

Geomorphological classification of post-caldera volcanoes in the Buyan–Bratan caldera, North Bali, Indonesia

Mitsuru Okuno¹, Agung Harijoko², I Wayan Warmada², Koichiro Watanabe³, Toshio Nakamura⁴, Sachihiro Taguchi¹, Tetsuo Kobayashi⁵

¹ Department of Earth System Science, Faculty of Science, Fukuoka University, Fukuoka, Japan

² Department of Geological Engineering, Gadjah Mada University, Yogyakarta, Indonesia

³ Department of Earth Resources Engineering, Faculty of Engineering, Kyushu University, Fukuoka, Japan

⁴ Institute for Space-Earth Environmental Research, Nagoya University, Nagoya, Japan

⁵ Emeritus Professor, Kagoshima University, Kagoshima, Japan

e-mail: okuno@fukuoka-u.ac.jp

Abstract. A landform of the post-caldera volcanoes (Lesung, Tapak, Sengayang, Pohen, and Adeng) in the Buyan–Bratan caldera on the island of Bali, Indonesia can be classified by topographic interpretation. The Tapak volcano has three craters, aligned from north to south. Lava effused from the central crater has flowed downward to the northwest, separating the Tamblingan and Buyan Lakes. This lava also covers the tip of the lava flow from the Lesung volcano. Therefore, it is a product of the latest post-caldera volcano eruption. The Lesung volcano also has two craters, with a gully developing on the pyroclastic cone from the northern slope to the western slope. Lava from the south crater has flowed down the western flank, beyond the caldera rim. Lava distributed on the eastern side from the south also surrounds the Sengayang volcano. The Adeng volcano is surrounded by debris avalanche deposits from the Pohen volcano. Based on these topographic relationships, Sengayang volcano appears to be the oldest of the post-caldera volcanoes, followed by the Adeng, Pohen, Lesung, and Tapak volcanoes. Coarse-grained scoria falls around this area are intercalated with two foreign tephra: the Samalas tephra (1257 A.D.) from Lombok Island and the Penelokan tephra (ca. 5.5 kBP) from the Batur caldera. The source of these scoria falls is estimated to be either the Tapak or Lesung volcano, implying that at least two volcanoes have erupted during the Holocene period.

1. Introduction

The Buyan–Bratan caldera on the island of Bali, Indonesia, is approximately 6 km × 11 km in area and contains three lakes (Tamblingan, Buyan, and Bratan). The post-caldera volcanoes (Lesung, Tapak, Sengayang, Pohen, and Adeng) are distributed from the center to the south of the caldera (figure 1). This caldera was previously thought to be less active than the neighboring volcanoes to the east, the Batur caldera and the Agung volcano [1]. The eruptive history of the caldera may provide important information to determine the development of the geothermal system [2]. To reconstruct a detailed Holocene eruptive history of this caldera volcano, we observed its geomorphological features and conducted a field survey on the tephra stratigraphy.



