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RESEARCH ARTICLE

Typology of Indonesian Stratovolcanoes: Insights from Geomorphological and Geological Aspects

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Abstract. Stratovolcano is the most dominant volcano type in Indonesia; however, our understanding of the correlation between geomorphological and geological aspects on stratovolcano is still lacking. To reduce such a gap, we provide the first general typology of Indonesian stratovolcano (number of analyses=154). Several parameters were evaluated, including average radius ($\overline{r}$), average slope ($\overline{S}$), surface roughness (RMS), bulk-rock compositions, mineralogy, and deposit characteristics. Four types were identified: (1) small-least dissected cones, (2) broad-dissected cones, (3) extremely broad-dissected cones with caldera, and (4) residual-highly dissected cones. Type I is typically small ($\overline{r}$=2.1 km), steep ($\overline{S}$=19.80^{O}), rough (RMS=88.8), dominated by basic to intermediate rocks, having abundant mafic minerals with minor hydrous minerals, and primarily consisting of lava flows and scoria. Type II has moderate values of $\overline{r}$, $\overline{S}$, and RMS(8.8 km, 15.2^{O}, and 47.7, respectively), predominantly intermediate in composition, poor in mafic minerals and rich in hydrous minerals, and having abundant pumice and lava domes. Type III is typically large ($\overline{r}$=18.1 km), gently-sloped ($\overline{S}$=9.2^{O}), smooth (RMS=40.1), rich in felsic rocks and felsic minerals, and includes thick ignimbrite deposits. Type IV has moderate size ($\overline{r}$=8.2 km), is gently-sloped ($\overline{S}$=10.7^{O}), rough (RMS=56.8), and rich in ultrabasic rocks and mafic minerals with common exposure of intrusions. We conclude that the evolution from type I to III corresponds to the maturation stage, whereas the formation of type IV represents the erosional stage. Moreover, rainfall precipitation degree (Pr) also controls stratovolcano morphology, where higher Pr decreases $\overline{S}$ and RMS values, and increase $\overline{r}$ value.

1. Introduction

Indonesia lies in an active subduction zone between Eurasia, Indo-Australia, and Pacific plates, with an approximated subduction speed of (at most) 7-9 cm/year (Brehme et al. 2014; Marliyani et al. 2019). This active subduction is therefore responsible for the formation of volcanic arcs, ranging from the western to the eastern side of Indonesia (Fig. 1). Volcanism in the western side (i.e., Sumatra) is relatively older than that of the eastern side (Katili 1975). Because magmatic differentiation is a time-dependent process (McBirney 2007), western volcanism generally produces felsic rocks (abundant rhyolite with minor basalt) (Leo et al. 1980; Rock et al. 1982; Fiantis et al. 2011; Dahren et al. 2012; Forni et al. 2019; Rohiman et al. 2019; de Maissoneuve and Bergal-Kulvikas 2020; Nurfiani et al. 2021; Suhendro et al. 2022), whereas the middle (Java to Sumbawa) and eastern volcanisms (Flores, Banda, Sulawesi, and Halmahera) are characterized by intermediate (mostly andesite with rare dacite) and basic rocks (mostly basaltic andesite with abundant basalt), respectively (i.e., Whitford et al. 1977; Jezek and Hutchison 1978; Leo et al. 1980; Varne 1985; Wheller et al. 1986; Leterrrier et al. 1990; Tatsunmi et al. 1990; Hartono 1994; Harahap and Abidin 2006; Setidjadji et al. 2006; Handley et al. 2007; Sendjadja et al. 2009; Gertisser et al. 2012a, b; Jeffery et al. 2013; Beleusov et al. 2015; Fontjin et al. 2015; Harijoko et al. 2017; Bani et al. 2017, 2020, 2021; Deegan et al. 2021; Faral et al. 2021; Suhendro et al. 2021; Harijoko et al. 2021).

Almost all volcanoes in Indonesia are classified (at least qualitatively) as stratovolcanoes (Verstappen 1994). Some of them have experienced catastrophic phase, i.e., caldera-forming eruption (e.g., Toba, Rinjani, Tambora, Maninjau; Chesner and Rose 1992, Vidal et al. 2015, Suhendro et al. 2021, Suhendro et al. 2022). Noteworthy, most of these stratovolcanoes are located adjacent to urban living, making the vulnerability of volcanic eruptions becomes high (de Maissoneuve and Bergal-Kulvikas 2020). By evaluating their geomorphological (i.e., size, slope, roughness, shape) and geological aspects (i.e., magma compositions, petrology, mineralogy, deposit characteristics, eruption style), we attempt to provide the first general typology of Indonesian stratovolcano, in which can be used as a basic knowledge for better risk assessment and hazard mitigation.

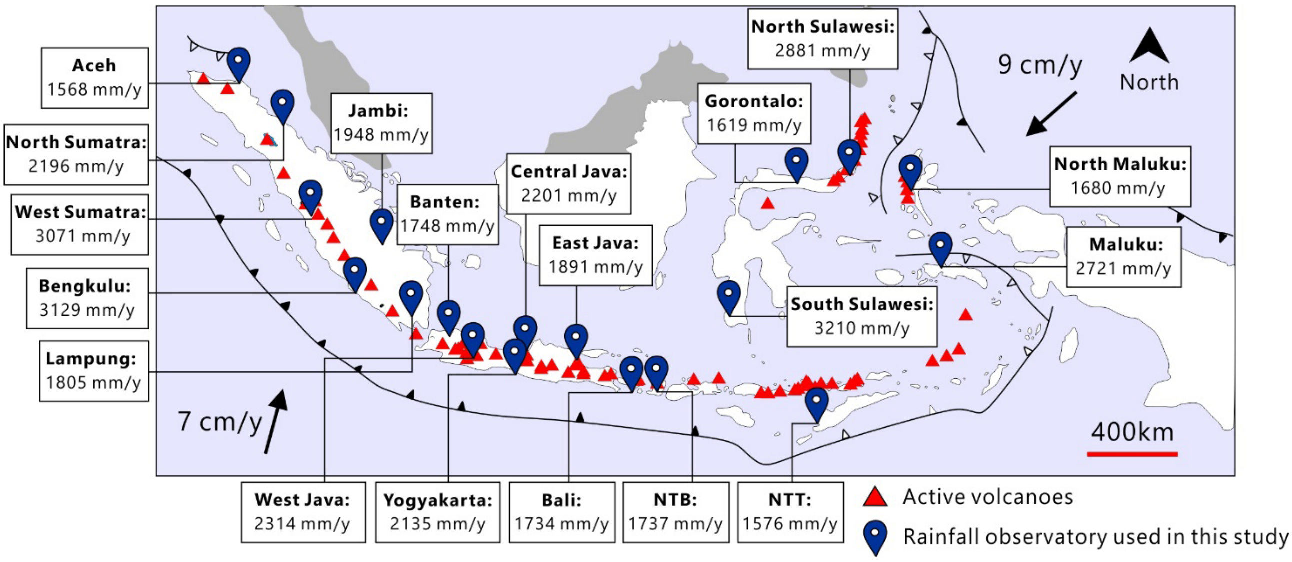

Figure 1. A map showing the regional tectonic settings and distribution of active volcanoes (shown by red triangles) and some rainfall precipitation observatories (shown by blue pin) in Indonesia. The reported rainfall data corresponds to the average precipitation rate per five years (from 2011 CE to 2016 CE; bsi.go.id). Black arrow indicates the direction of the subduction.

