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# Volume Estimation of the Thickest Scoriaceous Tephra-Fall Deposits on the South-Southeastern Flank of Mt. Raung

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ABSTRACT. Thick scoriaceous tephra-fall deposits are widely distributed in the south to the southeast flank of Mt. Raung, indicating the existence of past large explosive eruptions. The deposits are relatively young as they are situated near the surface. Scoriaceous tephra-fall deposits can be divided into four layers from bottom to top: Scoria Fall 1, Scoria Fall 2, Scoria Fall 3, and Scoria Fall 4. There is no time gap between these layers, as evidenced by the deposits not being separated by any weathered layer or soil, suggesting that the deposits represent an eruptive product of a single active period. We estimated the volume of the deposits using isopach maps following the Weibull method to identify the magnitude of the eruption. We limited the estimation to Scoria Fall 2 and Scoria Fall 3 deposits, which were consistently exposed at 13 and 9 observation points, respectively. The volume of Scoria Fall 2 is ~0.54 $km^3$, and Scoria Fall 3 is ~0.26 $km^3$, making the total volume 0.8 km3 (VEI 4).

**Keywords:** Mt. Raung · Scoria fall · Tephra-fall deposits · Volcanic explosivity index · Volume estimation.

## 1 INTRODUCTION

The explosive volcanic eruption ejects the volcanic materials, and either is a pyroclastic fall. This eruption occurs when magma erupts to the surface and forms an eruption column (Bronto, 2010). The eruption column is a buoyant plume of tephra and gas rising into the atmosphere (Cas & Wright, 1987). The convective column or plumes transport pyroclasts and volatiles into the atmosphere, then distributed by the winds (Sparks, 1986). The distribution of ejecta can be informed by the volcanic explosivity index (VEI) of the eruption that produced the ejecta. The larger eruption produced a higher volume of product, a higher convective column or plumes, and a wider ejecta distribution. The velocity and direction of the wind also influenced ejecta distribution, especially the geometry and the size of a deposit (Walker, 1973; Wilson et al., 1978; Cas & Wright, 1987). The VEI can be estimated using the information from the calculated volume of erupted materials. Mt. Raung is an active volcano with caldera morphology and a diameter area of 1.7 × 2.2 $km^2$ (Center of Vulcanology and Geological Hazard Mitigation [CVGHM], 2014). Large-scale explosive eruptions can form the caldera morphology. One of the largest eruptions of Mt. Raung has been recorded; Mt. Raung experienced a VEI 5 scale in 1586 (CVGHM, 2014). There are two massive pyroclastic fall deposits in Mt. Raung reported from the geological map

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by (Sutawidjaja et al., 1996), those are 1) Rjp1, pumiceous tephra-fall deposits distributed in the west-northwest flank of Mt. Raung and 2) Rjp2, scoriaceous tephra-fall deposits distributed in the south-southeast flank of Mt. Raung. Studying the erupted materials, such as tephra fall deposits, helps figure out the dynamics of paleo-volcanic and historical eruptions for hazard mitigation. The study of tephra fall deposits gives the information of volume erupted, mass erupted, column height, and intensity of an eruption (Walker, 1973; Sparks et al., 1997; Burden et al., 2013). This research reports the first estimation of the volume of the thickest scoriaceous tephra-fall deposits to identify the magnitude of eruption producing the deposits based on isopach maps. Isopach maps are commonly used to estimate magnitude by measuring tephra deposits' thickness and contouring the data (Klawonn et al., 2014a).

## 2 GEOLOGY OF MT. RAUNG

Mt. Raung is one of East Java, Indonesia's most active Quaternary volcanoes. This volcano has a $1.7 \times 2.2$ km$^2$ wide caldera on the peak (CVGHM, 2014), likely related to a large eruption in the past. The volcanic activity of Mt. Raung divided by Sutawidjaja et al. (1996) into three periods from the oldest to the youngest (Figure 2) those are 1) Old Raung Volcanism, which produced pyroclastic flow and lahar deposits, 2) Gadung Volcanism, that produced lavas, cinder cones, volcanic debris avalanche deposits, pyroclastic flow deposits, and lahars, and 3) Young Raung Volcanism, which produced lavas, cinder cones, debris avalanche deposits, lahars, pyroclastic flows, and pyroclastic falls. Scoriaceous tephra-fall deposits (Rjp2) are produced by Young Raung Volcanism activity. On average, the eruption of Mt. Raung has a VEI 2 scale but can reach a VEI scale of 4–5 (Global Volcanism Program, 2013). Based on the volcanic activity record of Mt. Raung (CVGHM, 2014), this volcano experienced paroxysmal eruption events in 1586, 1597, 1638, 1890, 1953, and 1956. Also, the shortest and longest eruption periods between two eruptions are 1 year and 90 years, respectively. The last activity of Mt. Raung is recorded in July 2022.