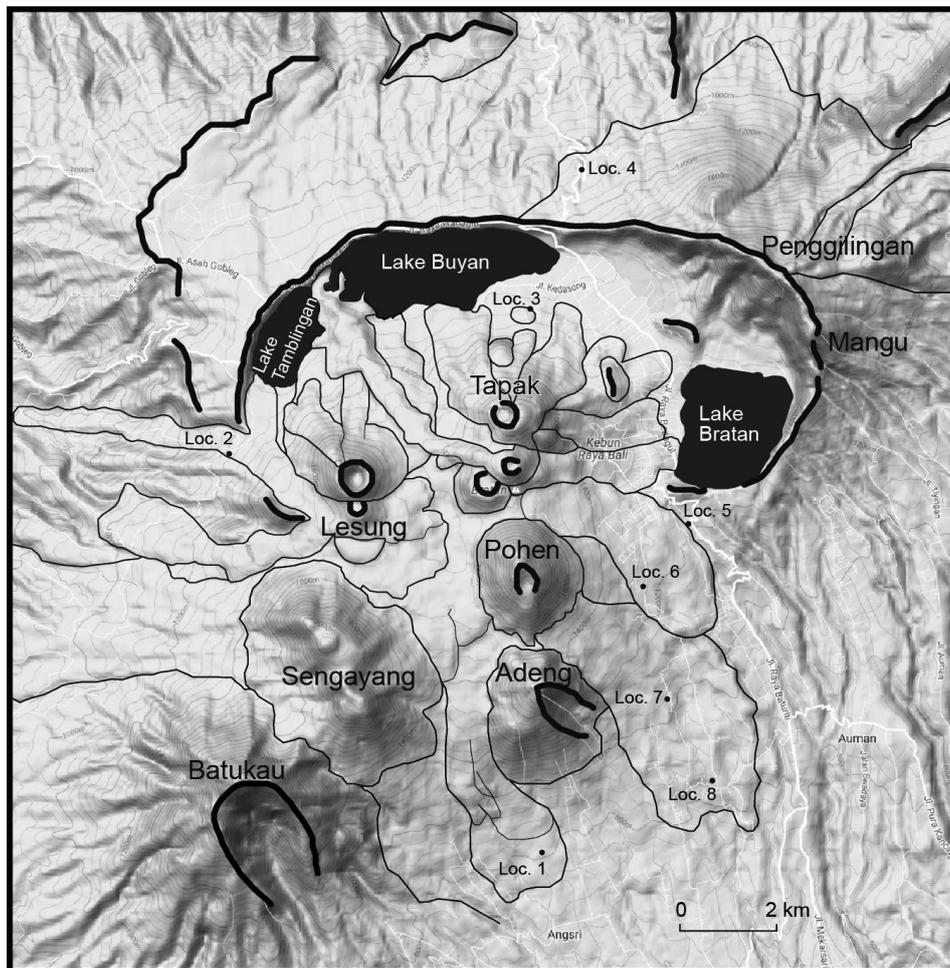


Figure 1. Geomorphological map of the Buyan–Bratan caldera, showing locations of selected outcrops. Thick lines indicate caldera cliffs and the crater rim. Moderately thick lines indicate geological unit boundaries. Thin lines indicate flow boundaries within units. Google Maps (terrain view) was used as the base map.

2. Geomorphology

Based on the topographic relationships (figure 1), the Sengayang volcano is the oldest of the post-caldera volcanoes, followed by the Adeng, Pohen, Lesung, and Tapak volcanoes. The Tapak volcano has three craters, aligned from north to south, which can be correlated with each subdivided edifice. Lava from the central crater has flowed downward to the northwest, dividing the Tamblingan and Buyan Lakes. This lava has covered the tip of the lava flow from the Lesung volcano. The central edifice of the Tapak volcano covers a part of the south crater, and the direction of eastward lava flow is controlled by the north edifice. Therefore, the central edifice is a product of the latest eruption among the post-caldera volcanoes. Southward lava flow from Tapak has reached the south foot of the Adeng volcano (figure 2). This topography has been built by a series of eruptions during the Holocene. However, the lower edifice of this volcano may predate the Holocene. Some parts of the old lava flows have been exposed on the northern slope, such as Location 3 (figure 3).

The Lesung volcano has two craters, and a gully developing on the pyroclastic cone from the northern to the western slope. Lava from the south crater has flowed down to the western flank beyond the caldera rim (figure 4). The horizon of this lava flow is estimated to be near the Penelokan tephra [3] from the Batur caldera [4]. The debris avalanche deposits (figure 5) distribute on the southeastern foot of the Pohen volcano. However, no clear collapsed landform is remained on this volcano. These topographic features indicate that the sector collapse and rebuilt were occurred in Pohen volcano before the Holocene activities of Tapak volcano.



Figure 2. An occurrence of the youngest lava flow on the southern foot of the Adeng volcano (Location 1). Only the Samalas ash (1257 A.D.) covers this lava.



Figure 3. Outcrop of lower lava flow on the northern slope of the Tapak volcano (Location 3). The stratigraphic position of this lava remains unclear.



Figure 4. Lava flow and scoria falls on the western slope (Location 2) of the Buyan–Bratan caldera. (a) Four coarse-grained scoria falls above the lava flow. The scale of the lava is 1 m. (b) Penelokan tephra, which erupted from the Batur caldera (ca. 5.5 kBP), is distributed only outside of the lava.



Figure 5. Outcrop of a debris avalanche deposit on the southeastern slope of the Adeng volcano (Location 8).

3. Tephra stratigraphy and AMS radiocarbon dates

Ashfall layers from the Samalas volcano eruption (1257 A.D.) on the island of Lombok (figure 6) [5, 6, 7, 8] and the Penelokan tephra are useful in establishing the tephra stratigraphy around this caldera. The Penelokan tephra corresponds to the Blingkan ignimbrite at ca. 5.5 kBP [9]. At the foot of the post-caldera volcanoes, coarse scoria falls [10, 11] are intercalated with two foreign tephras (figure 2).



Figure 6. Occurrence of the Samalas tephra (1257 A.D.) on the southeastern slope of the Pohen volcano (Location 7).

Four accelerator mass spectrometry (AMS) radiocarbon dates (figure 7) from Location 4 on the northern slope of the caldera indicate that the two most recent scoria eruptions occurred at ca. 1.1 and

2.5 kBP, respectively [12]. One more AMS radiocarbon date, 1175 ± 25 BP [12], was obtained from charcoal fragments immediately below southward lava flow from Tapak volcano at Location 1 (figure 2). It is consistent with stratigraphic relation with the Samalas tephra. Based on the thickness and grain size of these scoria falls (Locations 5, 6, and 7) above the Penelokan tephra, we estimate that they originated from the Tapak or Lesung volcano. Therefore, at least two volcanoes erupted during the Holocene period.

