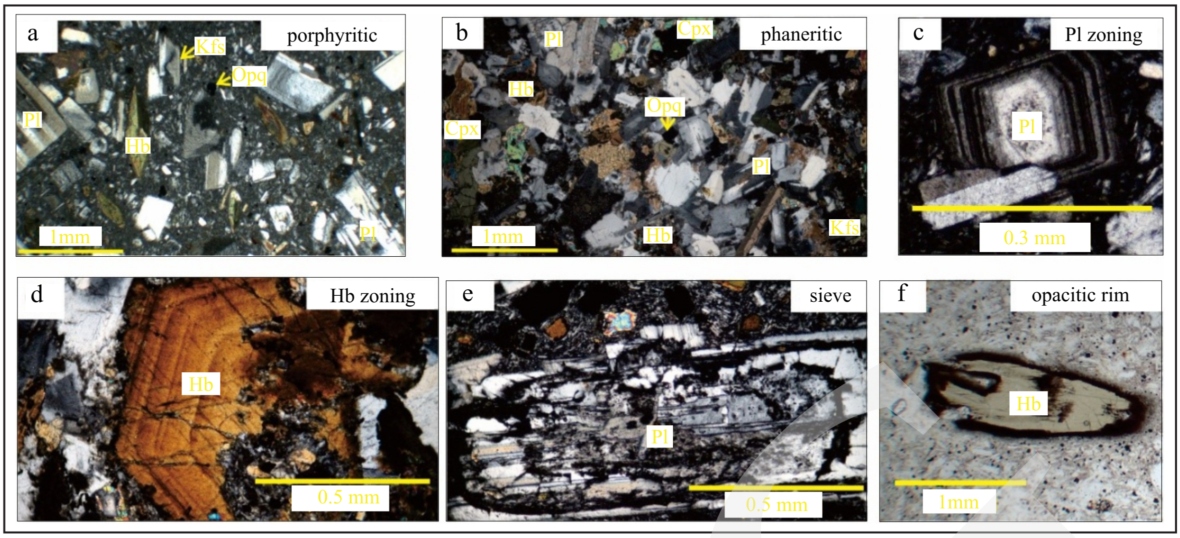

Figure 9. Igneous rock textures (a-b) and mineral textures (c-f) of Lasem and Senjong volcanic rocks. (a) porphyritic (hyalopilitic) in hornblende andesite; (b) phaneritic in microdiorite; (c) plagioclase zoning; (d) hornblende zoning; (e) sieve texture in plagioclase; and (f) opacitic rim in hornblende. Cpx = clinopyroxene; Gls= volcanic glass; Hb= hornblende; Kfs= K-feldspar; Opx= orthopyroxene; Opq = opaque minerals; Pl= plagioclase.

roxene and clinopyroxene is in the most basaltic lava (~53% SiO_2).

Lasem block and ash flow deposits have 59-62%SiO_2 content,fall withinthe range of SiO_2 content in Lasem lava. This similarity indicates that the block and ash flow deposits of Lasem generally originated from lava dome and lava flow collapse. Meanwhile, the most silicic product of Lasem contains ~65% SiO_2, generates ignimbrite deposits (PF 2).

Bivariate plot of major oxide and SiO_2 shows the decreasing concentration of FeO, CaO, MgO, TiO_2, and P_2O_5 as SiO_2 increases. On the other hand, $Al_2O_3$and Na_2O show a positive correlation with SiO_2 (Figure 5). LILE, HFSE, and LREE show a positive correlation with SiO_2, while MREE and HREE show a negative correlation (Figure 6). These patterns are typical element behavior that occurs due to fractional crystallization in the magma chamber.

The SiO_2 variation in chronological order is presented in Figure 10. The plot shows several fluctuating silica content patterns. This probably due to the repeated injection of basaltic magma into pre-existing differentiated magma. Gertisser and Keller (2003) proposed that the cyclic variation of SiO_2 over the past 2000 years activities of Merapi volcano may related to the injection of new batches of primitive magma into the more differentiated pre-existing magma in the magma chamber. The continuous and large supply of basaltic magma injection could prevent further magma differentiation process so that the pre-existing magma does not significantly change into a more evolved composition.

The possibility of basaltic magma injection is also confirmed by zoning texture in plagioclase and hornblende (Figure 9), indicating frequent magmatic composition changes within the magma chamber. Sieve texture in plagioclase also supports evidence of injection of hot basaltic magma. It indicates that plagioclase is dissolved into melt because of chemical inequilibrium as new magma supplies are injected into more evolved pre-existing magma (Winter, 2013).

