JOURNAL OF GEOSCIENCES INSIGHTS
2023, VOL. 1, ISSUE 1, pp. 14-25
https://doi.org/10.61577/jgi.2023.100003

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ORIGINAL ARTICLE

OPEN ACCESS

Andesitic flow rheology of Mount Popa volcano, Myanmar

Kyi Khin[1], Nang Sandi Lwin[2], Aung Moe[3] and Chit Min Thu[4]
[1]Deep Tunnel Sewerage System-Phase 2, PUB, Singapore
[2]Department of Geology, Taunggyi University, Taunggyi, Myanmar
[3]Saarlandstr. 40, 67061 Ludwigshafen, Germany
[4]Yadanabon University, Mandalay, Myanmar

ABSTRACT

Mount Popa is a conspicuous dormant volcano, which lies on the volcanic island arc (NS-trending central volcanic line) through the Central Myanmar Basin tectonically. The rheology of lava flows is determined by the phenocryst distribution in the andesitic rocks of Mount Popa, Myanmar. Particularly, the andesitic rock units are differentiated as V1-flow andesite, Nagale-Legyingon plateau andesite, Popa plateau andesite, V3-flow andesite, and V4-flow andesite. The different flow units are megascopic ally very similar in color and texture to porphyritic andesite or augite andesite but different in grain size, and the amount of phenocryst. The phenocryst distribution is graphically correlated with the Newtonian and non-Newtonian flow to interpret the rheology of lava flow during the Pliocene-Holocene eruption of the Mount Popa volcano. A new method which is simplest and practiced to identify the porphyritic andesitic rocks or lava flows not only for the stratigraphy but also the rheology.

KEYWORDS

Mount Popa; Andesitic lava flow; Newtonian and non-Newtonian flow; Lava rheology

ARTICLE HISTORY

Received 7 August 2023; Revised 19 September 2023; Accepted 28 September 2023

Introduction

The Mount Popa area under the present investigation is situated in the Central Myanmar Basin and is underlain by various orderly succession of Cenozoic sedimentary strata and some igneous and metamorphic rocks which is possibly the older basement of Central Myanmar Basin [1,2]. It is noteworthy that the volcanics of the Mount Popa area are located on the central volcanic line which is tectonically known as the volcanic arc, passing through the Wuntho massif, Monywa volcanic, and Mount Popa areas from north to south. Throughout the Pliocene time, the fluvial sedimentation of the Irrawaddy Formation took place in the Central Myanmar Basin with intermittent volcanism occurring in the Mount Popa area and most of the pyroclastic rocks are interbedded with a fluvial deposit of the upper Irrawaddy Formation [3,4].

This study was initiated due to noticeable differences in the phenocryst distribution in the augite andesitic flows between the andesitic tephra. The statistical analysis of the phenocryst distribution indicated the absolute difference between these andesitic flows, and carried out the interpretation of the rheology of the lava flow, especially in augite minerals as phenocryst distribution with flow viscosity. Thus, the statistical study of the phenocryst distribution in the andesitic flows was interpreted as the rheology of lava flow by Newtonian and non-Newtonian flows which are usually used in dynamic recrystallization in magmatic petrology. This study was first introduced for the method to evaluate the rheology of the lava flow in different andesitic flows in the field investigation. However, differences in the distribution of mafic phenocrysts, especially augite crystals, have been identified in the different andesite flows. The study area, Mount Popa Volcano is a typical dormant volcano (latest eruption: 8000) [5], which rises majestically above the surrounding ground in the central part of Myanmar (Figures 1 and 2). The Mount Popa area lies on a belt named the Central Volcanic Line (Figure 1) documented as a calc-alkaline typed volcanic island arc at the Central Myanmar Basin in the West Myanmar Block along the Sunda Arc [3,6].

The volcanic area of Mount Popa was first studied by Chhibber [11], who described old volcanic rocks, as basement rocks that interbedded with the sediments of the Irrawaddy Formation and young volcanic rocks composed of andesitic, and pyroclastic flows forming a composite cone of the Mount Popa (1518 m above sea-level), (Figure 2). The old volcanic rocks are placed in the Upper Pliocene and young volcanic rocks are occupied during the Pleistocene to Holocene [3,5]. Young volcanic rocks mainly covered an area of 153 square km in the studied area (Figure 3), comprising a steep-sided, slope angle of about 25°-30°, forming composite cone-shape topography rising 1150 m above the surrounding plain (Figure 2). The composite cone, covering approximately 90 square km of moderately rugged terrain, consists of basaltic andesite and basalt flows, that form coarse porphyritic rocks and scoria (Figures 3) [3,4].

Most of the basaltic andesite shows a porphyritic texture with plagioclase, augite, and olivine as phenocrysts, however, is generally named augite-andesite [3]. Although there are various volcanic rock types, the augite-andesite rocks are quite similar in color, texture, composition, and nature of exposure.

*Correspondence: Kyi Khin, Senior Engineer, DTSS2 Department. PUB, Singapore BLK 402#05-16, Admiralty Link, Singapore 750402, e-mail: kyikyaw2@gmail.com