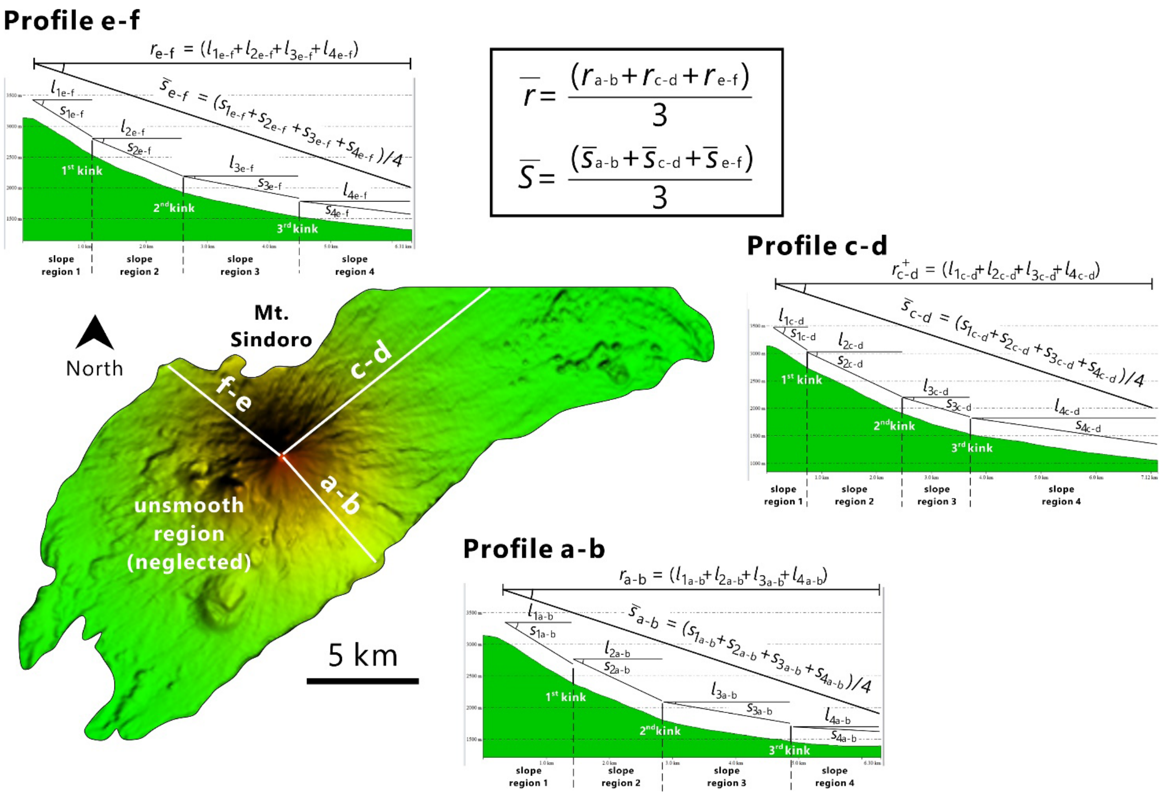

Figure 2. Representative example of image processing steps to obtain bulk radius ($\bar{r}$) and bulk slope ($\bar{S}$). Note that we neglected the unsmooth region (e.g., the SW flank of Mt. Sindoro) to avoid data noise.

We selected Indonesia as the field of this study because: (1) it is known as a country with one of the densest volcano distributions on earth (de Maissoneuve and Bergal-Kulvikas 2020), (2) comprise wide-range magma compositions (i.e., from picrobasalt or foidite to rhyolite or phonolite) (Leterrier et al. 1991, Carn and Pyle 2001, Alloway et al. 2004), and (3) host various types of hazards (i.e., lava flows, lava domes, pyroclastic falls, pyroclastic density currents (PDCs), lahars, debris avalanches, and tsunami) (Rubin et al. 1989, Sigurdsson and Carey 1989, Thouret et al. 2007, Williams et al. 2019). These conditions allow us to evaluate stratovolcano in high frequency (number of analyzed volcano=154) with diverse variable. Finally, we believe that our typology has been representative enough to represent the general characteristics of Indonesian stratovolcano.

2. Methods

Our geomorphological analyses include the measurements of average slope, average radius, and surface roughness. These data were combined with geological aspects and rainfall precipitation rate.

Average slope and radius

First, we made a 2D-cross sectional profile for each volcano using Path Profile tool in Global Mapper 20 to determine the average slope ($\bar{s}$). To obtain $\bar{s}$, we have to qualitatively identify the number of 'kink' (a sharp change in slope) to identify slope region (Fig. 2). Subsequently, we measured the slope (s) and length (l) of each slope region (Fig. 2). The average slope ($\bar{s}$) and radius (r) of each 2D-cross sectional profile can be obtained by following equations:

$$\bar{s} = \sum_{n=1}^{N} s_n / N \quad (1)$$

$$r = \sum_{n=1}^{N} l_n \, (l_1 + l_2 + l_3 + \ldots l_n) \quad (2)$$

where $\bar{s}$ is the average volcano slope in degree (°), $\sum_{n=1}^{N} s_n$ is a summation of the volcano slope on each slope region s_n in degree (°), N is the number of slope region, r is the volcano radius, and $\sum_{n=1}^{N} l_n$ is a summation of the volcano length on each kink l_n in km.

Three (up to four) 2D-profile images were used, depending on the surface conditions (for instance, parasitic cone-bearing flanks were avoided as it may cause data noise; Fig. 2) to represent the whole volcano radius and slopes. Each parameter values ($\bar{s}$ and r) were then averaged in order to obtain the bulk average slope ($\bar{S}$) and bulk radius ($\bar{r}$) (Fig. 2). Hereafter, $\bar{r}$ is classified into three categories: (1) small (<5 km), (2) moderate (5-10 km), (3) large (10-20 km), and (4) extremely large (> 20 km). While $\bar{S}$ is classified into five types: (1) very gentle ($\bar{S}$ value is smaller than 5.0°), (2) gentle (5.1–10.0°), (3) moderate (10.1–15.0°), (4) steep (15.1–20.0°), and (5) extremely steep (>20.1°). The representative $\bar{S}$ and $\bar{r}$ data are presented in Supplementary file1.

Surface roughness

Surface roughness values were obtained by processing the digital elevation model (DEM) image of each volcano using roughness tool in Qgis software (Fig. 3), following the basic concept on the equation of Shepard et al. (2001):

$$RMS = \left[\frac{1}{n-1} \sum_{n=1}^{N} (z(x_i) - \bar{z})^2\right]^{1/2} \quad (3)$$

where RMS is the surface roughness, n is the number of sample points, $z(x_i)$ is the surface point's height at x_i, and $\bar{z}$ is the average height of the profile over all x_i. Hereafter, RMS is classified into three categories: (1) small (<50), (2) moderate (50.1-100), and (3) high (>100). The representative surface roughness data are presented in Supplementary file 1.

Geological information

We compiled the geological information (for each analyzed volcano) from various scientific sources, including geological maps, research articles, or online datasets provided by Smithsonian Institution (http://volcano.si.edu) and Pusat Volkanologi Mitigas Bencana Geologi (http://vsi.esdm.go.id). The geological data includes information such as bulk-rock compositions, deposit and mineralogy variations, recorded eruption scale, and its status. For statistical purposes, the absence and the existence of each given parameter are scored by 0 and 1, respectively. For instance, a volcano is consisted of basaltic and basaltic andesite rocks; this means that basalt and basaltic andesite are scored by 1, whereas the score of other compositions (andesite, dacite, rhyolite) is 0. Subsequently, each parameter was summarized and reported as a number fraction. The representative geological data are presented in Supplementary file 1.

Our rock composition data involves both sub-alkaline and alkaline magmatic affinities. Thus, terminologies such as basalt, andesite, and phonolite are not applicable in this study. To accommodate the rock name for both magmatic affinities, we tend to name the compositions ultrabasic, basic, evolved basic, intermediate, felsic, and evolved felsic. Ultrabasic corresponds to the least evolved member, including picro-basalt and foidite in sub-alkaline and alkaline magmatic affinities, respectively. Basic comprises basalt (sub-alkaline), trachybasalt, tephrite, and basanite (alkaline). For evolved basic, the sub-alkaline affinity is represented by basaltic andesite, while the alkaline affinity is represented by basaltic trachyandesite and phonotephrite. Intermediate represents andesite (sub-alkaline), and trachyandesite and tepriphonolite (alkaline). Felsic corresponds to dacite (sub-alkaline), trachyte, and phonolite (alkaline). Finally, evolved felsic is represented by rhyolite, both for sub-alkaline and alkaline affinities.