## 3 METHODOLOGY

Samples and field data are assembled using the spot sampling method covering Mt. Raung in all directions except the northeast flank. Scoriaceous tephra-fall deposits can be discovered only in the south-southeast flank. Observation points in the proximal and distal areas cannot be collected due to data limitation and access availability. Scoriaceous tephra-fall deposits are observed in thirteen observation points, and tephrostratigraphy is built accordingly. Field data of the deposits collected includes thickness, structure of the deposits, composting material, the average size of clasts, and contact between each layer. The correlation is built from the tephrostratigraphic records and the physical characteristics of the deposits. This study estimates the volume of the erupted materials using isopach maps data. The correlation and the physical characteristics of the deposits generate isopach maps. The calculation of the volume of erupted materials follows Bonadonna and Costa's method (2012) and is used to assess the Volcanic Explosivity Index (VEI) of the eruption.

## 4 RESULTS AND DISCUSSION

### 4.1 Tephrostratigraphy

Tephrostratigraphic records of scoriaceous tephra-fall deposits are made in thirteen observation points distributed in the south-southeast flank of Mt. Raung. The correlation is built according to tephrostratigraphic records. Scoriaceous tephra-fall deposits of Mt. Raung can be divided into 4 layers from bottom to top: Scoria Fall (SF) 1–4. These deposit layers are produced by the same eruptive period because each layer is not separated by any soil or weathering layer. The discovery of soil or weathering layer indicates a significant time gap between the deposition period of each layer. Scoria Fall (SF) 1 can be found in three observation points (RNG51, 52, and 35), has a thickness range of 1.5–9 cm, has a massive structure, has a grain size range of <1–20 mm, and is composed of scoria fragments and lithics. Scoria Fall (SF) 2 can be found in all sites (RNG01, 47, 46, 56, 54, 04, 05, 50, 51, 52, 39, 35, and 38), has a thickness range of 2-40 cm, has a normal gradation and a massive structure, has a grain size range of <1–