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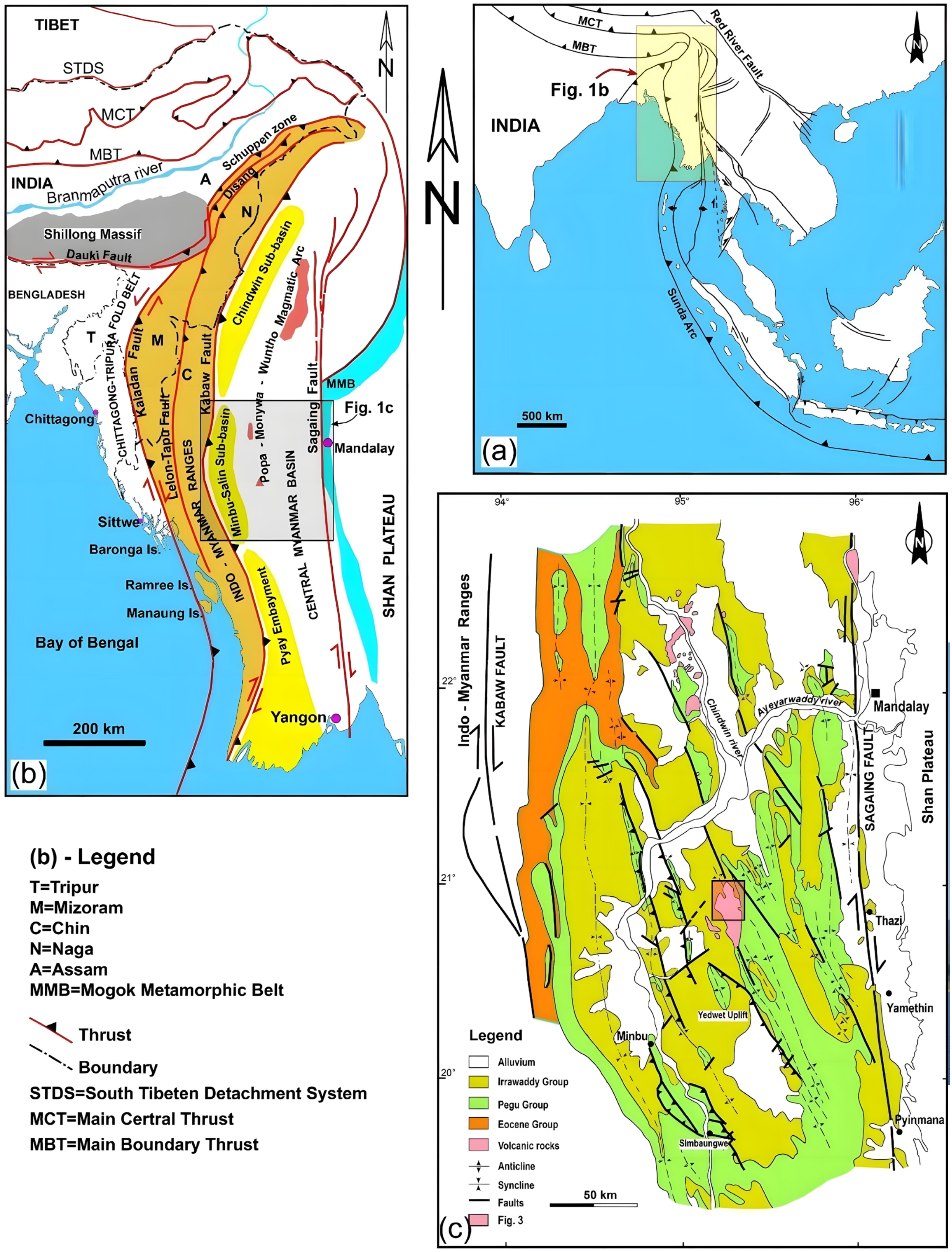

Figure 1. (a) Schematic map of Southeast Asia showing major tectonic boundaries [7]. The location of Figure 1b is marked. (b) Schematic map of West Myanmar, modified from Khin K et al., showing major tectonic units [8]. The location of Figure 1c is marked. (c) The structural map of the Central Myanmar Basin (modified after Bender, Pivnik et al., Kyi Khin et al.) showing the central volcanic line (Popa-Monywa-Wuntho Magmatic Arc) and Mount Popa volcano [7,9,10].

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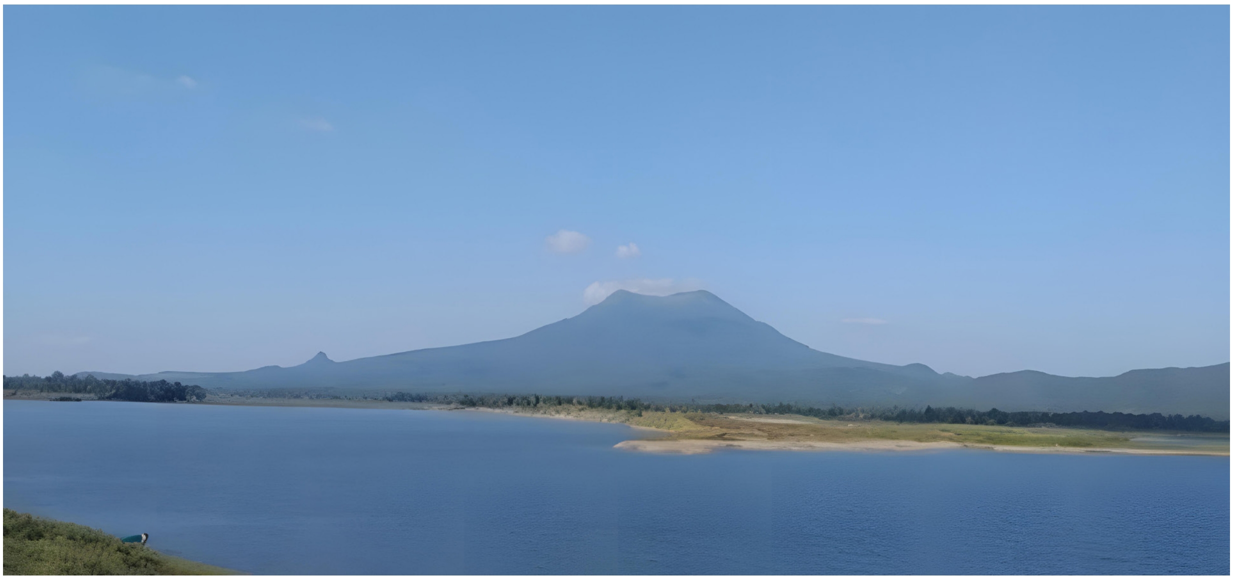

Figure 2. The composite cone of the Mount Popa volcano rises majestically above the surrounding ground (Looking North).

Regional Geology

Geomorphologically and tectonically, Myanmar has been divided into four main regions trending north-south, as described by Stamp [12], Chhibber [11], Tainsh [13], Maung Thein [14-17], and Win Swe [18]. These four regions are from west to east: (1) the Rakhine Coastal Region, (2) the Indo-Myanmar Ranges, (3) the Central Myanmar Basin, separated into forearc and backarc troughs by the central volcanic line, and (4) the Shan Plateau Highlands (Figure 1). The Rakhine Coastal Region as a foreland basin [19] is occupied at the front of the accretionary prism known as the Indo-Myanmar Ranges occupied the detached fold and thrust system developed primarily in Neogene sediments, extending northward to the Surma Basin, Bangladesh, situated at the southern base of Shillong Massif.