Deposit variations comprise pyroclastic materials (pyroclastic fall and pyroclastic density currents, PDCs), lava flows, lava domes, lahars, debris avalanches (hummocky; Mount Shasta, see Crandell et al. 1984), and tsunami deposits.

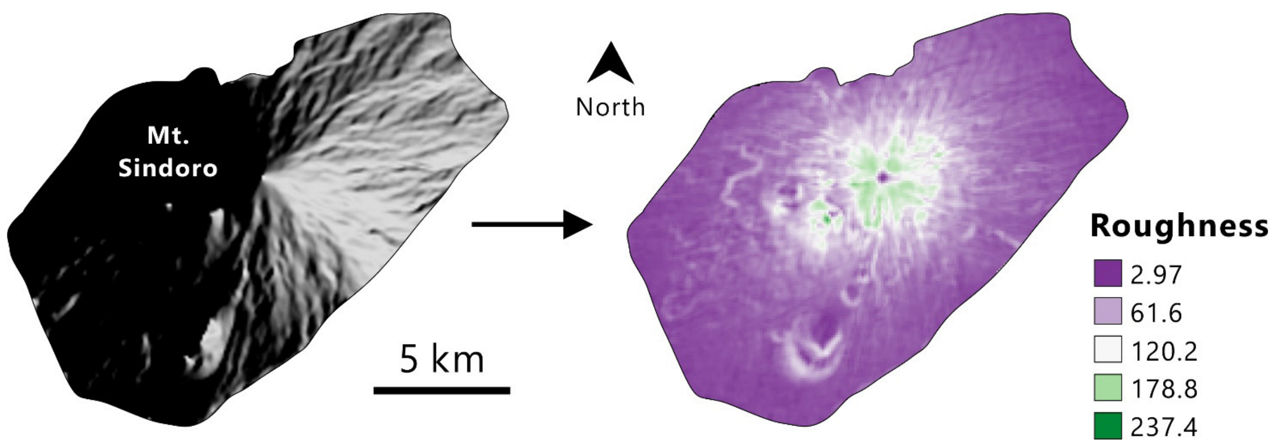

Figure 3. Representative example of image processing step to obtain the surface roughness (RMS). Note that high RMS value is generally obseved around summit region, where the erupted materials are predominantly large and have irregular surface textures.

Mineralogy variations include quartz (Qz), sanidine (Pl), plagioclase (Pl), clinopyroxene (Cpx), orthopyroxene (Opx), phologopite (Phl), amphibole (Amph), biotite (Bt), olivine (Ol), apatite (Apa), Fe-Ti Oxides (Ox), Leucite (Lct), and Nepheline (Nep).

Juvenile associations include the information on whether such deposits contain pyroclastic materials such as pumice, scoria, and/or breadcrust bombs. If there is no report regarding the juvenile component, we tend to report them as 'no information'.

The eruption scale indicates the range of volcanic explosivity index (VEI) that ever occurred on each volcano. However, our eruption scale data might include significant error because VEI information on most of the Indonesian volcanoes is generally lacking.

The volcano status is represented by three stages, following the Indonesian government's regulations as follows: active (type A), dormant (type B), and extinct (type C). Active means that the volcano has experienced an eruption since 1600 CE. Dormant indicates that the volcano has not erupted since 1600 CE but is still active. Extinct means that the volcano is considered as a 'dead volcano' and has no chance of erupting.

Rainfall precipitation rate

We also compiled the rainfall precipitation rate data from all observation stations in Indonesia. Such datasets are available online and freely accessible at bps.go.id (provided by Badan Pusat Statistik). The provided data is represented by the average precipitation rainfall rate per five years, ranging from 2011 CE to 2015 CE (Fig. 1). Note that each rainfall precipitation observation occupies regional-scale data (up to a hundred km^2), hence there are no specific rainfall precipitation observatories for each volcano. We use the shortest distance between the rainfall observatory location with volcano (d) for data selection. For instance, we selected Kualanamu observatory in North Sumatra to represent the rainfall precipitation rate of Toba caldera, as it has the shortest d compared to the neighboring observatory locations (e.g., Sultan Iskandar Muda observatory in Aceh, or Sicicin observatory in West Sumatra). The representative rainfall precipitation data are listed in Supplementary 1.

3. Results and Disscusion

Correlation between slope, radius, and roughness

The correlation between $\bar{r}$ and $\bar{S}$ results in two patterns: (1) negative correlation, and (2) positive correlation (Fig. 4a). Similar patterns are also observed in the correlation between $\bar{r}$ and RMS (Fig. 4b). In the first pattern (blue arrow; Fig. 4), as the volcano size increase, the average slope and surface roughness decrease and vice versa (for instance, if the volcano is small, the average slope and surface roughness is high). While in the second pattern (red arrow; Fig. 4), as the volcano size decreases, the average slope and surface roughness decrease and vice versa.

Stratovolcano classification

Based on the qualitative observation of volcano morphology (bulk radius ($\bar{r}$), bulk average slope ($\bar{S}$), and bulk surface roughness (RMS) we define stratovolcano into four types: (1) small-least dissected cones (type I), (2) broad-dissected cones (type II), (3) extremely broad-dissected cones with caldera (type III), and (4) residual-dissected cones (type IV) (Fig. 4). Type I is characterized by the 'perfect cone shape' (e.g., Mount Inerie and Ebulobo in Flores), small $\bar{r}$ (0.7–4.8