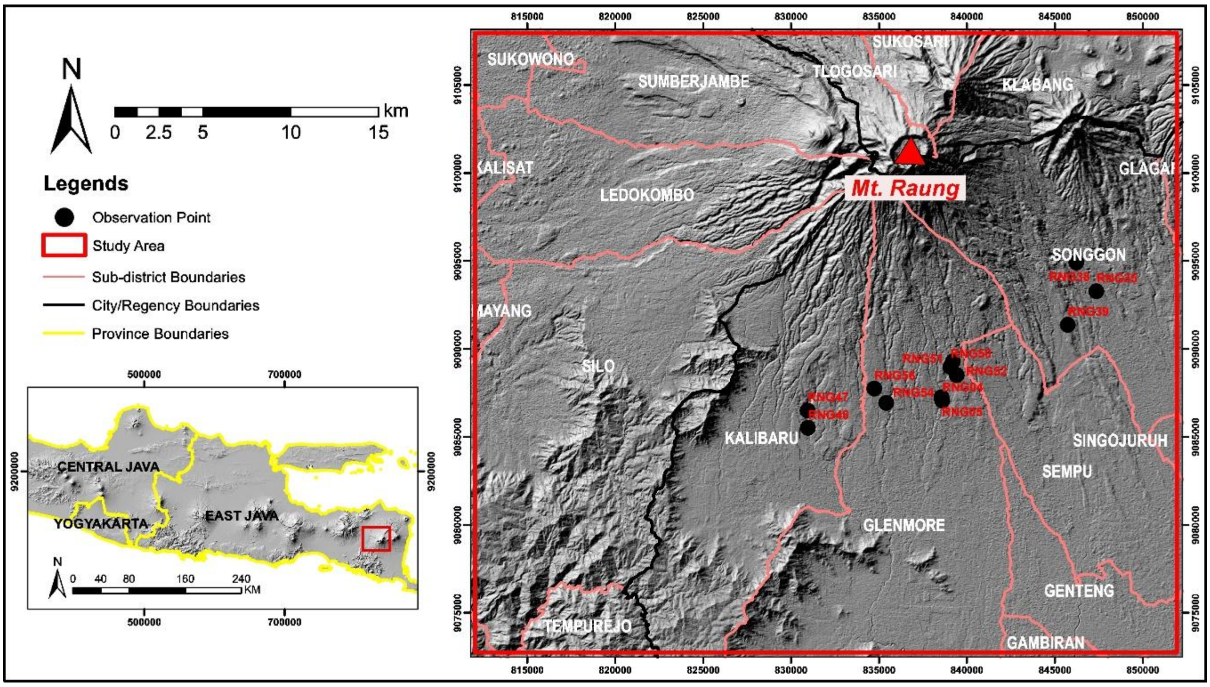


FIGURE 1. The location of Mt. Raung and observation points in this study are based on DEMNAS SRTM by CGIAR-Consortium for Spatial Information (2018) and Badan Informasi Geospasial (2018).

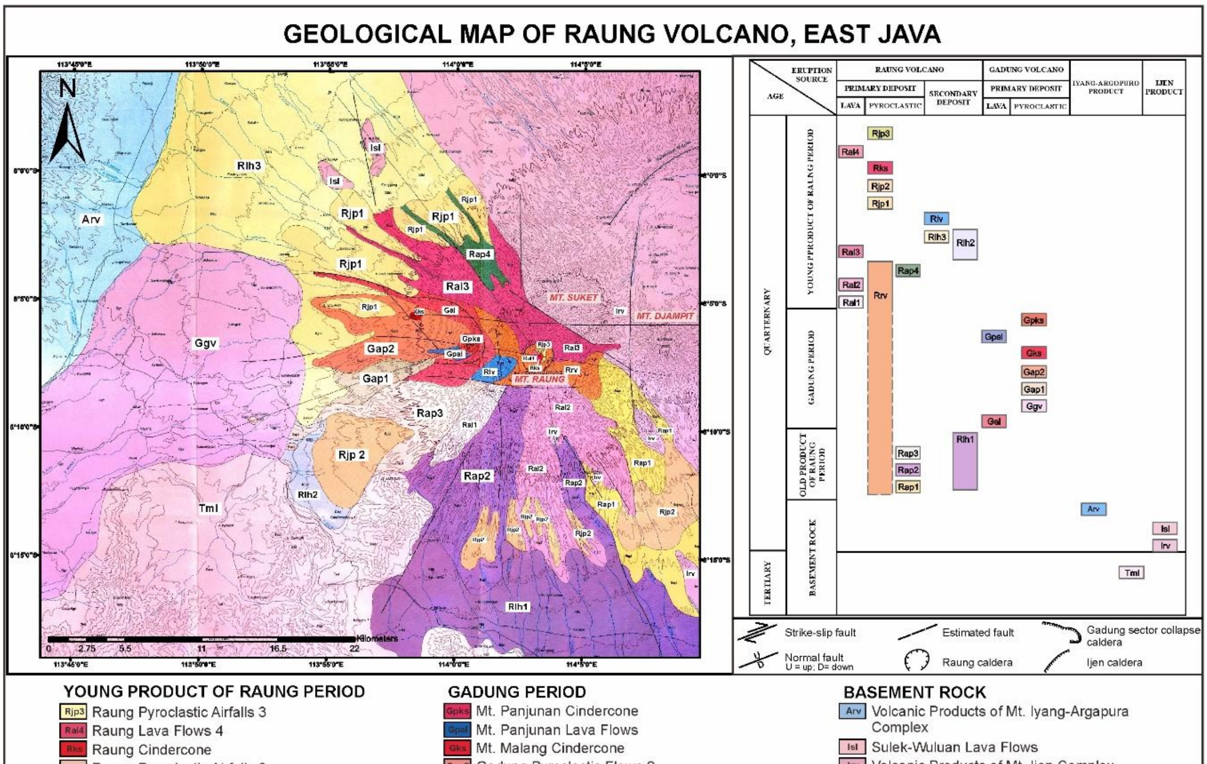


FIGURE 2. Geological map of Raung Volcano, East Java (Sutawidjaja *et al.*, 1996).

