Re-interpretation of distribution of Lautan Pasir caldera-forming eruption products, Bromo-Tengger Caldera Complex, East Java

R M P P Gunawan¹, G Ikhwanushova¹, A Harijoko²*, H E Wibowo¹ and A Setianto¹

¹Geological Engineering Department, Faculty of Engineering, Universitas Gadjah Mada, Yogyakarta, Indonesia
²Central Study of Disaster, Universitas Gadjah Mada, Yogyakarta, Indonesia
*E-mail: aharijoko@ugm.ac.id

Abstract. We present the result of morphostratigraphic analysis and geological field observation to identify the distribution of scoria flow deposit related to the caldera-forming eruption of Lautan Pasir caldera as the youngest caldera in Bromo-Tengger caldera complex. Morphostratigraphic analysis derived from digital elevation model and volcanic stratigraphy shows that products of Lautan Pasir caldera-forming eruption(s) mainly distributed to the north filled up the Sapikerep valley, and further to the north formed Sukapura distal fan. While to the south, it filled the valley between Ijo and Old Semeru. Field observation in the deeply dissected part of Sapikerep valley found two massive pyroclastic flow deposits separated by lava flow. Above the lava flow is scoria rich pyroclastic flow deposit typical of Lautan Pasir caldera-forming eruptions. Below the lava flow is scoria poor pyroclastic deposit of older products, most likely, of Ngadisari caldera. The distribution of Ngadisari caldera-forming eruption products is very limited considering the following massive volcanism of Lautan Pasir caldera. This outcrop might provide the key information to further reconstruct the volcanism stage of Bromo-Tengger caldera complex

1. Introduction

The difficulty in identifying caldera edifices in the caldera complex makes caldera-forming study very challenging. Since a caldera complex morphology represents overlapping calderas of different ages [1], it caused difficulty in determining the volcanic units on the field and eventually made the fieldwork less effective. The limited access to the outcrop and large deposit distribution also gives more challenge to the volcanologist who works in this area. Many studies used remote sensing analysis to make interpretations of the volcanic units (e.g., [2], [3]). This method helps reconstruct caldera edifices and determine observation points for more efficient fieldwork.

The order of the formation in the volcanic area can be represented in a morphostratigraphic map. A morphostratigraphic unit represents lithology on a particular landform and its relative age with the other units [4]. The early studies of morphometric analysis were mostly applied on monogenetic volcanoes (e.g., [5], [6], [7], [8]) because their formation process is thought to be less complicated than that on polygenetic volcanoes. There are also morphostratigraphy studies on stratovolcanoes and caldera (e.g., [2], [3]) that used this method to determine morphostratigraphic units and proposed morphometric
parameters in characterizing volcanic edifices using Digital Elevation Model (DEM). This method is necessary to understand the historical of volcanism of a volcanic complex which is important to the hazard assessment [11]. We applied this method to a caldera complex morphology such as the Bromo-Tengger in East Java, Indonesia. Here, we tried to combine several morphological aspects based on DEM data’s derivation to determine the caldera edifices in the Bromo-Tengger caldera complex.

We here combine the DEM-derived topographic map, geological map, and fieldwork observation to make a morphostratigraphic map of the Bromo-Tengger caldera complex. We propose an alternative interpretation of the distribution of the Lautan Pasir caldera-forming eruption products and supported by field evidences.

2. Geological Background
Bromo-Tengger caldera complex shows a complicated formation process represented by its complex morphology (landform) and various lithologies. This caldera complex is part of Quaternary volcanic arc in the east side of Java Island [12]. The volcanic products are divided generally into two groups, old (before Lautan Pasir caldera-forming) and young (after Lautan Pasir caldera-forming) Quaternary volcanic deposits [9]. Based on a geological map with a scale of 1:50,000, Zaennudin et al. [10] proposed that the Bromo-Tengger caldera complex is formed of three caldera-forming activities. These activities were estimated to come from Ijo, Ngadisari, and Lautan Pasir caldera-forming processes.