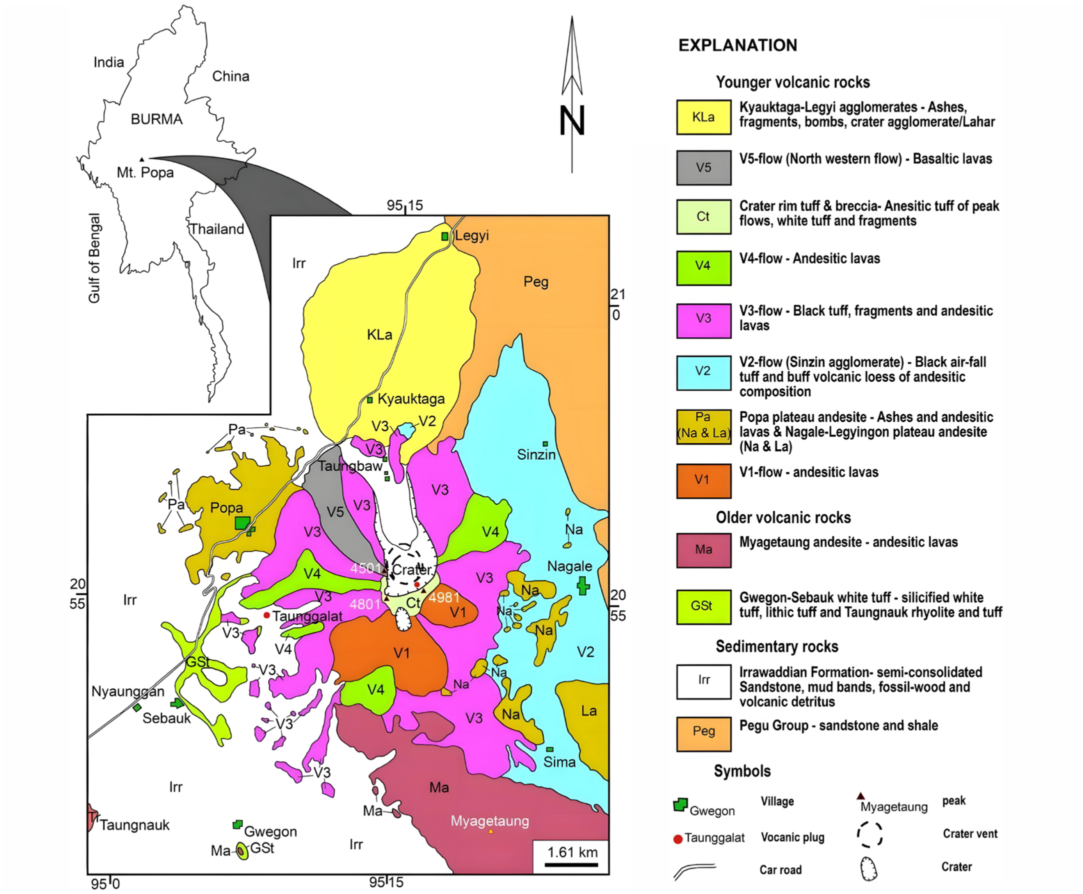

Figure 3. Geological map of the Mount Popa area, Kyaukpadaung Township, Myanmar [3].

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The Indo-Myanmar Ranges known as an accreted terrane, extend north-south for 1600 km, broaden northwards, and pass a maximum of 230 km from the Kabaw Valley in the east to the Kaladan Fault in the west [8,10,20]. Maurin and Rangin used the outer wedge (known as the foreland basin) for the detached fold and thrust system developed primarily in Neogene sediments, the inner wedge (known as an accretionary prism) for the folded and thrust region of predominantly Triassic to Oligocene section [19,21], and the core for the most eastern and tectonically complex zone. The thick Mesozoic-Cenozoic flysch deposits of the Indo-Myanmar Ranges are typically poorly fossiliferous, and difficult to differentiate, particularly in the accretionary prism [22-24]. The thick Mesozoic-Cenozoic flysch deposits of the IMR are typically sparse fossiliferous and difficult to distinguish, particularly in the accretionary prism [22-24] (Figure 1b).

In the Central Myanmar Basin, the forearc basin consists of the Chindwin sub-basin, the Minbu-Salin sub-basin, the Pyay embayment at the eastern base of the IMR, composed of molassic sediments, faulted contact with accretionary flysch sediments at the eastern base of the IMR. The backarc basin comprises the Bago Yoma-Sittoung sub-basin, Bhamo sub-basin, and Hukaung sub-basin, composed of molassic sediments, in contact with the Sagaing Fault from the Shan Plateau Highlands. Southwards-prograding deltaic sedimentation with syn-tectonic deep-marine slope to shallow marine sandstones is recorded in Neogene siliciclastic sequences in the westernmost part of the Rakhine Coastal Region [25,26]. Southward-progressing deltaic sedimentation with deep-sea syntectonic inclination to shallow marine sandstones is recorded in Neogene siliciclastic sequences in the westernmost part of the Rakhine Coastal Region [25,26] (Figure 1b,1c).

Shan Plateau Highlands including the Shan Scarps zone form a narrow north-south-trending zone, occupying the east of the Sagaing Fault, which can be further subdivided into Shan Scarp zone including the Paunglaung-Mawchi Zone, the Diamictite Belt, and the Mogok Metamorphic Belt, and Shan Plateau zone (including Plateau Landmark), (Figure 1b). The study area of Mount Popa lies in the Central Myanmar Basin, underlain by sequentially stacked Cenozoic sedimentary strata and some igneous and metamorphic rocks. The age of the first volcanism in the Mount Popa area could be Late or Post-Miocene [3] to the Holocene [5]. The Mount Popa area lies in the central volcanic line running north-south through the Wuntho Massif, Monywa-Shinmataung, Mount Popa, Tharawaddy, Twente-Natshingon, and active volcanoes of Burren, and Narcondam Islands to the south (Figure 3) [3].

Andesitic Flows

The Mount Popa volcanic area constitutes volcanic rocks, which can be stated from older to younger, such as Gwegon-Sebauk white tuff, Taungnauk rhyolite, silicified tuffs, Myagetaung late, and associated tuffs, interbedded black tuff and ash, V1-flow andesite, Popa plateau andesite, and Nagale-Legyingon plateau andesite, V2-flow agglomerate, V3-flow andesite, V4-flow andesite, V5-flow basalt, and Kyauktaga-Legyi agglomerate (Northern debris flow) (Figure 3). Five flows of andesite (Figure 3) have been described in ascending order in age, such as V1-flow andesite, Popa plateau andesite, Nagale-Legyingon plateau andesite, V3-flow andesite, and V4-flow andesite. These andesitic rocks are identical in grey color and porphyritic texture and are composed of augite phenocrysts in the groundmass.

The andesitic rock units of V1-flow andesite, Nagale-Legyingon plateau andesite, Popa plateau andesite, V3-flow andesite, and V4-flow andesite are very similar in color and texture but different in size and quantity of phenocrysts. Megascopically, these units are generally light grey in color with a porphyritic texture, consisting of black large phenocrysts of pyroxene and whitish patches of feldspar laths. Microscopically, these units comprise the phenocrysts of fresh augite and plagioclase, embedded in a microcrystalline groundmass of feldspar laths and granules of augite, olivine, and magnetite in a glass groundmass (Figure 4). Possibly, for this reason, the research works of Stephenson and Marshall and Belousov et al. did not mention the andesitic rocks of different flows in their map view on the cone with explanations [27,28].