60 mm, and is composed of scoria fragments and lithics. Scoria Fall (SF) 3 can be found in all sites, except RNG01, 47, 56, and 54, has a thickness range of 7–35 cm, has a normal gradation and a massive structure, has a grain size range of <1–40 mm, and is composed of scoria fragments and lithics. Scoria Fall (SF) 4 can be found in RNG05 and 38, has a thickness range of 5–16 cm, has a massive structure, has a grain size range of <1–20 mm, and is composed of scoria fragments and lithics. Volume estimation of the eruption is focused on the thickest layers of the scoriaceous tephra-fall deposits sequence, which are Scoria Fall (SF) 2 and 3 layers, considering their widely spread distribution. Stratigraphic correlation is shown in Figure 3, and a representative outcrop picture is shown in Figure 4.

### 4.2 Volume estimation of the thickest scoriaceous tephra fall deposits of Mt. Raung

Most approaches to get an estimated volume of tephra deposits currently use the relationship between thickness and area of isopach, which is the thickness based on field measurements (Daggitt *et al.*, 2014). This research also estimates the volume based on isopach maps, including the thickness and area of the contour line. The isopach maps also give crucial information, such as the patterns of tephra dispersal and the dominant wind direction that carries pyroclasts (Engwell *et al.*, 2015). The isopach maps are made using a free-hand method following the thickness distribution of deposits. In an ideal condition, tephra-fall deposits generally get thicker with larger fragments as they get closer to the eruption center. These deposits also have brittle characteristics, which make it easy to experience a thickness loss during secondary processes. The isopach maps are drawn, prioritizing the deposit with the largest thickness as key data due to the deposit characteristics. There are two main types of causes of uncertainty in tephra thickness data (Engwell *et al.*, 2013) those are 1) Correlated with the natural variation that is likely related to the physical process (deposition, remobilization, and preservation) and 2) Measurement accuracy because of the different measurement techniques. The distribution of tephra deposits' thickness is mostly controlled by the eruptive and atmospheric conditions than depositional processes (Engwell *et al.*, 2013). An axis line is drawn from the observation point with the largest thickness towards the eruption center. This axis line shows the direction of tephra distribution and wind that carries the materials. Then, the isopach contour line is drawn following the thickness distribution of the deposits. This contour line presents the estimated thickness of the deposits. The isopach maps are presented in Figure 5a–b.

Several methods have been proposed to estimate erupted material of tephra deposits relying on the isopach maps, such as the multi-segment exponential method (Pyle, 1989), the power-law method (Bonadonna *et al.*, 1998; Bonadonna & Houghton, 2005), and the Weibull method (Bonadonna & Costa, 2012; 2013). The erupted material's volume of Mt. Raung is estimated following the Weibull-fit method by Bonadonna and Costa (2012). This method considers the Weibull parameters to describe important deposit thinning features and provide information such as the eruption magnitude (Bonadonna & Costa, 2012). Those parameters are: 1) the characteristic decay length of deposit thinning in kilometers ($\lambda$), 2) a thickness scale in centimeters ($\theta$), and 3) shape parameters ($n$). The isopach maps are converted to a plot of two-dimensional logarithmic thickness versus the square root of the area and fit with continuous functions (Klawonn *et al.*, 2014b). The functions are integrated considering the Weibull parameters to generate a total volume. The estimated volume of SF2 and SF3 are 0.54 $km^3$ and 0.26 $km^3$, respectively (Table 1). The minimum total volume of explosive eruption event of Mt. Raung producing sequence of the scoriaceous tephra-fall deposit is 0.8 $km^3$. This volume is produced by the eruption event categorized in VEI 4 (Newhall & Self, 1982).