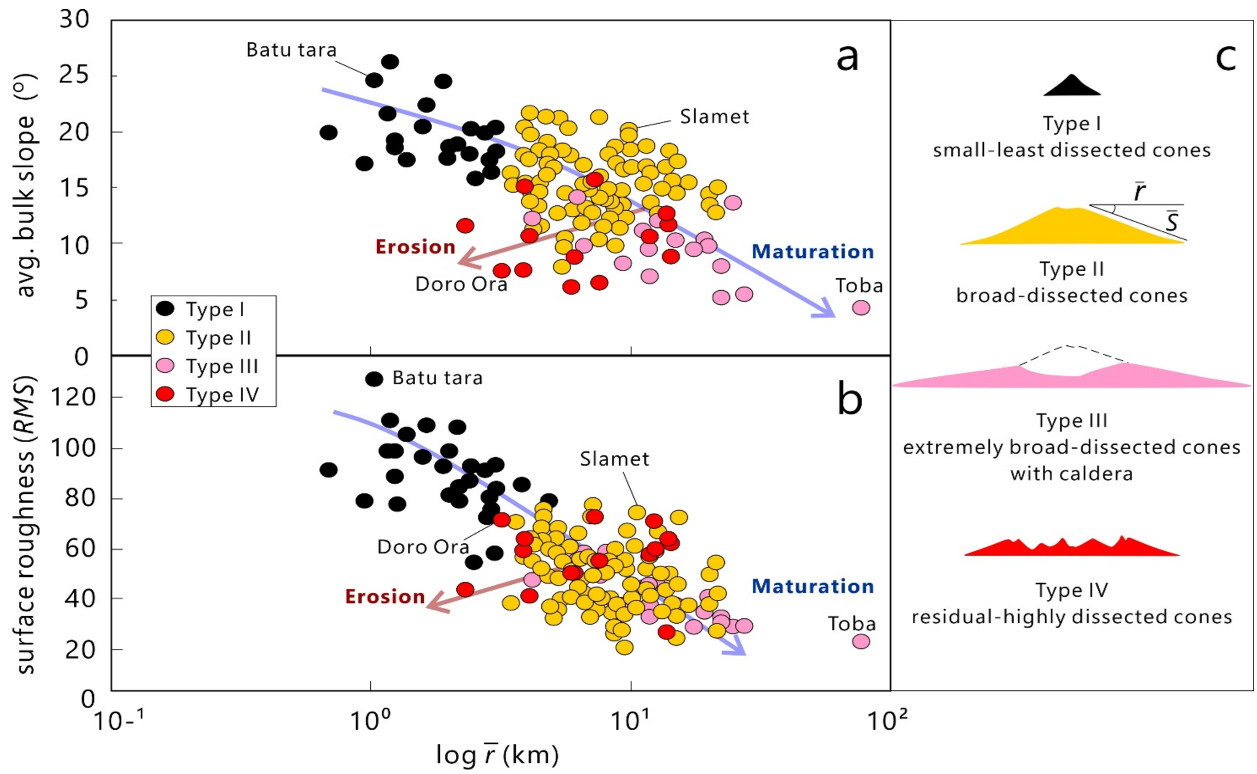

Figure 4. Correlation between bulk volcano radius with (a) bulk average slope, and (b) surface roughness. The negative correlation regime indicates maturation stage, from type I to III. While the positive correlation implies the erosional stage when the volcano has been extinct. Representative 2D-profiles for each type are shown in (c). Note that and correspond to average radius and slope (see methods section).

km, avg. of 2.1 km), steep to extremely steep $\overline{S}$ (16.3–26.2°, avg. of 19.8°), and moderate to high RMS values (55–130, avg. of 88.8) (Fig. 4a and 4b). Type II is characterized by more complex cone shapes relative to type I (for instance, it has parasitic cones and/or more than one crater, such as Mount Slamet in Java), gentle to extremely steep $\overline{S}$ (8.0–21.3°, avg. of 15.1°), and small to moderate RMS values (19.7–75.7, avg. of 47.7) (Fig. 4a and 4b). Type III is characterized by the occurrence of caldera structure (e.g., Rinjani in Lombok and Tambora in Sumbawa), having small to extremely large $\overline{r}$ (4.1–76.7 km, avg. of 18.1 km), very gentle to moderate $\overline{S}$ (4.4–14.3°, avg. of 9.2°) (Fig. 4a and 4b), and small to moderate RMS values (21.0–59.6, avg. of 40.1). Type IV shows highly irregular and deeply-incised surface morphology (e.g., Ringgit-Beser in East Java), having small to large $\overline{r}$ (2.2–14. km, avg. of 8.2 km), gentle to steep $\overline{S}$ (6.0–15.8°, avg. of 10.7°), and small to moderate RMS values (25.0–74.1, avg. of 56.9) (Fig. 4a and 4b).

Correlation between stratovolcano types with geological data

Type I is characterized by the narrow variation of magma compositions, with a dominant basic to intermediate rock compositions (i.e., Stolz et al. 1988; Rubin et al. 1989; Carn et al. 2000; Turner et al. 2003; Kushendratno et al. 2012; Rachmat et al. 2016) (Fig. 5). In terms of mineralogy, type I is typically rich in mafic minerals such as clinopyroxene and olivine and lacks felsic minerals such as quartz and sanidine (Fig. 6). Hydrous minerals rarely occur, but amphibole is more common than biotite (Fig. 6). Lava dome and lahars are rare features in type I, as the common products are lava flows and pyroclastic deposits (fall and PDCs) (i.e., Ratman and Yasin 1978; Koesoemadinata and Noya 1989; Koesoemadinata et al. 1994) (Fig. 5). In some cases, type I stratovolcanoes may generate tsunamis if they are located in/and or near the ocean (e.g., Anak Krakatau in Sunda strait and Banda Api in Banda Ocean; Williams et al. 2019, Ashcraft 2021) (Fig. 5). Because type I is predominantly basic and evolved basic, scoria (and agglomerate) becomes the most common juvenile products (Fig. 5). In addition, type I tends to produce low-explosivity eruptions, varying from VEI 0 to VEI 3 (e.g., Soputan in North Sulawesi) (Kushendratno et al. 2012; Kunrat 2017; Pandara 2017) (Supplementary file 1). In terms of activity, most of type I stratovolcanoes are considerably active and dormant, and none of them are extinct (Fig. 5).

Type II has a relatively wider rock compositions than type I, from basic to evolved felsic with a predominantly intermediate rock composition (i.e., Wheller and Varne 1986; Cloproth 1989; Beleusov et al. 2015; Prambada et al. 2016; Primulyana et al. 2017; Wibowo 2017; Sabila and Abdurrachman 2018; Pratama et al. 2019; Saing et al. 2020) (Fig. 5). Such magmatic differentiation is accompanied by the decreasing amount of olivine and increasing amount of orthopyroxene and hydrous minerals (i.e., McBirney 2007; Jeffery et al. 2013; van der Zwan et al. 2013; Mulyaningsih et al. 2016) (Fig. 6). Lava domes and lahars are common products, together with the pyroclastic deposits and lava flows (i.e., Djuri 1973; Apandi and Sudana 1980; Bennet et al. 1981; Aspden et al. 1982; Rock et al. 1983; Cloproth 1989; Suwarna et al. 1989; Alzwar et al. 1992; Santosa and Atmawinata 1992; Amin et al. 1993a, b; Mangga et al. 1993; Samodra 1994; Silitonga and Kastowo 1995; Condon et al. 1996; Rosidi et al. 1996; Effendi et al. 1998; Hammer et al. 2000; Thouret et al. 2007; Bronto et al. 2012; Surono et al. 2012; Bowers 2019; Nakada et al. 2019) (Fig. 5). Some type II stratovolcanoes also produced debris avalanche deposits (observed as a hummocky; Crandell et al. 1984) (Fig. 5), and those hummocky-producing stratovolcanoes have a typically large 'amphitheater' structure (e.g., Mount Galunggung in West Java and Mount Gadung in East Java) (Budhitrisna 1986, Bronto 1989; Moktikanana et al. 2021). Similar to type I, some type II stratovolcanoes can produce tsunamis, depending on the geographical location (e.g., Mount Rokatenda in Paluweh, NTT; Primulyana et al. 2017). Both pumice and scoria are common juvenile products in type II (Fig. 5). There are some evidences that type II stratovolcanoes are capable of producing mild-explosive eruptions (at most VEI 5) such as Mount Salak in West Java, and Mount Gamkonora in Halmahera (Harpel et al. 2019; Siebert et al. 2010) (Supplementary file 1). In terms of activity, the number of active and dormant volcanoes was found to be equal, with some of them have been extinct (Fig. 5).

Type III has the most abundant felsic and evolved felsic rock compositions among all of types (i.e., Sitorus 1990; van Gerven and Pichlert 1993; Reubi and Nicholls 2004; de Maisonneuve and Bergal-Kulvikas 2020; Suhendro et al. 2022), indicated the ubiquitous presence of felsic minerals such as quartz and sanidine, and the significant decrease in olivine and pyroxenes (Figs. 5 and 6). PDC deposit is the most common pyroclastic product observed in type III (especially in the flank region, together with the abundant lahars), and lava flows and lava domes that generally formed inside the caldera (Fig. 5) (i.e., Silitonga 1973; Santosa 1991; Rusmana et al. 1991; Gafoer et al. 1992, 1993; Santosa and Suwarti 1992; Mangga et al. 1994; Koesmono et l. 1996; Effendi et al. 1997; Purbo-Hadiwidjoyo et al. 1998; Ryu et al. 2013; Harijoko et al. 2016; Suhendro et al. 2016; Abdul-Jabbar et al. 2019, Adani et al. 2019, Angkasa et al. 2019). Some of type III also produces hummocky deposits such as Rinjani caldera in Lombok (Malawani et al. 2020). Similar to type I and II, type III can generate tsunamis if the volcano is located adjacent to and/or in the ocean such as Krakatau, Rinjani (Samalas), and Tambora calderas (Mandeville 1996; Mutaqin et al. 2021; Stothers 1984) (Fig. 5). At this stage, several intrusive rocks (i.e., dyke) can be observed around the caldera margin (Fig. 5) without forming a 'volcanic neck' morphology. Pumice is the most common juvenile product observed in type III, the richest among the other types (e.g., Chesner and Rose 1992; Wahyudin et al. 2009; Vidal et al. 2016; Suhendro et al. 2021; Suhendro et al. 2022) (Fig. 5). Moreover, the VEI also increases to (at most) VEI 8, represented by the Toba caldera in North Sumatra (Chesner and Rose 1992). Worthy to note, most of type III volcanoes are still active (Fig. 5).