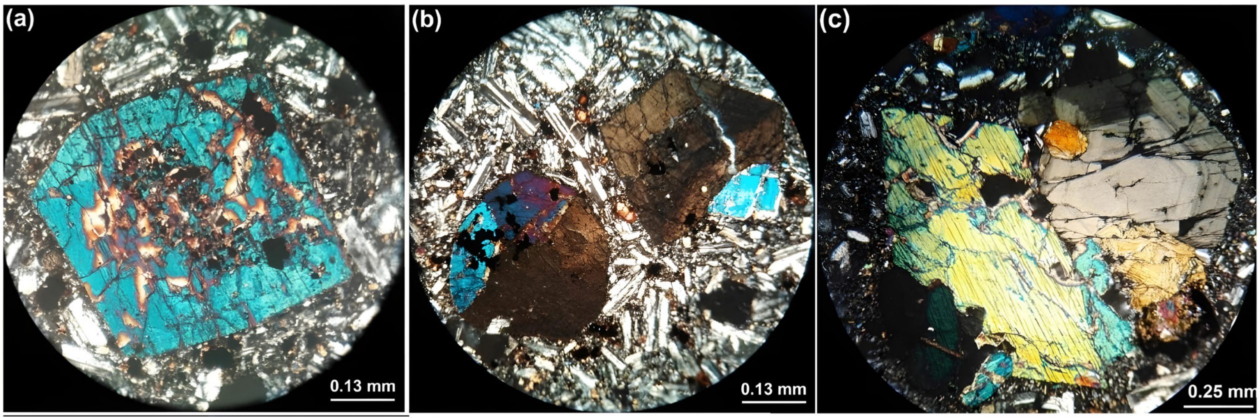

Figure 4. Photomicrographs under XPL (cross polarised light), (a, b). showing six-sided augite phenocrysts, and (c). showing six-sided augite and plagioclase phenocrysts in a microcrystalline groundmass of feldspar laths and granules of augite, olivine, and magnetite in a glass base.

Method of Study

In this study, the rock units of andesite are generally called augite andesite, but the geological was mapped by aerial photogeology. Additionally, the microscopic study also confirmed that augite phenocryst in the groundmass, thus, the method is sufficient for the geological map of the volcanic area. Likewise, the study is not only statistical analysis in petrographic analysis but also correlates with the rheology of

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the lava flow, because, the augite phenocrysts are the main mafic constituents for the andesitic lava flow of the study area.

Determination of the number of mafic phenocrysts especially augite crystals using a pocket hand lens (25X), a divider, and a ruler at each outcrop is done within a unit area per outcrop, i.e., 1 inch x 1 inch. A unit area is first demarcated on the surface of a rock sample or an outcrop (Figure 5), which is at least three reliable unit areas per outcrop. Secondly, the number of distributed phenocrysts is counted manually in the unit area. And then, the sizes of each counted phenocryst are accurately measured with a divider and ruler. The mafic crystals of the groundmass are neglected in counting, because of unmeasurable (only black spots). The augite crystal phenocrysts are almost round in shape which means length and width are generally the same.

Before selecting the unit area, the sample should be represented by the andesitic flow as same as geological sampling for thin section, geochemical analysis, and dating analysis. In the statistical analysis, the manual measurement has human error as a constant factor in every measurement. Although flow structures are very common under the microscope, however, this method is only for the megascopic study and is not affected in the microscopic study with these phenocrysts (Figure 4).

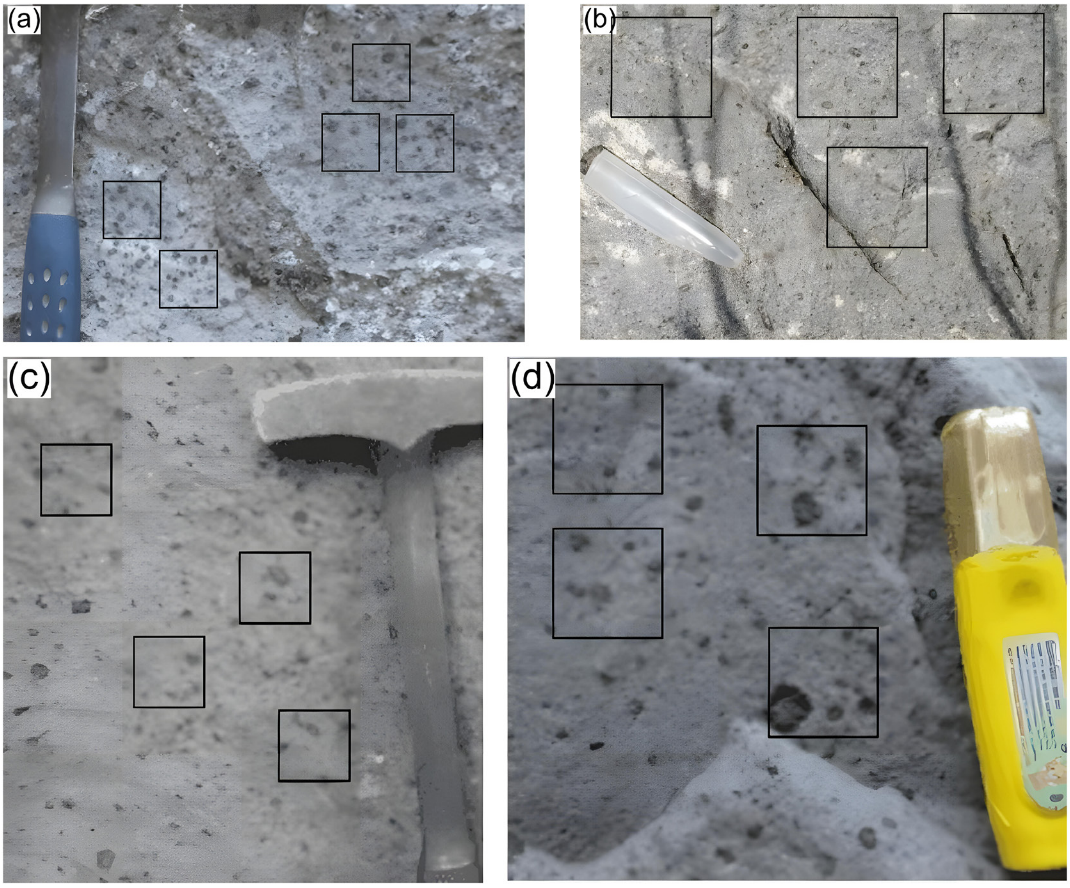

Figure 5. Photographs showing the demarcated one-unit area (1 inch x 1 inch) to be counted on the surface of different andesitic flow samples. (a). Popa plateau andesite, (b). Nagale-Legyingon plateau andesite, (c), V1 flow andesite, (d). V4 flow andesite.