## 5 CONCLUSION

The sequence of scoriaceous tephra-fall deposits of Mt. Raung is divided into four SF 1–4 layers. The calculated volume estimation of SF2 is 0.54 $km^3$, and SF3 is 0.26 $km^3$. The total volume is 0.8 $km^3$, indicating the eruption's VEI magnitude is VEI 4. This is considered to be

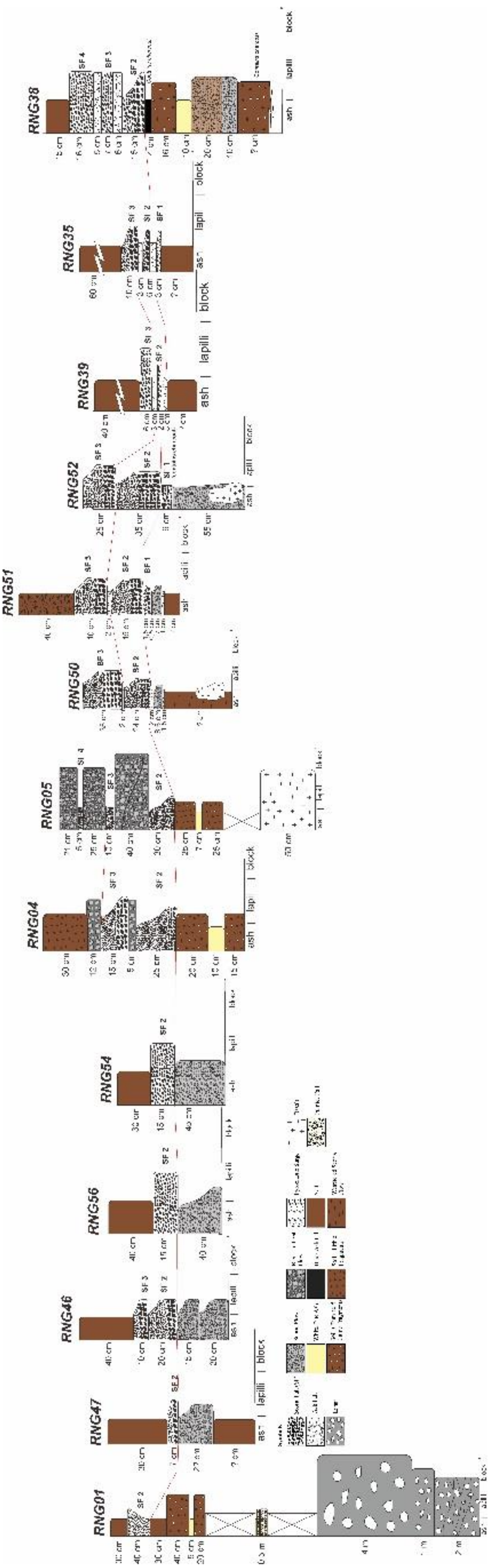


FIGURE 3. Stratigraphy of Mt. Raung scoriaceous tephra-fall deposit divided into four units of SF1-4. Stratigraphic correlation from the thirteen observation points is done at the SF2 and SF3 layers.