Type IV is characterized by the extensive number of ultrabasic rocks, the richest among the other types (i.e., Edwards et al. 1994; Prasetya 2010) (Fig. 5), indicated by the decreasing amount of plagioclase, orthopyroxene, and the increasing amount of olivine (i.e., Suwarti and Wikarno 1992; Edwards et al. 1994) (Fig. 6). The absence of lava dome becomes the hallmark of type IV, together with the increasing number of observed intrusions in the form of 'volcanic neck' morphology (e.g., Ringgit-Beser in East Java; Edwards et al. 1994, Pendowo and Samodra 1997). Juvenile products (pumice or scoria) are rarely observed, as the information on juvenile products is lacking in type IV. There are no reports regarding explosivity degree (VEI) on type IV. In addition, all type IV stratovolcanoes have been extinct.

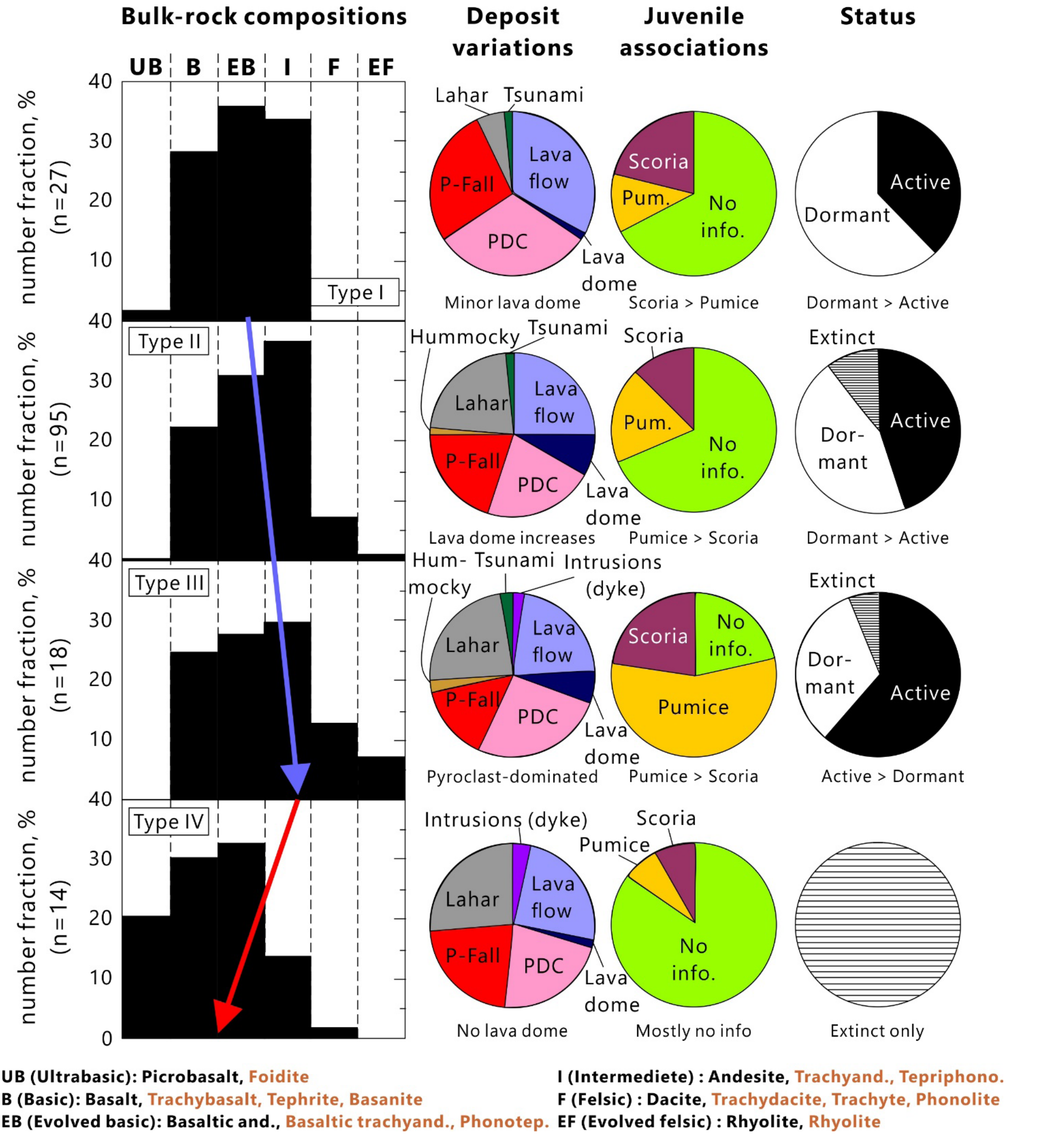

Figure 5. Correlation between stratovolcano types with geological parameters such as bulk-rock compositions, eruption products, and status. Black and orange colours in the explanation of rock compositions represent sub-alkaline and alkaline magma affinities, respectively. See the text for a more detailed discussion.

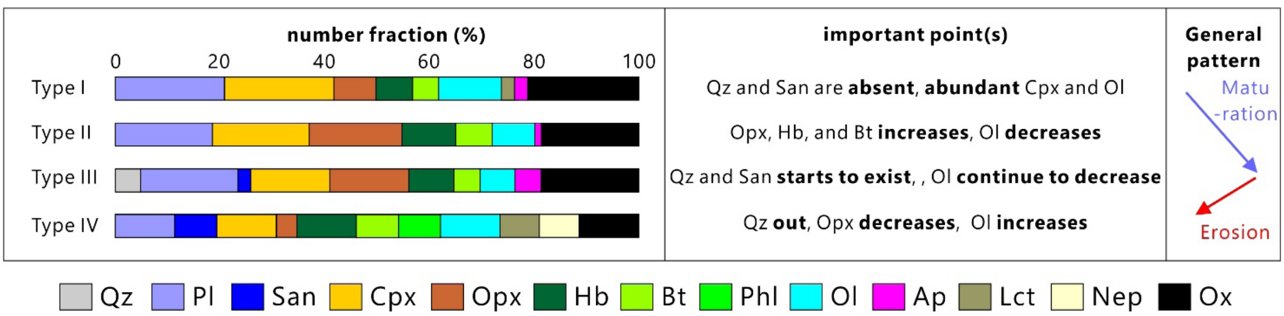

Figure 6. Variations in mineral assemblages toward the evolution of stratovolcano. Note that the abundance of mafic minerals (especially olivine) decreases, while the abundance of felsic minerals (e.g., quartz and sanidine) increases toward the maturation stage (from type I to III). On the other hand, the number of mafic minerals increases again, accompanied by the vanishment of felsic minerals toward the formation of type IV.