The numbers of mafic phenocrysts especially augite crystals in the unit area of different rock types are listed in Table 1. The size of the phenocryst ranges, from 0mm (<0.5mm) to 11mm, and the total amount of phenocrysts per unit area is easily seen in Table 1. In order to express the number of phenocrysts attempted at least 10 samples of the same rock type were taken from different localities.

The total numbers of each grain-size variation in the same rock samples were collected and the grain size percentages throughout the data. The data from each rock unit was statistically processed to determine the distribution of phenocrysts in a unit area.

Calculation of each rock unit is done by the following formula for the mean value:

$$Xm = \frac{1}{n} \sum_{i=1}^{i=n} Xi \qquad (1)$$

Xm = arithmetical mean value
n = number of phenocrysts
Xi = individual value
for the Standard deviation of the average value:

$$\sigma = \sqrt{\frac{\sum (Xi - Xm)^2}{n-1}} \qquad (2)$$

Then, based on the data of total measurement, the histograms in size frequency % versus the size of phenocryst (mm) were drawn to show the differences in various andesitic rock types. Their differences are revealed by histograms in Figure 6, arithmetical differences in Figure 7, and statistical differences in Table 1.

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Table 1. Measurement of mafic phenocryst in andesitic rock type of Mount Popa.

Size (mm)	Countable No.	Percentage	Size (mm)	$(Xi-X_m)^2$
10-11	3	1.6	31.5	196.5
9 -10	-	-	-	-
8 -9	-	-	-	-
7 -8	5	2.6	36.5	120.4
6 -7	5	2.6	30	64.8
5 -6	5	2.6	26	39.5
4 -5	10	5.3	40.5	27.5
3 -4	24	12.7	78	18.8
2 -3	48	25.4	108	4.1
1 -2	82	43.4	97.5	125.1
0-1	7	3.7	3.5	25.3
Total	189	99.9	451.5	622
V1- flow andesite (10 samples)				
Size (mm)	Countable No.	Percentage	size (mm)	$(xi-x_m)^2$
8 -9	1	0.3	8.5	49
7 -8	-	-	-	-
6 -7	1	0.3	6.5	25
5 -6	2	0.6	11	32
4 -5	6	1.7	25	43
3 -4	37	10.2	120	100.5
2 -3	68	18.7	147	45
1 -2	119	32.8	150.8	15.9
0-1	129	35.5	60	141.6
Total	363	100.1	528.8	452
Nagale-Legingon plateau andesite (10 samples)				
Size (mm)	Countable No.	Percentage	size (mm)	$(xi-x_m)^2$
5 -6	1	0.2	5.5	16.8
4 -5	4	0.9	16	27
3 -4	46	10.6	145	143.7
2 -3	68	15.7	151	51.8
1 -2	157	36.2	193.8	13.7
0-1	157	36.2	78.5	134
Total	426	99.9	581.6	387
Popa plateau andesite (10 samples)				
Size (mm)	Countable No.	Percentage	size (mm)	$(xi-x_m)^2$
6 -7	2	0.2	13	61.4
5 -6	-	-	-	-
4 -5	2	0.2	9	24.8
3 -4	18	1.9	55.5	80.3
2 -3	74	7.8	158.5	104.4
1 -2	397	41.8	476.8	41
0-1	457	48.1	216.8	125.1
Total	950	100	929.6	437
V3-flow andesite (10 samples)				
Size (mm)	Countable No.	Percentage	size (mm)	$(xi-x_m)^2$
6 -7	1	0.3	7	28.1
5 -6	22	6.4	114	268
4 -5	9	2.6	36	47.6
3 -4	14	4.1	45	33
2 -3	82	23.9	184.5	29.9
1 -2	133	38.8	163	38.2
0-1	82	23.9	38.5	124.7
Total	343	100	588	569.5
V4-flow andesite (10 samples)				

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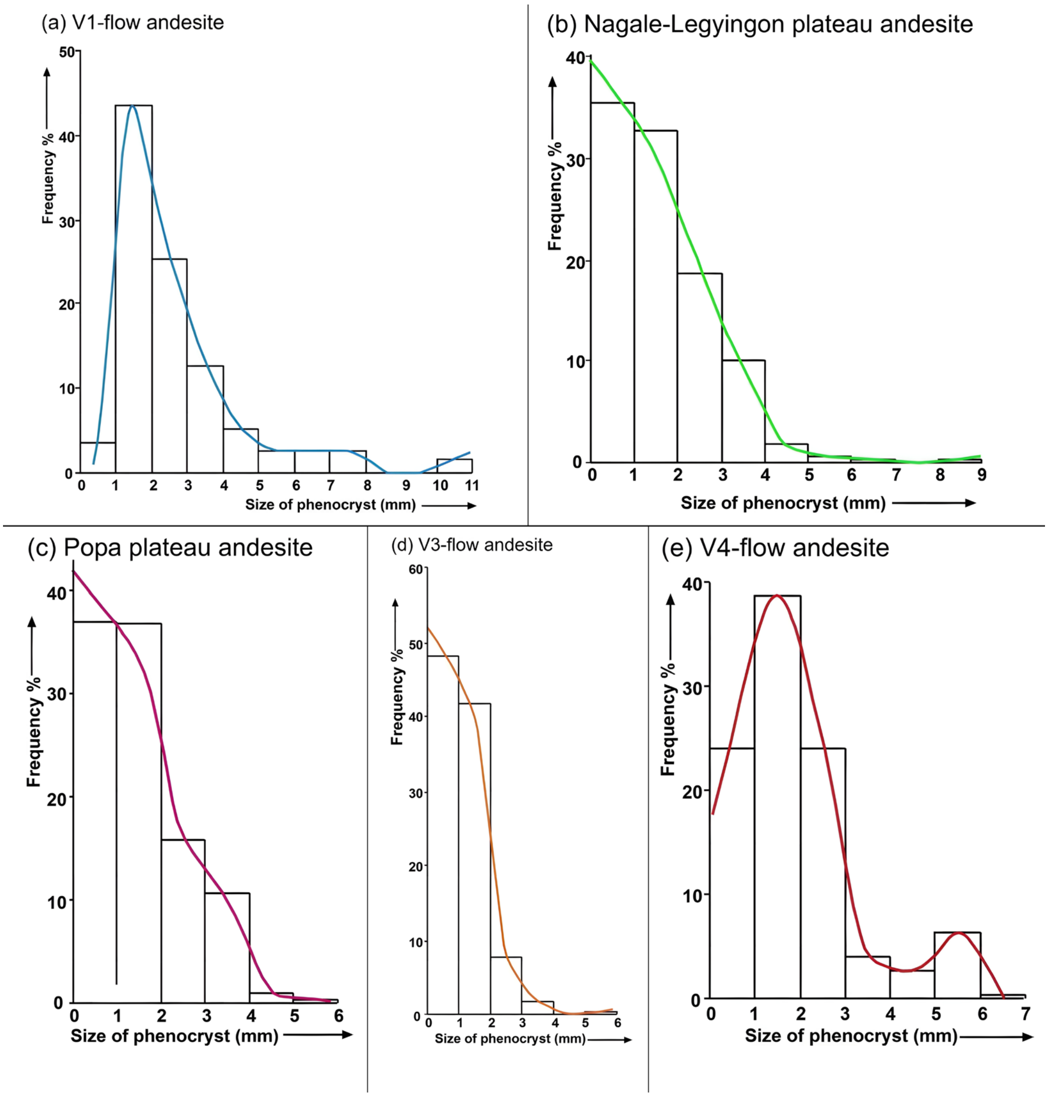

Figure 6. Mafic phenocryst distribution histogram of different andesitic flows in Mount Popa area.