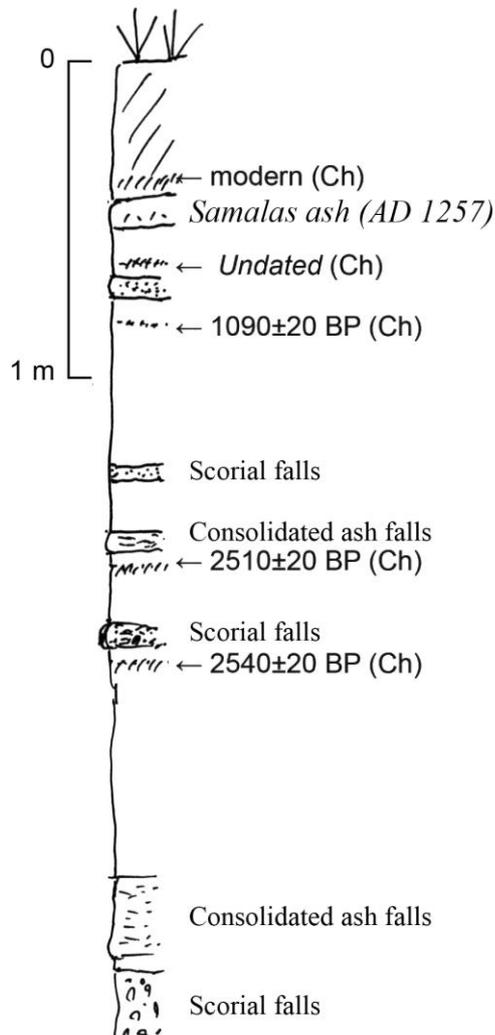


Figure 7. Columnar section and AMS radiocarbon dates [12] from the northern slope of the caldera (Location 4).

4. Conclusions

The geomorphological classification map can provide framework of eruptive history of the post-caldera volcanoes in the Buyan–Bratan caldera. Combination with tephra stratigraphy as well as AMS radiocarbon dates implies that at least Tapak and Lesung volcanoes have erupted during the Holocene period. The Tamblingan and Buyan Lakes were divided by the youngest lava flow from the Tapak volcano. Furthermore, the other youngest lava flow (ca. 1.1 cal kBP) has reached the south foot of the Adeng volcano (figure 2). More detail tephra-stratigraphy and radiocarbon chronology should be determined to refine their eruptive history during Holocene period.

Acknowledgement

This work was partly supported by JSPS KAKENHI (B) Grant Number 24360153 and funds from the Central Research Institute of Fukuoka University (Number 167002). The comments by the reviewers and editor improved the manuscript.

References

- [1] Ryu S Kitagawa H Nakamura E Itaya T and Watanabe K 2013 *J. Volcanol. Geotherm Res* **264** 107–16
- [2] Purnomo B J and Pichler T 2015 *J. Volcanol. Geotherm. Res.* **304** 349–58
- [3] Kobayashi T Harijoko A Warmada I W Watanabe K Nagata T Nakamura T Taguchi S and Okuno M 2016 Eruptive sequence of the Penelokan eruption from Batur caldera, North Bali, Indonesia. *Proc. Int. Meeting Eruptive History Informatics 2015-2* (Fukuoka: Fukuoka University) 35–9
- [4] Wheller G E and Varne R 1986 *J. Volcanol. Geotherm. Res.* **28** 363–78
- [5] Fontijn K Costa F Sutawidjaja I Newhall C G and Herrin J S 2015 *Bull. Volcanol.* **77** doi:10.1007/s00445-015-0943-x
- [6] Lavigne F Degeai J-P Komorowski J-C Guillet S Robert V Lahitte P Oppnheimer C Stoffel M Vidal C M Surono Pratomo I Wassmer P Hajdas I Hadmoko D S and de Belizal E 2013 *Proc. Natl. Acad. Sci. USA* **110** 16742–7
- [7] Vidal C M Komorowski J C Metrich N Pratomo I Kartadinata N Prambada O Michel A Carazzo G Lavigne F Rodysill J Fontijn K and Surono 2015 *Bull. Volcanol.* **77** 73
- [8] Vidal C M Metrich N Komorowski J C Pratomo I Michel A Kartadinata N Robert V and Lavigne F 2016 *Sci. Rept.* doi: 10.1038/srep34868
- [9] Sutawidjaja I S 2009 *J. Geol. Indonesia* **4** 189–202
- [10] Watanabe K Yamanaka T Harijoko A Saitra C and Warmada I W 2010 *J. SE Asian Appl. Geol.* **2** 283–90
- [11] Yamanaka T Harijoko A Warmada I W Itaya T and Watanabe K 2009 Petrochemical and geochronological characterization of Bratan Caldera, Bali, Indonesia. *Proc. Int. Symp. on Earth Science and Technology 2009* 249–52
- [12] Okuno M Harijoko A Warmada I W Nakamura T Taguchi S and Kobayashi T 2017 AMS Radiocarbon dating of Holocene tephra from post-caldera volcanoes of Buyan-Bratan caldera, North Bali, Indonesia *Abst. 14th Int. Conf. on Accelerator Mass Spectrometry* (Ottawa: University of Ottawa) #183