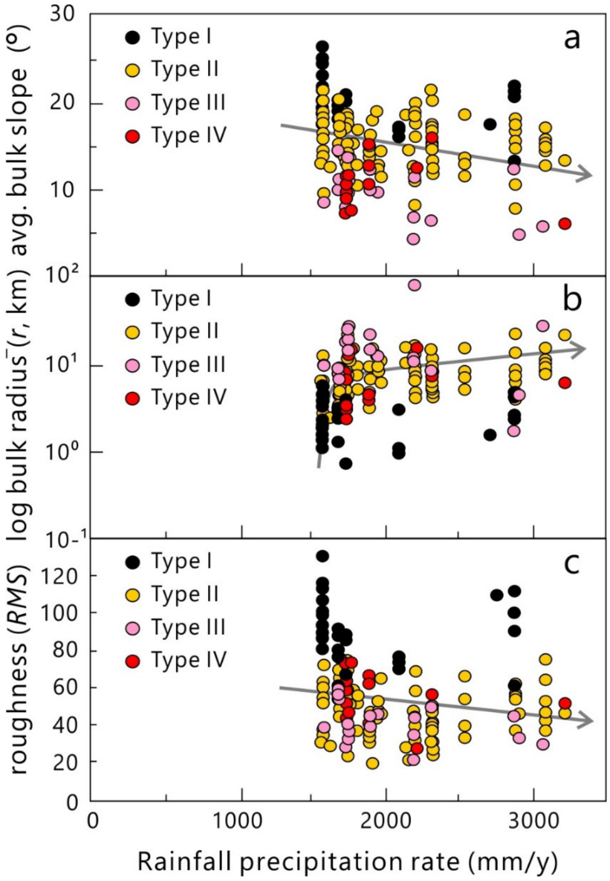

Figure 7. Correlation between rainfall precipitation rate with (a) bulk average slope, (b) bulk radius, and (c) surface roughness. It is found that the rainfall intensity seems to control the geomorphological parameters of volcanic edifice via erosional processes.

Correlation between geomorphological parameters with rainfall

The rainfall precipitation rate (Pr) shows a negative correlation with average slope ($\overline{S}$) (Fig. 7a). Moreover, because $\overline{S}$ is negatively correlated with bulk volcano radius ($\overline{rr}$) and positively correlated with surface roughness (RMS), the correlation between R and RMS with Pr results in positive and negative correlation, respectively (Fig. 7b, c). However, note that type I stratovolcanoes (as shown by black dots) have an elevated RMS values under the given Pr (Fig. 7c).

Discussion

The evolution of stratovolcano: maturation stage

The most important indicator to identify the evolution of stratovolcano can be seen in the correlation between $\overline{S}$, $\overline{r}$, and RMS (Figs. 4a and 4b). In the negative correlation regime, the correlation between these parameters indicates the maturation stage: from a small stratovolcano with steep slopes and high surface roughness into a larger stratovolcano with gentler slopes and smaller surface roughness. This process occur simultaneously with magmatic accumulation-differentiation, leading to the formation of a larger magmatic system with higher silica content. As a result, the eruptive behaviour (i.e., eruption style) and intensity (possibsle VEI) changes. This suggest that each stratovolcano type poses a differrent level of threat to human. Interestingly, such a pattern was also observed in the Philippines volcanoes (Paguican et al. 2021).

During the early stage (type I), volcanoes are fed by predominantly volatile-undersaturated (especially H_2O and CO_2; Edmonds and Woods 2018) mafic magmas, which are rich in mafic minerals and poor in hydrous minerals (Figs. 5 and 6). Because volatile plays an important role in providing the overpressure and controlling the degree of explosivity (Toramaru 2006, Toramaru 2014, Carichi et al. 2014, Suhendro et al. 2022), type I stratovolcanoes tend to produce effusive and/or low-explosivity eruptions such as Hawaiian and Strombolian types, with the maximum known explosivity index of 3 (Kushendratno et al. 2012, vsi.esdm.go.id) (Supplementary file 1). As a result, aa' lava (a type of lava with irregular surface textures due to the fast-colling process of low viscosity magma; Sigurdsson 2000), scoria, and breadcrust bombs become the most common products in type I (Fig. 8). Because scoria clasts are typically having irregular surface textures compared to pumice, and breadcrust bombs indicate the largest size in the classification of pyroclastic material (Fisher 1966) (Fig. 8), type I volcanoes have a typically rough surface texture (avg. RMS value of 88.8, coarsest among all stratovolcano type) (Fig. 8). Moreover, because volcano size (or volume) has strong dependance on time (Sigurdsson 2000), a small-type I volcano (avg. $\overline{r}$ of 2.1 km) can be considered as a young volcano with short eruptive history. Because of this short residence time, type I is ought to experience the least intensive erosional processes, thus limiting the formation of lahars. This may be the reason why type I volcanoes are typically steep (avg. of 19.8°) (Fig. 9); the ring plain region (a gently sloped volcanic terrain that consists of lahar deposits; see fig. 9 in the chapter of composite volcanoes, Sigurdsson 2000) is still underdeveloped. Some of the representative type I volcanoes are Karangetang, Inerie, and Batu Tara (Fig. 10).

Going to the next stage (type II), the magma evolves (higher silica content) due to the longer cooling history, producing abundant intermediate rocks with a minor presence of felsic members (Fig. 5). This is accompanied by the depletion of mafic minerals (especially olivine), together with the elevating hydrous minerals and volatile contents in the magma chamber (Fig. 6). As the volatile content increase (preexisting bubbles; Toramaru 2014, Carichi et al. 2014, Suhendro et al. 2022), magma chamber overpressure also increases. This is the reason why mild-explosive eruptions (at most VEI 5) and pumice (as the main product) are commonly observed in type II (Siebert et al. 2010; Harpel et al. 2019; Utami et al. 2021) (Supplementary file 1). Furthermore, blocky lava flows and/or lava domes form if effusive eruption occurs under viscous magma conditions (higher silica content results in higher magma viscosity; McBirney 2007). Note that blocky lava flows and pumice have smoother surface area relatives to aa' lava and scoria, respectively (Fig. 8), making the average RMS values of type II smaller than that of type I (avg. RMS of 47.7 and 88.8, respectively). Moreover, longer volcano residence time is therefore responsible for enlarging the volcano size (avg. $\overline{r}$ of 8.8 km) via accumulation of erupted materials, as well as reducing the volcano slope (avg. slope of 15.1°) via more intensive erosional processes (indicated by a more developed ring plain region that mostly consist of lahar deposits) (Fig. 9). Some of the representative type II volcanoes are Sinabung, Merapi, Kelud, Agung, Gamalama, and Ile Lewotolok (Fig. 10).

Type III marks the longest residence time of active volcanoes. This condition led magmas to experience the most extensive cooling process, forming abundant felsic and evolved felsic rocks via magmatic differentiation (Fig. 5). Consequently, the number of mafic minerals (pyroxenes and olivine) significantly decreased, and gave rise to the formation of felsic minerals such as quartz and sanidine (Fig. 6). During this stage, supersaturation of preexisting bubbles might have been developed (generally > 5 wt. % of H_2O; Edmonds and Woods 2018), leading to a larger magma chamber overpressure (Wohletz and Woods 2002, Caricchi et al. 2014). Subsequently, when the overpressure exceeds the critical strength of roof rocks, a colossal eruption occurs (Carichi et al. 2014). This eruption may evacuate tens to thousands of cubic kilometers of magma from the chamber, causing a sudden emptying of the magma chamber and ultimately, generating a caldera collapse (Sigurdsson 2000) (Fig. 9). Because the volcanic center collapses (which is the domain of the steepest slope in a volcanic edifice; Fig. 2), and this caldera-forming eruption commonly produce widely disperse (up to 100 km from the vent) and thick ignimbrite deposits (up to hundreds of meter thickness) (Chesner and rose 1992; Alloway et al. 2004; Vidal et al. 2016; Suhendro et al. 2021; Suhendro et al. 2022), the bulk average radius and slope significantly decreases (avg. of 18 km and 9.1°, respectively) (Figs. 5 and 9). Moreover, the domination of pumice and ash materials (due to the high degree of magma fragmentation) in the caldera-forming eruption deposits (which cover the whole volcanic edifice) played an important role in smoothing the surface area, indicated by the smallest RMS value (avg. of 40.1) (Figs. 8 and 9). Afterward, effusive eruptions usually dominate the post-caldera activities, producing abundant lava domes and blocky and/or aa' lavas, depending on magma viscosity (Figs. 6 and 8). Some of the representative type III volcanoes are Toba, Maninjau, Bromo, Rinjani, and Tambora (Fig. 10).