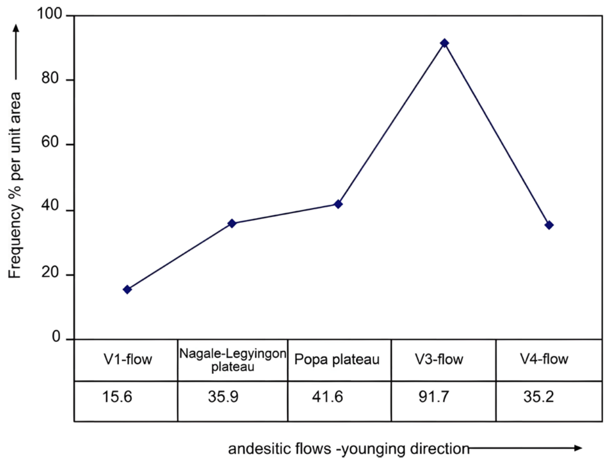

Figure 7. Mafic phenocryst frequency percentage (%) per unit area versus different andesitic flows in the younging direction.

Results

Clustering is known as non-Newtonian flow (Viscous) and non-Clustering is known as Newtonian flow (less Viscous) indicates the phenocryst concentration only on the magma suspension which was strongly pseudoplastic non-Newtonian in behavior. In general, more crystal concentration indicates higher viscosity and more crystals can make the suspension non-newtonian, all other things being equal [29].

A numeric model of lava flow emplacement is proposed as rheological properties (viscosity, yield strength) of lava using the size versus frequency in the Newtonian and non-Newtonian arithmetical models. Measurement of mafic phenocryst in andesitic rocks of Mount Popa is shown in Table 1 which displayed frequency percentage per unit area versus rock types and indicated arithmetically differences in the amounts of mafic phenocrysts in different andesitic rocks or flows in the study area.

The data were statistically calculated, using (Xm) as the mean, (σ) as the standard deviation, and the size range of mafic phenocrysts. The mean values of phenocryst sizes are different between andesitic rocks (Table 1). The oldest V1-flow andesite has the greatest range of size in 0.6-4.28 mm across and shows the highest value (1.84) in the standard deviation (Table 2).

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Table 2. Statistical differences of mafic phenocrysts in different andesitic lava flows.

Name of andesitic flow	Nos. of samples determined	Ranges of size (mm)	Av. nos. of phenocryst per unit area	Mean of size (mm)	Standard deviation
V1-Flow	10	0_11	18.9	2.44	1.84
Nagale-Legyingon	10	0_9	36.3	1.46	1.1
Popa plateau	10	0_6	42.6	1.37	0.55
V3-flow	10	0_7	95	0.98	0.98
V4-flow	10	0_7	34	1.71	1.29

The histograms of various andesitic rocks were plotted by size-frequency percentage versus the size of phenocryst (mm). The histograms for V1-flow andesite and V4-flow andesite reveal that the mafic phenocrysts are distributed in log-normal distribution with negative skewness, (Figure 6a,6e), and the histograms for Popa plateau andesite, Nagale-Legyingon plateau andesite, and V3-flow andesite distinguish in negative exponential function (Figure 6b-6d).

Statistical characteristics of mafic phenocrysts in andesitic flows are shown in Table 2, in which the V1-flow and V4-flow manifest themselves as non-Newtonian rheology in a clustering group (Figure 8a) whereas the V3-flow is characterized as Newtonian rheology in an anti-clustering group (Figure 8b). The Popa plateau andesite and Nagale-Legyingon plateau andesite are almost in an anti-clustering group as Newtonian fluid and then a plateau flood andesite. Model analysis shows the volume percentage of phenocryst including plagioclase, olivine augite, and groundmass (Table 3).

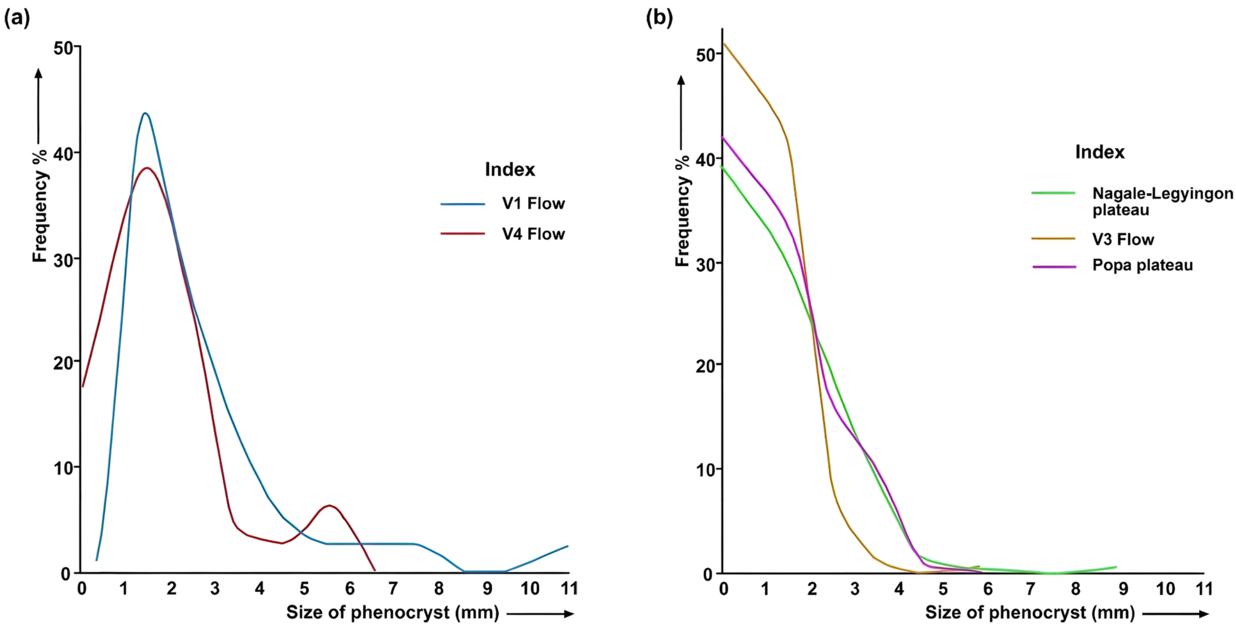

Figure 8. Comparison of the phenocryst distribution in different andesitic flows of Mont Popa. (a) andesitic flows on the Popa volcanic cone showing clustering (non-Newtonian), (b) flood andesitic flows anti-clustering (Newtonian), but V3 flows on the Popa volcanic cone.