A similar pattern in the spider diagram plots and REE diagram (Figure 7) suggests that Lasem and Senjong are related to the same deep magma source. It is also confirmed by Ba/Zr plot against SiO_2, in which both Lasem and Senjong rocks overlap each others and does not show particular trend through increasing silica number (Figure 8c). However, separated trends between Lasem and Senjong Volcano were spotted in the K/Rb and Rb/Nb *vs.* SiO_2 plots (Figure 8a and 8b). These distinct trends might related to distinct

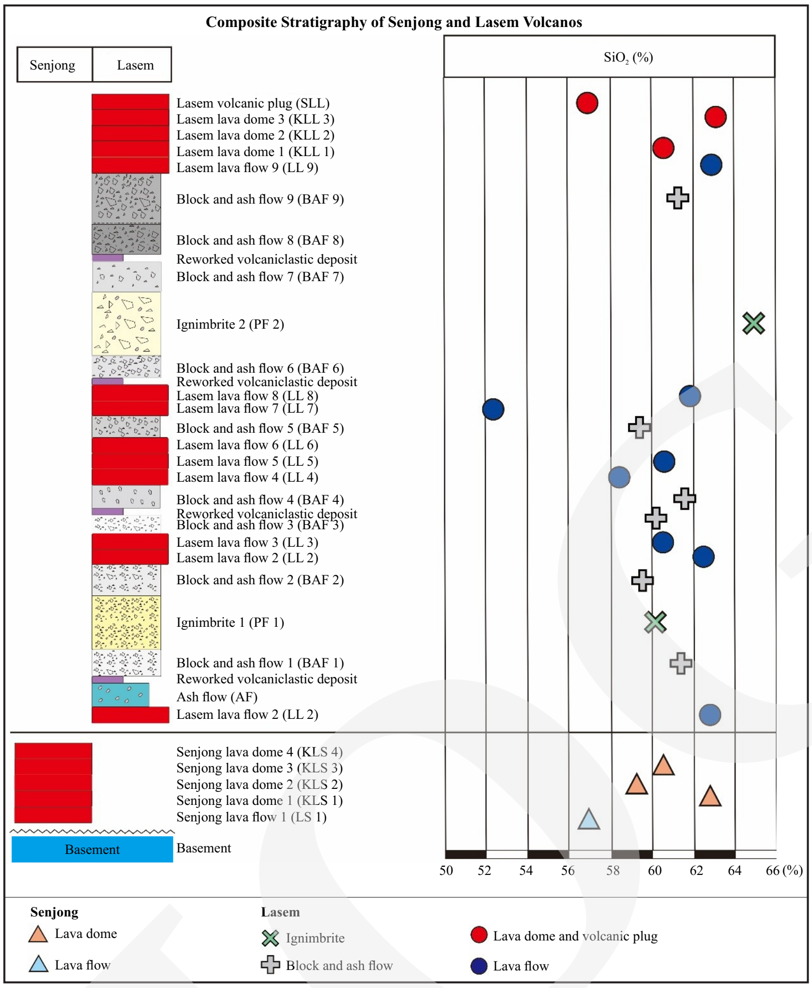

Figure 10. A combination of composite stratigraphy of LSVC products and the silica content shows that up and down variations of the silica content might correspond to new basaltic magma supply into the pre-existing differentiated magma in the magma chamber. Chronological order based on cross-cutting relationship is presented in the geologic map.

magmatic differentiation paths of the two magmas prior to eruption. The simplified conceptual model of Lasem and Senjong magma generation is presented in Figure 11.

The separation of K and Rb is strongly influenced by amphibole fractionation (Shaw, 1968). Amphibole has a wide range and variety of compositions. Butler *et al*. (1962) have reported differences in the K/Rb ratio that related to the crystallization of different types of amphibole in Northern Nigeria igneous rock. The difference in K and Rb ratio in Lasem and Senjong magmas may also be caused by variations inamphibole composition in these two magma types. Further discussion regarding the differences in amphibole composition in the two magmas of LSVC needs to be confirmed with mineral chemistry data.