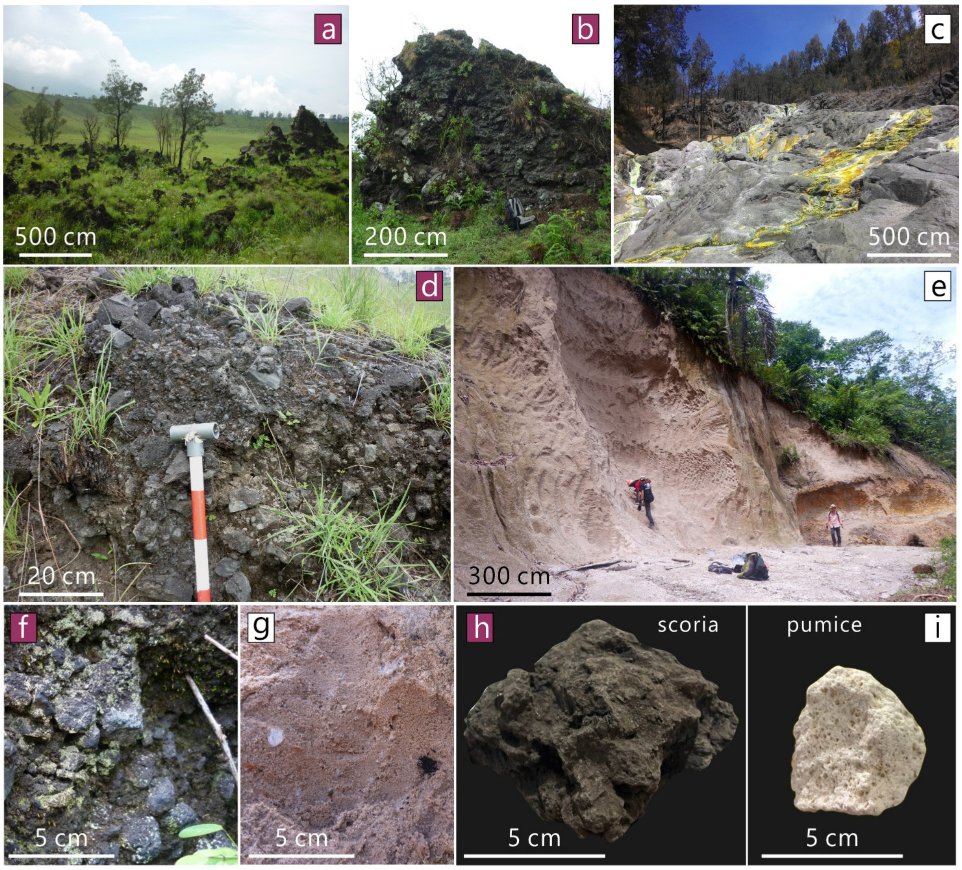

Figure 8. (a, b) aa' lava and (c) blocky lava flows from the Ijen volcanic complex. Note that aa' lava flows have coarser surface textures than that of blocky lava. (d, f, h) agglomerates and scoria from the Ijen volcanic complex, showing coarser and more irregular grains than the ignimbrite deposits and pumice from Maninjau (e, g, i). Note that images with maroon label boxes correspond to rocks with less evolved compositions than the white ones (basaltic andesite for maroon boxes and rhyolite for white boxes; Suhendro et al. 2016 and Alloway et al. 2004).

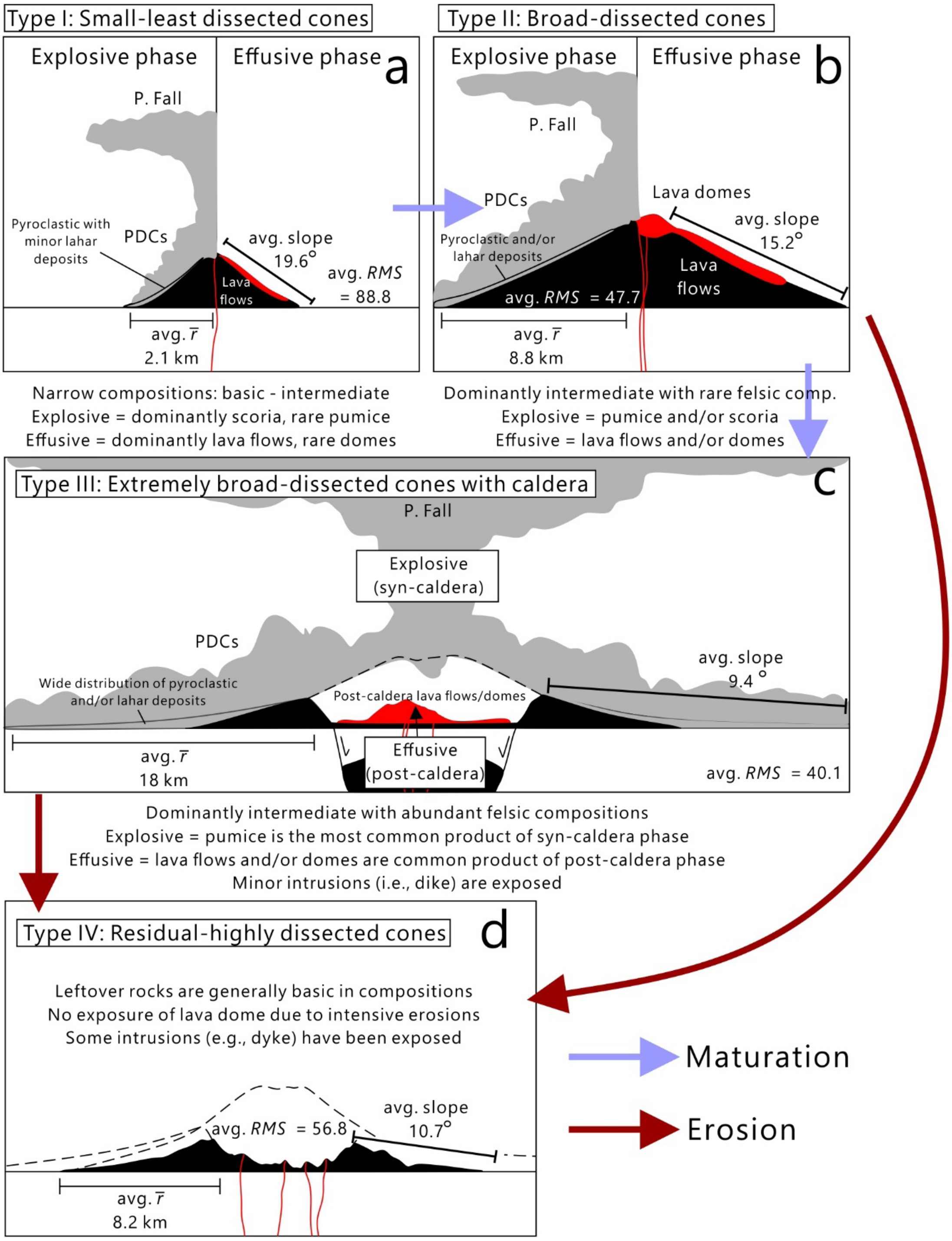

Figure 9. Cartoon showing the temporal evolution of stratovolcano. See the text for a more detailed discussion.