Based on the study from Zaennudin et al. [10], Old Tengger volcanism is commonly produced andesitic lava and formed another volcanic cone called Sedaeng volcanic cone. Ngadisari caldera-forming eruption generated lava and ignimbrite that filled the Sapikerep Valley and distributed widely to Madura Strait. On the other hand, the Lautan Pasir deposit consists of pyroclastic fall, pyroclastic flow, basaltic lava, and andesitic lava. Post-caldera volcanism is remarked by several monogenetic volcanoes inside the Lautan Pasir caldera namely Mt. Widodaren, Mt. Kursi, Mt. Segara Lor, Mount Segara Kidul, Mt. Bromo, and Mt. Batok [9]. The most recent volcanic activity in the Bromo-Tengger caldera complex, by the writing of this report, came from Mt. Bromo on December 23rd – 29th 2020 [13].

3. Methods
Essential aspects of morphostratigraphy study are landform morphology, lithology, and the relative order of age. Therefore, the morphostratigraphic units defined here considers the volcanic sources, deposit distribution, and erosional process displayed on the surface shape variation. This study used DEM with a maximum spatial resolution of 8.5 m from open source DEMNAS (tides.big.go.id/DEMNAS) and a geological map of Bromo-Tengger with a scale of 1:50,000 [10]. Spatial data were obtained using software like ArcGIS 10.5, Global Mapper, PCI Geomatics, and Google Earth Pro. These data were processed to produce several maps such as hillshade, slope, ridge alignment, and drainage pattern. Based on these maps, the morphostratigraphic units were determined.

Volcanic sources and deposit distribution in the Bromo-Tengger caldera complex were determined by hillshade, slope, and ridge alignment, as well as lithology types from the geological map and fieldwork observation. Hillshade and slope maps are generated in ArcGIS by hillshade and slope tool, respectively. Hillshade map was made from the sum of 4 data with 270°, 315°, 45°, and 90° light directions by weightedSUM tool. It represents a 3D relief of the area. Meanwhile, the slope map shows a 2D relief variation of the area. Also, the hillshade map derived from DEM was processed using the PCI Geomatics software algorithm to show the volcanic product direction presented in the rose diagram. This result needs to be corrected manually by the lineament of the ridge. Combining the distinctive features on data of 3D relief, 2D relief, and volcanic direction, we delineated the geomorphologic units. Furthermore, these geomorphologic boundaries need to be compared with the geological map and volcanic deposits observed on the field.

The erosional process is one of the causes of the landform variation in the volcanic area. This process affected the valley depth and eventually the drainage pattern on a river basin [14]. The determination of the drainage pattern used here is derived from the drainage map. This map was made by hydrology tool in ArcGIS. The river network from this map was compared with the pattern on the drainage model [15].
Another important parameter to determine the drainage pattern is drainage density (Dd) which calculated by the equation (1) from [16]:
\[
Dd = \frac{\sum L}{A}
\]

where Dd is drainage density (km/km²); ΣL is total river length on a basin (km); and A is basin area (km²). This equation was commonly used in river basin studies [14], [17] but still can be useful in this study to interpret the resistance of rocks to erosional processes in the volcanic area [18]. In addition, the variation of the valley depth due to different lithology and erosional process need to be considered. In this study, the measurement of the highest and the lowest points on a valley morphology was done by Global Mapper software.

Another important criterion of morphostratigraphy is the order of formation which is reflected in the cross-cutting relationship of each unit. Thus, we determined the morphostratigraphic maps based on 1) eruption sources; 2) cross-cutting relationship; 3) drainage density; 4) lithology types; 5) degree of erosion on each unit. Then we validated the unit by making sections to ensure that every unit has distinctive characteristics. Finally, the morphostratigraphy of the Bromo-Tengger caldera complex is presented on a map with a scale of 1:50,000, and the unit's name used here is principally similar to Brahmantyo and Bandono [19].