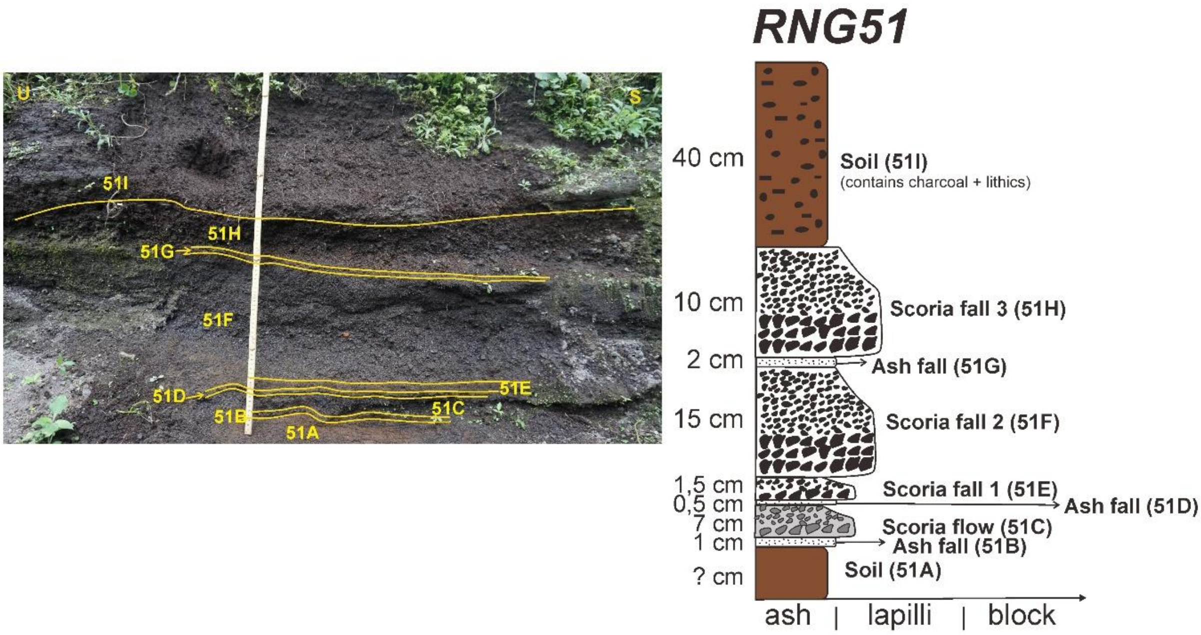


FIGURE 4. Outcrop and lithologic column of scoriaceous tephra-fall deposit at RNG51. Yellow stick scale resembles 1 m height.

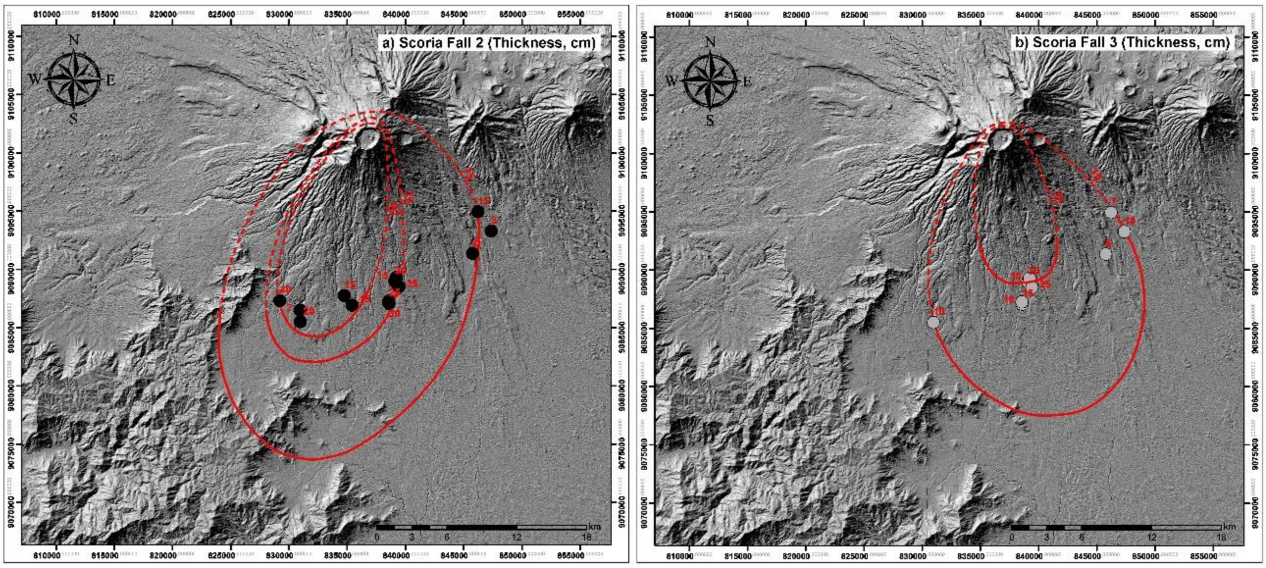


FIGURE 5. Isopach map of the thickest scoriaceous tephra-fall deposits layer (a) Scoria Fall (SF) 2 deposits (b) Scoria Fall (SF) 3 deposits. All the maps are based on DEMNAS SRTM (Badan Infromasi Geospasial, 2018).

TABLE 1. Summary of isopach parameters and estimation results of volume.

| Fall deposit | Thickness (cm) | Isopach area ($km^2$) | $\lambda$ (km) [7] | $\theta$ (cm) [7] | $n$ [7] | Volume ($km^3$) [7] |
|---|---|---|---|---|---|---|
| Scoria Fall (SF) 2 | 40<br>35<br>15 | 121<br>59<br>313 | 46.34 | 11.4 | 0.9 | 0.54 |
| Scoria Fall (SF) 3 | 35<br>10 | 74<br>273 | 31.37 | 10.28 | 0.77 | 0.26 |

an underestimated number because of limited data availability.