Table 3. Model composition (volume percent) of the andesitic rock types.

	V1-flow	Nagale-Legyingon	Popa plateau	V3-flow	V3-flow	V4-flow
Phenocryst	46	30	25	41	37	25
Plagioclase	28	17	5	12	11	8
Augite	10	11	15	24	24	16
Olivine	8	2	5	5	2	1
Groundmass	54	70	75	59	63	75

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The present method is applied to differentiate different clusters, and it is very simple. Newtonian and non-Newtonian behaviors of anti-clustering and clustering directly showed a common concept that is practical to apply, although it is not an empirical estimated value.

Lava Rheology

The calculation of viscosity during crystallization combines thermodynamic modeling and empirical rheological models [29]. The terms Newtonian rheology or Newtonian fluid and non-Newtonian rheology or non-Newtonian fluid were originally used by Sparks et al., who studied the transport of xenoliths in magmas [30]. They indicated that slower-moving magmas might contain consequently the higher phenocryst content and exhibit yield strength. When the particle concentration (crystal fraction on the crystal shape and size distribution) is low, the physical behavior of magma is controlled by the viscosity of the melt phase which is Newtonian [31]. If the crystal fraction becomes too high, the viscosity is no longer controlled by the melt phase that is non-Newtonian [31,32]. The rheology of the erupted lava considering the observed crystallization sequence, through melts based on chemical composition, crystal content, and shape, showing the viscosity to depend strongly on the crystallization sequence [29].

Pinkerton and Sparks indicated magma rheology, which is required to understand many magmatic and volcanic processes, i.e., magma behaves as Newtonian fluid in the supra liquidus temperatures and non-Newtonian fluid in the sub-liquidus temperatures [33].

Lava rheology has been measured using various techniques, e.g., shear stress versus shear rate, and shear stress versus strain rate which explain the viscosity with increasing strain rate [34-37] however, the viscosity of igneous melts has been empirically estimated value from their chemical composition and temperature conditions [38,39].

Magma behaves not only as Newtonian fluids (common igneous melt) but also as non-Newtonian fluids (some magmas). An aphyric magma may have appeared in a Newtonian behavior before the eruption, then changed to a non-Newtonian style that develops a yield strength as quench crystallization takes place [37].

In Figure 9 size versus frequency, size (log) versus cumulative no. (log) and linear versus logs are indicated by the anti-clustering (Newtonian) and clustering (non-Newtonian) in which the flow law is usually used in dynamic, recrystallization, which is accommodated by diffusion creep (plastic flow) and dislocation creep (superplastic flow) or a combined process. The size distribution is statistically defined as log-normal and negative exponential, which are related to the flow law.

The size distribution shows a negative exponential distribution as anti-clustering, Newtonian flow, or non-viscous body moving by simple shear is measured for the ductility in diffusional creep. The exponential distribution is a very skewed continuous distribution. Its rise is vertical at zero, on the left, and it descends gradually, with a long tail on the right. The non-viscous flow moves with respect to the (plastic) steady-state Newtonian flow. In this case, the mean grain size remains constant, leading to slower or steady-state strain rates during the flow (Figure 9).

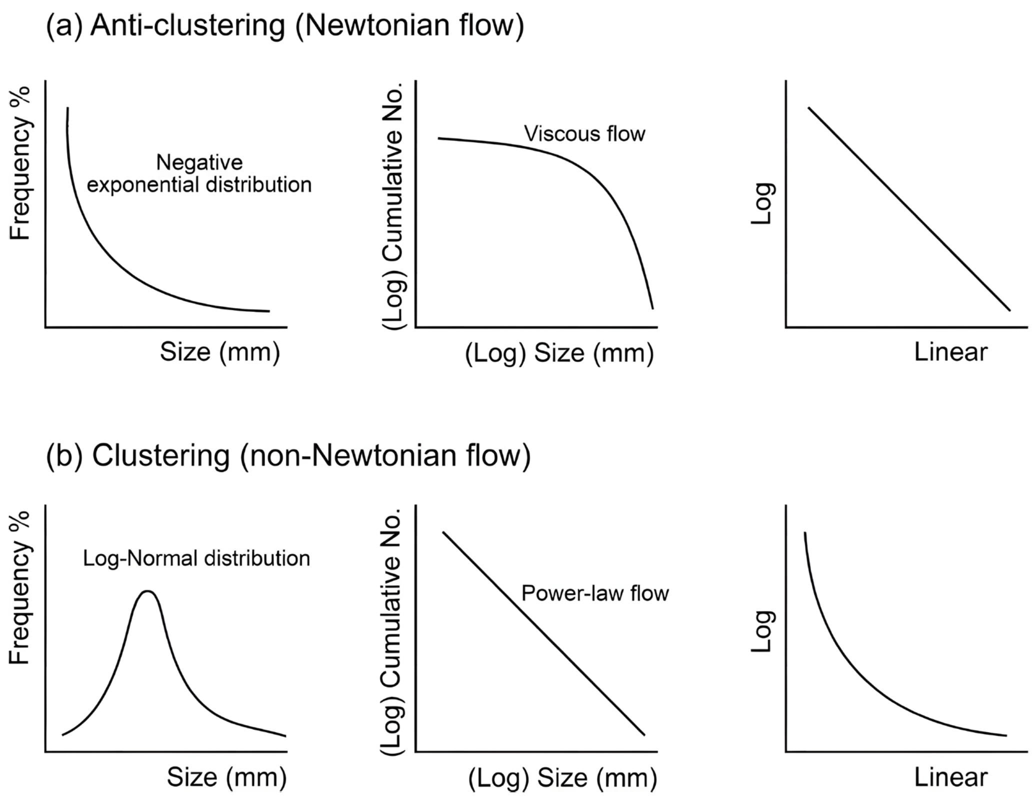

Figure 9. Diagrams showing characteristics of basic statistical flow law, (a) Anti-clustering (Newtonian flow), (b) Clustering (non-Newtonian flow).

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The size distribution shows both log-normal distributions as clustering as non-Newtonian flow or viscous body moving by pure shear, which is measured for the super-plasticity in dislocation creep. Power-law flow moves with respect to the super-plastic non-Newtonian flow. In this case, the grain size is variable during the flow, leading to faster strain rates during the flow (Figure 9).