4. Results and Discussion

The identification of the morphostratigraphic units of the caldera edifices in the Bromo-Tengger caldera complex helps to infer the stage of caldera-forming events. The combination of DEM-derived maps and secondary data from previous study used to determine the geomorphologic units of the area. Then, we identified the lithology and determined prospective location based on these geomorphologic units. As a result, the Bromo-Tengger caldera-forming order could be interpreted based on the characteristics of each unit.

4.1. Volcanic edifice determination

Caldera complex morphology consists of several caldera edifices. Each edifice represents a phase of formation. During the phases, the older volcanic products could be covered by the younger deposits. This condition makes volcanic edifice determination is difficult [20]. Meanwhile, each formation phase in caldera complex commonly consisted of different type of rocks and deposited on different period of time. Hence, the morphostratigraphic map will show the relation of each volcanic edifice.

Based on eruption sources, cross-cutting relationship, drainage density, lithology types, and degree of erosion, there are five caldera edifices comprising the Bromo-Tengger caldera complex (Figure 1). Each unit has distinctive characteristics of morphostratigraphic parameter shows in Table 1. Higher drainage density in an area indicates weaker and impermeable subsurface material, sparse vegetation, and higher relief [14]. High Dd values in the Bromo-Tengger caldera complex is shown in the edifices of Ngadisari caldera volcanism, Ijo caldera volcanism, post-Lautan Pasir caldera volcanism, and Lautan Pasir caldera volcanism which dominantly consisted of pyroclastic deposits. Meanwhile, lower Dd value is shown in the Old Tengger edifice which dominantly consisted of lavas that is higher resistant and low moderate relief. The exceptionally high value of Dd (7.59) is shown in Sapikerep valley. This can be caused by the confined morphology that intensify erosional process as represented on its deepest valley depth (67 m) and highest Dd value in compare to the other units.
Figure 1. Edifice map of Bromo-Tengger Caldera Complex showing caldera and crater wall. The biggest caldera is Lautan Pasir, the eastern part of Lautan Pasir caldera is Ngadisari caldera and the western part of the Lautan Pasir caldera is Ijo crater.

Table 1. Morostratigraphic parameter of caldera edifices in the Bromo-Tengger caldera complex.

| Unit area (km²) | River length (km) | Drainage density (km/km²) | Slope (°) | Valley depth (m) | Lithology | Edifice |
|----------------|------------------|---------------------------|----------|-----------------|-----------|---------|
| 1018           | 3721.24          | 3.65                      | 17       | 58              | Tengger lava | Old Tengger volcanism |
| 11             | 69.68            | 6.45                      | 12       | 31              | Ijo pyroclastic deposit | Ijo caldera volcanism |
| 56             | 307.21           | 5.51                      | 17       | 31              | Ngadisari pyroclastic deposit | Ngadisari caldera volcanism |
| 14             | 105.22           | 7.59                      | 20       | 67              | Lautan pasir lava and pyroclastic deposit | Sapikerep valley |
| 298            | 1309.73          | 4.39                      | 17       | 30              | Lautan Pasir pyroclastic deposit | Lautan Pasir caldera volcanism |
| 18             | 93.39            | 5.26                      | 7        | 12              | Intra-cone pyroclastic deposit | Post-Lautan Pasir caldera volcanism |
4.2. Fieldwork and lithology identification
Checking the lithology variation in the field on each interpreted morphostratigraphic unit is essential. Several observation points in deeply dissected valley which preserved various lithologies from different eruption sources [9] was chosen to be representative of this method. The location, stratigraphy data, and outcrop description refer to Alghifari [21]. The outcrop varied of alternating pyroclastic fall and flow deposit (Figure 2a, 2b) which sometimes lied on brown older pyroclastic flow deposit (Figure 2c). In between them, there were pyroclastic surge deposit layers. At another location, older pyroclastic flow deposit found bellow basaltic lava (Figure 2d).