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## REFERENCES


Badan Informasi Geospasial. (2018). DEMNAS: Seamless Digital Elevation Model (DEM) dan Batimetri Nasional.

Bonadonna, C., & Costa, A. (2012). Estimating the volume of tephra deposits: A new simple strategy. Geology, 40(5), 415–418. https://doi.org/10.1130/G32769.1

Bonadonna, Costanza, & Costa, A. (2013). Plume height, volume, and classification of explosive volcanic eruptions based on the Weibull function. Bulletin of Volcanology, 75(8), 1–19. https://doi.org/10.1007/s00445-013-0742-1

Bonadonna, Costanza, & Houghton, B. F. (2005). Total grain-size distribution and volume of tephra-fall deposits. Bulletin of Volcanology, 67(5), 441–456. https://doi.org/10.1007/s00445-004-0386-2

Bronto S. (2010). Geologi Gunung Api Purba. Geological Agency of the Ministry of Energy and Mineral Resources.

Burden, R. E., Chen, L., & Phillips, J. C. (2013). A statistical method for determining the volume of volcanic fall deposits. Bulletin of Volcanology, 75(6), 1–10. https://doi.org/10.1007/s00445-013-0707-4

Cas, R. A. F., & Wright, J. V. (1987). Volcanic Successions Modern and Ancient: a geological approach to processes, products, and successions. In Volcanic Successions Modern and Ancient: a geological approach to processes, products, and successions.

Center of Vulcanology and Geological Hazard Mitigation. (2014). Data Dasar Gunung Api Raung.

CGIAR-Consortium for Spatial Information. (2018). SRTM 90-m DEM Digital Elevation Database

Daggitt, M. L., Mather, T. A., Pyle, D. M., & Page, S. (2014). AshCalc-a new tool for the comparison of the exponential, power-law and Weibull models of tephra deposition. Journal of Applied Volcanology, 3(1), 1–8. https://doi.org/10.1186/2191-5040-3-7

Engwell, S. L., Aspinall, W. P., & Sparks, R. S. J. (2015). An objective method for the production of isopach maps and implications for the estimation of tephra deposit volumes and their uncertainties. Bulletin of Volcanology, 77(7). https://doi.org/10.1007/s00445-015-0942-y

Engwell, S. L., Sparks, R. S. J., & Aspinall, W. P. (2013). Quantifying uncertainties in the measurement of tephra fall thickness. Journal of Applied Volcanology, 2(1). https://doi.org/10.1186/2191-5040-2-5

Global Volcanism Program (2013, November). Raung (263340) in [Database] Volcanoes of the World

Klawonn, M., Houghton, B. F., Swanson, D. A., Fagents, S. A., Wessel, P., & Wolfe, C. J. (2014a). Constraining explosive volcanism: Subjective choices during estimates of eruption magnitude. Bulletin of Volcanology, 76(2), 1–6. https://doi.org/10.1007/s00445-013-0793-3

Klawonn, M., Houghton, B. F., Swanson, D. A., Fagents, S. A., Wessel, P., & Wolfe, C. J. (2014b). From field data to volumes: Constraining uncertainties in pyroclastic eruption parameters. Bulletin of Volcanology, 76(7), 1–16. https://doi.org/10.1007/s00445-014-0839-1

Newhall, C. G., & Self, S. (1982). The volcanic explosivity index (VEI): an estimate of explosive magnitude for historical volcanism. Journal of Geophysical Research, 87(C2), 1231–1238. https://doi.org/10.1029/jc087ic02p01231

Pyle, D. M. (1989). The thickness, volume, and grainsize of tephra fall deposits. Bulletin of Volcanology, 51(1), 1–15. https://doi.org/10.1007/BF01086757

Sparks, R. S. J. (1986). The dimensions and dynamics of volcanic eruption columns. Bulletin of Volcanology, 48(1), 3–15. https://doi.org/10.1007/BF01073509

Sutawidjaja, I. S., Suparman, Sitorus, K. (1996). Geological Map of Raung Volcano, East Java. Vulcanological Survey of Indonesia.