Discussion and Conclusion

Magma, the compound liquids consist of solid particles suspended in a fluid, and solid-fluid mixtures in bulk are known to behave like non-Newtonian fluids [40]. Logically, solid particles can interact with fluid and thereby create particle dispersion in a flow by gravity. So, phenocryst distribution in a magma flow is affected by gravity force on a single particle and buoyancy with a viscosity of magma.

Likewise, Komar has been given the net force [40], Fg as,

$$F_g = \pi/6\ (\rho s\text{-}\rho)\ g\ D3 \qquad (3)$$

(ρs-ρ)=density difference between the solid phenocrysts and the surrounding fluid magma, D=spherical grains of diameter, g=gravity

Generally, the density of the solid particle is greater than that of the fluid so that the net force acts directly downward. If the gravity force is excluded, e.g., $\rho s = \rho$, net force (Fg) becomes zero.

Komar indicated the equation of fluid flow in the dyke or sill, using an empirical relation for the apparent viscosity of the phenocryst suspension, and noticed the phenocryst-poor margins to a phenocryst-rich center [40]. However, the present study observed the interaction of phenocryst concentration and lava flow viscosity by clustering and non-clustering. Komar also observed the profiles of phenocryst concentration only on the magma suspension were strongly pseudoplastic non-Newtonian in behavior [41].

The method of the present study is very practical and convenient during the fieldwork for the very similar features of porphyritic andesite in the Mount Popa area. The measurement for the size versus frequency is a very simple method and easy to collect in the fieldwork too.

The rheology of the lava flow is generally interpreted as the porphyritic andesites of the Popa volcanic area. The reliability of the method of the present study found that the viscous lava flows do not spread far on the cone, stating the nature of flows as flow andesite (V1-flow andesite, V3-flow andesite, V4-flow andesite), and flood andesite (Popa plateau andesite, Nagale-Legyingon plateau andesite) in the Mount Popa area (Figure 10). Thus, andesitic flows are observed as a non-Newtonian (viscous) flow and flood andesites are indicated as Newtonian (less viscous) flow (Figure 9).

And also, the erupted lava is considerably viscous because the lava flows do not spread far, and form shapeless boulders as they cool in the Mont Popa area [3]. Additionally, the features of the cone shape with composite volcano type formed a very steep slope of the cone near the top, and the explosive nature of the eruption resulted in lava and pyroclastics.

Stephenson and Marshall discussed that the Mount Popa on the cone consisting of almost entirely undifferentiated basaltic andesite and basalt possibly exploited earlier formed weaknesses and rose to the surface faster and allowed no time for fractionation [27]. Therefore, the later period of the young

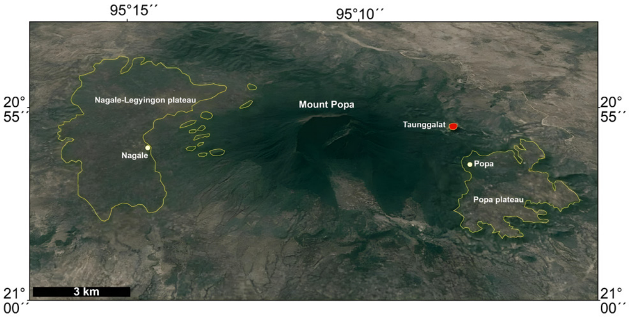

Figure 10. Satellite image showing Mount Popa volcanic cone and Plateaux of Popa plateau and Nagale-Legyingon plateau, (Looking South).

volcanic activity is occupied by basic igneous composition, comprising the high-hydrous compounds, e.g., hornblende, augite, olivine, and so on, the building of composite cone with a very gentle slope of about 25°-30°.

On the other hand, phenocryst interaction with lava flow is interpreted as sub-viscous to aqueous due to the negative exponential distribution to log-normal distribution (Figure 9a). Additionally, calc-alkaline basalts are generally considered to have high water contents [42,43] compared to other common basalt types. In contrast, low-viscosity magmas flow faster, forming lava flows that cover thousands of square kilometers. The low-viscosity magmas allow gases to escape easily, but high-viscosity magmas can build up gas pressure, leading to violent eruptions [44]. Viscosity and slope can also influence flow length, with lower viscosities and steeper slopes promoting longer but thinner flows.

Phenocryst distribution and rheology of lava flow are strongly related, with the non-Newtonian flow behaving as the apparent viscosity of pseudoplastic materials like a fast-moving lava flow appears to be more fluid, whereas the Newtonian flow acts as a lower apparent viscosity of ductile materials, a fast-moving lava flow seem to be less fluid. High-viscosity lavas flow slowly and typically cover small areas. If reducing heat fluxes, and hence core cooling rates increased insulation which allowed even high-viscosity lava flows to extend farther than might be expected based on their rheology [44].

Although the V3-flow andesite lies on top of the cone, it shows exceptional (Clustering) non-Newtonian flow behavior. The regular and repeated flow of highly viscous lava from volcanoes can slowly build up and spread over many square kilometers and solidify to form plateaux (Figure 10). Composite volcanoes have explosive eruptions with the following characteristics of andesitic magma, which is lower in temperature, and contains more silica and a lot of dissolved gases when it reaches the surface.

The central volcanic line including Mount Popa has documented a calc-alkaline volcanic island arc in the West Myanmar Block along the Sunda arc [6,3], in which, calc-alkaline basalt has higher water contents [42,43]. The Mount Popa volcanic area consists of the old volcanic consisting of rhyolite, rhyodacite, and trachyandesite (latite), and the young volcanic consisting of basaltic andesite and basalt, in the usual concept of magma chamber development in vertical differentiation. However, in the Mount Popa area, lack of time for fractionation indicated the age of the reverse rock

https://doi.org/10.61577/jgi.2023.100003

sequence indicated rhyolite (oldest) to basalt (youngest) according to Moe and Stephenson & Marshall [3,27]. Likewise, flood andesites (Popa plateau andesite, Nagale-Legyingon plateau andesite) are not only older than the flow andesite on the cone but also have more viscosity. The flood plateau andesite applied high clustering of phenocryst in the viscous flow as a non-Newtonian fluid, whereas flow andesite indicated anti-clustering phenocryst in less viscous flow as Newtonian fluids.

In conclusion, the present study aims to introduce a new method that is simplest, practical, and reliable to identify not only stratigraphy or geological mapping of the lava flow in volcanic terranes but also the rheology of the lava flow.

Acknowledgment

The authors are deeply indebted to the reviewers and an anonymous reviewer for their constructive and valuable comments and suggestions, which have substantially improved the manuscript. The authors are greatly indebted to Dr. Win Naing, former Lecturer, Geology Department, University of Yangon for his guidance.

Disclosure statement

No potential conflict of interest was reported by the authors.

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