![Figure 2](image)

**Figure 2.** Volcanic deposit variation around Bromo-Tengger caldera complex. (a) and (b) pyroclastic flow and pyroclastic fall layers of Lautan Pasir caldera volcanism at STA 20 and STA 15, respectively; (c) contact of pra-Ngadisari caldera deposit and Lautan Pasir caldera deposit at STA 25 in Sukapura distal fan; (d) Ngadisari caldera pyroclastic deposits at STA 27.
The deposit sequence observed from the distal (STA 25, STA 27) to the proximal area (STA 15, STA 16). The variation of the stratigraphy in the valley shows distinctive characteristics of each unit (Figure 3). We divided the lithology units in this area into three groups, they are (1) Lautan Pasir caldera-forming deposit; (2) Pre-Lautan Pasir deposit; and (3) Ngadisari caldera-forming deposit. The first unit is composed of grey, scoria rich pyroclastic flow which is called as Sukapura breccia, and ash to lapilli fall deposit sometimes occurred in between the flow deposits. The second unit consisted of andesitic lava with coarse texture, lahar deposit, a basaltic lava with medium texture, brownish pyroclastic flow, and alternating fall deposit with surge deposit from lower to upper position, respectively. The last unit is comprised by grey pyroclastic flow with less scoria content than that in the second unit. The name of the unit is assumed to be the process contributed to the deposition of each sequence.

Figure 3. Stratigraphy sections of the Bromo-Tengger caldera deposit, showing the variation of Lautan Pasir and Ngadisari caldera volcanism, which make up the deeply dissected valley.

4.3. Interpretation of the distribution of caldera-forming eruption products of Lautan Pasir Caldera

The identification of the caldera edifices in this study is based on the morphostratigraphic parameters and the lithology checking on the designated locations. The results of this study showed that there are three calderas in the Bromo-Tengger caldera complex. These are Ijo caldera, Ngadisari caldera, and Lautan Pasir caldera. Product of Ijo caldera is distributed on the southeastern part of the Bromo-Tengger caldera complex. Products of Ngadisari caldera is likely distributed inside the Sapikerep valley and mostly are covered by following products of Lautan Pasir caldera.

This interpretation is built from field evidence of the two massive pyroclastic flow deposits separated by lavas. The scoria rich pyroclastic deposits above the lava represents the youngest caldera-forming
eruption event of Lautan Pasir caldera. The lava itself might resembles the construction phase of Lautan Pasir volcano. While the scoria poor pyroclastic flow deposit below the lava might represents the older caldera-forming eruption event of Ngadisari caldera. However, the outcrop of this deposit is very limited. These chronological events are supported by morphostratigraphic analysis showing higher drainage density of Ngadisari edifice than that of Lautan Pasir.

5. Conclusion
There are five volcanism phases resulting the Bromo-Tengger caldera complex morphology. These phases based on morphostratigraphy analysis are Old Tengger, Ijo, Ngadisari, Lautan Pasir, and Post-Lautan Pasir volcanism. The determination of each morphostratigraphic unit is deducted from DEM-derived maps in combination with geological maps and field observation to interpret eruption sources, cross-cutting relationship, drainage density, lithology types, and degree of erosion. We determined the several observation points that can show the variation in lithology as one of criteria in defining the morphostratigraphic unit. Furthermore, Lautan Pasir deposit is characterized by a scoria rich pyroclastic deposit above the lava flow while Ngadisari deposit is characterized by a scoria poor of older products bellow the lava flow in deeply dissected valley. To sum up, most of the Lautan Pasir deposits filled up Sapikerep valley to the north and further formed the Sukapura distal fan, also it filled the valley between Ijo and Old Semeru. In contrast, Ngadisari deposit is limited to be found considering the following massive volume of Lautan Pasir products.

Acknowledgments
This research is conducted by the financial support of PDUPT number 2566/UN1.DIT-LIT/DIT-LIT/LT/2019 by Ministry of Education and Cultural of Indonesia.