The evolution of stratovolcano: erosional stage

To reach this stage, a volcano (either from type III or directly from type II) should undergo into the inactive stage in order to accommodate effective erosional processes. Because erosion generally starts from the outermost part of a volcanic edifice, a relative enrichment of basic rocks (which are mostly preserved in the inner part of a volcano) is expected to occur (Fig. 5). The high abundance of ultrabasic rocks (the highest among all types), the absence of lava domes, and the exposure of intrusive bodies (e.g., dyke; observed as volcanic neck (Edwards et al. 1994)) also does not deny this idea (Fig. 5). Consequently, the portion of mafic minerals (especially olivine) increases and the number of plagioclases decreases (Fig. 6). There is no enough information about juvenile materials, as most of the deposits may have been eroded due to the intensive erosional processes (Fig. 5). However, it is known that some type IV volcanoes may still preserve their juveniles (i.e., Lasem volcano) (Abdillah et al. 2019; Moktikanana et al. 2019). Finally, the extensive erosion on type IV is responsible for decreasing the average size and average slope (8.2 km and 10.7°, respectively), as well as increasing the RMS value due to a highly irregular surface texture (Fig. 9). Some of the representative type IV volcanoes are Muria, Lasem, Ringgit-Beser, and Baturape (Fig. 10).

Based on our findings, we can confirm that the stratovolcano morphology has a strong dependence on time. In particular, time controls the degree of magma differentiation (which is important in controlling the eruptive products that will construct the volcanic edifice) and the intensity of the erosion. Because western Indonesia experienced longer volcanism-magmatism history than the eastern part (Katili 1975), type II and III are typically abundant in Sumatra and Java, while type I is more common in the vicinity of Flores, Banda, and Halmahera (Fig. 10). In addition, it is difficult to see the spatial pattern of type IV because the data is lacking.

The role of rainfall intensity

Indonesia is an archipelagic country with a heterogeneous rate of rainfall precipitation. For instance, the rate of rainfall precipitation in Sumatra Barat (West Sumatra) exceeds 3070 mm/year, whereas Nusa Tenggara Barat (NTT) only comprises 1576 mm/year (Badan Pusat Statistik; bps.go.id) (Supplementary file 1). Because of this condition, it is therefore important to evaluate whether rainfall precipitation rate plays a significant role in controlling the morphology of stratovolcano or not.

Interestingly, as mentioned in the results section, the rainfall precipitation rate (Pr) is negatively correlated with the average slope ($\bar{S}$) (Fig. 7a), where low Pr and high Pr represents a steep and gentle stratovolcano, respectively. Because the correlation between $\bar{r}$ and Pr is positive (Fig. 7b), it is therefore inferred that erosion intensity (which is controlled by Pr) is a time-dependent process. This strongly suggests that higher rainfall precipitation rate and longer volcano residence time generally result in higher sediment flux due to longer history of erosional processes, in agreement with Inbar et al. (1998). Such sediments are therefore transported to the distal region, forming a ring plain that mostly consists of lahar deposits (Sigurdsson 2000). Consequently, the formation and growth of ring plain modify the volcano landscape (especially in the aspect of slope), from a steeped slope into gently-sloped stratovolcano (Fig. 9).

It is more difficult to interpret the correlation between Pr with surface roughness (RMS) (Fig. 7c). Although the general trend indicates a negative correlation, type I stratovolcano characteristically shows a highly elevated RMS among the other types (under the given rainfall intensity) (Fig. 7c). One possible factor for these phenomena is volcano residence time. As explained above, type I stratovolcanoes are typically young and mafic (Fig. 5), hence the eruptions are relatively weak, i.e., Hawaiian and Strombolian. Such eruption styles do not produce significant amount of ash (due to the low fragmentation intensity), resulting in predominantly large-sized (mostly lapilli with abundant bombs; Rodriguez-Gonzales et al. 2012) and irregular surface materials (scoria- and bomb-rich deposits) (Fig. 8). The short eruptive history coupled with the domination of large-sized and irregular surface materials prevents the rocks from intensive erosional processes, making the RMS value high (Fig. 7c).

4. Conclusion

This is the first study that provides a detailed classification of Indonesian stratovolcano based on geomorphological (i.e., size, slope, and surface roughness) and geological aspects (i.e., rock compositions, mineralogy, and eruptive products). We classify stratovolcanoes into four types as follows: (1) small-least dissected cones, (2) broad-dissected cones, (3) extremely broad-dissected cones with caldera, and (4) residual-highly dissected cones. The evolution from type I to type III corresponds to the maturation stage, while transformation from type III (or directly from type II) to type IV indicates the erosional stage. Toward the maturation stage, the stratovolcano becomes large, having a gentle slope and smooth surface roughness. This is accompanied by a more extensive magmatic differentiation process and more explosive eruptive behavior (at most caldera-forming eruption). Toward the erosional stage, stratovolcano becomes small but has a gentler slope and coarser surface roughness. Moreover, such intensive erosion is responsible for exposing the basic rocks and intrusive bodies that mostly existed inside the volcanic body. Furthermore, we also found that rainfall precipitation ratio also plays an important role in controlling size, slope, and surface roughness. Namely high rainfall precipitation ratio causes the decrement of average bulk slope and surface roughness and the increment of volcano size due to the more intensive erosional processes.

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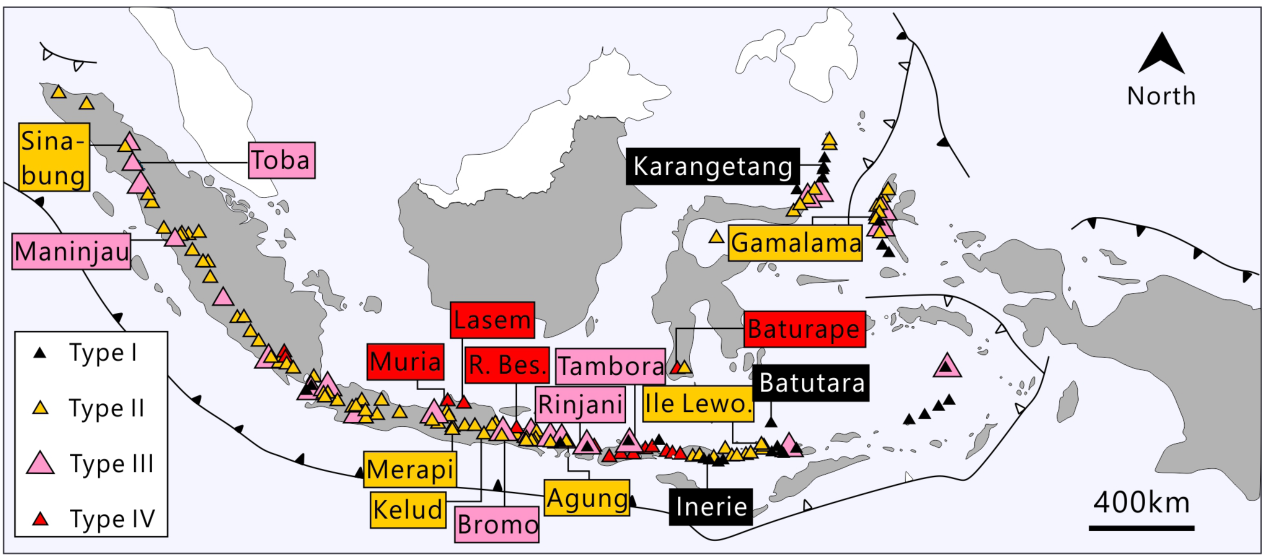

Figure 10. Typology distribution of stratovolcanoes in Indonesia. Black, orange, pink, and red triangles denote type I, II, III, and IV, respectively. Note that type I is more common in the east, while type II and III are dominant in the west.

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