Magma Evolution

As aforementioned above, within the lifespan of LSVC, High K/Rb type magma dominates Lasem magmatism while Low K/Rb type magma dominates magmatism in Senjong Volcano. The temporal evolution shows that Lasem and Senjong magma have a relatively narrow silica range (56-64%) accompanied by several fluctuations of silica contents (Figure 10). It can be inferred that silica fluctuations may be attributed to the fractional crystallization process combined by repeated injection of more basaltic primitive magma into the magma chamber as the dominant mechanism of magma differentiation in LSVC. It is worth noting that the highest silica content (~65%) might result in ignimbrite deposit, as shown by PF 2, which is the most explosive product of LSVC.

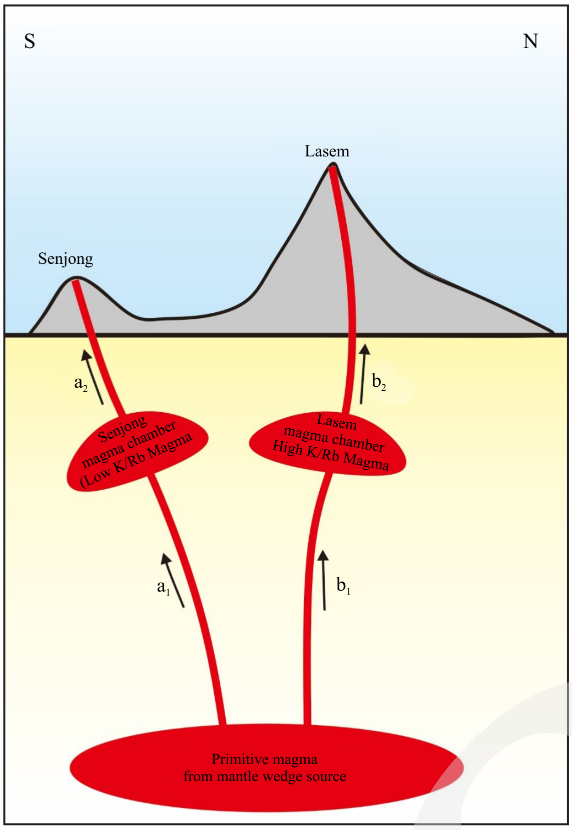

Figure 11. Conceptual model of magma generation beneath LSVC. The model shows that Senjong Low K/Rb magma and Lasem High K/Rb magma were originated from the same deep magma source, but went to the surface through distinct differentiation paths and separated magma chambers. Senjong Low K/Rb magma follows (a) path, while the latter Lasem High K/Rb magma follows (b) path.

Thin section observation confirms porphyritic, vitrophyric, trachytic, pilotaxitic, hyalopilitic, and glomeroporphyritic textures in the volcanic rock samples. The mineralogical compositions of Lasem and Senjong volcanic rocksinclude the phenocryst of plagioclase, K-feldspar, hornblende, clinopyroxene, orthopyroxene, and opaque minerals, withplagioclase microlites and volcanic glass as groundmass. Plagioclase shows zoning and sieve texture. Opacitic rim and zoning texture also present in hornblende.

Lasem and Senjong volcanic rocks varies from basaltic trachyandesite to trachyte. Geochemical data confirm two different magma types of Lasem and Senjong: Low K/Rb magma and High K/Rb magma. Low K/Rb magmarelated to the volcanism of Senjong, whileHigh K/Rb magma corresponds to Lasem volcanism. These two magmas are derived from the same magma source but likely undergone different processes in two separated magma chambers. The evolution of Lasem and Senjong magma is influenced by fractional crystallization and repeated injection of more basaltic magma, as evidenced by the frequent changes in SiO_2 content and plagioclase textures such as sieve and zoning.

Conclusion

Lasem pyroclastic density current deposits are mainly distributed on the eastern and northern flank of the volcano, with minor occurrences on the southern and western flank. These deposits reflect spatial and temporal changes. There are three types of PDC deposits in Lasem: (1) block and ash flow deposits (BAF 1-9), ignimbrite deposits (PF 1-2), and ash-flow deposits (AF).

Senjong lava units consist of 1 lava flow (LS 1) and four lava domes(KLS 1-4), while Lasem lavas are comprised of 9 lava flows (LL 1-9) andfour lava domes (KLL 1-3 and SLL). The outcrops of the lava flow in Lasem are concentrated in the southern part, extending up to 6 km from the volcanic center. Lasem and Senjong lavasare pyroxene andesite, hornblende andesite, and microdiorite.

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