References
[1] Cole J W, Milner D M and Spinks K D 2005 Calderas and caldera structures: a review Earth Sci. Rev. 69 1-26
[2] Espinasa-Pareña R and Martín-Del Pozzo A L 2006 Morphostratigraphic evolution of Popocatépetl volcano, México Conf. Paper in Geol. Soc. Am. Special Paper 402 pp 101-123
[3] Grosse P, van Wyk de Vries B, Euillades P A, Kervyn M and Petrinovic I A 2012 Review: systematic morphometric characterization of volcanic edifices using digital elevation models Geomorphology 136 114-131
[4] Lowe J J and Walker M C J 1984 Reconstructing Quaternary environments (New York: John Wiley & Sons)
[5] Perter 1972 Distribution, morphology, and size frequency of cinder cones on Mauna Kea volcano, Hawaii Geol. Soc. Am. Bull. 83 3607-12
[6] Wood C A 1980a Morphometric evolution of cinder cones J. of Volcanology and Geothermal Research 7 387-413
[7] Wood C A 1980b Morphometric analysis of cinder cone degradation J. of Volcanology and Geothermal Research 8 137-160
[8] Settle M 1979 The structure and emplacement of cinder cone fields Am. J. Sci. 278 1089-1107
[9] Zaennudin A 1990 Stratigraphy and nature of the stratocone Mt. Cemara Lawang in Bromo-Tengger Caldera, East Java, Indonesia Master thesis (New Zealand: Victoria University of Wellington)
[10] Zaennudin A, Hadisantono R D, Erfan R D and Mulyana A R 1994 Peta Geologi Gunungapi Bromo-Tengger, Jawa Timur Geological map (Bandung: Pusat Penelitian dan Pengembangan Geologi)
[11] Freski Y R 2017 Morphostratigraphy of Young Lawu Volcano, Central Java and East Java Province, Indonesia in the hazard assessment of future eruption Master thesis (Yogyakarta: Universitas Gadjah Mada)
[12] Van Bemmelen R W 1949 *The geology of Indonesia* Vol. 1A (The Hague: Government Printing Office)

[13] Global Volcanism Program 2020 *Report on Tengger caldera (Indonesia)* In: Sennert, S K (ed), *weekly volcanic activity report*, 23 December-29 December 2020 Smithsonian Institution and US Geological Survey

[14] Rai P K, Mohan K, Mishra S, Ahmad A and Mishra V N 2014 A GIS-based approach in drainage morphometric analysis of Kanhar River Basin, India *Appl. Water Sci.* DOI 10.1007/s13201-014-0283-y

[15] Zhang L and Guilbert E 2012 A study of variables characterizing drainage patterns in river networks *Intl. Archives of the Photogrammetry, Remote Sensing and Spatial Info. Sci. XXXIX-B2* 29-34

[16] Horton R E 1945 Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology *Bull. Geol. Soc. Am.* 56 275-370

[17] Albaroot M, Al-Areeq M, Aldharab H S, Alshayef M and Ghareb S A 2018 Quantification of morphometric analysis using remote sensing and GIS techniques in the Qa’Jaharan Basin, Thama Province, Yemen *Int. J. of New Tech. and Research* 4 Issue 8 12-22

[18] Sipahutar S R, Sukiyah E and Sulaksana N 2018 Morphometry and morphotectonic of Cianten and Cisaat watershed on Quaternary volcanic terrain, Garut, West Java *J. of Geological Sci. and Applied Geol.* 2

[19] Brahmantyo B and Bandono 2006 Landform classification for geomorphology mapping on a scale of 1:25.000 and application for spatial planning (Indonesian Language) *Jurnal Geoplika* 1 1-7

[20] Thouret J C 1999 Volcanic geomorphology-an overview *Earth-Sci. Rev.* 47 95-131

[21] Alghifari R 2019 *Sapikerep valley pyroclastic deposits of Bromo-Tengger caldera complex, Sukapura, Lumbang, Kuripan, and Wonomerto, Probolinggo Regency, East Java* Undergraduate final report (Yogyakarta: Universitas Gadjah Mada)